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# Energy demand of liquefaction and regasification of natural gas and the potential of LNG for operative thermal energy storage

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ABSTRACT

The world trade volume of Liquefied Natural Gas (LNG) is increasing year by year. Unlike gaseous natural gas (NG), which is transported through a fixed network of pipelines, LNG offers more flexibility to both the exporters and the importers as it can be transported between any pair of exporting and receiving LNG terminals. The LNG process, consisting of liquefaction, transportation, storage, and regasification of LNG, is accompanied by certain energy demands. The paper focuses on the evaluation of the chain of energy transformations involved in the LNG process. Based on the review of existing information, the entire process is evaluated from the view of the potential use of LNG for direct storage of cold and indirect storage of power. The analysis of the existing data shows that the overall efficiency of using LNG for operative energy storage depends very much on the technologies involved and on the overall capacity of the particular technology. The combination of energy-efficient liquefaction technologies and regasification technologies with energy recovery makes it possible to employ LNG as an energy storage medium even when transported over large distances.

## 1. Introduction

Worldwide consumption of natural gas (NG) has been steadily growing in recent years. There are several factors that have together contributed to the intense use of NG in many applications. Developed countries are calling for the decrease in the environmental impact of combusting fossil fuels for transportation, electricity production, heat, and cold. The use of NG is advantageous because NG has the lowest emissions per released Joule of energy among all fossil fuels. Kumar et al. [1] reported that $CO_2$ emissions from stroke engines running on NG dropped by around 20% and by 80% for $NO_x$. Combustion of carbon and oil emits significantly more pollutants, which has recently lead to restrictions on the use of these fuels. The future low-carbon power industry is supposed to renounce carbon and oil completely. The vacancy left by carbon and oil in the energy market has been taken by NG and renewable energy sources. However, increased use of renewable energy sources is limited by the availability of energy storage leading to NG being preferred to produce electrical energy. Another factor contributing to the popularity of NG is the price of produced energy. The price includes not the only the cost of the NG itself but also the price of the technologies necessary for energy transformation as well as for the subsequent minimisation of environmental impact, ecological fees, and carbon credits. Thanks to the composition of methane, the combustion of NG emits the smallest amount of $CO_2$ per unit of released energy out of all fossil fuels.

The vast availability of NG further promotes its use. New technologies for the extraction and transportation of NG, developed in the last several decades, contribute to the increasing worldwide demand for NG. The deposits of NG in the Earth's crust are assumed to be relatively sufficient and the prices are expected to be stable for several years. The broad application potential of NG is another benefit of this fuel and NG can be used in all plants that use a combustion process to produce

*Abbreviations:* AGFCS, Automotive gas-filling compressor station; BC, Brayton cycle; C3MR, Propane mixed refrigerant; CCS, Carbon capture system; CHP, Combined heat and power; CNG, Compressed natural gas; COP, Coefficient of performance; DMR, Dual mixed refrigerant; FLNG, Floating liquefied natural gas; FSRU, Floating storage regasification units; HFO, Heavy fuel oil; JT, Joule-Thomson; LNG, Liquefied natural gas; MCFC, Molten carbonate fuel cell; MFC, Mixed fluid cascade; NG, Natural gas; ORC, Organic Ranking cycle; RC, Rankine cycle; SMR, Single mixed refrigerant

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electrical energy, heat and, indirectly, cold. The NG-plants producing electrical energy are units with flexible operations and outstanding operating parameters. These plants have been in high demand because they complement renewable energy systems that inherently cannot provide stable and uninterrupted supply of electricity. Natural gas is a fuel suitable for road transport, railroad transport, and shipping transport. Consumption of NG in road transport has increased thanks to compressed natural gas (CNG), used particularly in personal vehicles and city buses. The use of liquified natural gas (LNG) as a fuel has gradually spread to cargo transport as well. The popularity of LNG is reflected in the growing number of trucks running on LNG. Song et al. [2] reported that there were 100,000 trucks running on LNG that consumed around 5 $Gm^3$ of NG. That number is very small compared to the number of diesel trucks but still it represents a non-negligible share (about 2.4%) of heavy-duty vehicles.

These facts, combined with a good shelf life and the relatively easy transportation of LNG over long distances, have to lead to serious growth in the global trade of this fuel. LNG represents the energy source with the most intensive development in the world. Dong et al. [3] made a brief historical overview of world's LNG consumption from 1964 (when the production reached 80,000 t) to 2004 (the consumption of 0.1318 Gt). The latter number corresponds with the production reported by Kirillov et al. [4]. On the other hand, NG consumption predicted for 2010 was higher (2.5 Gt). This major increase in consumption reflects accelerating growth of the global market with NG. Overall annual growth from 1970 to 2004 is said to be 20.34% and 7.31% from 1994 to 2004. Zhang et al. [5] applied gravity modelling to LNG trade flows to analyse the factors and mechanisms that influence LNG trade. Factors such as economics, supply and demand, price, energy structure, trade feasibility, and politics were considered. The analysis was carried out for a period of time from 2004 to 2015. The global LNG trade increased from 177.09 $Gm^3$ in 2004 to 302.25 $Gm^3$ in 2015. Fig. 1 presents the LNG trade volumes published by International Gas Union [6] for 1990–2016 with the identification of a number of LNG exporting and importing countries.

Kanbur et al. [7] state that if the current trends continue, the worldwide consumption of LNG will increase by 1.7–2.2% every year, making NG the second most important energy source by 2030. Its predicted growth of consumption is 39% between 2010 and 2030 [8]. The same source predicts that in 2030, natural gas may cover 25% of energy demand in the world. Nowadays, one-third of all the worldwide trade with NG is transported in the form of LNG [9]. Paltrinieri et al. [10] report that the worldwide rise in the consumption of LNG is predicted to be 1.3% per year with the exact numbers of 3.2 $Tm^3$ NG in 2010 to 5.2 $Tm^3$ NG in 2040, while the EU only had a steady 2% rise per year in the last 10 years. The study further informs about the current state of LNG terminals where there are 60 terminals operating in 18 countries and 180 terminals under construction. Yoon et al. [11] confirm the ongoing growth in consumption and importance of NG as one of the world's most important energy source. The advantages of this source are stressed here, namely the “cleanness” resulting from the fact that a) combustion of LNG produces virtually no particulate matter due to the absence of nucleation particles; b) it produces less gaseous emissions than other fossil fuels, such as $NO_X$ and $CO_2$, thanks to better mixing of the fuel and oxidiser; and c) regasified LNG produces insignificant amounts of sulphurous emissions thanks to the liquefaction process that removes most of the sulphur that NG might contain. The economic profitability of transportation of NG in the form LNG over long distances is also mentioned. The number of regasification plants is reported to be over 100 in the year 2018, meaning the number of plants almost doubled from 60 plants reported in 2015 [10].

Many deposits of NG are in remote off-shore locations; therefore, long under-sea pipelines would have to be built for delivering NG to coastal liquefaction terminals. Since the mid-1990s, investors started projects on the building of floating LNG facilities (FLNG). The company Shell started operation of the first worldwide FLNG facility in 2011. FLNG technology can unlock off-shore NG resources that are technically difficult to extract or too small for building a pipeline connection to a shore. FLNG facilities utilise similar technologies for LNG liquefaction, storage, and offloading as the on-shore plants. There are two main design constraints on FLNG in comparison to the on-shore plants. The FLNG technology needs to be rather compact, due to limited space, and it needs to withstand the movements of the vessels or the floating platforms that it is installed on.

The main advantage of LNG for transportation and storage is that LNG occupies 600-times less volume than gaseous NG. The density of LNG is approximately 400 $kg/m^3$. LNG is kept at almost atmospheric pressure and at the temperature of − 162 °C during transportation and storage. Liquefaction of NG is an energy-demanding process and based on the performance evaluation of real-life liquefaction terminals, the energy need of the process was determined to be equivalent of up to 10% of the supplied NG [12]. The energy spent on the liquefaction process is not entirely wasted. A certain part of it can be recovered by the utilisation of cold from LNG. The amount of usable cold is given by thermophysical properties of NG and corresponds to 830 kJ/kg of LNG [9]. This cold energy can be recovered during the regasification process, see Fig. 2. Regasification is carried out either in port terminals before NG is transported via gas lines or directly before the use of NG. With respect to the amount of LNG transported worldwide, Agarwal et al. [13] quantified the global amount of cold energy at 12 GW per annum. The exploitation of cold from LNG is quite limited at present. Most of the available cold is wasted during the regasification process when LNG is heated up by water or ambient air [9].

Wasting of cold results in higher prices of NG and it reduces the overall efficiency of this primary energy source. That is why promising ways of utilising cold from LNG in the regasification process should be explored and implemented. Several theoretical studies have recently focused on potential applications of cold energy in power, heat, and cold production, see Fig. 3. Many papers have been published lately, discussing various parts of the LNG chain (conversion, transportation, and utilisation). However, most papers failed to grasp the details of energy requirements and energy gains of the LNG technology. The share of energy consumed, and energy recovered during the LNG treatment is influenced by the current state of the relevant technologies. And these

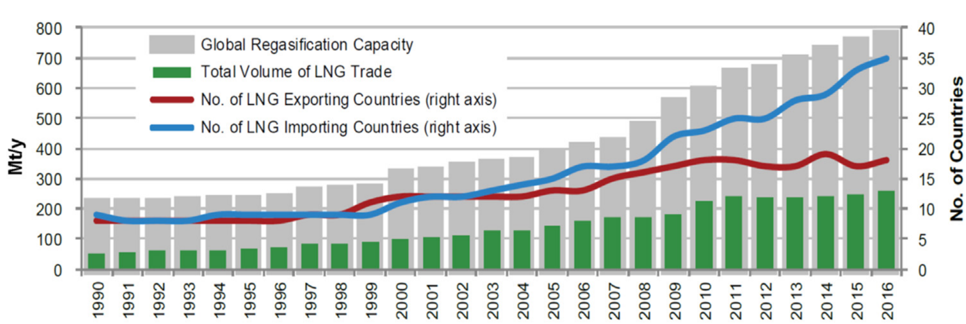


**Fig. 1.** LNG trade volumes for 1990–2016 (adapted from [6]).