Thermodynamic analysis of direct expansion configurations for electricity production by LNG cold energy recovery

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Abstract

In the present paper, after a brief review of the perspectives of the various schemes proposed for electricity generation from the regasification of Liquefied Natural Gas (LNG), a detailed analysis of two particular direct expansion solutions is proposed. The purpose is to identify the upper level of the energy that can be recovered with the aim of electricity production, using configurations with direct expansion.

The analysis developed resorting to a simplified thermodynamic model, shows that using a direct expansion configurations with multistage turbine, values of power production typical of optimized ORC plant configurations (120 kJ for each kg of natural gas that flows through the plant) can be obtained. The development of a direct expansion plant with multistage turbine and internal heat recovery systems could permit to approach the production of more than 160 kJ for each kg of flowing liquefied natural gas. Considering values of the mass flow rate typical of LNG gas stations (e.g. 70 kg/s); this correspond to an output power ranging between 8.3 MW and 11.4 MW.

Keywords: Liquefied Natural Gas (LNG); Cold energy recovery; Electricity generation; Thermodynamic conversion cycle; Direct expansion.

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Nomenclature

e	specific exergy, kJ/kg
e_p	specific exergy referred to the pipelines boundary conditions, kJ/kg
h	specific enthalpy, kJ/kg
ℓ_{max}	maximum available specific work, kJ/kg
m	mass flow rate, kg/s
m'	mass flow rate for the recovery heat exchanger, kg/s
m^*	mass flow rate of natural gas produced, kg/s
p	pressure, bar
P	pumping power, W
Q	heating power, W
s	specific entropy, kJ/kg K
T	temperature, °C
T_0	reference temperature, K
v	specific volume, m^3/kg
x	steam quality, %
W	mechanical power, W
Δe	exergy difference, W

Subscripts, acronyms and abbreviations

0	referred to the environmental state
cr	critical value
gross	gross value
HEX	heat exchanger
HP	high pressure
is	isentropic value
LNG	Liquefied Natural Gas
LP	low pressure
M	mixing heat exchanger
MP	medium pressure
net	net value
ORC	Organic Rankine Cycle
PL	low pressure pump
PH	high pressure pump
PM	medium pressure pump
ref	reference value for LNG (at pressure p_0 = 1 bar)
RHE	recovery heat exchanger
TE	turbo-expander
TL	low pressure turbine
TH	high pressure turbine

TM	medium pressure turbine
VNG	Vaporized Natural Gas

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. Regasification of the LNG requires about 800 kJ/kg of heat energy. At a receiving terminal, LNG needs to be evaporated into gas at environmental temperature and at the required pressure before fed into the gas distribution system. The topic of LNG cold energy recovery for both electricity production and 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 the oldest and one of the most important in the world concerning LNG facilities, as it can be clearly evidenced, analyzing papers like [3] and [4].

Most LNG terminals regasify the liquid using the thermal energy of seawater or of the warm seawater effluent from a power plant, destroying in this way all physical exergy available. During the liquefying process, a large amount of mechanical energy is consumed due to the refrigeration thus 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 the recovery of cold energy contained in LNG. Several thermodynamic schemes can be proposed for electricity production [4-6]. Other LNG cold energy utilization ways can be air separation, material freezing, intake air cooling, dry ice production and refrigeration in chemical industry [7].

The regasification process essentially consists of two operations: pumping up the liquid gas mixture to the pressure of the distribution grid and heating up 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 the 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 concern the mode of heat transfer and the type of the loop: this can be an "open loop" (the fluid change) or a "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.

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: they basically belong to three particular options. The methods discussed in the literature are direct expansion cycle schemes [4-5]; Organic Rankine Cycle (ORC) with intervening media or more complex cascading Rankine cycle configurations [8-9]. While the direct expansion cycle directly uses LNG as working fluid for expansion in turbine, 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 Brayton cycle with perfect gas cycle has been considered [10-12] as well as different non conventional configurations mentioned under the name of combined cycle, providing a combination of different thermodynamic cycles and operating fluids [13-16]. In particular, in [13] and [14] the proposed combined system consists of the Rankine cycle with ammonia–water mixture as working fluids; [15] presents a novel power plant consisting of a combination of a closed Brayton cycle with a steam Rankine cycle, arranged in series, while in [16] a combined cycle using a gas turbine and a pure NH_3 Rankine cycle coupled with the natural gas vaporization process has been chosen as the most advisable one to be installed. Different thermodynamic systems like those based on Stirling cycle and Kalina cycle have been proposed, but in general those can be considered only preliminary studies and non-commercial solutions, as argued in [4] and [17]. Considering the important handling capacity of typical regasification stations, often of the order of magnitude of 50-100 kg/s of natural gas, the potential for practical applications of the LNG cold energy for electricity generation should be further explored. As previously discussed several thermodynamics schemes are proposed employing conventional and non conventional conversion cycles and different heat sources: sensible heat of the seawater is often used as energy input, but sometimes a high temperature heat source is used [18]. For this reason it is not easy to compare the various options available for energy recovery and in particular for electricity generation.

In the present paper, after a general analysis of the perspectives of the various possible processes to produce electricity from the regasification a detailed analysis of two advanced direct expansion configuration is performed. The two cold energy recovery systems are modelled with equations of mass and energy balance. Using the thermodynamic model a sensitivity analysis with respect the main operating variables is carried out with the aim of discussing the technological perspectives of this kind of solutions aimed to produce electricity in LNG regasification terminals.

2. LNG cold energy recovery and power generation: general considerations

LNG is produced by cryogenic refrigeration of natural gas at about -162 °C and atmospheric pressure. Liquefying natural gas is a high energy consumption process. It is estimated that producing one kg of LNG, assuming the composition of CH_4 and considering an higher pressure of the process of about 55 bar (the critical pressure of CH_4 is 46 bar) a minimum compression work of about 850-900 kJ/kg is necessary; this value can be calculated, knowing the thermodynamic data of CH_4, considering the change in enthalpy of natural gas (at a temperature of 15-25 °C and atmospheric pressure) and a pressure higher than the critical one assuming a three stage compression an isentropic efficiency in the range between 0.8 and 0.85 [19].

If the real configurations of liquefaction plants are considered, the energy consumption is sensibly higher than the theoretical value considered before. Quiang and co-authors in [20] considered an amount of energy required of about 3000 kJ/kg. Gerasimov et al. in [21] proposed a plant in which the amount of energy consumed is of about 2500-2800 kJ/kg. In a textbook on Natural Gas, [22], Medici analyzed a refrigeration cycle using a ternary mixture of refrigerants as working fluid, identified the level of 1900 kJ/kg as a possible technical minimum for the energy required for compression in practical applications.

Considering that with the conventional 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, [1]. 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 830 kJ per kg of LNG. Considering the typical annual handling capacity of the various LNG receiving terminals (usually estimated in some million of tons for each year), as discussed in papers like [23], the cold energy that can be available is an amount that cannot be ignored. It is clear that the potential for practical applications of LNG cold energy should be further explored in order to define optimized solutions. The natural gas output pressure required from 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 60-80 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 the environmental conditions, in this particular case defined using the temperature T_0 = 15 °C and the reference pressure p_0 = 1.013 bar) can be given. In particular, the specific exergy in the various states can be calculated by means of the equation:

$$e = (h - h_0) - T_0 \cdot (s - s_0) \tag{1}$$

The maximum available specific work, ℓ_{max} is obtained as a difference between the exergy available in the reference state, e_{ref} and the final exergy value imposed by the pipelines specifications, e_p :

$$\ell_{max} = e_{ref} - e_p \tag{2}$$

Table 1 summarizes the thermodynamic data for the typical conditions for the transport of LNG (T=-161.5 °C and p=1.013 bar) and at environmental conditions (T=15 °C and p=1.013 bar) and the various operating conditions imposed by the pipelines; the values of the maximum available energy that can be obtained for each kg of LNG, in the different typical conditions imposed by the technical specification of the pipeline, are also provided in the right column of Table 1. Considering that the final pressure (in the range between 25 and 80 bar) 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 (Fig. 1), several possible options for the recovery can be considered and it is difficult to define the best technology in general. Hence if configurations based on a simple Rankine cycle or Brayton cycle are those that permit higher values of power generation if pressure required in the pipeline is lower than 25-30 bars, for higher pressures, the direct expansion can be reconsidered as a possible alternative. In order to use LNG cold energy to generate electricity, several different generation processes can be designed. In the following section these various options are briefly reviewed.

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]	e [kJ/kg]	ℓ_{max} [kJ/kg]
LNG reference condition	1.013	-161.5	-286.50	4.934	1012.94	-
Environmental conditions	1.013	15	601.20	11.530	0	1012.94
Combined cycle stations	27	15	573.40	9.761	481.94	531.00
Local distribution	35	15	564.70	9.604	518.48	494.46
Long-distance pipelines	70	15	525.50	9.143	612.12	400.82
Maximum pressure	150	15	442.80	8.529	706.34	306.60

2.1. Direct Expansion Cycle

The direct expansion conversion is basically the simplest configuration for power production. In this system, represented in Fig. 2, LNG is firstly compressed up to a pressure higher than the user's need (point 2) then is heated and regasified through an evaporator by means of seawater (point 3); thereafter the vapour is used to drive the turbine-generator (point 4) and finally reheated again to reach the ambient temperature (point 5).

LNG direct expansion cycle is considered simple and suitable for small LNG regasification stations 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 approaches the level of 100 bar. After expansion in the turbine, where power is generated, its pressure decreases to the gas-supplying pressure. Considering conventional schemes, based on simple expansion, where the maximum pressure of the natural gas is 150 bar and the final pressure in the pipeline is of the order of 70-80 bar (a value typical for long-distance distribution pipelines) the amount of net power that can be generated by turbine can be easily estimated, using the thermodynamic tables of CH_4, in the order of 20 kJ/kg, being about 60 kJ/kg the enthalpy change in the turbine and about 40 kJ/kg the specific enthalpy required for the pump: 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 states that if the high pressure after gas expansion is needed, direct expansion cycle is not suitable to be used; considerations about the low efficiency level of the simple direct expansion configurations are in [4]. According to the ideas exposed in the literature, this method is inefficient because during the vaporization and heating process, which, almost all the LNG thermal exergy is yielded to the heat source and only the mechanical exergy is exploited when passing from high pressure to the pressure of the pipeline. But the simplified scheme of Fig. 2 can be improved in order to increase the output power considering the imposed boundary conditions of pressure and the possible evolution of the thermodynamic cycle like multistage expansion and internal heat recovery.

2.2. 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 this case an auxiliary fluid (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, thus heated by seawater and finally passed to the turbine to drive the generator so that the cycle is completed (Fig. 3). In this case the send out pump can be set at 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 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 Fig. 4, the available cooling capacity is non-isothermal, which implies a not perfect match in the heat transfer 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 [8-9]. For practical LNG cold power generation, ORC is most commonly proposed, sometimes using different configurations such as a binary mixture as working fluids and combined with a vapour absorption process or using a cascading mode; in this way the output power can overcome the value of 200 kJ/kg [24].

2.3. Brayton cycle

From a conceptual point of view another simple system for ~~obtaining work~~ producing electricity 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 it is important to remark that conventional Brayton cycles, using air as operating fluid, exhibit a quite low efficiency [10]. Better performances can be theoretically obtained from perfect gas cycles, selecting operating fluid such as argon, using a higher temperature of the hot source (Fig. 5) or a more complex configuration with Brayton cycle and a cascading Rankine cycle.

Table 2. Working fluids for cryogenic Brayton gas cycles [10]

Fluid	Molecular mass [g/mol]	T_{cr} [K]	p_{cr} [bar]
N_2	28.0	126.2	33.98
Air	28.96	132.52	37.66
Ar	39.948	150.86	48.98
O_2	32.0	154.58	50.43
CH_4	16.043	190.56	45.99

3. Analysis and optimization of direct expansion recovery configurations

Electrical power can be generated from LNG terminal by direct expansion of the vaporized LNG. As briefly discussed in the previous section, the basic direct expansion configuration, even if simple from a technical point of view, appears to be not convenient from the perspective of energy recovery. In the conventional schemes the direct expansion is obtained considering 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 it is well known from the thermodynamics, for obtaining higher energy productions, it is necessary the application of more complex thermodynamic cycles, considering different steps of expansion and the mass flow rate extraction at intermediate pressure levels. A more convenient configuration is the one in which LNG is regasified and it is expanded in two or three stages with intermediate reheat. In this case the maximum pressure can be higher than the pressure required by the distribution pipeline (in case of long pipelines this value is of the order of 60-80 bar).

3.1 Analysis of basic configuration with two or three pressure levels

The first configuration considered for electricity generation using cold energy recovery is represented by the plant schematized in Fig. 6 and the corresponding qualitative thermodynamic diagram is reported in Fig. 7.

This thermodynamic cycle represents the first meaningful evolution of the basic scheme analyzed and discussed in section 2.1, utilizing multistage expansion. In this case four different pressure levels are considered with the only boundary condition imposed by the value of the maximum pressure, in the present analysis fixed at 150 bar and the power can be increased operating with two different turbo-expanders, one at high pressure and the second at low pressure and with a partial extraction of steam from the high pressure turbine. This particular configuration can be optimized modifying the values of the two mid pressure levels: for each value of the pressure different values of the mass flow rates can be defined. In order to evaluate quasi-optimal configuration by means of a sensitivity analysis, a mathematical model can be written: it consists of mass balance (Eqs. 3-7) and energy balance equations (Eqs. 8-10). For the sake of simplicity, it is assumed that LNG is totally composed as CH_4 and treated as a pure substance. Considering m* as the reference mass flow rate of the natural gas flowing from LNG tank through the system and directed to the pipeline (e.g. 1 kg/s), the following balance equations can be written:

$$m_1 = m_2 = m_{8*} = m_8 = m* \tag{3}$$

$$m_2 + m_{11} = m_3 \tag{4}$$

$$m_4 + m_9 = m_5 \tag{5}$$

$$m_7 - m_8 = m_9 + m_{10} \tag{6}$$

$$m_{11} = m_3 - m* \tag{7}$$

$$m_2 h_2 + m_{11} h_{11} = m_3 h_3 \tag{8}$$

$$m_4 h_4 + m_9 h_9 = m_5 h_5 \tag{9}$$

$$m* h_2 + \left(m_3 - m*\right) h_{11} = m_3 h_3 \tag{10}$$

From the previous equations it is possible to obtain the values of the various mass flow rate of natural gas, identified with reference to the schemes of Fig. 6 and Fig. 7 as m_3, m_5, m_7 and m_{10} as a function of the mass flow rate of natural gas flowing through the plant and directed to the pipeline m* so it results:

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

$$m_5 = m_3 \cdot \frac{\left(h_9 - h_4\right)}{\left(h_9 - h_5\right)} \cdot m* \qquad \rightarrow \qquad m_5 = m_6 = m_7 = \frac{\left(h_{11} - h_2\right)}{\left(h_{11} - h_3\right)} \cdot \frac{\left(h_9 - h_4\right)}{\left(h_9 - h_5\right)} \cdot m* \tag{12}$$

$$m_{10} = \frac{\left(h_3 - h_2\right)}{\left(h_{11} - h_3\right)} \cdot m* \tag{13}$$

According to the model described before, the amount of power that can be produced is calculated as the sum of the two different contributions corresponding to the high pressure and low pressure expansion:

$$W_{HP} = m_7 \cdot (h_7 - h_8) + (m_7 - m^*) \cdot (h_8 - h_9) \tag{14}$$

$$W_{LP} = m_{10} \cdot (h_{10} - h_{11}) \tag{15}$$

Using similar considerations, the three values of the pumping power, referred to low, medium and high pressure, P_{1-2}, P_{3-4} and P_{5-6} can be evaluated, thus the net power that can be produced is obtained as:

$$W_{net} = W_{HP} + W_{LP} - (P_{1-2} + P_{3-4} + P_{5-6}) \tag{16}$$

Considering the values of the different variables (in this case the two values of the intermediate pressures), being the maximum pressure fixed at 150 bar and the pressure imposed by the pipeline at 80 bar, a lot of possible configurations can be proposed. For each solution the value of W_{net} can be obtained: the values of the enthalpy in the different point are obtained by means of the thermodynamic tables of CH_4 contained in the utility CATT (Computer Aided Thermodynamics Tables), from the textbook [25].

The configuration considered is the one that corresponds to the maximum net power produced W_{net} as defined with Eq. (3). It is obtained as a result of a sensitivity analysis with respect to the values of the two intermediate pressures. In particular the optimal values obtained for the two intermediate pressures are 4 bar and 35 bar. The thermodynamic states of the whole recovery cycle are reported in Table 3. The two values of the output power W_{HP} and W_{LP} are obtained assuming isentropic efficiency of 0.85 for the high pressure (operating between 150 and 35 bar) and 0.9 for the low pressure turbine (operating between 35 bar and 4 bar).

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	

Considering the data of Table 3, it is possible to observe the values of the pumping power related to the various pressure increases, P_{1-2}, P_{3-4} and P_{5-6}. It is interesting to observe especially the last value which seems to be quite relevant with respect to the specific expansion enthalpy.
Using the data of Table 3 and the mathematical model assumed, working with quantities expressed per unit mass of natural gas flowing to the pipeline, the results reported in Table 4 can be obtained. In particular Table 4 summarizes all the mass flow rate ratios and the specific power correspondents to the different stage of turbine and to the three pumps.

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

From the analysis of the results of Table 4 it is possible to understand that, considering configurations like the one with the three pressure levels (4 bar, 35 bar and 150 bar), an electricity generation of the order of magnitude of 120 kJ for each kg of natural gas regasified can be obtained. This value is similar to the one typical for conventional ORC cycles and corresponds to a second law efficiency of 28%. Assuming a LNG mass flow rate, typical of various regasification terminals in the world, of 70 kg/s, that corresponds to a nominal annual production rate of about $3.5*10^{9}$ m^3 of natural gas. an output power of about 8.37 MW can be obtained, as the product of the defined mass flow rate ($m^* = 70$ kg/s) and the term W_{net} / m^* in Table 4. Higher values of the specific output power could be obtained considering values of the maximum pressure higher than 150 bars. The particular value of the mass flow rate is selected because it is in the range of the plants reported in [23] and because it corresponds to the planned annual send-out capacity of the terminal for LNG regasification operating in Italy, at Panigaglia.

3.2. Analysis of more complex configurations with recovery heat exchangers

Further improvements of the direct expansion cycle analyzed in Fig. 6 and 7 can be obtained considering the plant reported in the sketch of Fig. 8. This configuration is the one that, considering the imposed boundary conditions of the maximum operating pressure, permits the maximization the energy recovery for electricity production. The results is obtained, according to the sensitivity analysis obtained varying the values of the intermediate pressures, the efficiency increase with respect to the results analyzed in the previous section, is the result of the internal heat recovery (regeneration) obtained by means of the introduction of a new heat exchanger (RHE). With reference to the scheme of Fig. 8, considering all the mass and energy conservation equations, a system of equations, similar to the one reported in section 3.1, can be written. Using boundary conditions similar to those assumed for the basic cycle of Fig. 6 (final pressure of the level required for long distribution pipelines, maximum pressure of 150 bar, isoentropic efficiency of pumps and turbines equal to 0.9 and efficiency of the RHE equal to 0.95), working on the intermediate pressure levels and optimizing the ratios among the various streams, it is possible to obtain a specific power production of 130 kJ for each kg of natural gas flowing through the plant, while considering the final pressure in the pipelines at 60 bar (instead of 80 bar), the level of 163 kJ/kg can be approached. In this case three different pressure levels are considered: 4 bar, 10 bar and 27 bar. The Second Law efficiency of the recovery cycle is quite close to 0.4. Like for the recovery configuration analyzed in the previous section, a sensitivity analysis has been developed; several configurations have been analyzed modifying the values of the various mass flow rates, considering as fixed the values of the upper pressure (150 bar) and the number of pressure levels. The data of the optimized configuration are summarized in the Tables 5 and 6. Table 5 provides the thermodynamic states while Table 6 contains all the values of mass flow ratios and the specific power of each component (pumps and turbines).

Table 5. Data referred to the various Thermodynamic states of the direct expansion cycle with recovery heat exchangers: configuration of maximum electricity generation

State	T [°C]	p [Mpa]	v [m^3/kg]	h [kJ/kg]	s [kJ/kgK]	X
1	-161.50	0.1013	0.002367	-286.50	4.934	0
1’	-161.50	0.1013	0.550100	223.80	9.504	1
2	-161.20	1.0	0.002364	-284.20	4.936	
3	-124.00	1.0	0.002780	-147.30	5.988	0
3’	-124.00	1.0	0.063670	268.10	8.773	1
4	-123.00	2.7	0.002765	-142.50	5.988	
5	-98.97	2.7	0.003362	-33.74	6.657	0
5’	-98.97	2.7	0.021350	259.30	8.340	1
6	-85.50	15.0	0.003111	6.04	6.658	
6*	-78.27	2.7	0.029330	336.30	8.759	
7	-78.70	15.0	0.003251	34.59	6.808	
8	15.00	15.0	0.007871	442.80	8.529	
9is	-45.90	6.0	0.013860	352.50	8.529	
9	-43.50	6.0	0.014270	361.50	8.569	
10*	15.00	6.0	0.022080	536.80	9.253	
10	15.00	6.0	0.022080	536.80	9.253	
11is	-39.40	2.7	0.039870	441.40	9.253	
11	-35.61	2.7	0.040800	450.90	9.293	
12	15.00	2.7	0.052400	573.40	9.761	
13	-85.60	0.4	0.235400	379.20	9.879	

Table 6. Details of the direct expansion optimized recovery configuration

Mass flow ratio	Power ratio	Values
m'/m^*		0.3703
$(m-m^*-m')/m^*$		0.2600
$(m-m^*)/m^*$		0.6303
m/m^*		1.6303
	W_{HP}/m^*	132.548 kJ/kg
	W_{MP}/m^*	54.148 kJ/kg
	W_{LP}/m^*	50.496 kJ/kg
	W_{gross}/m^*	237.191 kJ/kg
	P_L/m^*	2.362 kJ/kg
	P_M/m^*	6.599 kJ/kg
	P_H/m^*	65.463 kJ/kg
	P/m^*	74.424 kJ/kg
	W_{net}/m^*	162.767 kJ/kg

Analyzing the data of the Tables 5 and 6 it is possible to observe that in the optimized configuration the first two streams, represented by mass flow rates m'/m^* and $(m-m^*-m')/m^*$ are balanced and assumes similar values (0.37 and 0.26), while the third value is approximately double of the others: 0.67.

An increase of about 43 kJ/kg can be obtained and this corresponds to a percentage increase of 35% with respect to the basic recovery configuration, analyzed in the previous section and represented in Fig. 6 and in Fig. 7. Assuming the data of Table 6, in particular the term W_{net}/m^* and the mass flow rate of 70 kg/s, the output power can approach the value of 11.40 MW.

3.3 Feasibility of the technical solutions proposed

In order to better understand the potential for the practical development of the advanced direct expansion configurations proposed in the present paper for electricity generation in LNG regasification plants, an analysis of the technological background is of primary importance. Concerning the various components of the plant, turbo-expander technology plays an important role in the perspective of a practical development of the two solutions proposed. Considering the available technology and the various components, the only critical element is represented by the high pressure of turbo-expander, even if, given the open literature sources, analyzing the available technology of turbo expander-generator configurations a pressure of 150 bar is guaranteed by some manufacturers: pressure up to 200 bar with output power up to 15 MW operating with pure or mixed fluids including natural gas, petrochemical products, hydrogen, air, steam, etc., like [26].

So the development of a configuration like the one represented in Fig. 6 appears to be possible and a valid alternative to ORC based plants, that are rather complex and involves the use of an auxiliary fluid and of the solutions represented by combined cycles consisting of two cascading Rankine cycles, like the one proposed in [27]. A possible technological problem is represented by the low temperature at the end of expansion. If the two expanders at medium pressure level are considered, the final theoretical temperature as reported in Table 5 are -72.5 °C (point 9) and -97.2 (point 11), values well below the zero level.

Those low temperature values can determine some additional structural problems. So the development of a configuration like the one of Fig. 8 appears to be also possible even if some additional problems connected to the operating mode of the various recovery heat exchangers have to be analyzed.

4. Conclusions

In the present paper the problem of electricity generation using LNG cold energy in regasification stations has been analyzed with the specific aim to evaluate the perspectives of advanced direct expansion configurations.

After a preliminary analysis of the various conventional options, a specific three pressure level configuration with multistage has been analyzed and modelled. Considering an upper limit for the higher pressure (150 bar) and a boundary condition imposed by the pipeline at a level 60-80 bar (a pressure typical for long pipelines), a potential of power production of 120 kJ for each kg of natural gas flowing through the system have been estimated: this value corresponds to the typical values declared for optimized systems based on ORC, but the resulting plant appears to be surely less complex. Analyzing configurations that include multistage expansion and recovery heat exchangers, it is possible to obtain further increase of the specific power production up to a level of more than 160 kJ for each kg of natural gas regasified.

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 natural gas at a temperature well below the environmental temperature and ideal heat exchangers configurations), the results that can be obtained with a Thermodynamic analysis of the proposed recovery cycles 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. For given operating conditions and with correct matching between working fluid and energy conversion cycle, it is possible to obtain very similar performances in a number of different cases: ORC cycle, Brayton cycle and direct expansion.

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Figure captions

Figure 1. T-s diagram for LNG at various pressures

Figure 2. Direct expansion systems for power production: conventional scheme

Figure 3. LNG cold energy recovery with Rankine Cycle With Intervening Media

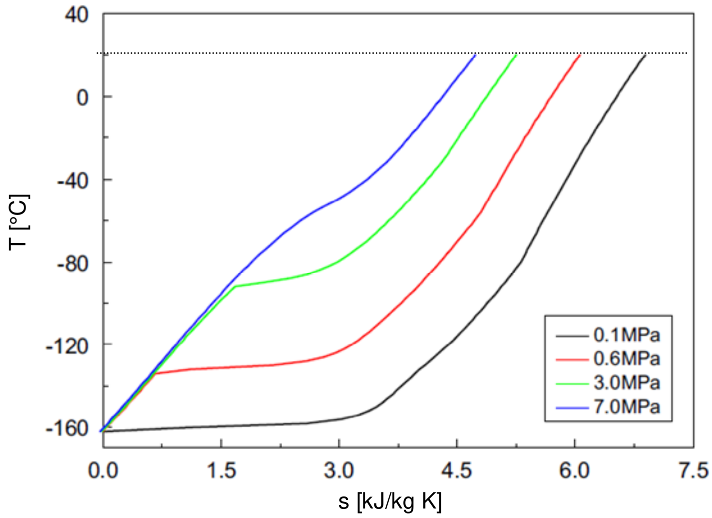
Figure 4. The cooling capacity of supercritical LNG in relation to Rankine cycle

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

Figure 6. Electricity generation with direct expansion cycle: basic multi-pressure configuration analyzed

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

Figure 8. Electricity generation with direct expansion cycle: multi-pressure configuration with recovery heat exchangers



40
0
-40
-80
-120
-160
T [°C]
0.0
1.5
3.0
4.5
6.0
7.5
s [kJ/kg K]
0.1MPa
0.6MPa
3.0MPa
7.0MPa

Fig. 1.

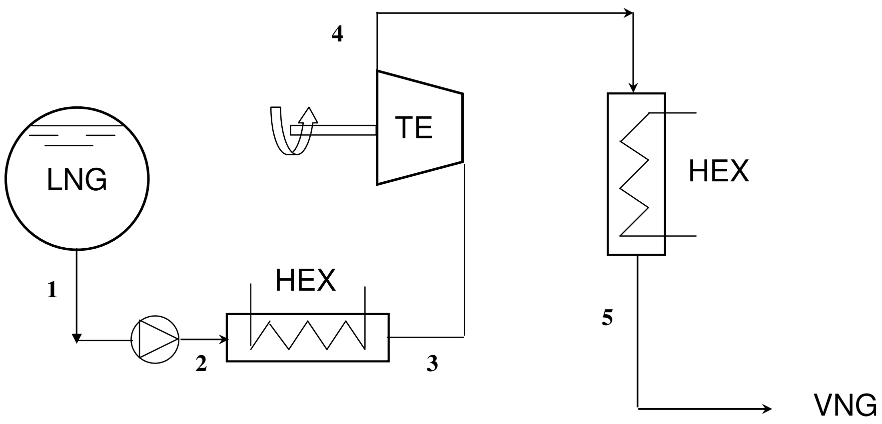


Fig. 2

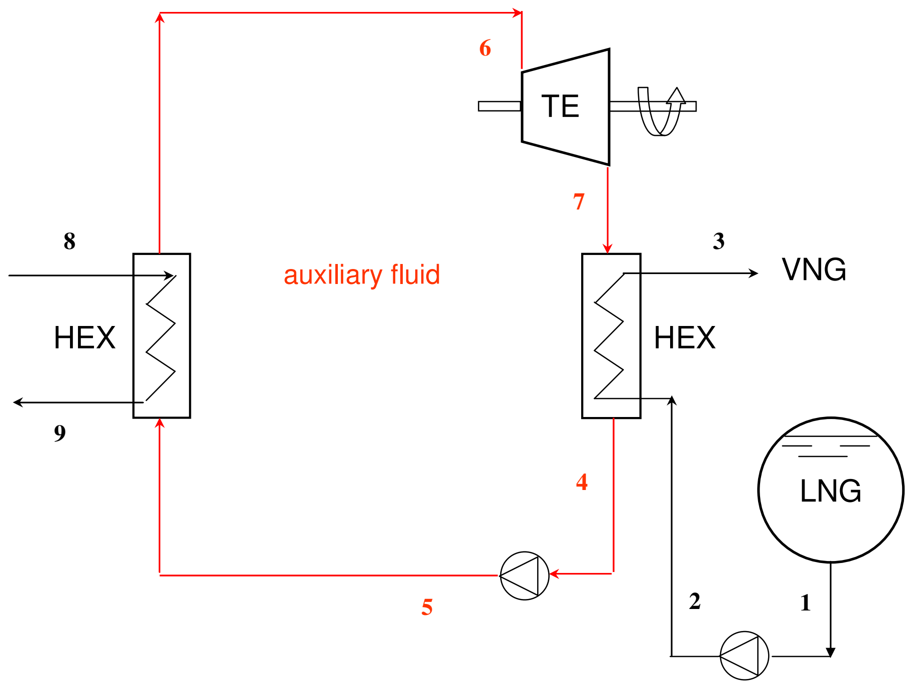
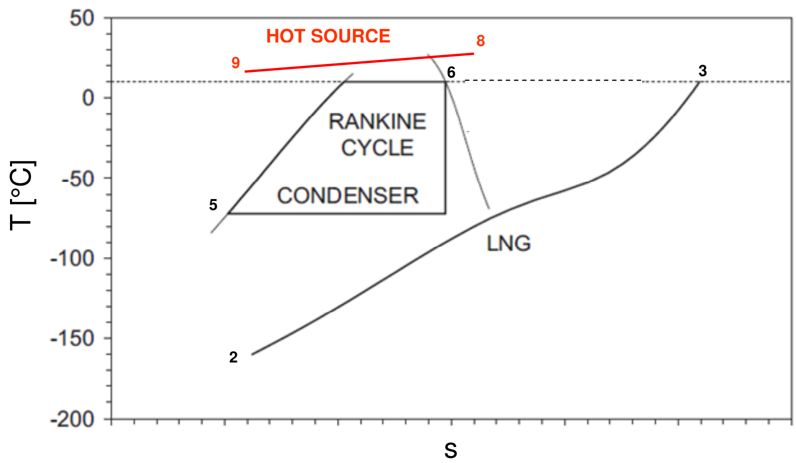


Fig. 3



HOT SOURCE
9
8
6
3
RANKINE
CYCLE
CONDENSER
5
LNG
2
50
0
-50
-100
-150
-200
T [°C]
S

Fig. 4

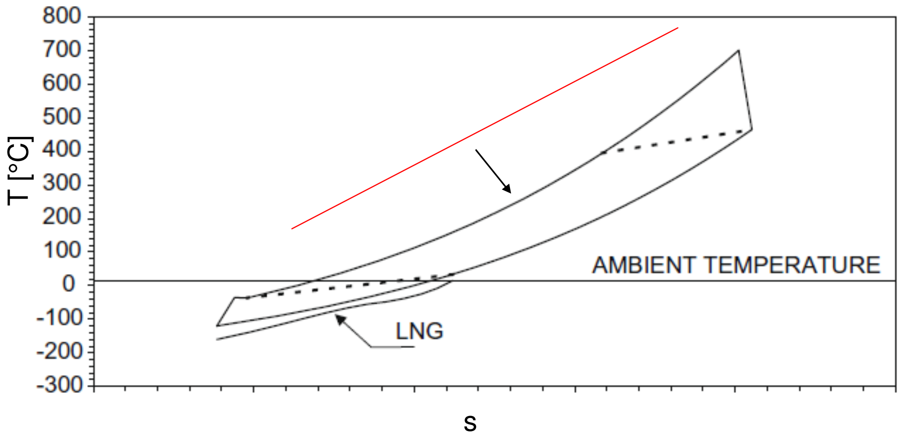

800
700
600
500
400
300
200
100
0
-100
-200
-300
T [°C]
AMBIENT TEMPERATURE
LNG
s

Fig. 5

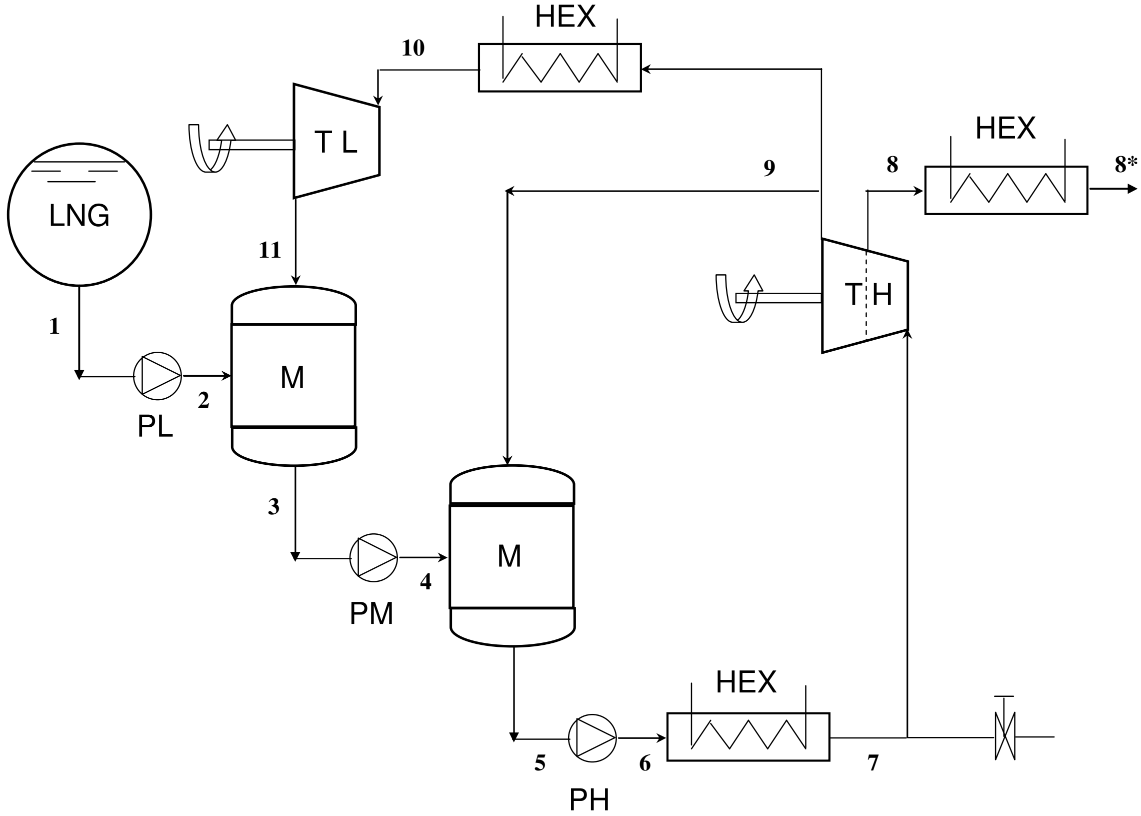


Fig. 6

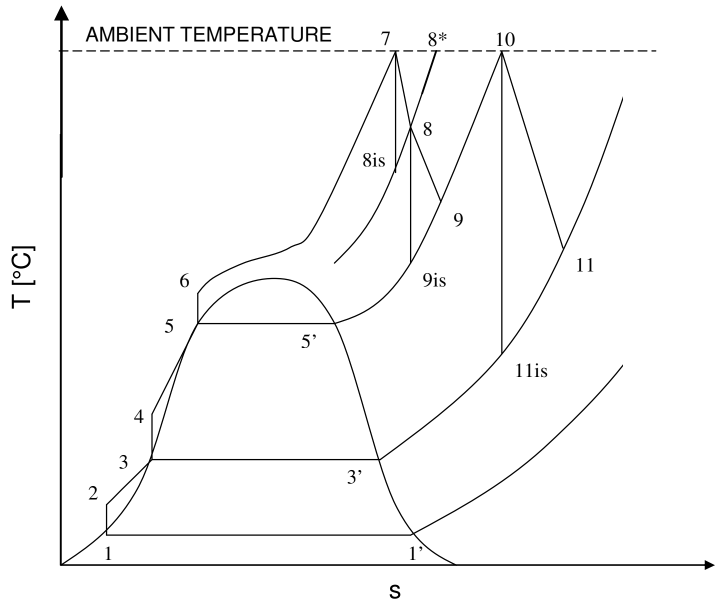
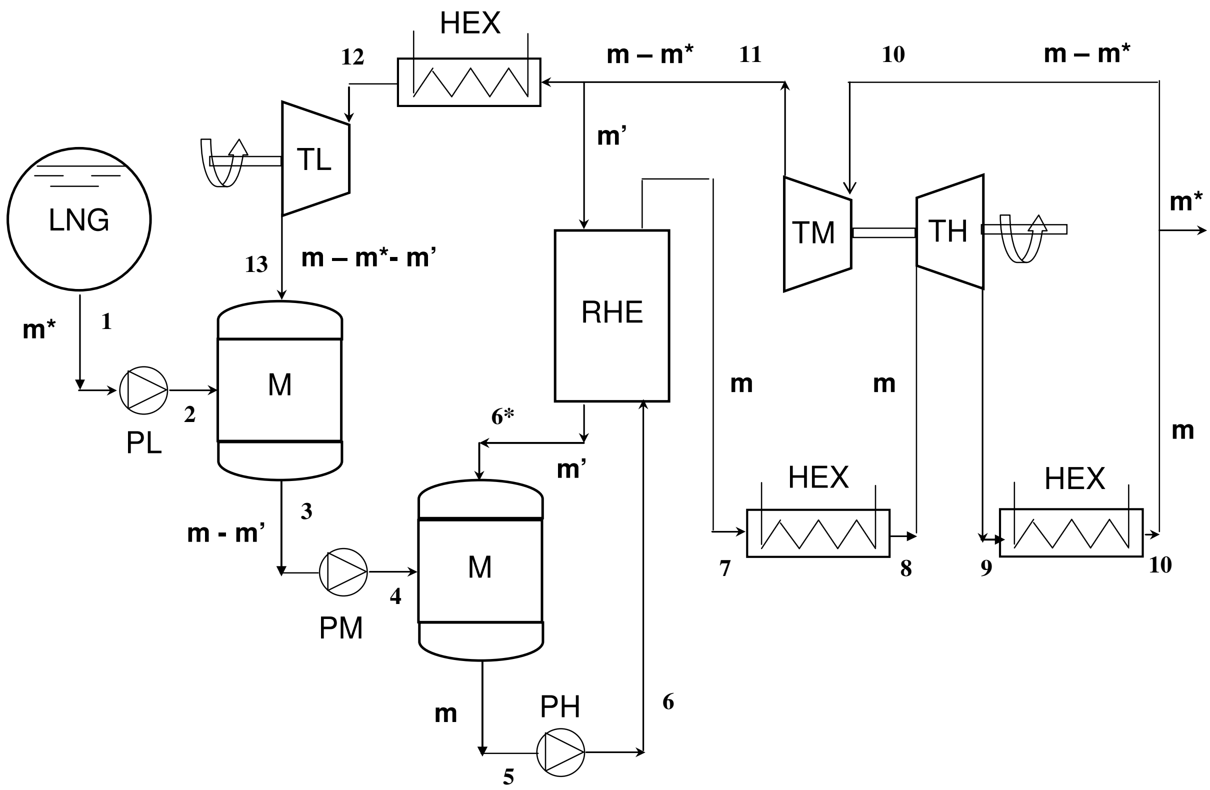


Fig. 7



HEX
12
m – m*
11
10
m – m*
m'
TL
LNG
TM
TH
m*
13
m – m*- m'
RHE
m*
1
M
m
m
PL
2
6*
m
m'
HEX
HEX
3
m - m'
M
7
8
9
10
PM
4
m
PH
6
5

Fig. 8