Possibilities of Liquefied Natural Gas (LNG) use for power generation

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Abstract. Liquefied natural gas (LNG) has an important role in the global industry and energy balance. The use of this energy carrier has been increasing for last decades. The broad development of the LNG sector has been noticeable in the search for new supply directions by natural gas customers. An important option to transport the gas is to convert it into liquid natural gas (LNG) and convey it using insulated LNG tankers. At receiving terminals, the LNG is unloaded into storage tanks and then pumped for the required pressure, vaporized and compressed for final pipeline transmission to natural gas pipeline system. The LNG production process consumes a considerable amount of energy. This energy is stored in LNG as cold energy. At an unloading terminal, LNG is evaporated into gas phase at ambient temperature before pumping into the natural gas transmission system. Seawater or ambient air are commonly used for the regasification process of the LNG. In process of regasification the large part of energy stored in LNG may be recovered and used for electricity generation. In the presented paper a general analysis of the various thermodynamic schemes proposed for power production from regasification has been made. Direct expansion cycle, Rankine cycle and Brayton cycle are analyzed in presented case.

1. Introduction

Liquefied natural gas (LNG) has an increasingly role in the global natural gas market. Natural gas is a relatively clean energy source, which produces much less pollution than coal or oil. During liquefaction process the natural gas volume is reduced by the ratio of 1/600. Through this volume reduction liquefied natural gas can be transported by ships and stored in storage tanks. In the next step the LNG is pumped to required pressure and transformed into vapor phase. Vaporized natural gas is transferred into pipeline system. LNG production is a high energy consuming process. This energy is stored in LNG and it is known as "cold energy". On the other hand the vaporization process also needs a high amount of energy. Different sources state that vaporization process consumes about 800 kJ/kg [1,2] of heat energy or for regasification of 42.5 million normal cubic meters of natural per day the 0.95 MJ of heat energy per hour is needed [3]. Normally the sea water is used for regasification of LNG, the most common processes used for regasification are ORV (Open Rack Vaporizers - used in areas with availability of relatively warm water) and SCV (Submerged Combustion Vaporizers). SCV process is complex process, LNG flows through steel tubes submerged in a water bath. Water is heated by flue gases from burning a fuel gas (generally the Boil Off Gas from terminal is used as fuel gas).
Large part of "cold energy" stored in LNG may be recovered and used for power generation. First steps for use the "cold energy" for power generation are considered in literature since the 90s of 20th century [4]. Generated power in part may be used for terminal needs and the remaining part of energy may be introduced into power supply system. Through the possibility of using LNG for electricity production, the role of LNG increases not only in the natural gas market, but also in the electricity market. Impact of LNG on energy market is considered in next section. Also some methods and thermodynamic processes utilized for "cold energy" use in power production are presented in below sections of this paper.

2. LNG role in global energy market
In recent years, the importance of LNG in the international trade of natural gas has increased gradually. While in 2002 the LNG share accounted for 25.8%, it increased to 29.2% in 2008, and reached 32% in 2016 [5]. In absolute terms, LNG production increased from 143 to 346.6 billion cubic metres. Of course, this upward trend in LNG trade would not have been possible without significant investments in new liquefaction and regasification installations. The capacity of liquefaction facilities grew from 181 billion cubic metres in 2002 to 424 bcm in 2015, while regasification capacity grew from 388.3 bcm (in 2002) to 1080 bcm. EU countries with highest-capacity LNG terminals are (bcm/y): Spain with 63.4, the United Kingdom with 56.5, and France with 22.5. In 2015, LNG imports to these countries were as follows (billion cubic metres): the United Kingdom 13.8, Spain 13.6, and France 6.5 [6,7]. In recent years, LNG imports have accounted for less than 20% of EU’s total natural gas imports. It is good to mention that in 2016 LNG started to be commercially supplied to Poland, and thus, after the LNG terminal had been built in Świnoujście, Poland became part of the global LNG market. LNG deliveries are based on a long-term agreement from Qatar as well as on spot contracts (the U.S. and Norway). In 2016, Poland was supplied with 0.96 bcm, which accounted for 6% of the total natural gas consumption [8]. In 2017, a decision was made to extend the regasification capacity of LNG terminal in Świnoujście from 5 to 7.5 bcm per year. Increased LNG supply to Poland may be used, among others, for energy purposes. In 2016, gas-fired CHP plants generated 5.78 TWh of electricity, which accounted for 3.5% of the total electricity production. Taking into consideration current investments in gas-steam blocks, a rising share of electricity based on natural gas is to be expected in the future.

3. LNG as a source of power generation
LNG is produced by liquefaction of natural gas in cryogenic conditions. Boundary of cryogenics conditions is described as the boiling temperature of methane at about -162°C (111 K) at normal pressure (101.325 kPa). Methane is a main component of LNG (about 90% in "Heavy LNG" with high ethane and propane molar content and above 95% in Light LNG). It causes that boiling temperature of LNG is close to boiling temperature of pure methane. Liquefaction of natural gas is high energy consuming process. Compression of pure methane before liquefaction from atmospheric pressure to 5.5 MPa requires about 800-860 kJ/kg of compression work (energy) with 80-85% compressor efficiency assumption [1,2]. Certainly, real liquefaction processes need more energy than simple thermodynamic compression process. Examples presented in literature show that liquefaction process needs 700-850 kWh of energy for liquefaction of 1 kg of LNG (2.5-3 MJ/kg). The most common probably value is 2.9 MJ/kg. It should be considered that about 0.85 MJ/kg is stored in LNG as "cold energy". This amount of energy cannot be ignored in energy balance of LNG. "Cold energy" may be estimated with theoretical considerations from regasification processes to assumed ambient temperature. The "cold energy" should be used for energy purposes, especially for power generation. Possibilities of "cold energy" use also depend on vaporization process parameters as output pressure of natural gas after regasification process. In typical cases output pressure range varies from 2.5 MPa for combined cycle stations to 8.0-8.5 MPa for pipeline transportation system inlet. Required output pressures for typical uses of LNG with energy availability are presented in Table 1. One condition has to be fulfilled - the output pressure has to be much higher than ambient barometric pressure. LNG
temperature vs entropy diagram shows wide range of opportunities for 'cold energy' recovery, which depends on assumed output pressure [1,2]. The suitable energy recovery technology should be precisely selected for assumed output pressure.

**Table 1.** Parameters for typical uses of natural gas with theoretical work available (exergy) (calculated with Refprop software). The reference state for enthalpy and entropy corresponds with thermodynamic conditions for bubble point of LNG, for exergy analysis the reference state corresponds with typical ambient conditions.

| Application                        | Pressure, MPa | Temperature, K | Enthalpy, kJ/kg | Entropy, kJ/(kg·K) | Flow exergy, kJ/kg |
|------------------------------------|---------------|----------------|-----------------|-------------------|-------------------|
| LNG storage conditions             | 0.1013        | 111            | -               | -                 | 967.84            |
| Typical ambient conditions         | 0.1013        | 288            | 877.75          | 6.40              | -                 |
| Natural gas distribution network   | 0.4           | 288            | 874.31          | 5.71              | 194.73            |
| Combined cycle stations            | 2.5           | 288            | 850.99          | 4.75              | 449.38            |
| Natural gas high pressure pipeline | 8.0           | 288            | 785.89          | 4.01              | 598.48            |

Maximum work (energy) $L_{\text{max}}$ available stored in LNG results from conservation equation of energy changes is given by formula [9-11]:

$$dL_{\text{max}} = dq - dh = T_0 ds - dh$$

where: $q$ - heat, $s$ - entropy, $h$ - enthalpy, $T_0$ - ambient temperature.

The LNG from the initial conditions (indexes $s$) at storage process goes to equilibrium conditions at atmospheric pressure (indexes 0). The available work is called an exergy of LNG and it is given by formula for the liquefaction process from initial to equilibrium conditions:

$$B = (h - h_0) + T_0 (s_0 - s) = c_p (T_e - T_0) + T_0 \int_{T_e}^{T_0} \frac{dq}{T} - T_0 \cdot R \int_{p_s}^{p_0} \frac{dp}{p}$$

where: $B$ - exergy, $c_p$ - isobaric heat capacity, $R$ - gas constant, $T$ - temperature, $p$ - pressure.

Exergy of LNG is composed from two parts (exergy $B_c$ as a result of cold energy and pressure exergy $B_p$) and they may be written as:

$$B_c = c_p (T_e - T_0) + c_p \cdot T_0 \cdot \ln \frac{T_0}{T_s}$$

$$B_p = -T_0 \cdot R \int_{p_s}^{p_0} \frac{dp}{p} = T_0 \cdot R \cdot \ln \frac{p_s}{p_0}$$

Ambient conditions and pressure in the tank are the main factors which have an impact on characteristics of the cold exergy and pressure exergy of LNG. These factors are also important for
applications for the LNG 'cold energy'. Changes of enthalpy and flow exergy for assumed application cases are respectively presented in figures 2 and 3.

**Figure 1.** Temperature - entropy diagram for natural gas for various pressures.

**Figure 2.** Temperature - enthalpy diagram for natural gas for various pressures.
4. Thermodynamic processes used for power generation with LNG use

The power generation with use the ‘cold energy’ of LNG may be processed in several thermodynamic processes. In this section the most popular schemes are presented. The most considered processes are: direct expansion process, Rankine cycle and Brayton cycle.

4.1. Direct Expansion Cycle

From thermodynamic point of view the simplest cycle for power generation is the direct expansion. In first step in this cycle Liquefied Natural Gas is pressurized to high pressure (higher than user required) and next it is heated and transformed into vapor phase through the evaporator. Seawater is the common medium used for regasification of LNG. The gaseous phase propels the turbine generator. The scheme of cycle is presented in figure 4.

![Figure 4. LNG direct expansion cycle scheme.](image-url)
In the case where LNG would be pressurized and regasified in 12-15 MPa and the input pressure for natural gas pipeline system is 7-8 MPa, expansion of natural gas in this range of pressures generates significant amounts of energy. If the energy generated in expansion is greater than power required for pressurization and LNG transformation into gas phase the process of direct expansion is effective. Direct expansion cycle is suitable for small-scale regasification stations, with some modifications and optimization of process it may be used also in larger plants. The basic disadvantage of this solution is lack of heat sources for LNG regasification in different localizations for small-scale regasification plants. Availability of water is connected with special environmental issues, due to this factor localizations near the sea coast will be preferred for this solution [1,2].

4.2. Rankine Cycle

The Rankine cycle is one of the most popular options for power generation. Liquefied Natural Gas is used for cooling the condenser where working fluid (i.a. propane) is liquefied (LNG is used as source of cold). Next the working, auxiliary fluid is pumped and transformed into gaseous phase in heater. Seawater may be used as heat source for vaporization of auxiliary fluid. Finally vaporized auxiliary fluid expands in turbine which drives generator to produce electricity. From turbine auxiliary fluid is transferred to condenser to close the cycle. In some cases the natural gas after regasification of LNG in condenser has too low temperature. In this situation the additional heat exchanger should be placed in the system [12]. Scheme of simple Rankine cycle is presented in Figure 4. The main limitation of Rankine cycle is output pressure of regasified natural gas. In basic applications it should be higher than 3 MPa, in this situation high output pressure does not match well with cooling capacity of condenser. With typical, conventional Rankine cycle configurations the amount of generated energy is estimated in the range of 40-120 kJ/kg. Modified and complex configurations of this cycle may recover up to 200 kJ/kg of energy [2].

![Figure 5. Scheme of typical Rankine cycle with auxiliary fluid.](image-url)
4.3. Brayton Cycle

Closed Brayton cycle is another system for power generation by the "cold energy" of LNG. Cold energy stored in LNG stream is thermodynamically known. Due to this fact the auxiliary fluids should be chosen with very narrow conditions. Critical temperature of auxiliary fluid should be about 5-15 K higher than LNG temperature. The best auxiliary fluids for this use are nitrogen with critical temperature 126 K and air with critical temperature 133 K. The temperature of LNG is estimated on the level of 111 K. The auxiliary fluid is pressurized in compressor connected with turbine and then it is directed to heater, next warm auxiliary fluid propels turbine-generator. In the following step auxiliary fluid is cooled in heat exchanger where LNG is regasified. To close the cycle the cold auxiliary fluid goes to compressor. Scheme of use the Brayton cycle is shown in Figure 6. Use of the simple Brayton cycle has a relatively low efficiency because of fact that theoretical conditions are considered in comparison to real gas conditions. The "cold energy" of LNG is only partially used in this case [2].

![Figure 6. Scheme of Brayton cycle use for power generation.](image)

5. Possibility of using LNG in microcogeneration

The idea of sustainable development and climate policy leads to a growing importance of distributed energy resources in the modern model of energy industry. These units are not subject to principles of central distribution and can be directly connected to low-voltage or medium-voltage networks. Distributed installations can have capacity ranging from a few kilowatts to a dozen of megawatts. Most of them can use LNG as fuel because of its easy availability. Gaseous fuels in the combustion process transfer to the atmosphere a much lower number of harmful pollutants, which makes these fuels more environmentally friendly. Prosumer energy is part of distributed generation that includes smaller power sources. The prosumer is an entity that both produces and consumes electricity. The produced electric power is used for the prosumer’s own needs, and any surplus electricity is sold back to the grid. One of the major legal acts defining support for distributed energy is the act on renewable energy sources of 20 February 2015 (Dz.U./Polish Journal of Laws of 2015, item 478). It defines micro installations as energy resources with maximum electric power of 40 kWe or thermal power not exceeding 120 kWt that can be connected to electrical grid with maximum rated voltage of 110 kV[19,21,22]. The most popular power installations based on gaseous fuels are systems working in...
Cogeneration; this combined heat and power generation can be 30-40% more effective compared to separated systems. It translates directly into lower fuel consumption, and hence into lower operating costs and reduced emission of pollutants to the environment. It is mainly possible thanks to the reduction of losses, which in the case of separated generation are very high. Micro-cogeneration is a type of cogeneration related to devices with maximum power up to 50 kWel. Devices with power up to 15 kWel can be connected directly to a three-phase grid [22]. The mCHP systems are most common in local housing that produces its own electricity and heat with a possibility to return surpluses back to the grid. The target group that this technology is dedicated to are buildings that consume heat and electric power. Especially where heat is used the whole year round, also in summer – whether it is for domestic hot water production or technological processes. Micro-CHP systems achieve about 90% efficiency. The micro-CHP systems offer a variety of usage thanks to their small size and relatively easy installation. The co-generation systems using LNG as fuel may include: reciprocating engines, gas turbines, Stirling engines, and a reciprocating steam engine. Reciprocating engines with internal combustion chamber are able to work using natural gas as fuel. Other advantages of combustion engines used in cogeneration are low capital expenditure and their easy maintenance. In turn, vibration, noise and exhaust emissions are the main drawbacks in the use of engines in single-family installations. The next system used in cogeneration is a gas turbine powered mainly by natural gas, but after some modifications it is possible to burn also biogas or waste gases. A clear advantage of gas micro turbines is its small size, reliability and low noise emission. Unfortunately, this entails relatively high investment costs, which are much higher compared to piston engines. In the Stirling engine, fuel most commonly used is natural gas, but the Stirling engine can also be powered with heat from a renewable source. What characterizes the external combustion engine is a low price per unit of energy produced and high reliability. However, the use of expensive materials and complexity of the construction makes the price to installed capacity ratio almost twice as high as piston engines. A cogeneration system based on a reciprocating steam engine is used by steam generators used for combined heat and power generation, which is used commercially. It is not yet a very widespread technology, but there are companies that offer such products. The leading companies in this area are: Spilling, Tenza, Lion-energy [16-20]. Due to the high unit costs of this type of equipment, they are not in competition with small co-generators. Micro-cogeneration is one way to use LNG in order to both generate electricity and heat and solve the problem of reliability of electricity supply. Using distributed energy in the power system is part of the global concept that consists of creating the so-called Smart Grids which are intelligent power supply systems based on the balanced distribution of electricity and heat from various generation systems.

6. Conclusions

In addition to its conventional role in the natural gas market, Liquefied Natural Gas (LNG) may also be a energy source for power generation. Power produced from "cold energy" of LNG is used partially to maintain the regasification process at the LNG receiving terminals, as these processes require a significant contribution of energy. Improving and modifying LNG power generation processes with use LNG "cold energy" results in increased power generated in these processes. Excess of this energy may be delivered into the national energy market through appropriate adaptation of the energy transmission networks or into local energy market in the immediate vicinity from the LNG terminal. It is also possible to use local LNG regasification units to produce electricity for own or local needs. The basic thermodynamic processes used in power generation with use LNG "cold energy" are: the direct expansion of the regasified and pressurized natural gas, the Rankine cycle and Brayton cycle with use an auxiliary fluid which expands and propels the turbine. For the pressures to 3 MPa the suitable option for power generation are simple Rankine cycle and Brayton cycle, for higher pressures the direct expansion of regasified LNG or other complex processes based on modified Rankine or Brayton cycles should be considered.
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References
[1] Franco A, Casarosa C, 2014 Thermodynamic and heat transfer analysis of LNG energy recovery for power production Journal of Physics: Conference Series, 547
[2] Franco A, Casarosa C, 2015 Thermodynamic analysis of direct expansion configurations for electricity production by LNG cold energy Applied Thermal Engineering 78 649-57
[3] Ersoy H K and Demirpolat S O, 2009 Using liquefied natural gas cold energy for power generation: case study for Marmara Ereğlisi receiving terminal Journal of Energy Institute 82 11-18
[4] Liu H and You L, 1999 Thermodynamic analysis of the use of pressure exergy of natural gas Energy Convers. Manag. 40 1515–25
[5] www.bp.com
[6] Janusz P, Kaliski M and Szurlej A, 2015 The ‘shale gas revolution’ and changes on the LNG market Gospodarka Surowcami Mineralnymi/Mineral Resources Management 31 3 5-24
[7] International Energy Agency 2016 Natural Gas information (Paris)
[8] Minister Energii 2016 Sprawozdanie z wyników monitorowania bezpieczeństwa dostaw paliw gazowych za 2015 r. (Warsaw)
[9] Bisio G, 1995 Characteristics and applications of the cold heat exergy of liquefied natural gas Energy 20 2 161-67
[10] Łaciak M 2013 Zwiększenie efektywności energetycznej odparowania oraz bezpieczeństwa magazynowania skroplonego gazu ziemnego (LNG), (Krakow, AGH)
[11] Łaciak M 2013 Thermodynamic processes involving liquefied natural gas at the LNG receiving terminal Archives of Mining Sciences 58 2 349
[12] Łaciak M, Nagy S and Włodek T, 2014 Combined heat and power systems in liquefied natural gas (LNG) regasification processes AGH Drilling, Oil and Gas Quarterl 31 198
[13] Ho Yong L and Kyong Hoon K, 2015 Energy and Exergy analyses of a Combined Power Cycle using organic rankine cycle and the cold energy of liquefied natural gas Entropy 1 76412
[14] Wang H, Shi X and Che D, 2013 Thermodynamic optimization of the operating parameters for a combined power cycle utilizing low temperature waste heat and LNG cold energy Appl. Therm. Eng. 59 490–97
[15] Szargut J and Szczygieł I, 2009 Utilization of the cryogenic exergy of liquid natural gas (LNG) for the production of electricity Energy 34 827–37
[16] Skorek J and Kalina J, 2005 Gas cogeneration systems (Warsaw: WNT)
[17] Paska J, 2010 Distributed generation of power and heat (Warsaw: OWPW)
[18] Matuszczek P, 2016 Development of prosumer energy generation on the example of CHP Przegląd Elektrotechniczny 1 107-10
[19] Guide to priority programmes of NFOŚiGW [National Fund for the Protection of Environment and Water Management] for 2015-2020 2014 (Warsaw)
[20] Beith R, 2011 Small and micro combined heat and power (CHP) system: Advanced design and applications (Oxford: Woodhead Publishing)
[21] Maghanki M M, Ghobadian B, Najafi G and Galogah R J Micro combined heat and power (MCHP) technologies and applications Renew. Sustain. Energy Rev 28 510-24
[22] Act on the Amendment of the Renewable Energy Sources Act and Certain Other Acts 2016 (Dz. U. 2016 No 925)