RECOVERY OF CRYOGENIC ENERGY IN LNG REGASIFICATION

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Scope of this work is to present methods of processing LNG in a plant where its cryogenic content is recovered, mainly to generate power and/or to improve power generation. The energy market will continue to be pushed by a continuously increasing demand. According to a forecast published by U.S. EIA (International Energy Outlook 2010 – Highlights, U.S. Energy Information Administration, release date: May 25, 2010), after the recession that began in 2007 and continued in 2009 causing a world energy demand contraction in the near term, the world energy consumption is expected to increase by 49% from 2007 to 2035 (in particular an 84% increase will occur in nations outside the Organization for Economic Cooperation and Development). World net electricity generation is presumed to significantly increase by 2035.
Moreover the tendency, particularly evident in Italy, is to reconvert fuel oil and coal plants into combined cycles: as it is well known natural gas is the fossil fuel preferred in that type of power stations; and for that reason it is increasing its weight among the energetic sources.
This consideration has led us to value if it is convenient and feasible to integrate the production of the electric energy and the regasification of LNG, being gas and electricity two goods whose demand grows in the same way.
Use of LNG as cold source of an integrated power cycle should allow to avoid the energetic waste due to the conventional regasification recovering part of the energy utilized in the liquefaction process.

1. INTRODUCTION

Natural gas is the world's third source of primary energy, after oil and coal (Fig. 1). The world consumed 3047.78 Bm^3 (billion cubic meters) of natural gas in 2009 (Eni, 2010a).
This source is the cleanest burning fossil fuel and produces less emissions and pollutants than crude oil or coal. Since the early 1970s, natural gas world reserves have steadily increased at an annual rate of 5% (Eni, 2010a). Similarly, the number of countries with known reserves has also increased from about 40 in 1960 to about 85 presently.
At the present time natural gas provides the 45% of the total energy demand in Italy (the consumption in 2009 was 76.25 Bm^3) with a production/consumption ratio showing a decreasing trend: from 0.30 in 1998 to 0.14 in 2015 and 0.10 in 2009 (Eni, 2010a).
Italy is one of the biggest consumers of foreign gas in Europe, second only to Germany, and the fourth importer of natural gas in the world. The dismantlement of nuclear power plants and the opposition to coal have moved the energetic policy toward an increasing exploitation of natural gas for civil and industrial uses, so that, since the second half of the 1980s, its annual rate of growing has exceeded that of all the other primary sources (Eni, 2010a; 2010b).
This is mainly due to the fact that natural gas remains the most important fuel for electricity generation in Italy. Electricity generation, whose demand has increased of 7.3% in the first three months of 2010 (Eni, 2010b), is less expensive with natural gas than with oil as the primary source, and natural-gas-fired generating plants are less capital-intensive than plant that use coal, nuclear or most renewable energy sources (EIA, 2010).

The aching point of the Italian situation is the absence of primary energetic sources that could free our country from the energy dependence on the rest of the world.

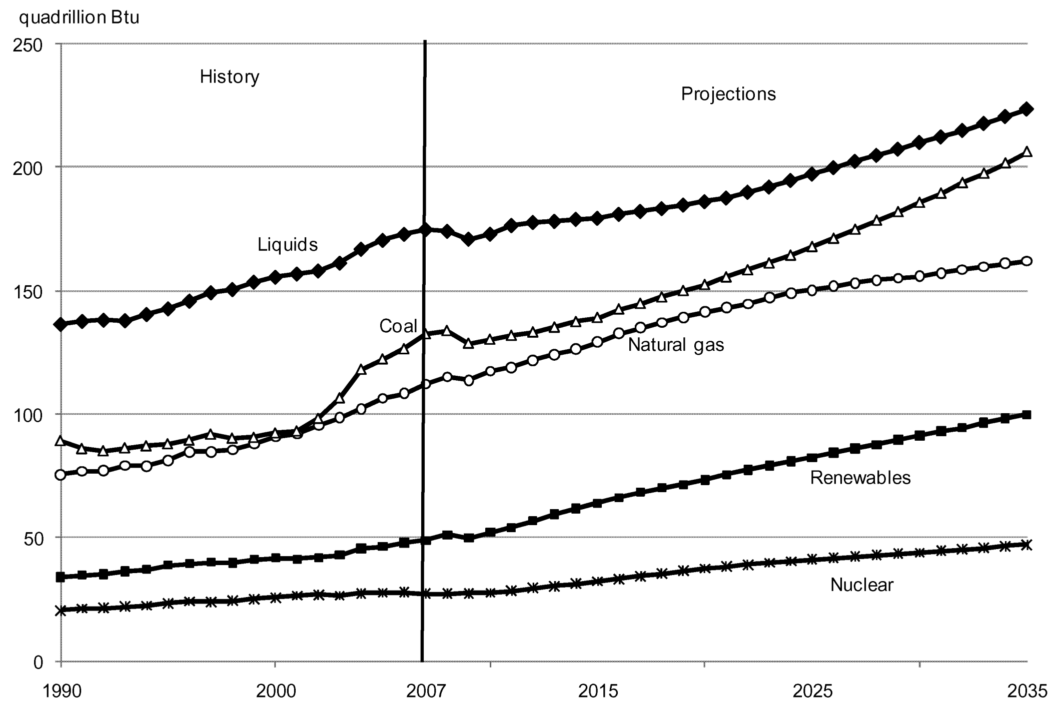

Fig. 1: world marketed energy use by fuel type, 1990-2035 (source: EIA, International Energy Statistics database (as of November 2009), web site www.eia.gov/emeu/international. Projections: EIA, World Energy Projection System Plus (2010)).

The 2005 winter events about the reduction of Russian natural gas supply, that involved Italy in an unannounced energetic crisis, and critical situations (for instance between Iran and Turkey or Russia and Ukraine) have spotlighted the necessity of a more rational exploitation of the energy sources, the "fragility" of the pipeline importation system directly controlled by the unstable geo-political situations, and the consequent unacceptable repercussions on people with increasing costs.

In Italy there are only four pipelines to import natural gas for a total amount in 2009 of 75.31 Bm^3 and these structures limit the Italian gas market and narrow it to few providers (Russia, Algeria, Libya and North Europe) (Eni, 2010a).

With the present economic and political situation in Italy, one possible solution could consist in an alternative and less binding energetic exploitation of the sources than the pipeline system.

Liquefied natural gas (LNG) shipping, 2.89 Bm^3 to Italy in 2009, could allow to negotiate with more suppliers in the world for a more competitive market.

Moreover LNG has a further energetic benefit: during its regasification, in order to send it to the national distribution network, its "cold", released during the regasification process, could be exploited to produce other forms of energy.

Fig. 2: GNL Adriatico Porto Levante (RO) regasification terminal (source: www.adriaticlng.com)

Unfortunately, the only operative import and regasification terminals of LNG in Italy are located in Panigaglia, the oldest one with its two tanks of 50000 m^3 each, and at Porto Levante offshore (RO), opened in 2010 (Fig. 2). New LNG facilities are in project in Italy (Table 1) and natural gas will undoubtedly emerge as the dominant fuel, first for power generation, then, in the longer-term, for transportation - a far more demanding energy transition.

Table 1: Regasification terminals in Italy at 2010 (source: Autorità per l'Energia Elettrica e il Gas, http://www.autorita.energia.it/it/dati/infragas3.htm)

Company	Location	Status	Capacity [SBm^3/y]
GNL Italia	Panigaglia (SP)	working	3.5*
Terminale GNL Adriatico	Offshore Alto Adriatico - Porto Levante (RO)	working	8
Brindisi LNG	Brindisi	authorized	8
OLT (Offshore LNG Toscana)	Livorno	authorized	4
Nuove Energie	Porto Empedocle (AG)	authorized	8
Edison, BP, Solvay	Rosignano Marittimo (LI)	authorization pending	8
LNG MedGas Terminal	Gioia Tauro (RC)	authorization pending	12
Gas Natural Internacional	Taranto	authorization pending	8
Erg Power & Gas, Shell Energy Italia	Rada di Augusta (SR)	authorization pending	8
Terminale Alpi Adriatico (Endesa Europa 100%)	Trieste	authorization pending	8
Gas Natural	Zaule (TS)	authorization pending	8

*submitted request in 2007 for increasing the capacity from 3.5 to 8 SBm^3/y.

The increase in the use of natural gas is inevitable and desirable, before we can reach the “carbon free” energetic system. We all wish that such “carbon free” system will be adopted, even against our interests of technical operators in the hydrocarbons field (we must take example from Sheikh Jamani, that said “it is not necessary to wait for exhaustion of oil to end its era, since the stone age did end because the man by his talent learned to forge the metals, not certain because the escorts of stone exhausted”).
But the full substitution of the hydrocarbons is not possible in the short period.

2. THE UTILIZATION OF LNG CRYOGENIC ENERGY

Till now the numerous studies about the possible LNG utilizations have led to different solutions, which all have a common denominator: the “cold” can be used advantageously by integrating the LNG terminal with other facilities (Price, 2003).
Some possible uses are (Hirakawa and Kosugi, 1981):
1) integrating with cryogenic facilities (air separation, frozen foods, dry ice, etc.);
2) generating electrical power;
3) integrating with power generation;
4) integrating with petrochemical/chemical facilities.

2.1 Integration with cryogenic facilities

Facilities that can utilize lower temperatures are preferred because they can take full advantage of the “cold” available from the LNG (Price, 2004).
Air separation units are often considered due to the direct use of low temperatures in the process.
For air separation using LNG cryogenic energy, the electric power consumption is reduced by half.
Other direct applications of cryogenic energy include the production of liquefied carbonic acid and dry ice, and the use of cryogenic energy for cold storage warehouses.
Cryogenic energy is also being used for the reliquefaction and recapture of the boil off gas that is emitted from LNG tanks. The critical constraint with this method is locating such a facility adjacent to the terminal to achieve close coupling of the processes. Also, the facility using the “cold energy” must run at design capacity continuously to support the LNG terminal operation.

2.2 Electric power generation

Electric power generation can be achieved using expansion of the vaporized LNG or using a Rankine cycle system with an intermediate heat-transfer fluid.
Also, combinations of the two technologies have been used. These systems were developed in several Japanese terminals that generate 10 MW of power. These systems are quite complex and expensive to install and operate. High electrical power pricing is needed for this method to be economically feasible.

2.3 Integration with power generation

Another option that offers strong economic impact is integrating the LNG terminal with a combined-cycle-power generation facility (Cotana and Pispola, 2005; Hisazumi et al.,1998; Kaneko et al., 2004). In this approach, the power plant is the sink for the LNG cold and using seawater for vaporization or fired vaporization is eliminated. Capital costs and environmental impacts are dramatically lowered via this method (Price, 2003). Integration is often accomplished using a glycol/water heating loop to capture the cold energy, which is applied in the power cycle. The cooling can be applied in different ways:
1) inlet chilling of the turbine air. The inlet air is easily chilled to 10°C with the glycol/water. In warm climates, this chilling can allow the turbine to produce about 10% additional power. The only “cost” to the power plant is the inlet chillers, which are a small investment for such a large power boost;
2) condensing steam in the power cycle. The heat medium can be used to condense the steam in the power cycle instead of cooling water. The glycol/water simply replaces the cooling water in the steam condensers. The cooling water system (cooling tower, pumps, etc.) can be eliminated or significantly reduced in size with this

integration. The heat medium is available at a lower temperature and allows an additional boost of 1-2% in the combined cycle power.
3) cooling the exhaust of gas turbines. In an application at the Zeebrügge terminal Belgium (Inside Energy. LNG, 2008), the exhaust gases from a gas turbine are cooled by a circulating stream of water, which after being heated is used to regasify LNG. The flue gas-water contact is realized in a packed tower; that has the advantage of recovering also the latent heat from the condensation of water vapor in the turbine exhaust, with an increase in efficiency, and to give reduced emissions of heat and water vapor to the atmosphere.
In addition to these listed benefits, other advantages are possible:
1) fuel supply for power generation directly from the LNG terminal;
2) power supply from generation to the LNG terminal;
3) integration of operating and maintenance organizations;
4) sharing of common utilities and infrastructure (buildings, firewater, potable water, etc.).

2.4 Integration with chemical facilities.

The LNG "cold" can be used beneficially in many other process facilities. The LNG vaporization is typically accomplished with a heat medium such as glycol/water. This medium is used for process cooling in the adjacent process facility. By using this heat medium, seawater intake, large piping and outfall facilities can be eliminated. The heat medium can be designed with a much larger temperature ΔT, such that the flow rates handled are much smaller than in a typical seawater ORV (open rack vaporizer) system.

3. RANKINE CYCLE WITH A HYDROCARBON MIXTURE

Standard facilities for producing electricity during natural gas regasification can be modified in order to take the maximum advantage from the energy required for LNG vaporization. In particular, in this work, a novel configuration for a Rankine cycle is analyzed: the use of an hydrocarbon mixture as the working fluid is discussed.

3.1 "Standard" Rankine cycle: the Osaka system LNG cryogenic power generation plant

In this Rankine cycle, the working fluid is propane and the heat source is seawater.
LNG cryogenic energy is used to condense the propane coming out from the expander while seawater is employed to vaporize the compressed propane and to heat the stream of natural gas after the regasification (Osaka Gas, 2011). A flow scheme of the Osaka Gas Cycle is reported in Fig. 3.
The main advantage of this cycle is the production of electricity by exploiting the heat available from a natural source, but this aspect has its own drawbacks. The first one is that the seawater utilization limits the maximum cycle pressure, since the boiling temperature of propane at the maximum cycle pressure must be lower than the seawater temperature. The second one is the large seawater flow rate needed. The limitation on the maximum cycle pressure leads to a moderate efficiency of this type of cycle.

3.2 Proposed Rankine Cycle

The Rankine cycle proposed in this work is a Rankine cycle with a three-way heat exchanger in which the working fluid is a hydrocarbon mixture whose composition is reported in Table 2.
The use of a mixture instead of a pure fluid has been extensively studied elsewhere (Nava and Locatelli, 2006): the composition of the mixture sets its flow rate (at a given flow rate of LNG to be regasified) and thus it is directly linked to the power that can be produced by the Rankine cycle.
The configuration of the proposed cycle is shown in Fig. 4.
The proposed cycle has been simulated and optimized by means of the Aspen HYSYS® process simulator (Aspen HYSYS®, 2008). The following data have been used as the basis for the design:
1) the LNG flow rate has been set to 5311 kmol/h (1 Gm^3/y for 8400 h/y);
2) the adiabatic efficiency of the expander is 85%. This is a reasonable values for average-size machineries (Guarnone, 2006);
3) pump efficiency is 75%;

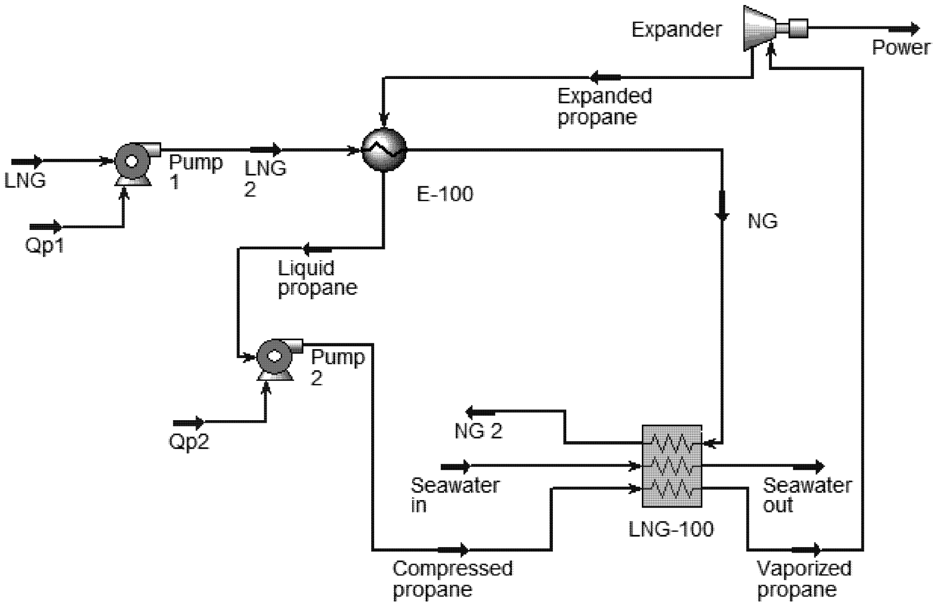

Fig. 3: typical flow scheme of an Osaka gas cycle.

Table 2: Composition of the working fluid

Compound	Mole %
methane	30 %
ethane	10 %
propane	30 %
n-butane	10%
n-pentane	10 %
n-hexane	10 %

4) each heat exchanger must have an *UA* value that does not exceed 1×10^7 kJ/(°C h);
5) the allowed minimum approach in each heat exchanger is 5°C.
The optimization has been aimed to maximize the cycle efficiency (η) defined as the ratio between the net (produced) electric power and the power required by the Heater (see Fig. 4):

$$\eta = \frac{\dot{W}_{el}}{\dot{Q}} \quad (1)$$

It has been chosen to resort to an external heating source (e.g., a fraction of the natural gas produced by the rigasification plant) for the working fluid in order to maximize the electricity production. The temperature of the stream 24 has been set to 500°C in order to avoid thermal cracking phenomena.
The variables subjected to optimization have been:
1) the cycle ΔP (i.e., the pressure of the streams 21 and 25);

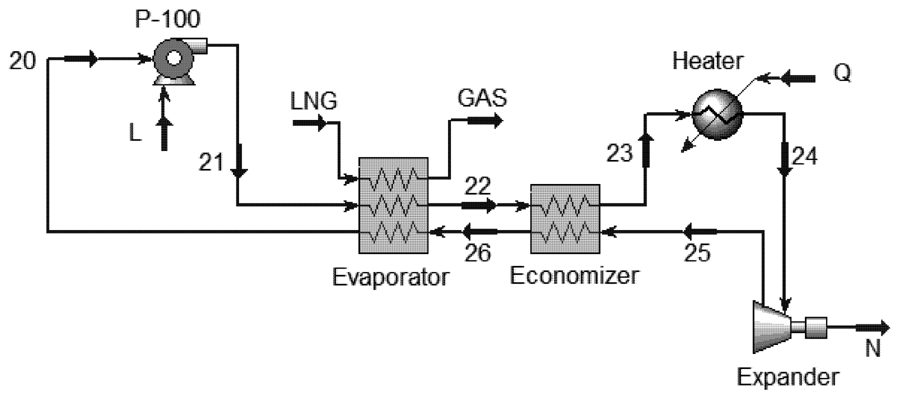

Fig. 4: proposed Rankine cycle flow scheme.

2) the temperatures of the streams 20 and 22;
3) the flow rate of the working fluid.
The optimum set of adjustable variables has allowed to obtain a cycle efficiency equal to 0.5174.
In the following, a more detailed description of the cycle is given.
LNG from the storage tank is pumped to a suitable pressure, which is typically 70 bar to meet pipeline inlet pressure. In the simulation it has been supposed that the LNG is pure methane: depending on the composition of the LNG, a separation step (in order to recover the C_{2+} fraction) before the regasification can be required (Gamba et al., 2008) in order to meet the law requirements for sending the natural gas to the distribution network.
The pressurized LNG stream is heated (and gasified) into the Evaporator (a three-way heat exchanger) by the working fluid stream 26 to the network temperature of about 15°C. The heat absorbed during LNG regasification (in addition to the power absorbed by the high pressure stream of working fluid – stream 21) is provided by the working fluid condensation.
The working fluid stream 20 is pumped to 140 bar (stream 21) and heated in the Evaporator by the low pressure stream 26 from the Economizer.
The heated fluid is preheated in the Economizer to about 285°C by the stream 25 coming out from the Expander. Then, stream 23 is heated to 500°C.
The high–pressure and high-temperature stream 24 is then expanded to 4 bar in the Expander in order to generate mechanical power and thus electricity. Stream 25 (the expanded working fluid) is utilized in the Economizer to preheat the high pressure working fluid and is subsequently condensed at cryogenic temperature in the Evaporator.
Table 3 summarizes the main data of the proposed Rankine cycle.

Table 3: Main data of the proposed Rankine cycle

Parameter	Value
Working fluid flow rate	4504 kmol/h
Net electric power	2.025×10^4 kW
Inlet heating power	3.913×10^4 kW
Evaporator UA	5.434×10^6 kJ/(°C h)
Evaporator minimum approach	6.6°C
Economizer UA	5.815×10^6 kJ/(°C h)
Economizer minimum approach	5.6°C

In order to complete the discussion about the modified Rankine cycle, the temperature profiles in the Evaporator and in the Economizer are shown in Figs. 5–6.

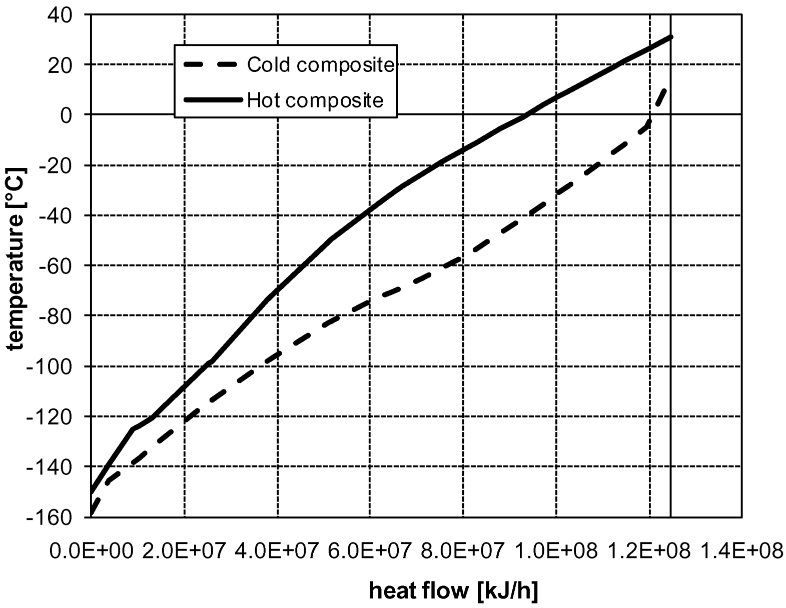

Fig. 5: temperature profiles in the Evaporator for the proposed Rankine cycle.

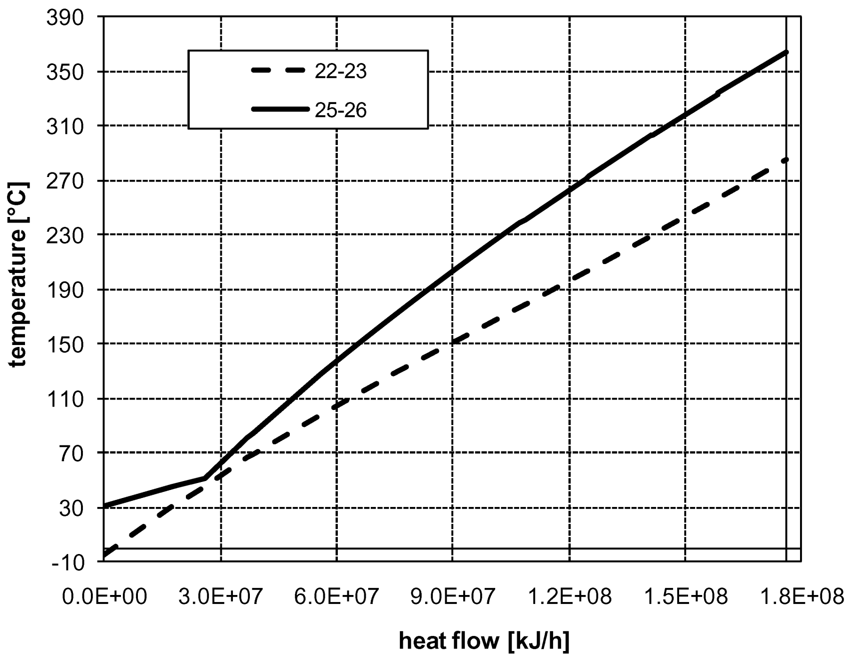

Fig. 6: temperature profiles in the Economizer for the proposed Rankine cycle.

It is clear how the economizer is the heat exchanger characterized by the highest heat duty. As a matter of fact, in this heat exchanger, the liquid working fluid vaporizes by heat exchange with itself thus minimizing the requirement of the external utility and allowing to employ a larger working fluid flow rate.
In the end, to highlight the importance of the composition of the working fluid, it deserves to be mentioned that the same modified Rankine cycle with a mixture 85% mol/mol propane and 15% mol/mol n-butane as working fluid presents an optimal set of adjustable variables that lead to an efficiency of 0.4280.
Table 4 summarizes the main data of the proposed Rankine cycle with such a propane-butane system while Figs. 7–8 show the temperature profiles in the Evaporator and in the Economizer. The Evaporator heat duty is substantially equal to the case of C_1-C_6 mixture since the main fraction of the energy exchanged in this equipment is absorbed by the LNG. On the other hand, the Economizer heat duty sensibly decreases mainly due to the decreased flow rate of the working fluid.

Table 4: Main data of the proposed Rankine cycle with a propane-butane mixture

Parameter	Value
Working fluid flow rate	3478 kmol/h
Net electric power	1.326×10^4 kW
Inlet heating power	3.307×10^4 kW
Evaporator UA	4.790×10^6 kJ/(°C h)
Evaporator minimum approach	5.1°C
Economizer UA	2.332×10^6 kJ/(°C h)
Economizer minimum approach	18.8°C

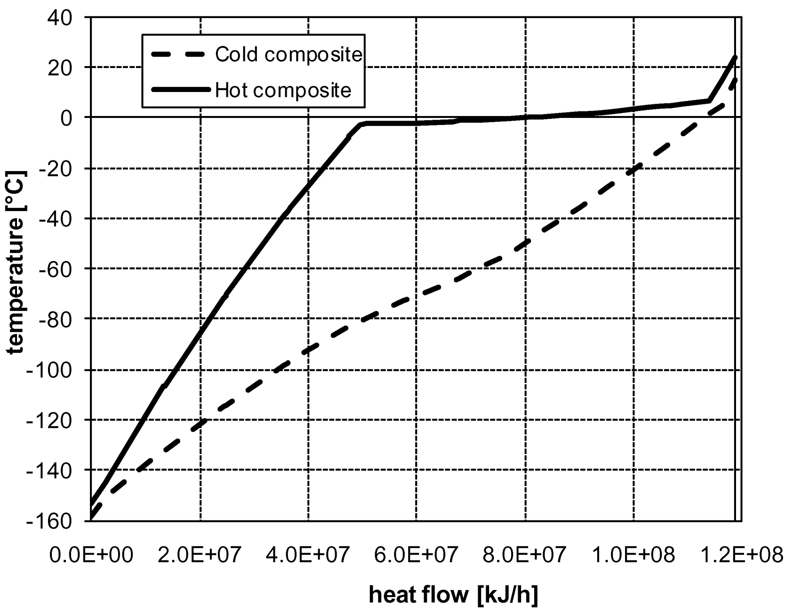

Fig. 7: temperature profiles in the Evaporator for the proposed Rankine cycle with propane-butane mixture.

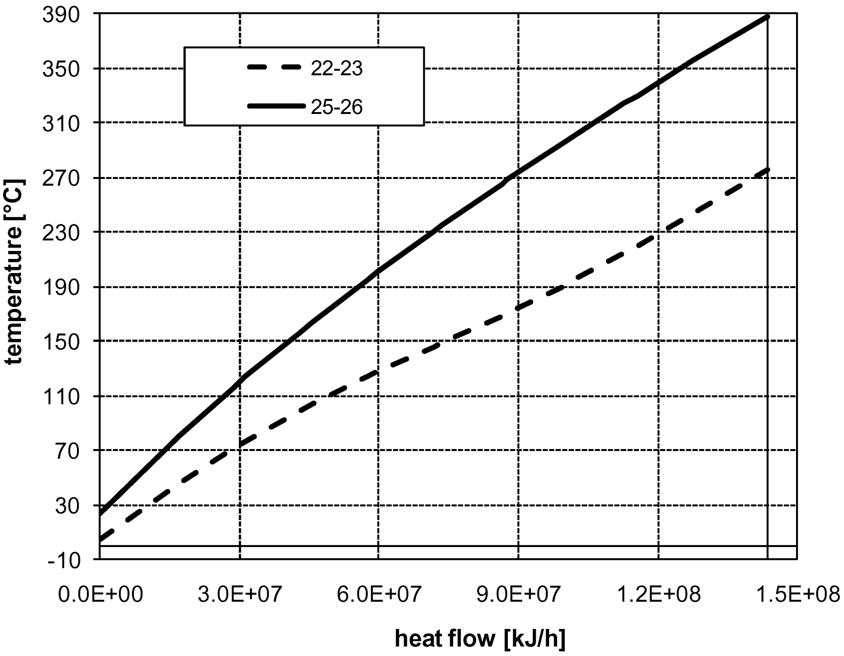

Fig. 8: temperature profiles in the Economizer for the proposed Rankine cycle with propane-butane mixture.

4. CONCLUSIONS

The constant growth of the energetic demand in the last years, the choice of giving up nuclear energy and the opposition to coal have addressed Italy towards natural gas.

But Italy is still connected by too few gas pipelines to countries characterised by a constant and critical political situation which reduces the energetic policy of our country and its economy to a situation of underdevelopment.

We need a more flexible and environmental friendly energetic market. The solution is LNG that can be shipped by-passing countries with critical geo-political situations. In fact, it can be sent from all the world so allowing the availability of a more competitive product, that otherwise couldn't arrive to the national market. From the energy point of view, the LNG regasification allows a double energetic production: the former comes from the classical use of natural gas through the national pipeline system, the latter from its cryogenic energy released during regasification. In this work, a Rankine cycle that uses a mixture as working fluid has been presented. The proposed configuration with the analyzed mixture has a high efficiency (0.5174) and the importance of the mixture composition has been pointed out by comparison between two cycles based on the same configuration and LNG flow rate but mixtures of different compositions as working fluid.

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