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# Thermodynamic and heat transfer analysis of LNG energy recovery for power production

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**Abstract.** 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 off-loaded into storage tanks and then pumped at the required pressure and vaporized for final transmission to the pipeline. The LNG production process consumes a considerable amount of energy, while the cold availability, as also known as cold energy, has been stored in LNG. At a receiving terminal, LNG needs to be evaporated into gas at environmental temperature before fed into the gas distribution system. Seawater is commonly used for the regasification process of the LNG. In the present paper, after a general analysis of the perspectives of the various thermodynamic schemes proposed for power production from the regasification, a detailed analysis of enhanced direct expansion system is carried out in order to identify the upper level of the energy that can be recovered. The analysis outlines that power production typical of optimized ORC plant configurations (120 kJ/kg) can be obtained with direct expansion solutions.

## 1 Introduction

A viable way to transport natural gas is to convert it into liquid natural gas (LNG) and convey it using insulated LNG tankers. At receiving terminals, the LNG is off-loaded into storage tanks and then pumped from storage at the required pressure and vaporized for final transmission to the distribution system. The LNG production process consumes a considerable amount of energy, while the cold availability, as also known as cold energy, has been stored in LNG. At a receiving terminal, LNG needs to be evaporated into gas at environmental temperature before fed into the gas distribution system. Seawater is commonly used for the regasification process of the LNG and such process needs about 800 kJ/kg of heat energy. The topic of LNG cold energy recovery both for power production and for different energetic uses is considered in the literature since the late 90s [1-2], mainly under the impulse of the Japanese experience, which is surely one of the most important in the world concerning LNG facilities.

Most LNG terminals regasify the liquid using the thermal energy of seawater or the warm seawater effluent from a power plant, destroying in this way all physical exergy. In the liquefying process, a large amount of mechanical energy is consumed in refrigeration process, so LNG contains a significant amount of cold energy (i.e. cryogenic exergy). If LNG is used as a fuel in a combined system, the waste heat of exhaust gases and the cold energy of LNG can be used at the same time. The

authors intend to focus the attention on the problem of cold the energy contained in LNG: several Thermodynamics schemes can be proposed for energy production [3-5].
The regasification process essentially consists of two operations: pumping up of the liquid gas up to the pressure of the distribution grid; heating of the natural gas up to the distribution temperature (typically in the range between 0 and 20 °C) using a heat exchanger. From a thermodynamic viewpoint, re-heating represents a net loss of available energy, which causes degradation of overall energy efficiency of the conversion chain.
The cold energy stored by the LNG could be recovered rather than directly taken off by seawater. The differences among the various regasification processes are the mode of heat transfer and the type of the loop: this can be an "open loop" (the fluid change) or "closed loop" (the operating fluid is always the same and there is a real thermodynamic cycle). Moreover a fundamental difference is the hot source: this can be at environmental temperature (basically the seawater) or at higher temperature.
Other LNG cold energy utilization ways can be air separation, material freezing, intake air cooling, dry ice production and refrigeration in chemical industry [6].
The cryogenic power generation is the most interesting option. There are several ways using the energy given off by LNG regasification to complete thermodynamic cycle to generate power, but they basically belong to three particular options. The methods are object of analysis in the literature: direct expansion cycle schemes [3-4]; Organic Rankine Cycle (ORC) with intervening media or more complex cascading Rankine cycle configurations [7-8]. While the direct expansion cycle directly uses LNG as working fluid, ORC uses seawater as the primary heat source and LNG as the heat sink with an auxiliary working fluid (usually a low boiling hydrocarbon) for power production in turbine.
In recent options including Brayton cycle with perfect gas cycle [9-12], different non conventional configurations that stands under the name of Combined cycle [13-15] and alternative thermodynamic systems like those based on Stirling cycle have been proposed too [16].
Considering the important handling capacity of typical regasification plants, the cold energy that can be available at LNG receiving terminal, often of the order of magnitude of 50-100 kg/s of natural gas, the potential for practical applications of the LNG cold energy should be further explored.
As previously discussed, in the literature by using the cooling capacity of LNG several thermodynamics schemes are proposed employing conventional and non conventional conversion cycles and different heat sources: typically sensible heat of the seawater is used as energy input, but often a high temperature heat source is used (in the range 60-1300 °C) [17]. For this reason it is not easy to have a clear comparison of the various available power production options.
In the present paper, after a general analysis of the perspectives of the various possible plant configurations to obtain power from the regasification a detailed analysis of the perspectives of direct expansion cycle is performed and a sensitivity analysis with respect to the various plant options and the various operating variables is carried out.

## 2. LNG Cold Energy Recovery and Power Generation: general considerations

LNG is produced by cryogenic refrigeration of natural gas at about -162 °C at atmospheric pressure. Liquefying natural gas is a high energy consumption process, and it is estimated that producing one kg of LNG, assuming the composition of $CH_4$ and considering an higher pressure of the process of 55 bar (the critical pressure of $CH_4$ is 46 bar) a compression work of about 800-860 kJ/kg is necessary (considering a compression efficiency in the range between 0.8 and 0.85).
If the real configurations of liquefaction plants are considered, the energy consumption is sensibly higher than the value considered before. Quiang and co-authors in [18] considers an amount of energy required of 850 kWh/kg correspondent to about 3 MJ/kg. Gerasimov et al. in [19] proposed a plant in which the amount of energy consumed is of about 700-800 kWh/kg (2.5-2.8 MJ/kg). In a textbook on Natural Gas, Medici considers a refrigeration cycle considering a ternary mixture of refrigerants, identifying the level of 1.9 MJ/kg as a possible minimum for the energy required for compression, [20]. Assuming real configurations, it is possible to identify the level of 2900 kJ/kg as a realistic value for the energy consumed in the process, and this is mainly electrical energy.

Considering that, and according to the advanced liquefaction processes about 2900 kJ/kg are consumed in the liquefaction process, the larger amount, about 2070 kJ/kg is dissipated as heat, but the remaining, estimating in the order of magnitude of 830 kJ/kg, called “cold energy” are stored in the LNG. It can be simply estimated with theoretical considerations that when the LNG is regasified to an ambient temperature of 20 °C, an interesting amount of the energy required for the liquefaction process could be theoretically recovered: this corresponds approximately to the value of 0.23 kWh per kg of LNG. Considering the typical annual handling capacity of various LNG receiving terminals (usually estimated in some million of tons for each year), the cold energy that can be available is an amount that cannot be ignored. It is clear that the potential for practical applications of the LNG cold energy should be further explored in order to define optimized solutions. The output pressure of natural gas required for LNG vaporizing terminals varies according to the pipeline requirements. The final pressure varies from 25-30 bar in case of combined cycle stations up to 80 bar typical for long distance distribution (table 1). According to the distribution requirements, an evaluation of the maximum available power (specific exergy difference, Δex, based on ambient temperature of 15 °C) can be given.

**Table 1.** Required pressure for several uses of NG and corresponding theoretical work available

| Application | p [bar] | T [°C] | h [kJ/kg] | s [kJ/kg K] | Δex [kJ/kg] |
|---|---|---|---|---|---|
| LNG initial condition | 1 | -161.5 | 442.80 | 8.529 | - |
| Combined cycle stations | 27 | 15 | 573.40 | 9.761 | 531.00 |
| Local distribution | 35 | 15 | 564.70 | 9.604 | 494.46 |
| Long-distance pipelines | 70 | 15 | 525.50 | 9.143 | 400.82 |
| Maximum pressure | 150 | 15 | 442.80 | 8.529 | 306.60 |

Considering that the final pressure must be much higher that the atmospheric one, and that according to the required pressure the T-s diagram for LNG has very different configurations (figure 1), several possible options for the recovery can be considered and it is difficult to define the best available technology. Hence if options based on a simple Rankine cycle or Brayton cycle are probably better for pressure up to 30 bar, for higher values, the direct expansion options can be reconsidered. In order to use LNG cold energy to generate electricity, several different generation processes can be designed, in the following section the various options will be briefly reviewed.

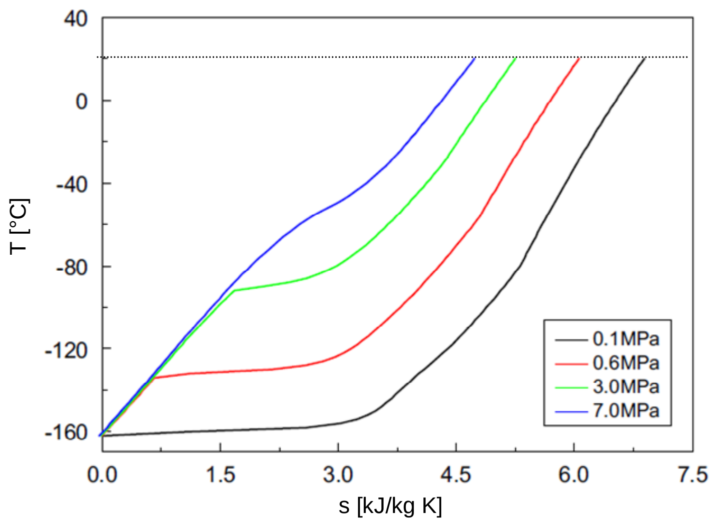


**Figure 1.** T-s diagram for LNG

## 3. The various options for electricity generation by LNG cold energy

The electricity generation by using the cold energy of LNG is possible by means of a variety of thermodynamic schemes. The more considered ones in the literature are the following: Rankine cycle, direct expansion cycle; gas expansion cycle (Brayton cycle) and combined cycles. In some papers options considering possible combination of the different options are also proposed such as Stirling cycle, but in general they represent more complex solutions.

### *3.1. Direct Expansion Cycle*

The direct expansion conversion is basically the simplest configuration for power production. In this cycle, LNG liquid is firstly compressed up to a pressure higher than the user's need then heated and regasified through evaporator by seawater and use the vapour to drive the turbine-generator. LNG direct expansion cycle is simple and suitable for small regasification station which supply low pressure natural gas. Nevertheless as previously discussed, in most cases the gasified LNG is requested at supercritical conditions, therefore it can be dispatched to long distance pipelines and consequently the maximum pressure level is over 100 bar. After expansion in the turbine, where power is generated, its pressure decreases to the gas-supplying pressure. Considering conventional schemes, where the maximum pressure of natural gas is 150 bar and the final pressure in the pipeline is on the order of 80 bar (typical of long-distance distribution pipelines) the amount of net power that can be generated by expansion turbine can be easily estimated in the order of 20 kJ/kg, being about 60 kJ/kg the difference of enthalpy in the turbine and about 40 kJ/kg the specific enthalpy required for the pumps: a very little amount with respect to the cold energy. The value can be somewhat higher for lower values of the final pressure required for the pipelines and low mass flow rates. Moreover some authors state that if the high pressure after gas expansion is needed, direct expansion cycle is not suitable to be used. The expansion cycle can be selected in different ways in order to maximize the power extracted. The simplified scheme of figure 2 can be improved in order to increase the output power considering the imposed boundary condition of the requested pressure.

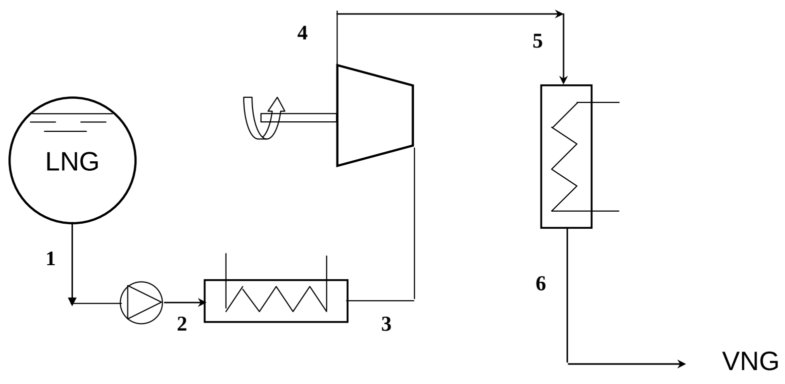


**Figure 2.** Direct expansion cycle

### 3.2. *Rankine Cycle with Intervening Media*

One of the most common options for power production is the use of LNG for cooling the condenser of a Rankine cycle which exploits sensible heat of the seawater as energy input. In the version of Rankine cycle, an auxiliary fluid (as for example propane R22, R23, R13B1 and, for the coldest applications, methane) is used for expansion within the turbine; LNG is used as low temperature source for the condenser. The auxiliary fluid is condensed by LNG and then pumped to evaporator heated by seawater and finally passed in turbine to drive generator to complete whole cycle (figure 3). As LNG need not expand to work, the send out pump can be set to the pipeline pressure level. In some cases, in order to reach the environment temperature, it is necessary to use additional heater. Even if with the Rankine cycle the high temperature can be selected with a certain grade of freedom, depending on the heat source available and the practical limit is only represented by the thermal stability of the organic fluid, the real limitation of the simple Rankine cycle stands in the fact that the gasified LNG is often required at a quite high pressure (more than 30 bars) so that, considering the thermodynamic scheme of figure 4 the available cooling capacity in non-isothermal, which implies a not perfect match with the condenser of the Rankine cycle. The conventional values for the energy recovery obtained with Rankine cycle can be estimated in the range between 40 and 120 kJ/kg, using conventional schemes [7-8]. For practical LNG cold power generation, ORC is most commonly used, in some cases using different configurations like a binary mixture as working fluids and combined with a vapour absorption process or using a cascading mode the output power can overcome 200 kJ/kg [21].

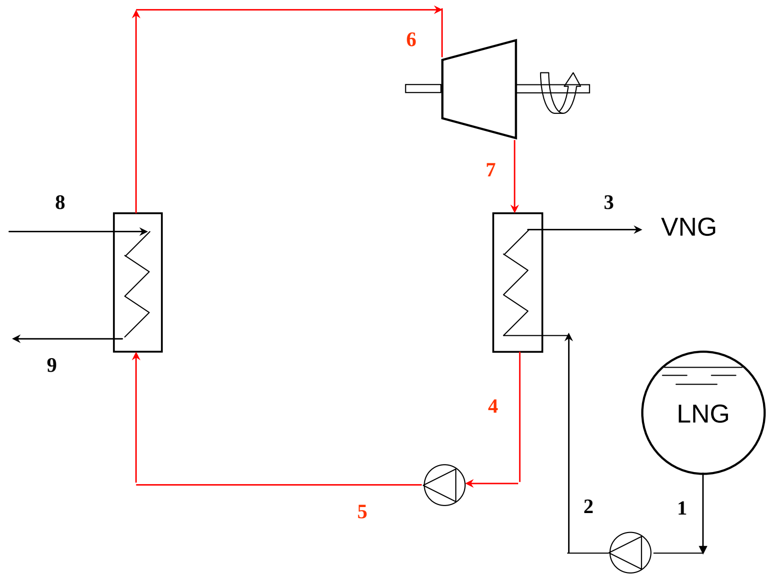


**Figure 3.** Rankine Cycle With Intervening Media

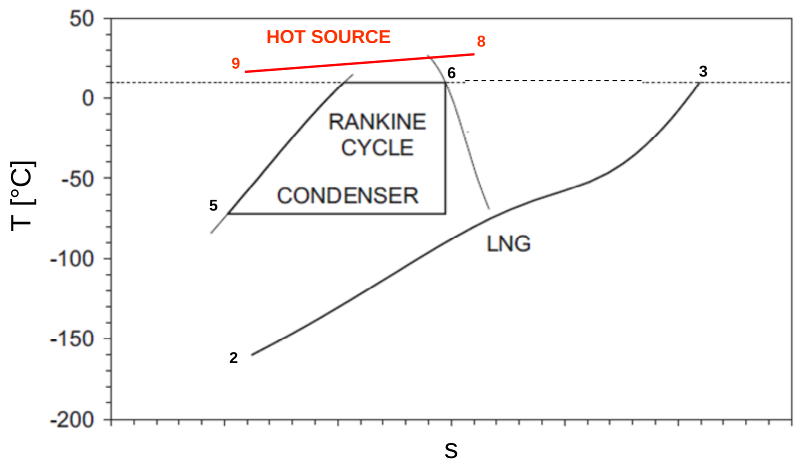


**Figure 4.** The cooling capacity of supercritical LNG in relation to Rankine cycle

*3.3. Brayton cycle*

From a conceptual point of view another simple system for obtaining work by the cold energy is the use of a fluid in a Brayton cycle. Since the level of cold in a LNG flow is thermodynamically predetermined, working fluids must be selected with a critical point which fits the LNG thermal capacity, i.e. 5-15 °C higher than the LNG temperature. Some possible operating fluids are reported in table 2. However ordinary Brayton cycles considering real gas conditions, exhibit a modest efficiency [9]; the problem is that the theoretical conditions are relative to real gas cycles and the cooling capacity of LNG is only partially used: a better exploitation is obtained from perfect gas cycles, selecting fluid such as argon, higher temperature of the hot source (figure 5) or a more complex configuration with a cascading Rankine cycle.

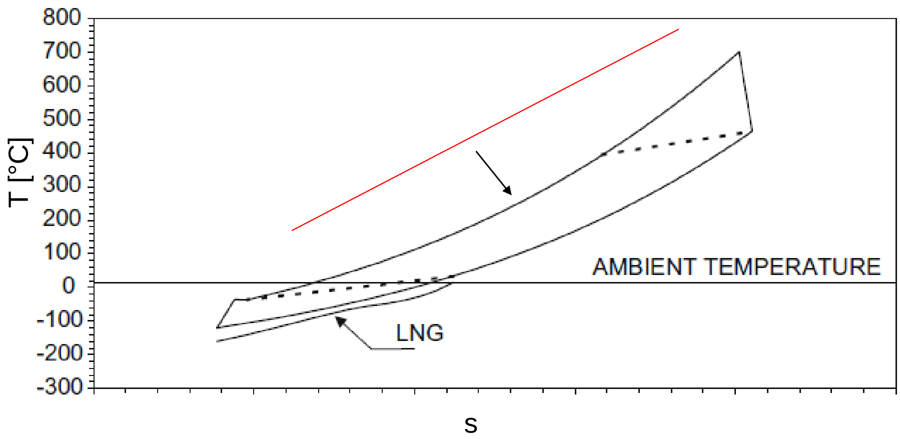


**Figure 5.** The cooling capacity of supercritical LNG in relation to high temperature Brayton cycle

**Table 2.** Working fluids for cryogenic Brayton gas cycles [9]

| Fluid | Molecular mass [g/mol] | Critical temperature [K] | Critical pressure [bar] |
|---|---|---|---|
| $N_2$ | 28 | 126.2 | 33.98 |
| Air | 28.96 | 132.52 | 37.66 |
| Ar | 39.948 | 150.86 | 48.98 |
| $O_2$ | 32 | 154.58 | 50.43 |
| $CH_4$ | 16.043 | 190.56 | 45.99 |

## 4. Analysis and optimization of direct expansion recovery configurations

As briefly discussed in the previous section, the basic direct expansion configuration appears to be not convenient from the perspective of energy recovery even if it is the more simplified and basic configuration. In the conventional schemes the direct expansion in only obtained with a single pressure level by means of pumping the LNG at a pressure well higher than the required one with a simple expansion. However, as well known from the Thermodynamics, for obtaining higher energy productions, it is necessary to divide the mass flow rates at different pressure levels. For this reason a more convenient configuration involves three different pressure levels, in which the maximum pressure is higher than the pressure required for the pipeline (80 bar). The configuration considered is represented in figure 6 with the corresponding thermodynamic diagram reported in figure 7. In this case four different pressure levels are considered with the only boundary condition imposed by the value of the maximum pressure fixed at 150 bar. This particular configuration can be optimized modifying the values of the two intermediate pressure levels: for each value of the pressure different mass flow rates can be defined. In order to evaluate optimal configuration, a mathematical model can be written: it consists of mass balance (Eqs. 1-5) and energy balance equations (Eqs. 6-12):

$$m_1 = m_2 = m_{8*} = m_8 = m^* \quad (1)$$

$$m_2 + m_{11} = m_3 \quad (2)$$

$$m_4 + m_9 = m_5 \tag{3}$$

$$m_7 - m_8 = m_9 + m_{10} \tag{4}$$

$$m_{11} = m_3 - m^* \tag{5}$$

$$m_2 h_2 + m_{11} h_{11} = m_3 h_3 \tag{6}$$

$$m_4 h_4 + m_9 h_9 = m_5 h_5 \tag{7}$$

$$m^* h_2 + \left(m_3 - m^*\right) h_{11} = m_3 h_3 \tag{8}$$

From the previous equations it is possible to derive the corresponding equation connecting the values of the various mass flow rate, identified with reference to the schemes of figures 6 and 7 as $m_3$, $m_5$, $m_7$ and $m_{10}$ as a function of the mass flow rate directed to the pipeline m*, that permits to evaluate the power that can be obtained with high and low pressure turbine and consequently:

$$m_3 = \frac{\left(h_{11} - h_2\right)}{\left(h_{11} - h_3\right)} \cdot m^* \tag{9}$$

$$m_5 = m_3 \cdot \frac{\left(h_9 - h_4\right)}{\left(h_9 - h_5\right)} \cdot m^* \quad \rightarrow \quad m_5 = m_6 = m_7 = \frac{\left(h_{11} - h_2\right)}{\left(h_{11} - h_3\right)} \cdot \frac{\left(h_9 - h_4\right)}{\left(h_9 - h_5\right)} \cdot m^* \tag{10}$$

$$m_{10} = \frac{\left(h_3 - h_2\right)}{\left(h_{11} - h_3\right)} \cdot m^* \tag{11}$$

Considering the various configurations analyzed, the better recovery conditions, corresponding to the three following pressure levels: 4 bar, 35 bar and 150 bar are reported in table 3. The data are obtained considering isentropic efficiency of 0.85 and 0.9 for the high and low pressure turbine.

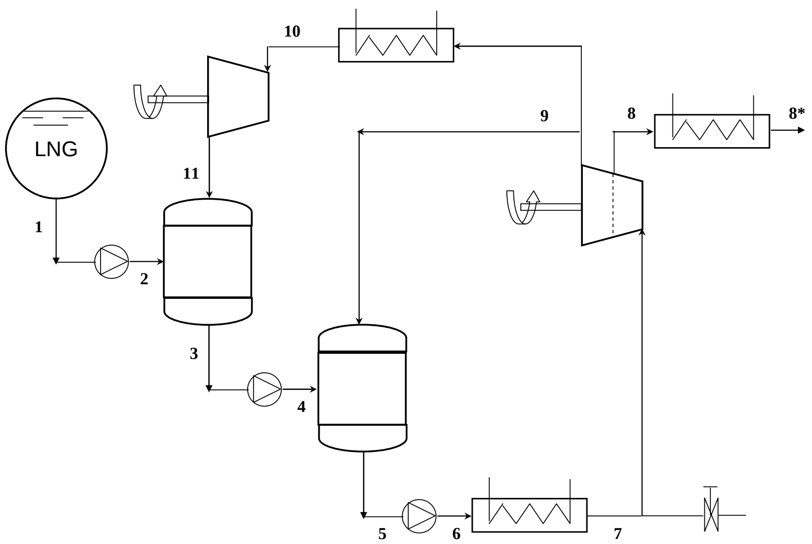


**Figure 6.** Direct expansion cycle configuration analyzed

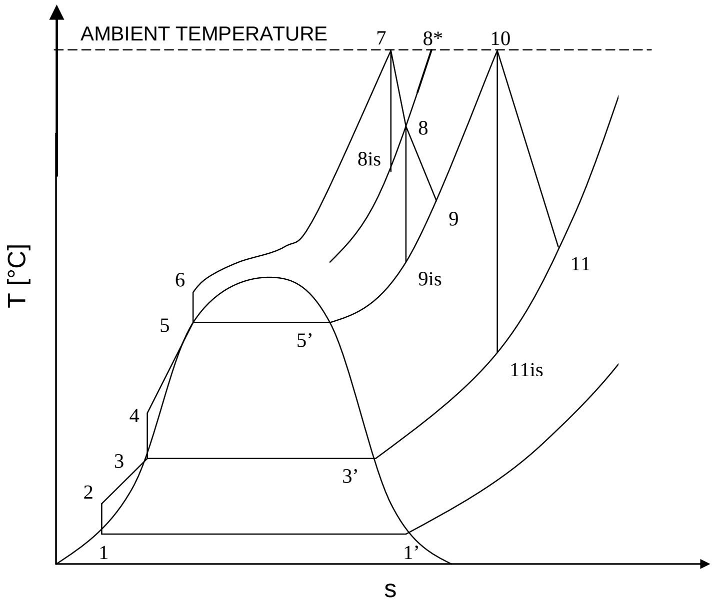


**Figure 7.** Direct expansion cycle considered: schematic T-s diagram

According to the model described before, the amount of power that can be produced as the sum of the two different contributions related to the high pressure and low pressure turbine respectively:

$$W_{HP} = m_7 \cdot (h_7 - h_8) + (m_7 - m^*) \cdot (h_8 - h_9) \tag{12}$$

$$W_{LP} = m_{10} \cdot (h_{10} - h_{11}) \tag{13}$$

**Table 3.** Data referred to the various Thermodynamic states of the direct expansion cycle

| State | T [°C] | P [MPa] | v [m³/kg] | h [kJ/kg] | s [kJ/kgK] | x |
|---|---|---|---|---|---|---|
| 1 | -161.5 | 0.1013 | 0.002367 | -286.5 | 4.943 | 0 |
| 1' | -161.5 | 0.1013 | 0.5501 | 223.8 | 9.504 | 1 |
| 2 | -161.4 | 0.4 | 0.002366 | -285.7 | 4.934 | |
| 3 | -141.7 | 0.4 | 0.002552 | -215.5 | 5.513 | 0 |
| 3' | -141.7 | 0.4 | 0.1543 | 252.7 | 9.075 | 1 |
| 4 | -141 | 3.5 | 0.002532 | -209.3 | 5.500 | |
| 5 | -91.22 | 3.5 | 0.003738 | 11.79 | 6.897 | 0 |
| 5' | -91.22 | 3.5 | 0.01477 | 239.9 | 8.151 | 1 |
| 6 | -90 | 15 | 0.003037 | -10.43 | 6.569 | |
| 7 | 15 | 15 | 0.007871 | 442.8 | 8.529 | |
| 8 | -25 | 8 | 0.01176 | 387.2 | 8.569 | |
| 9'is | -75.38 | 3.5 | 0.02104 | 318.7 | 8.569 | |
| 9 | -72.48 | 3.5 | 0.02187 | 329 | 8.620 | |
| 8* | 15 | 8 | 0.01689 | 542.9 | 9.142 | |
| 9is | -77.5 | 3.5 | 0.02041 | 310.8 | 8.529 | |
| 10 | 15 | 3.5 | 0.03978 | 564.7 | 9.604 | |
| 11is | -107.8 | 0.4 | 0.2044 | 330.5 | 9.603 | |
| 11 | -97.2 | 0.4 | 0.2193 | 353.9 | 9.740 | |

From the data of table 3, obtained by means of the utility CATT (Computer Aided Thermodynamics Tables) it is possible to calculate the pumping power related to the various pressure increases, $P_{1-2}$, $P_{3-4}$ and $P_{5-6}$; mainly the last value is quite relevant with respect to the specific expansion enthalpy.
Considering the data of table 3 and the mathematical model assumed, the detailed results reported in table 4 can be obtained. Analyzing the results of table 4 it is possible to understand that, considering configurations like the one with the three pressure level considered, levels of output power of the order of magnitude of 120 kJ/kg, values typical for conventional ORC cycles and corresponding to a second law efficiency of about 28%. Assuming a LNG mass flow rate, typical of various regasification terminals (about 70 kg/s corresponding to a nominal production rate of about $3*10^9$ $m^3$ of natural gas) an output power of about 8.37 MW can be obtained. Using similar boundary conditions used for the basic cycle of figure 6 (final pressure of the lever required for long distribution pipelines and maximum pressure of 150 bar, working on the thermodynamic cycle with the introduction of internal recovery heat exchangers permitting further heat recovery and optimizing the various mass flow rate ratios, it is possible to reach a specific power production approaching 160 kJ/kg, with a Second Law efficiency of the recovery cycle quite close to 0.4. Even if it seems that the additional energy recovery gives origin to a higher complexity of the LNG recovery plant, further improvements of the direct expansion exposed in the figures 6 and 7 appears to be suitable for more detailed analysis.

**Table 4.** Details of the direct expansion optimized recovery configuration

| Mass flow ratio | Power ratio | Values |
|---|---|---|
| $m_3 / m^*$ | | 1.1233 |
| $m_5 / m^*$ | | 1.9062 |
| $m_{10} / m^*$ | | 0.1232 |
| | $W_{HP} / m^*$ | 158.72 kJ/kg |
| | $W_{LP} / m^*$ | 25.98 kJ/kg |
| | $W_{gross} / m^*$ | 184.70 kJ/kg |
| | $P_{1-2} / m^*$ | 0.707 kJ/kg |
| | $P_{3-4} / m^*$ | 8.886 kJ/kg |
| | $P_{5-6} / m^*$ | 55.504 kJ/kg |
| | $P / m^*$ | 65.097 kJ/kg |
| | $W_{net} / m^*$ | 119.616 kJ/kg |
| | $Q_{6-7} / m^*$ | 863.94 kJ/kg |
| | $Q_{9-10} / m^*$ | 29.06 kJ/kg |

## 5. Conclusions

In the present paper the problem of energy production for LNG cold energy has been analyzed with the specific aim to evaluate the perspectives of simple direct expansion configurations. After a preliminary analysis of the various conventional options, a specific three pressure level configuration has been analyzed and tested. Considering an upper limit for the higher pressure (150 bar) and a boundary condition imposed by the pipeline at 80 bar, a potential of power production of about 120 kJ/kg have been estimated: this value being correspondent to the typical values declared for optimized systems based on ORC. Analyzing more complex configurations that include recovery heat exchangers, it seems possible to obtain further increase of the specific power production.
As concluding remark it is possible to state that though if the analysis reported in the present paper is based on some theoretical assumptions (e.g. the availability of high pressure turbines operating with

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natural gas at a temperature well below the environmental temperature and ideal heat exchangers configurations), the results that can be obtained with a Thermodynamic optimization of the cycle are very interesting if compared with the results obtained in some simplified analysis available in the literature about direct LNG expansion, based on single pressure configurations.

**References**

[1] Liu H and You L 1999 Characteristics and applications of the cold heat exergy of liquefied natural gas, Energy Conversion & Management **40** 1515-25.
[2] Kim T S and Ro S T 2000 Power augmentation of combined cycle power plants using cold energy of liquefied natural gas, Energy **25** 841–56.
[3] Zhang F and Yu X 2009 LNG Cold Energy Recovery and Power Generation, Proc. of Power Energy Engineering Conference, APPEEC Asia Pacific, 27-31 March, 2009.
[4] Dispenza C Dispenza G La Rocca V and Panno G 2009 Exergy recovery during LNG regasification: Electric energy production – Part one App. Thermal Engineering **29** 380–87.
[5] Zhang L and Tang Q 2012 Comparison of different power generation processes by LNG cold energy, 2012 ASRI Conference on Power and Energy Systems, AASRI Procedia **2** 31-38.
[6] Bisio G and Tagliafico L 2002 On the recovery of LNG physical exergy by means of a simple cycle or a complex system, Exergy, an International Journal, **2** 34-50.
[7] Wang J Yan Z Wang M and Dai Y 2013 Thermodynamic analysis and optimization of an ammonia-water power system with LNG as its heat sink, Energy **50** 513-22.
[8] Pu L Qu Z Bai Y Qi D Song K and Yi P 2014 Thermal performance analysis of intermediate fluid vaporizer for liquefied natural gas, App. Thermal Engineering **65** 564-74.
[9] Angelino G and Invernizzi C M 2011 The role of real gas Brayton cycles for the use of liquid natural gas physical exergy, App. Thermal Engineering **31** 827-33.
[10] Zhang N and Lior N 2006 A novel near-zero $CO_2$ emission thermal cycle with LNG cryogenic exergy utilization, Energy **31** 1666–79.
[11] Liu M Lior N Zhang N and Han W 2009 Thermoeconomic analysis of a novel zero-$CO_2$-emission high-efficiency power cycle using LNG coldness, Energy Conversion and Management **50** 2768–81.
[12] Shi X and Che D 2009 A combined power cycle utilizing low-temperature waste heat and LNG cold energy, Energy Conversion and Management **50** 567–75.
[13] Gómez M R Ferreiro Garcia R Romero Gómez J and Carril J C 2014 Thermodynamic analysis of a Brayton cycle and Rankine cycle arranged in series exploiting the cold exergy of LNG (liquefied natural gas), Energy **66** 927-37.
[14] Querol E Gonzalez-Regueral B García-Torrent J and Ramos A 2011 Available power generation cycles to be coupled with the liquid natural gas (LNG) vaporization process in a Spanish LNG terminal, Applied Energy **88** 2382–90.
[15] Lu T and Wang K S 2009 Analysis and optimization of a cascading power cycle with liquefied natural gas (LNG) cold energy recovery, App. Thermal Engineering **29** 1478–84.
[16] Dong H Zhao L Zhang S Wang A and Cai J 2013 Using cryogenic exergy of liquefied natural gas for electricity production with the Stirling cycle, Energy **63** 10-18.
[17] Choi I H Lee S Seo Y and Chang D 2013 Analysis and optimization of cascade Rankine cycle for liquefied natural gas cold energy recovery, Energy **61** 179-95.
[18] Qiang W Yanzhong L and Jiang W 2004 Analysis of power cycle based on cold energy of liquefied natural gas and low-grade heat source, App. Thermal Engineering **24** 539–548.
[19] Gerasimov V E Kuz’menko I F Peredel’skii V A and Darbinyan R V 2004 Introduction of technologies and equipment for production, storage, transportation, and use of LNG, Chemical and petroleum engineering **40** 31-35.
[20] Medici M 1974 Natural Gas Industry, Newnes-Butterworth UK.
[21] Liu Y and Guo K 2011 A novel cryogenic power cycle for LNG cold energy recovery Energy **36** 2828-33.