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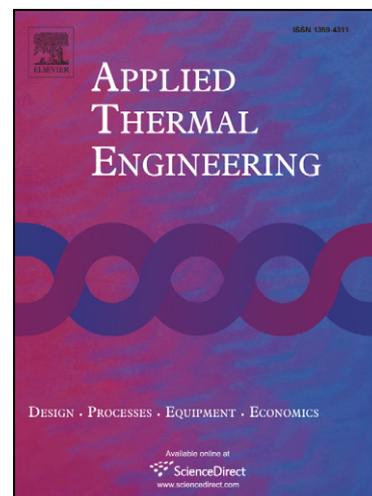
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EXERGY RECOVERY IN REGASIFICATION FACILITIES - COLD UTILIZATION: A MODULAR UNIT

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Abstract

The paper deals with the problem of cold recovery for direct utilization both in the site of regasification facility and far from it.

A modular LNG regasification unit is proposed having the regasification capacity of 2 billion standard cubic meters/year of gas. The modular plant is based on use of a Power Cycle working with Ethane or Ethylene which allows operation of cold energy transfer, contained in LNG to be regasified, in a range of temperatures suitable for multipurpose use of cold, reducing regasification process irreversibility. Some electric energy is produced by the Power Cycle, but the own mission of modular unit proposed is addressed to deliver cold suitable for industrial and commercial use in the proper

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temperature range. The option considers, also, the use of Carbon dioxide as a secondary fluid for transfer of cold from regasification site to far end users. This option seems very attractive due to expected wide future exploitation of LNG regasification in the World.

Results of a detailed thermodynamic and economic analysis demonstrate the suitability of the proposal.

Keywords: LNG Regasification - cold utilization; Carbon dioxide as secondary refrigerant ; Exergy and Economic Analysis; Safety of LNG Regasifiers

1. Introduction

The recovery of physical exergy of cold available during the regasification of LNG in a Regasification Plant is of capital interest. Cold contained in LNG has a great environmental impact, usually on the sea near the regasification site.

A suitable option [1-3] can be the production of electric energy recovering energy available as cold, using a cryogenic stream of LNG during regasification as cold source in an improved CHP Plant (Combined Heat and Power). In papers [1-2] main problems arising by feasibility study of a venture of this kind of Regasification facility have been extensively analyzed by Authors.

In past years some studies [4-9] have been carried out on the possibility of cold energy recovery in cold technology application facilities (e.g.: air liquefaction producing Nitrogen, Oxygen, Argon, deep freeze warehouse and cold storage warehouse, freezing process of foods etc.). The commercial application of cold near a regasification site has limitation and, usually, there the demand of cold is low, but due to expected wide future exploitation of LNG regasification in the World, possible applications far from the regasification site deserve a thorough analysis.

This paper deals with the problem of cold exergy recovery for direct cold utilization both in the site of regasification facility and far from it. A modular LNG regasification unit is proposed having the regasification capacity of $2 \cdot 10^9$ standard cubic meters/year.

Some results of a research carried out at DREAM-University of Palermo are reported. The research developed includes both cryogenic applications and industrial

use of cold at very low temperature inside the regasification site and cold utilization by end users far from the regasification site in deep freezing facilities and for space conditioning in the commercial sector (e.g.: Supermarkets and Hypermarkets)².

2. The regasification process

The Italian natural gas transmission system works with main pipelines at a pressure rating up to more than 70 bar, then the LNG regasified has to be sent in the transport pipeline at a pressure of the same order of magnitude. In principle it is possible (see Fig. 1, path AB'D'D) to pump natural gas at this pressure (D'D) after regasification at a low pressure (AB'B''B'''D'), but this option isn't applied in Europe.

When the regasification is carried out at low pressures and, then, the gas is compressed at the pressure required by pipelines, the pumping power (W_{NG}) is very high. Instead, if the LNG is pumped in liquid phase, at a pressure lying in the pressure rating range required by pipelines (hypercritical pressures) there is convenience because the pumping power (W_{LNG}) is lower (see Fig. 1, path ABCD).

The ratio W_{NG}/W_{LNG} is higher than 20 [1]. Moreover, with regasification at hypercritical pressures, the heat exchange by the LNG side is very good and heat transfer equipment is more reliable. The process proposed works at hypercritical pressures (pressure in the LNG regasification loop lies in the range 75÷80 bar) [1].

² research developed at DREAM University of Palermo in the framework of the Program "ORPA059444: "Innovazione tecnologica di sistemi energetici e loro componenti; metodologie di progettazione, verifica e simulazione"

A typical composition of LNG considered in the feasibility analysis of DREAM is that reported in Table 1 in which are included also main thermo-physical properties and both the higher and lower heating values³ of natural gas obtained after the regasification process. This kind of composition is quite usual for LNG processed in a regasification site.

The transport of natural gas by pipeline from gas field to the town or industrial sites in most cases is impossible, so there is need to transport LNG by ship. At the terminal of arrival a regasification process of LNG, which is processed and liquefied near well-head, returns it back to gas state before its transport in the pipeline network. Sometimes LNG contains other hydrocarbon products which are added during the process of liquefaction to transport these products with LNG at the regasification facility, then some components added will be separated before transport of gas to market by pipeline. In this case the LNG composition is different from that reported in Table 1 and the plants used are cryogenic facilities which in some cases become so complex that are seeming to a part of a modern oil refinery or a petrochemical plant⁴.

3. Delivery of cold recovering exergy of cold during regasification of LNG

Fig. 2 shows a process sheet of a modular multipurpose regasification facility, proposed by the Authors, to recover LNG physical exergy for cold utilization.

³ calorific values

⁴ a process of this kind was managed at Panigaglia, Italy in a regasification site belonging to ENI Group

The process includes both possibility to use cold at lower temperatures for industrial use and cold at higher temperatures for other use. The plant proposed [9] is modular and has a regasification capacity of $2 \cdot 10^9 \text{ Stm}^3/\text{y}$ when working 24 hour a day all a year around (270 days⁵).

A facility of such kind requires an intermediate Power Cycle working with a suitable fluid such as Ethane or Ethylene, the cycle can produce 3 MW of electric power. Cold at very low temperatures is delivered by LNG in the condenser, while in the vapor generator cold is delivered in a secondary fluid which transfer cold to end users. This plant structure allows operation of cold exergy transfer, contained in LNG to be regasified, in a range of temperatures suitable for multipurpose use of cold, reducing regasification process irreversibility. Some electric energy is produced by the Power Cycle, but the own mission of modular unit proposed is addressed to deliver cold suitable for industrial and commercial use in the proper temperature range.

Ethane can be used currently in a facility addressed only to regasify LNG, while Ethylene can be used in a facility where this product is available.

In the process represented in Fig. 2, which is that using Ethane, cold can be produced at lower temperatures suitable for industrial applications ($-80^\circ\text{C}/-90^\circ\text{C} \div -40^\circ\text{C}$) in the Heat Exchangers CU, CU1 and at higher temperatures (-35°C up to 0°C) in the Kettle type evaporators KE1, KE2, KE3 and in the Heat Exchanger CU2. Open

⁵ 270 days correspond to a seasonal characteristic period of year during which there is a high gas demand. In a typical modern Terminal having a regasification capacity of $8 \cdot 10^9 \text{ Stm}^3/\text{y}$ it can have four modular Units or a mix of CHP Units [1] and this kind of facility. The 270 days period of plant exploitation is conservative, considering that the growing demand of natural gas for electric energy generation gives a wide perspective on the possibility to consider a higher plant utilization factor.

Rack units will be used to manage the matching of duty. R. and D. on this subject now is in progress at DREAM, University of Palermo.

In Fig. 3 it is shown a drawing of a Spiral Wound Heat Exchanger as those selected for the CU, CU1 and CU2 units (Ethane in CU and LNG in CU1 and CU2 travel by the tube side and the secondary fluid by the shell side). Note that the Ethane condenser is also a heat exchanger of this kind⁶: LNG travels from tube side and Ethane from the shell side⁷.

In Fig. 4 it is shown a drawing of a Kettle type evaporator as that selected for the KE1, KE2 and KE3 units (secondary fluid travels by the tube side and Ethane by the shell side).

The main design criteria are the following:

- there is need to manage cold for some process different from cryogenic applications at a suitable temperature lying in a range allowing the use of available secondary fluids,
- the above criterion calls for use of a suitable power plant which is heated by heat released by secondary fluids carrying cold far from the regasification site (at end users),
- a part of cold available during the regasification process of LNG can be used inside the same regasification site area (e.g.: air liquefaction producing

⁶ But it has a liquid receiver installed downstream.

⁷ The same concern holds for CU1 and CU2, this operation is suitable as the LNG change of phase occurs in the hypercritical region.

Nitrogen, Oxygen, Argon, deep freeze industrial warehouse and cold storage warehouse, etc).

The main operating parameters of the power plant thermodynamic cycle (pressures and temperatures) shall be selected on the basis of the following criteria, considering that the working fluid changes phase during the cycle evolution:

- the lower pressure shall be higher than external atmospheric pressure to avoid air infiltration in the plant: in the feasibility analysis it was selected as 1.3 bar,
- the higher pressure shall be selected at a value allowing to have a temperature near -40°C , in dependence of working fluid selected.

In the paper results are presented for two working fluids:

- Ethane: lower pressure 1.3 bar ($t_{\text{sat}}=-83.85^{\circ}\text{C}$), higher pressure 7.8 bar ($t_{\text{sat}}=-39.91^{\circ}\text{C}$),
- Ethylene: lower pressure 1.3 bar ($t_{\text{sat}}=-99.45^{\circ}\text{C}$), higher pressure 14.0 bar ($t_{\text{sat}}=-41.22^{\circ}\text{C}$).

The pinch temperature difference in the condenser between the working fluid and LNG (at the exit of the device) is in both cases 10 K.

The power cycle working with ethylene is little different from that working with Ethane.

4. Modular Unit working with Ethane

The process is represented in Fig. 2. LNG to be regasified enters in the Ethane condenser at a temperature of 113 K (-160°C) and at exit it reaches a temperature of 179 K (-94°C). Then LNG goes in the train of CU1 and CU2 heat exchangers at a temperature of 179 K (-94°C) and it leaves at a temperature of 274 K (1°C). Cold released by LNG in the Ethane condenser is 18.43 MW, and cold power released in the CU1 and CU2 heat exchangers is respectively 9.5 MW and 16.1 MW. Cold at temperatures lying in the range -80°C/-35°C is released in the Ethane preheater and it can be used to satisfy a given industrial duty; the rated cold power released in the device is 4 MW. Cold power released in Kettle type evaporators has respectively the values: 3.55 MW in KE1, 14.2 MW in KE2 and 4.97 MW in KE3.

The electric power generated by the modular unit working with Ethane is 3 MW and the net efficiency (at busbar⁸) is 13.6%.

There are three set of Open Rack heat exchangers. Their operation is required in continuous operation of LNG regasification facility, when cold duty of a given device (CU, CU1, CU2, KE1, KE2, KE3) is insufficient to cover the whole need of heat for the regasification process.

5. Modular Unit working with Ethylene

⁸ note that this parameter for the case analyzed is of less meaning because it is defined as the ratio of electric energy delivered at busbar and the heat supplied to the cycle, effectively delivered as cold to the end users.

The process is represented in Fig. 5. LNG to be regasified enters in the Ethylene condenser at a temperature of 113 K (-160°C) and at exit it reaches a temperature of 164 K (-109°C). Then LNG goes in the train of CU1 and CU2 heat exchangers at a temperature of 164 K (-109°C) and it leaves at a temperature of 274 K (1°C).

Cold released by LNG in the Ethylene condenser is 14.24 MW, and cold power released in the CU1 and CU2 heat exchangers is respectively 17.56 MW and 12.21 MW. Cold at temperatures lying in the range -90°C/-35°C is released in the Ethylene preheater and it can be used to satisfy a given industrial duty; the rated cold power released is 4.25 MW. Cold power released in Kettle type evaporators has respectively the values: 2.66 MW in KE1, 10.66 MW in KE2 and 3.73 MW in KE3.

The electric power generated by the modular unit cycle working with Ethylene is 3.1 MW and the net efficiency (at busbar) is 18.0%.

There are three set of Open Rack heat exchangers. Their operation is required in continuous operation of LNG regasification facility when cold duty of a given device (CU, CU1, CU2, KE1, KE2, KE3) is insufficient to cover the whole need of heat for the regasification process.

6. Use of cold inside the regasification facility

In past years studies [4] have been carried out on the possibility of cold exergy recovery inside a regasification area (e.g.: air liquefaction producing Nitrogen, Oxygen, Argon, liquid Carbon dioxide and dry ice, etc.).

Cold available during regasification of LNG can be used at lowest temperatures to reduce energy need in the process of liquefaction of air, Nitrogen, Oxygen, Argon. Another application can be the liquefaction of Carbon dioxide or the production of dry ice. It would be possible also desalination of sea water with a freezing process.

Cold application at lowest temperature offer a wide perspective on suitable options [5], [8].

7. Use of cold outside the regasification facility

End use facilities, lying far away of the regasification terminal, require transfer of cold at a suitable distance from land-based regasification facilities. The relevant problems arising have capital weight due to lack of suitable secondary fluids. Among the secondary refrigerants available on the market almost isn't no one, compared to the old well known calcium chloride brine, which shows a remarkable better behavior. The reason is that when using such kinds of fluids heat transport is linked to sensible heat, then a large mass flow rate of liquid has to be circulated with special problems in the low temperature range where high viscosity increases the pumping power and many fluids can freeze.

Recently nanofluids and ice slurries have been proposed, but these seem no suitable for the kind of application analyzed. A reliable solution can be based, indeed, on the use of natural fluids such as Hydrocarbons (flammable) or Carbon dioxide; the feasibility

study performed in this work demonstrated that the use of Carbon dioxide should be preferred.

The possible applications in refrigerating facilities, for recovery and utilization of physical exergy of LNG during regasification, could be, as an example, of two kind: one pertaining to a cluster of end users made of agro-food factories, where need there is of cold for the freezing process of foods and to maintain these at low temperature; another pertaining to users such as supermarkets and hypermarkets where need there is of cold for space air conditioning, for the refrigeration of display cases and cabinets in the sales area and for foodstuffs preparation and cold storage in cold storage rooms. This kind of application have been analyzed at DREAM for the modular plant working with Ethane. The two clusters analyzed have a mean distance of 2 km from the regasification site.

A mean size regasification capacity in sites planned in the World is 8 billion Stm^3/y . A regasification facility such that proposed has a regasification capacity of 2 billion Stm^3/y . The power required by the cluster including Agro Food Factories amounts to 9 MW of cold delivered at a mean temperature of $-43\text{ }^\circ\text{C}$ ⁹. The end use in the hypermarket pertains mainly to the process of space air conditioning and a quantity of cold is required in the refrigeration utilities. The whole amount of power required is 7.5 MW¹⁰: 7.0 MW for space conditioning and 0.5 MW of cold of which 150 kW are delivered as cold at $-35\text{ }^\circ\text{C}$ and the remaining part as cold at $-15\text{ }^\circ\text{C}$.

The transfer of cold between the regasification facility and the clusters of Agro Food Factories and the Hypermarket takes place by means of two pipelines into which travels

⁹ e.g.: cold delivered in CU1

¹⁰ e.g.: part of cold delivered in KE2

carbon dioxide: in the feeding pipeline in liquid phase and in the return pipeline in gaseous phase. Carbon dioxide is liquefied in the regasification facility recovering cold available in the regasification process (Unit CU1). This secondary fluid is pumped in liquid phase, this option allows a considerable saving of pumping power (e.g.: for the gaseous phase shall be more than 30 time higher in the Case Study of the Agro Food Factories).

Carbon dioxide in liquid phase goes to the clusters of users and feeds evaporators of cold utilities, the gaseous phase returns back to the regasification facility where it is liquified and then pumped in the feeding pipeline.

7.1. Agro Food Factories

A process sheet of the condensation facility and of the liquid carbon dioxide pumping station lying in the regasification site¹¹ is reported in Fig. 6 (exchanger CU1, receiver A and carbon dioxide Liquid Pump). In the same Figure it is reported a schematic sheet indicating some clusters of end users (CLi), the liquid carbon dioxide storage system (Bi) installed ahead of the end users in a Factory. The gaseous phase returning from the evaporators goes in the receiver (Ci). From this device installed in each Factory it goes (almost dry) in a common receiver (C installed in the cluster area) and then it goes in the return pipeline collecting all the gaseous carbon dioxide returning from the whole cluster of Factories

¹¹ see Fig. 2, heat exchanger CU1

In Fig. 7 it is represented the process which takes place in the secondary line (which includes the carbon dioxide pipeline) on the p-h diagram. The line 1-2 indicates the condensation process of the gaseous phase which returns from the Agro Food Factories. The evaporation process takes place in the evaporators (at the end use, line 5-6). The pumping of the liquid phase is indicated by the line 2-3 and line 3-4 indicates the amount of pressure losses in the lines in which the liquid phase travels. Line 4-5 indicate for sake of simplicity the whole adiabatic throttling process which takes place in all evaporators¹².

The line 6-1 indicates the process which pertains to the pressure losses during the return of the gaseous phase.

The pipeline ahead of the end uses has a mean diameter of 8 inch (thickness 8.18 mm, pressure rating 40 bar, seamless steel API 5L).

The pipeline downstream of the end uses (return pipeline) has a mean diameter of 18 inch (thickness 11.13 mm, pressure rating 40 bar, seamless steel API 5L).

The insulation material is polyurethane foam, which has high thermal efficiency and is mechanically strong. The system is capable of working in a temperature range of -200 °C to 150 °C.

The condensation and pumping facility (in the regasification site) and the facility lying in the cluster will be monitored on-line by means of a master PC (cluster controller) which receives signals by the data acquisition and control peripherals

¹² For sake of simplicity pressure losses in the equipment aren't represented, note that these have been duly considered in the simulation.

(remote units, at the end uses). The main task of the supervision system will be to assure the right feeding of the evaporators at the end use.

7.2. Hypermarket

Fig. 8 shows a process sheet of the condensation facility and of the liquid carbon dioxide pumping station lying in the regasification site¹³ (exchanger KE2, receiver A' and carbon dioxide Liquid Pump). In the same Figure it is reported a schematic sheet of some end uses, the liquid carbon dioxide storage system (B') installed ahead of the end uses. In the receiver (C') goes the gaseous phase returning from the evaporators; from this device it goes (almost dry) in the return pipeline.

In Fig. 9 it is represented the process which takes place in the secondary line (which includes the carbon dioxide pipeline) on the p-h diagram.

The processes represented both for the end use at -35°C and for the end use at -15°C are seeming to those explained for the Fig. 7. Note that there is need here for a compressor (see Fig. 8) which pumps the gaseous phase coming out from the evaporators working at a lower temperature¹⁴ up to a pressure level suitable for mixing the gaseous phase with that coming out from the Air Treatment Units in the Hypermarket.

¹³ see Fig. 2, Kettle type evaporators KE2

¹⁴ Evaporators working at a lower pressure, which perform the duty to produce cold suitable for feeding the end uses at a mean temperature level of -35°C .

The pipeline lying ahead of the end users has a mean diameter of 6 inch (thickness 10.97 mm, pressure rating 80 bar, seamless steel API 5L).

The pipeline lying downstream of the end uses (return pipeline) has a mean diameter of 12 inch (thickness 17.48 mm, pressure rating 80 bar, seamless steel API 5L).

The insulation material is polyurethane foam, which has high thermal efficiency and is mechanically strong. The system is capable of working in a temperature range of -200 °C to 150 °C.

8. Thermodynamic analysis

Two series of numerical simulation are presented: one for a modular unit working with Ethane and another for a modular unit working with Ethylene¹⁵.

The numerical simulations have been performed with a software developed at DREAM in the context of the Programme “ORPA059444: Innovazione tecnologica di sistemi energetici e loro componenti; metodologie di progettazione, verifica e simulazione”, University of Palermo, Italy, using as a main tool the Engineering Equation Solver of S.A.Klein and A.Alvarado, Professional version 7.934.

8.1. Exergy analysis of CHP modular unit working with Ethane

¹⁵ The feasibility analysis of DREAM pertains to a lot of hydrocarbons products. The use of Ethane seems appropriate for the application examined in LNG regasification sites. In the paper the analysis performed with Ethylene is also presented. This fluid can be used if easy available near the site. The results of exergy analysis demonstrated that efficiency based on the 2nd Principle of Thermodynamics is a little higher than that for Ethane.

The performance simulation for the whole regasification facility, represented in Fig. 1, gives the main results reported in Fig. 10, 11, 12 for the Exergy analysis of each part of the process.

Fig. 10 reports results of Exergy analysis for the LNG regasifier.

The input exergy reported in Fig. 10 is the exergy of the stream of LNG to be regasified. This quantity includes the exergy of cold contained in the LNG stream to be regasified and the LNG liquid pumping power. The Dead State¹⁶ parameters used in the Exergy analysis are $p_0 = 1 \text{ atm}$ and $T_0 = 15 \text{ °C}$ (288.15 K). The rated flow rate of LNG to be regasified in the plant is 62.7 kg/s.

The exergy of LNG at inlet in the regasification facility (Ex_{LNG}) amount to 69,663 kW. Ex_{NG} is the exergy of the exit stream of NG regasified. Other items pertain to exergy delivered by the LNG stream in the Ethane condenser, in the heat exchangers CU1 and CU2 and to exergy losses along the flow path of LNG during the regasification process.

Fig. 11 shows a different detail of exergy analysis for the whole regasification plant, splitting each part of exergy exchanged in the regasification facility in two items: exergy recovered and exergy losses. They are considered: exergy recovered in the Ethane condenser (input to Ethane process stream), exergy transferred in cryogenic LNG heaters CU1 and CU2 to a given process, exergy losses in each device and items pertaining to pressure losses in the whole regasification facility.

¹⁶ The Dead State considered is restricted: this is a restricted form of equilibrium where only the conditions of mechanical and thermal equilibrium must be satisfied.

Analyzing the CHP plant working with Ethane, the splitting detail items of exergy delivered in the Ethane condenser have been derived with an appropriate methodology. The results obtained are reported in Fig. 12. The item P_{el} is the part of LNG exergy which is recovered as electric power produced by the Power Cycle working with Ethane. This cycle has a mean overall efficiency of 13.3% and it produces a rated power of 3.0 MW.

Other items pertain to exergy delivered in heat exchangers CU and in Kettle type evaporators KE1, KE2, KE3, to exergy recovered as mechanical work for driving Ethane pump (booster group GT_{EP}/EP , see Fig. 1), to exergy losses in each main device and exergy losses due to pressure losses along the Ethane-cycle loop.

8.1.1. Energy and Exergy efficiency parameters

The regasification facility is a cogeneration system which has the aim to produce electric power and cold in various temperature range and to regasify LNG.

In the plant working with Ethane cold is delivered to a secondary fluid or a cooling process in the heat exchangers CU, KE1, KE2, KE3 (see Fig. 1). At the same time Ethane is heated and it vaporizes. Cold duties of each device composes the whole cold duty of this part of the regasification facility. The condenser of Ethane Cycle is cooled by the LNG which is to be regasified. Moreover completion of the LNG regasification takes place in heat exchangers CU1 and CU2. Cold released in the equipment is also utilized.

a) *Energy Efficiency parameter (COP)*

An appropriate Energy efficiency parameter for such complex kind of modular plant is a COP. It can be estimated as the percentage recovered of cold energy supplied to the system (in the condenser of the Ethane Cogeneration Plant and in the LNG heat exchangers CU1 and CU2):

COP Ethane Cogeneration Plant

The COP for this part of the modular plant is defined by the formula:

$$COP_{EthCP} = \frac{P_{el} + Q_{CU} + Q_{KE1} + Q_{KE2} + Q_{KE3}}{Q_{condLNG}} \times 100 = \frac{ER}{Q_{condLNG}} \times 100 \quad (1)$$

$$ER = P_{el} + Q_{CU} + Q_{KE1} + Q_{KE2} + Q_{KE3} \quad (2)$$

for the case study analyzed $COP_{EthCP} = 161\%$.

COP of the whole Regasification Facility

The COP for the whole modular plant is defined by the formula:

$$COP_{Reg} = \frac{ER + Ex_{NG} + E_{CU1} + E_{CU2}}{Q_{LNG} + P_{LNG}} \times 100 \quad (3)$$

for the case study analyzed $COP_{Reg} = 201\%$.

b) Exergy Efficiency

The Exergy efficiency ζ for the modular plant can be estimated as the percentage recovered of cold exergy supplied to the system (the exergy of the LNG stream to be regasified).

Exergy efficiency of Ethane Cogeneration Plant

It is defined by the formula:

$$\zeta_{EthCP} = \frac{ExR_{EL} + ExR_{CU} + ExR_{KE1} + ExR_{KE2} + ExR_{KE3}}{ExR_{CO}} \times 100 = \frac{ExRE}{ExR_{CO}} \times 100 \quad (4)$$

$$ExRE = ExR_{EL} + ExR_{CU} + ExR_{KE1} + ExR_{KE2} + ExR_{KE3} \quad (5)$$

for the case study analysed $\zeta_{EthCP} = 35\%$.

Exergy efficiency of whole Regasification Facility

It is defined by the formula:

$$\zeta_{Reg} = \frac{ExR + ExNG + ExR_{CU1} + ExR_{CU2}}{ExLNG} \times 100 \quad (6)$$

for the case study analysed $\zeta_{Reg} = 64\%$.

It is worth of mention that ζ would be a 42% if the same Regasification Plant of Figure 1 regasifies LNG at a pressure below that pseudo-critical, as proposed in eastern countries. Moreover, ζ would be a 48% for a simple regasification plant based on Open Rack technology working at hypercritical pressure and a 32% when the same works at a pressure below that of the pseudo-critical state of LNG. Note that, the exergy “recovered” in both the last two cases is only that of the natural gas regasified.

8.2. Exergy analysis of CHP modular unit working with Ethylene

The performance simulation for the whole regasification facility, represented in Fig. 2, gives the main results reported in Fig. 13, 14, 15 for the Exergy analysis of each part of the process.

Fig. 13 reports results of Exergy analysis for the LNG regasifier.

The input exergy reported in Fig. 13 is the exergy of the stream of LNG to be regasified. This quantity includes the exergy of cold contained in the LNG stream to be regasified and the LNG liquid pumping power. The Dead State parameters used in the Exergy analysis are $p_0 = 1 \text{ atm}$ and $T_0 = 15 \text{ }^\circ\text{C}$ (288.15 K). The flow rate of LNG to be regasified in the plant is 62.7 kg/s.

The exergy of LNG at inlet in the regasification facility (Ex_{LNG}) amount to 69,663 kW. Ex_{NG} is the exergy of the exit stream of NG regasified. Other items pertain to exergy delivered by the LNG stream in the Ethylene condenser, in the heat exchangers CU1 and CU2 and to exergy losses along the flow path of LNG during the regasification process.

Fig. 14 shows a different detail of exergy analysis for the whole regasification plant, splitting each part of exergy exchanged in the regasification facility: exergy recovered in the Ethylene condenser (input in the Ethylene process stream), exergy transferred in cryogenic LNG heaters CU1 and CU2 to a given process, exergy losses in each device and items pertaining to pressure losses in the whole regasification facility.

The results obtained splitting detail items of exergy delivered and lost in the condenser for the Ethylene CHP cycle are reported in Fig. 15. The item P_{el} is the part of LNG exergy which is recovered as electric power produced by the Power Cycle working with Ethylene. This cycle has a mean overall efficiency of 18.0% and it produces a rated power of 3.1 MW.

Other items pertain to exergy delivered in heat exchangers CU and in Kettle type evaporators KE1, KE2, KE3, to exergy recovered as mechanical work for driving Ethylene pump (booster group GT_{EP}/EP , see Fig. 5), to exergy losses in each main device and exergy losses due to pressure losses along the Ethylene-cycle loop.

8.2.1. Energy and Exergy efficiency

In the plant working with Ethylene cold is delivered to a secondary fluid or a cooling process in the heat exchangers CU, KE1, KE2, KE3 (see Fig. 5). At the same time Ethylene is heated and it vaporizes. The cold duty of each device composes the whole cold duty for this part of the regasification facility. The condenser of the Ethylene Cycle is cooled by the LNG which is to be regasified. Moreover the completion of the LNG regasification takes place in heat exchangers CU1 and CU2. The cold released in the equipment is also utilized.

a) *Energy Efficiency parameter (COP)*

The COP for such complex kind of modular plant can be estimated as the percentage recovered of the cold energy supplied to the system (in the condenser of the Ethylene Cogeneration Plant and in the LNG exchangers CU1 and CU2):

COP of Ethylene Cogeneration Plant

For the case study analyzed using the definition (1) it is obtained:

$$\text{COP}_{\text{EthCP}} = 124\%.$$

COP of the whole Regasification Facility

For the case study analyzed using the definition (3) it is obtained:

$$\text{COP}_{\text{Reg}} = 183\%.$$

b) Exergy Efficiency

The Exergy efficiency ζ for the modular plant can be estimated as the percentage recovered of the cold exergy supplied to the system (the exergy of the LNG stream to be regasified).

Exergy efficiency of Ethylene Cogeneration Plant

For the case study analyzed using the definition (4) it is obtained:

$$\zeta_{EthCP} = 44\%.$$

Exergy efficiency of the whole Regasification Facility

For the case study analysed using the definition (6) it is obtained:

$$\zeta_{Reg} = 71\%.$$

It is worth of mention that ζ would be a 43% if the same Regasification Plant of Figure 5 regasifies LNG at a pressure below that pseudo-critical, as proposed in eastern countries. Moreover, ζ would be a 52% for a simple regasification plant based on Open Rack technology working at hypercritical pressure and a 36% when the same works at a pressure below that of the pseudo-critical state of LNG. The exergy “recovered” in both the last two cases is only that of the natural gas regasified.

9. Economic and Environmental analysis

An economic venture analysis has been carried out comparing some hypotheses of process management of modular unit proposed for the regasification of LNG:

- considering some forecast for cost of money, inflation, etc¹⁷,
- considering some scenarios to account for price volatility of energy products,
- considering selling price of electric energy produced in a regime of free market in the context of Electric Energy Stock Exchange in Italy[2],
- considering for natural gas a mean selling price in Italy weighted using real quantities sold [2].

Venture analysis was carried out comparing a given alternative for the management of process using the modular unit, “Alternative 1”, with a reference alternative which is based on the use of a regasification plant using OR (Open Rack Technology) having the same regasification capacity of the CHP Plant analyzed: “Alternative 0”.

The leading idea doing venture analysis is that:

- The use of modular unit allows the LNG regasification during plants exploitation producing some amount of electric energy and delivering cold suitable for industrial and commercial use in the proper temperature range.
- Thus, exploiting a modular unit, use of electric energy for pumping sea water to feed OR is avoided.
- Considering this hypothesis, regasification costs are included in a low range because, actually, only the incidence of regasification of LNG using the OR

¹⁷ see [2]: a sensitivity analysis of cash flows on Nominal Discount Rate (included in the range: 5÷15%) was performed

technology back-up system during the period of its operation is to be considered apart.

- The income to be considered is that of selling electric energy produced and cold delivered to end users and, moreover, the saving due to avoided expenditure of electric energy for pumping sea water to feed OR. Really, in the venture analysis the cost of regasification using modular unit proposed or OR technology, prudentially, are considered equal (although this leads to an overestimate of regasification cost using modular unit with the stated hypothesis).

In each analysis done, cash flows consider an initial capital investment equal to the whole cost expense to built and put in operation a modular unit. Analysis pertains to a comparison of performance of a modular unit proposed with an OR facility (considered as basis option) having the same regasification capacity as that of modular unit proposed. Prudentially, capital initial investment cost, thus, isn't that "differential"¹⁸ but the whole cost to built and put in operation a modular plant. Really, it is very difficult that a regasification site will work for a long time at its maximum capacity, thus "differential" initial capital investment cost could be considered (one modular unit has a regasification capacity of $2 \cdot 10^9 \text{ Stm}^3/\text{y}$ while a typical site of regasification $8 \cdot 10^9 \text{ Stm}^3/\text{y}$). Moreover, considering that a modular unit proposed represent a relative new technology, an additional capital investment cost was spread over the entire life period of venture in each year (25 years).

¹⁸ cost to built a modular unit minus cost to built an OR facility having the same regasification capacity; note that this last facility will be built to assure an emergency back-up system

In the venture analysis it is considered an escalation rate both for selling price of electricity and natural gas and for cost of LNG purchased, also an escalation rate was considered for man power and some other items [2].

Each venture analysis considers items composing cash flows both before tax and after tax. Tax rate [2] pertains to that of Italy, this, which, in the EU area, is lower only to that for Germany, amount to a whole 37.25% (this value has been stated in the analysis, although some financial incentive really can lower this value by a 10÷15%).

Present Worth before tax (PW_{bt}), Present Worth after tax (PW_{at}) and Present Worth of Revenue Requirements (PWR) were derived [2]. Using cash flow items composing PW_{at} , Return On Investment ($ROI_{at} = [\text{net casflow after tax} - \text{mean depreciacion charge}]/[\text{Capital Investment}]$) and Benefit Cost Ratio (BCR_{at} , IP in Italy: $[PW_{at} + \text{Capital Investment}]/[\text{Capital Investment}]$) were also derived. Time of return on investment was derived utilizing cumulated PWR during the years up to reach the value of initial capital expenditure (note that this value is higher than those derived using PW_{bt} or PW_{at}). Also, marginal costs of regasification were derived (both when using a modular unit or OR, prudentially, costs are assumed as equal). Marginal costs considered of electric energy produced and cold delivered to end users are those actual and those levelized on the entire venture life.

The economic analysis is based on a numerical simulations which has been performed with a software developed at DREAM. In the analysis some hypotheses of process management of the modular plant proposed for the regasification of LNG have

been compared. The simulation was carried out¹⁹ comparing a given alternative for the management of the process using the modular plant with a reference alternative which is based on the use of a regasification plant operating with Open Rack Technology.²⁰

The venture was considered in the analysis as a Project financing venture (all bond) and a reference cost of a loan, which will have a duration of 15 years was assumed with an interest rate of 8.00%.

Here main results of the economic analysis, considering nominal discount rate varying in the range 5-15%, for a modular unit working with Ethane are reported in Table 2.

Figure 16 reports results obtained for Time of return (by PWN_R analysis), while Figure 17 reports the trend of PW_{bt}, PW_{at}, PWN_R varying nominal discount rate varying in the range 5-15%.

The sharing of the amount between the three type of production was assumed: as 20% for the gas production, 80% for the production of cold and electricity, sharing these costs among them and considering their respective incidence on the co-production. The cost obtained for each item are the following: 0.07 c€/Nm³ for gas, 0.99 c€/kWh for cold and 0.51 c€/kWh for electric energy.

Table 3 shows some results obtained fixing the selling price for electric energy at 7.00 c€/kWh and for a set of selling price for the cold. Time of return (by PW_{at}) lies in the range 4.5÷15.5 years when the selling price for cold lies in the range 3.50 ÷ 1.00

¹⁹ for criteria on which the methodology used is based see [2], see also Appendix

²⁰ having the same regasification capacity of the modular unit analyzed

c€/kWh. Then the results obtained show the profitability of these modular regasification plants.

In the analysis it has been derived a reference price for cold produced far from the regasification site with a conventional cooling plant based on refrigerating equipment available on the market. The primary energy saving estimated for the regasification facility, considering the avoided demand to produce the amount of cold recovered, is 39.46 ktoe/y and cold reject avoided amount to 336,960.00 MWh/y. The avoided emission of CO₂ is of 88.61 kt/y.

10. Safety aspects in the management of regasification process

The recovery of cold during LNG regasification in applications pertaining cold technology put a great challenge, bearing in mind that the regasification site area should be near the potential end users of cold. But, this occurrence seldom happens because LNG is characterized by fire and explosion hazards, which pose many safety challenges to project managers and operators. Safety regulations require that LNG terminals to be surrounded by exclusion zones to protect neighbouring communities in the event of a pool fire or flammable vapour cloud [12]. Then it seems that availability of cold is proper for industrial use. Industrial facilities can be built inside the regasification terminal²¹.

²¹ e.g.: the agreement between “Gaz de France” and “L’Air Liquide” for the Terminal of Fos sur Mer - France addressed to the production of Nitrogen utilized by “Gaz de France” in the Terminal for gas adjustment

Cold should be utilized off the regasification site, but it is difficult to transfer cold at long distances due to unavailability of a suitable brine or safe fluids for such kind of application, this subject now requires R. and D. A possible option, proposed in this paper, can be the use of Carbon dioxide.

As far as it pertains to generation of electric energy and utilization of cold for the industrial use, the process will take place inside the regasification facility area, in the other cases the end users are far from the regasification area. Moreover, the layout of plants proposed considers properly the reliability of risk management during the process exploitation.

11. Conclusive remarks

The possible applications in refrigerating facilities for recovery and utilization of physical exergy during LNG regasification, here envisaged, is based on the use of a modular facility having a regasification capacity of $2 \cdot 10^9 \text{ Stm}^3/\text{y}$ (as a mean: 1/4 of the mean single regasification capacity of sites planned in the World: $8 \cdot 10^9 \text{ Stm}^3/\text{y}$).

The results of a feasibility study of the venture proposed, starting from conceptual design and with an analysis both thermodynamic and economic demonstrated the suitability and the profitability of the application proposed. This seems very attractive due to expected wide future exploitation of LNG regasification in the World.

As a mean, land-based regasification facilities in program in the World have a regasification capacity of $8 \cdot 10^9 \text{ Stm}^3/\text{y}$. Then, coupling modular units both of the type

proposed by the Authors [1-2] and of modular units addressed to cold recovery, the modular plants proposed offer a wide perspective.

Appendix - Definitions pertaining the Venture Analysis

For sake of clearness need there is to define main parameters involved in Venture Analysis [2]. Cash flow is defined as the movement of money both into the project (revenues) and out of the project (disbursements). Cash flows can be classified into: 1) Operational cash flows: Cash received or expended as a result of the company's core business activities, 2) Investment cash flows: Cash received or expended through capital expenditure, investments or acquisitions, 3) Financing cash flows: Cash received or expended as a result of financial activities, such as receiving or paying loans, issuing or repurchasing stock, and paying dividends.

Three kind of Cash flow are used in Venture Analysis done: 1) *Investment Cash flow before tax*, 2) *Investment Cash flow after tax*, 1) *Financing Cash flow after tax*:

CF_{bt} Investment Cash flow²² before tax:

$$CF_{bt} = R_i - (O_i + \Pi_i) \quad (\text{A-1})$$

R_i receipts (annual Cash inflows)

O_i disbursements (annual Cash outflows for operating expense including start-up cost, fuel, operation and maintenance)

²² all financial items in the analysis are in reported in current €

Π_i disbursements (annual Cash outflows for ad-valorem expense)

PW_{bt} Net Present Worth of venture before tax:

$$PW_{bt} = \sum_i \frac{R_i}{(1+r)_i} - \sum_i \frac{O_i + \Pi_i}{(1+r)_i} - I \quad (\text{A-2})$$

I initial investment

r nominal discount rate

CF_{at} Investment Cash flow after tax:

$$CF_{at} = R_i - (O_i + \Pi_i) - T_i \quad (\text{A-3})$$

$$T_i = \tau(R_i - O_i - \Pi_i - D_i^{\tau} - r_b f_b V_i) \quad (\text{A-4})$$

T_i annual tax Cash flow stream

τ annual overall tax rate

D_i^{τ} annual tax depreciation charge

r_b debt interest rate

f_b fraction of debt in the investment

V_i unrecovered value of investment at beginning year i

PW_{at} Net Present Worth of venture after tax:

$$PW_{at} = \sum_i \frac{R_i}{(1+r)_i} - \sum_i \frac{O_i + \Pi_i}{(1+r)_i} - \sum_i \frac{T_i}{(1+r)_i} - I \quad (\text{A-5})$$

BCR_{at} Benefit Cost Ratio:

$$BCR_{at} = \frac{PW_{at} + I}{I} \quad (A-6)$$

ROI_{at} Return On Investment:

$$ROI_{at} = \frac{\overline{CF}_{at} - D_i^B}{I} \quad (A-7)$$

\overline{CF}_{at} levelized Cash flow after tax

CF_{PWNR} Financing Cash flow after tax:

$$CF_{PWNR} = R_i - (O_i + \Pi_i) - T_i - [(D_i^B + r_b V_{wi}) - \tau(D_i^f + r_b f_b V_i)] \quad (A-8)$$

D_i^B annual book depreciation charge

V_{wi} whole amount of money on which must be paid interest at the end of year i

$PWNR$ Present Worth of Net Revenue:

$$PWNR = \sum_i \frac{R_i}{(1+r)_i} - \sum_i \frac{O_i + \Pi_i}{(1+r)_i} - \sum_i \frac{T_i}{(1+r)_i} - \sum_i \frac{[(D_i^B + r_b V_{wi}) - \tau(D_i^f + r_b f_b V_i)]}{(1+r)_i} \quad (A-9)$$

TR Time of Return on Investment based on $PWNR$:

Time of return on investment reported in results of Venture Analysis was derived utilizing cumulated $PWNR$ during the years up to reach the value of initial capital expenditure; note that this value is higher than those derived using PW_{bt} or PW_{at} .

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Nomenclature

BCR_{at}	Benefit Cost Ratio
CF_{bt}	Investment Cash flow before tax
CF_{at}	Investment Cash flow after tax
\overline{CF}_{at}	Levelized Cash flow after tax
$CFPWR$	Financing Cash flow after tax
COP	Coefficient of performance
E_{CU1}	Cold power delivered in CU1 (kW)
E_{CU2}	Cold power delivered in CU2 (kW)
Ex	Exergy (kW)
ExD	Exergy destroyed (kW)
ExL	Exergy of cold delivered during the regasification process of LNG (kW)
$ExLNG$	Exergy of LNG to be regasified (kW)
$ExNG$	Exergy of exit stream of NG regasified (kW)
ExR	Exergy recovered (kW)
LNG	Liquefied Natural Gas
NG	Natural Gas

P_{el}	Electric power generated in the Ethane/Ethylene Loop (kW)
P_{LNG}	Pumping power of LNG to be regasified (kW)
PW_{bt}	Net Present Worth of venture before tax
PW_{at}	Net Present Worth of venture after tax
$PWNR$	Present Worth of Net Revenue
$Q_{condLNG}$	Cold power delivered in Ethane/Ethylene condenser (kW)
Q_{CU}	Cold power delivered in CU (kW)
Q_{KE1}	Cold power delivered in KE1 (kW)
Q_{KE2}	Cold power delivered in KE2 (kW)
Q_{KE3}	Cold power delivered in KE3 (kW)
Q_{LNG}	Cold power delivered by LNG to be regasified (kW)
ROI_{at}	Return On Investment
TR	Time of Return on Investment based on $PWNR$
ζ	Exergy efficiency

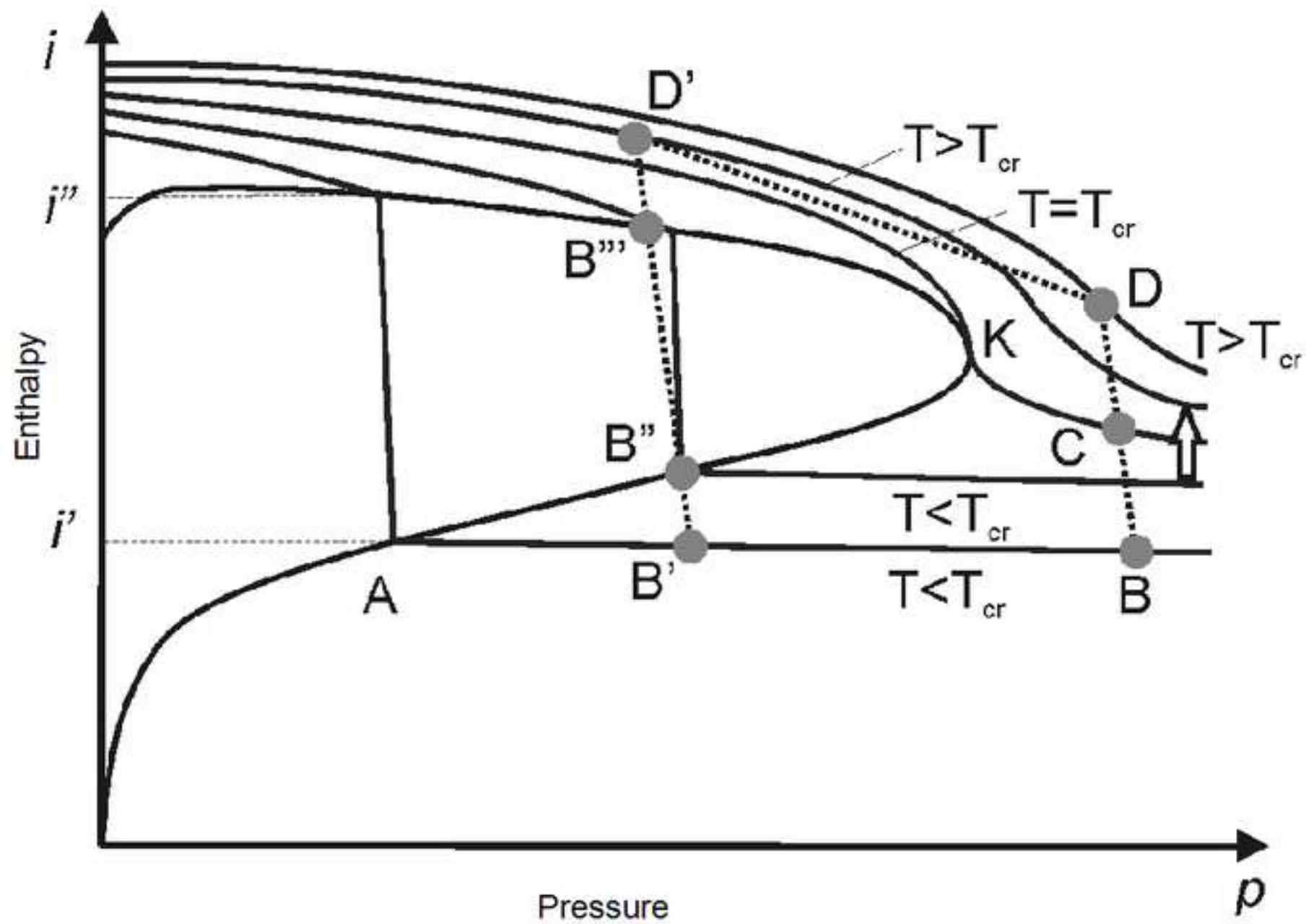
Subscripts

CO	Ethane/Ethylene condenser
CTR	Whole exergy in the regasification facility
CU	Heat exchangers CU
$CU1$	Heat exchangers CU1
$CU2$	Heat exchangers CU2
EL	Electric power

<i>GT</i>	Gas turbine
<i>KE1</i>	Heat exchangers KE1
<i>KE2</i>	Heat exchangers KE2
<i>KE3</i>	Heat exchangers KE3
<i>P</i>	Pressure losses along in the Ethane/Ethylene loop
<i>PS</i>	Pressure losses in the regasification facility
<i>PU</i>	Ethane/Ethylene pump
<i>Reg</i>	Regasification facility

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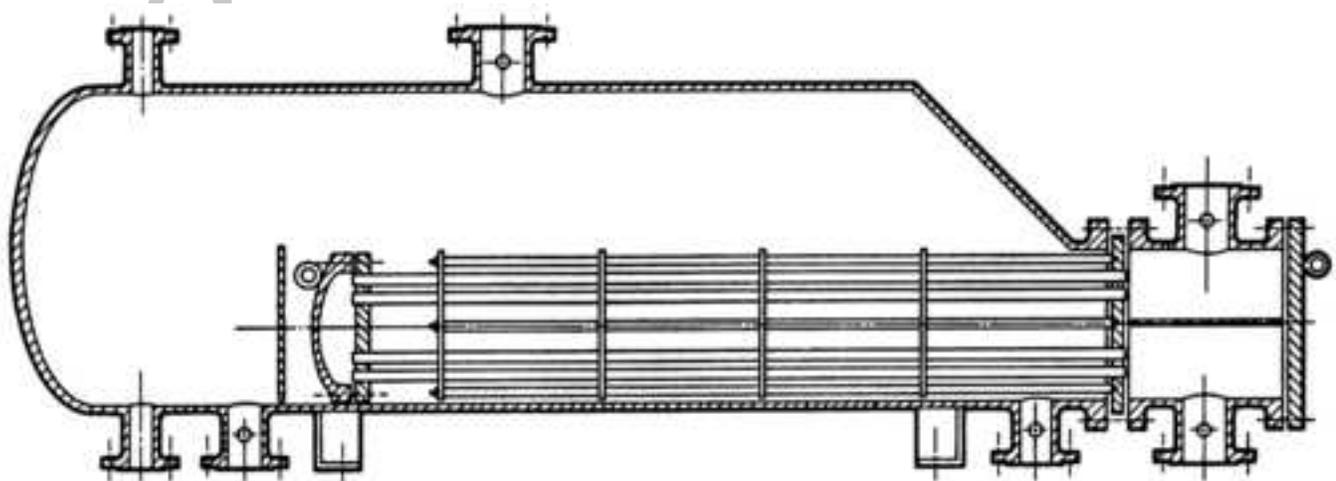
- Fig. 1. Thermodynamic process during regasification of LNG
- Fig. 2. A proposed process sheet for cold recovery during regasification of LNG
- Fig. 3. A detail a of a spiral-wound heat exchanger (Courtesy of Linde AG)
- Fig. 4. A schematic drawing of a Kettle - type evaporator
- Fig. 5. The process of modular unit working with Ethylene for regasification of LNG
- Fig. 6. The system for transfer and utilization of cold in Agro Food Factories
- Fig. 7. The cooling cycle for transfer and utilization of cold in Agro Food Factories (R-744 Diagram courtesy of IIR)
- Fig. 8. The system for transfer and utilization of cold in a Hypermarket
- Fig. 9. The cooling cycle for transfer and utilization of cold in a Hypermarket (R-744 Diagram courtesy of IIR)
- Fig. 10. Results of exergy analysis for the LNG regasifier working with Ethane
- Fig. 11. Input Exergy in Ethane condenser, in CU1 and CU2 and exergy losses
- Fig. 12. Results of exergy analysis for the Ethane cycle
- Fig. 13. Results of exergy analysis for the LNG regasifier working with Ethylene
- Fig. 14. Input Exergy in Ethylene condenser, in CU1 and CU2 and exergy losses
- Fig. 15. Results of exergy analysis for the Ethylene cycle
- Fig. 16 - Time of return (by PWNR analysis) varying the nominal discount rate (Regasifier working with Ethane)
- Fig. 17 - Trend of PWbt, PWat, PWNR varying the nominal discount rate(Regasifier working with Ethane)

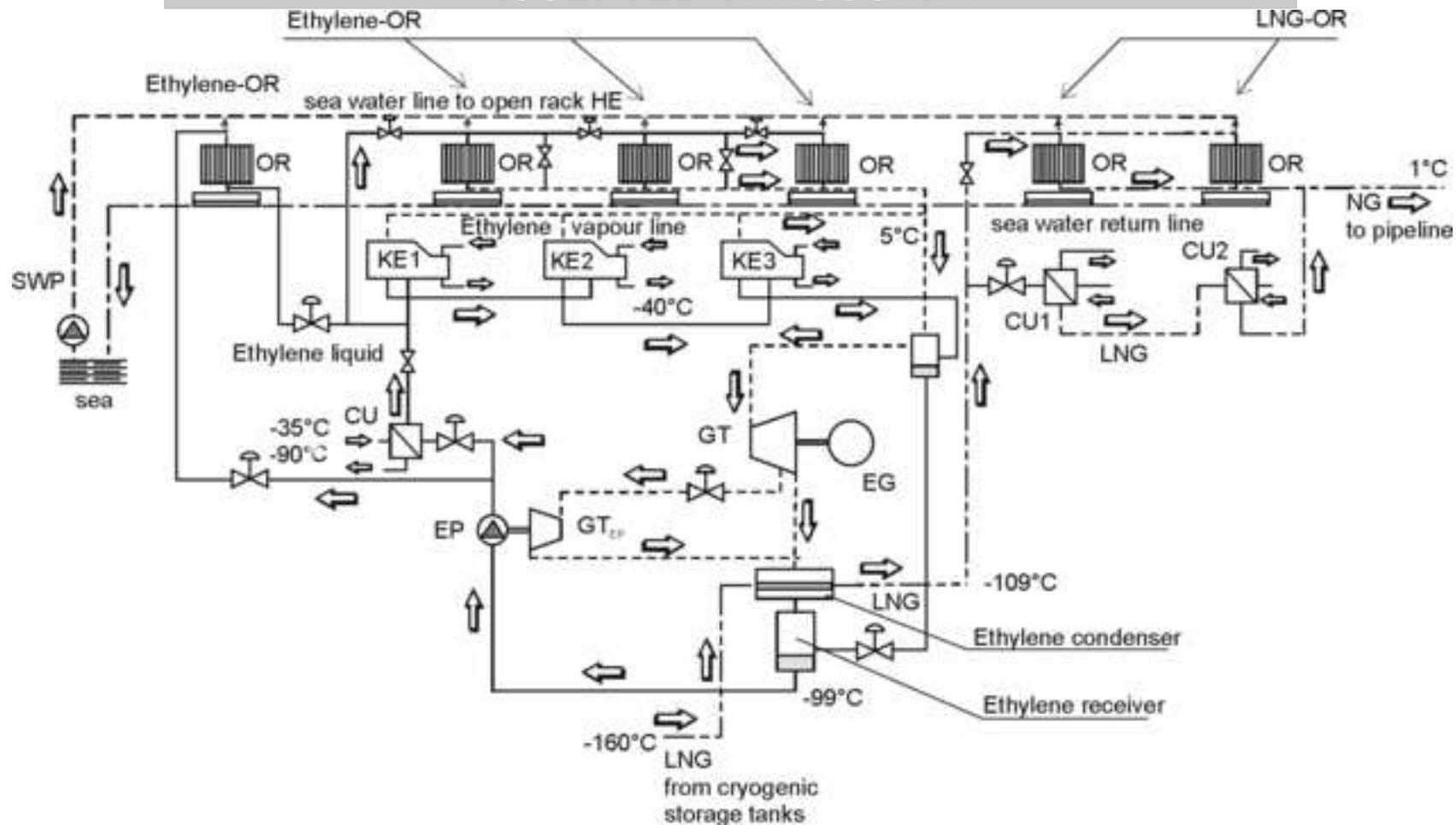


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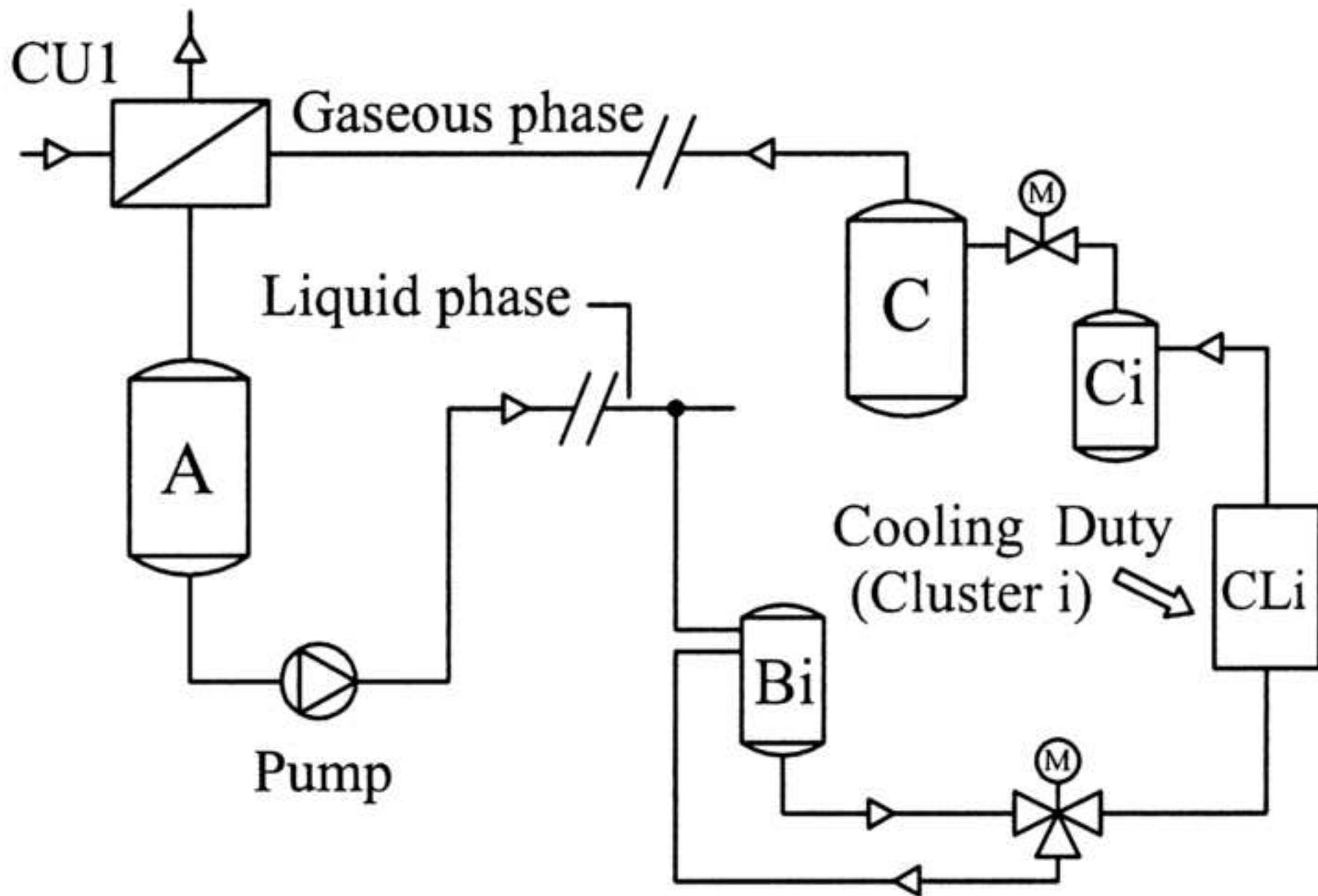


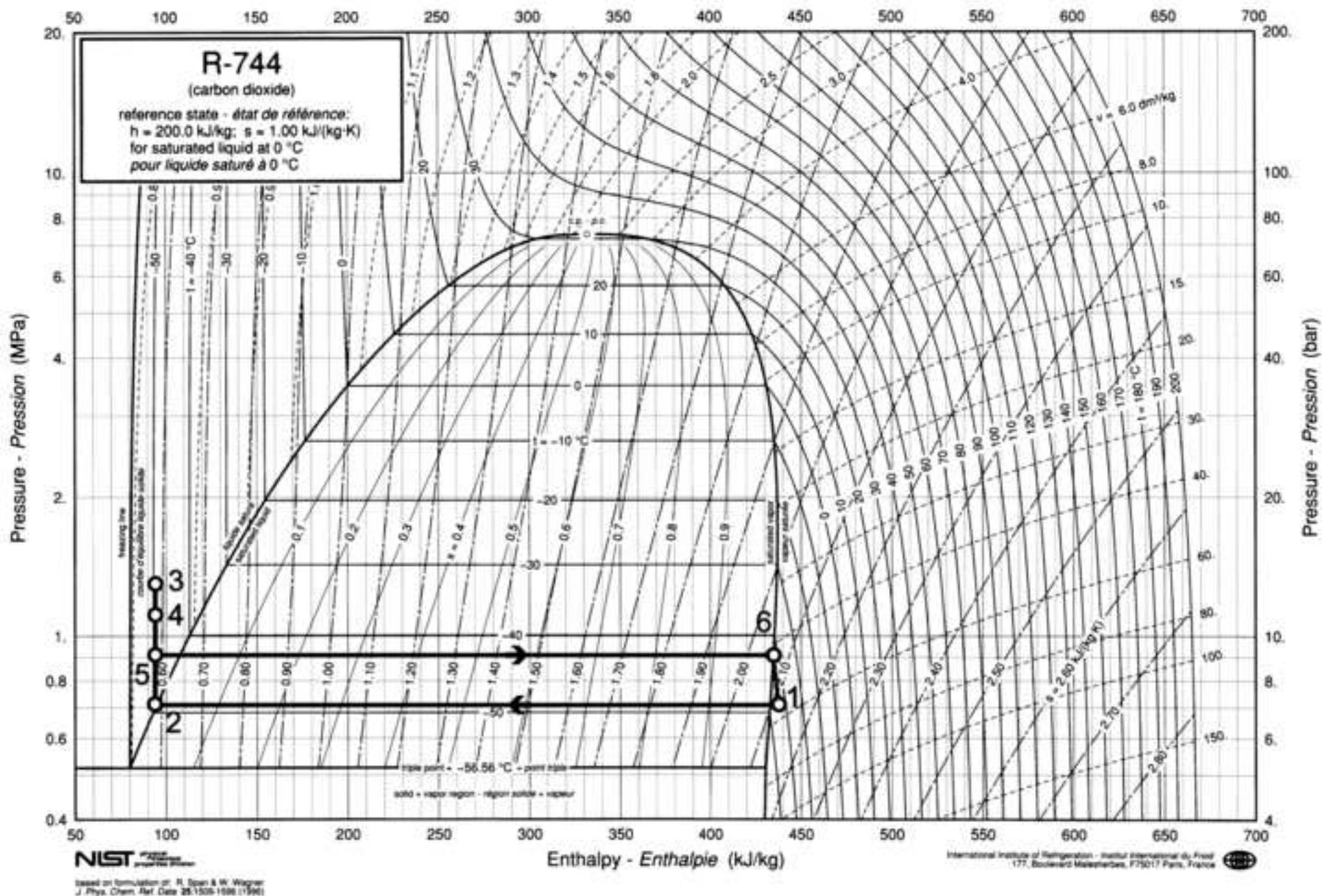
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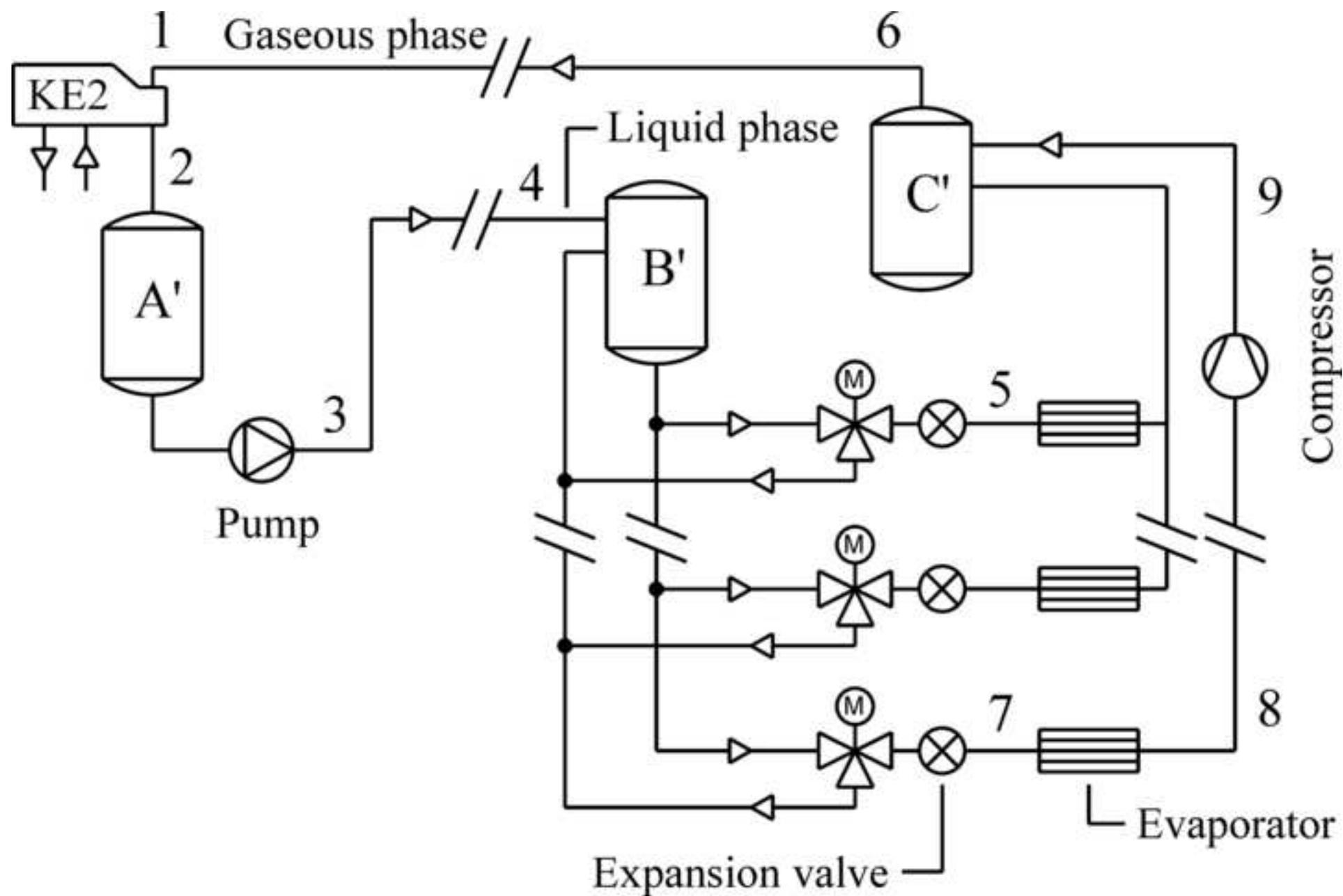


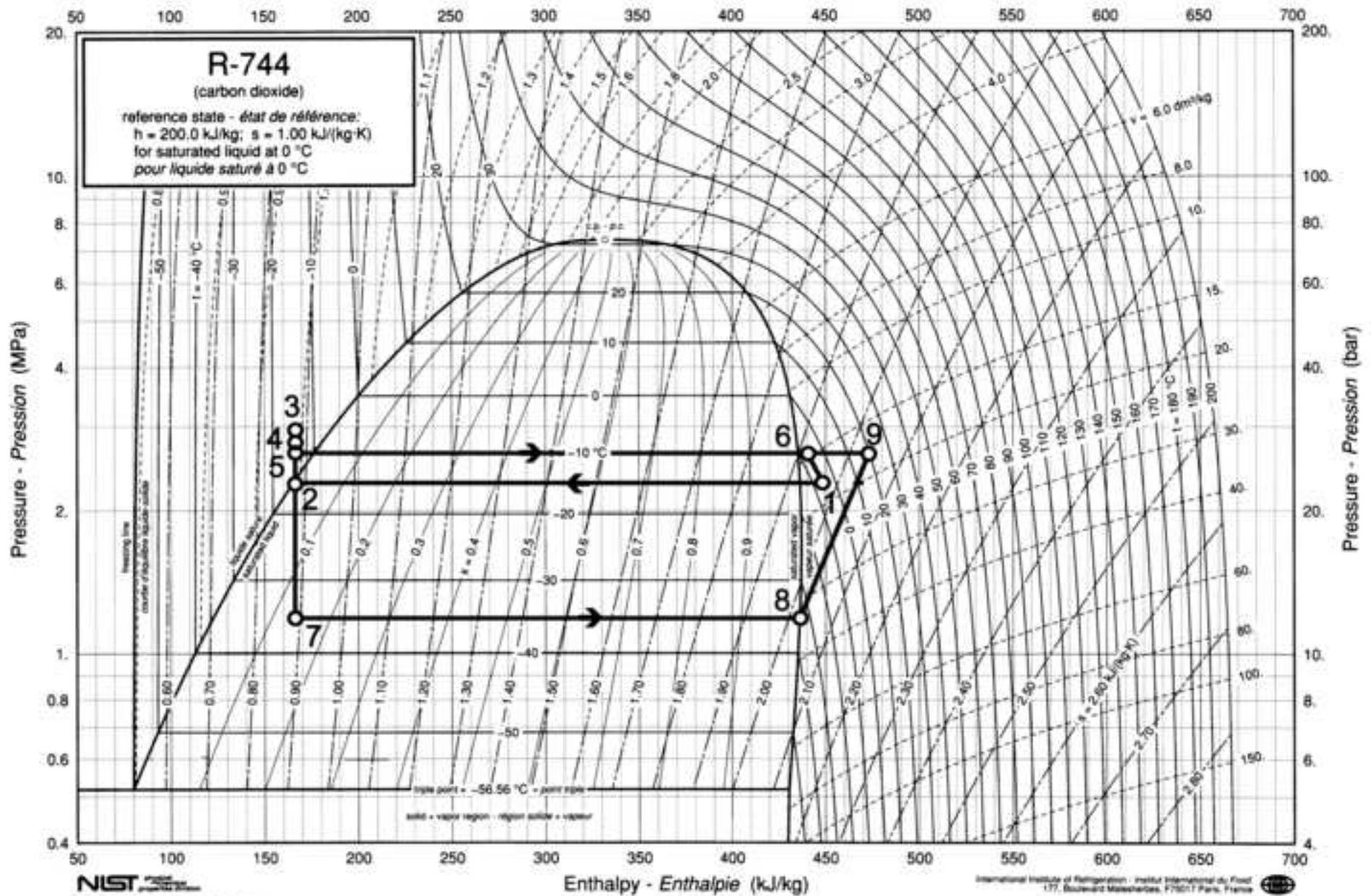
OR	Open Rack Heat Unit working with sea water
KE1	Kettle type evaporator 1: cold at -25°C, -30°C (Ethylene/Secondary fluid)
KE2	Kettle type evaporator 2: cold at -15°C, -25°C (Ethylene/Secondary fluid)
KE3	Kettle type evaporator 3: cold at 5°C, -15°C (Ethylene/Secondary fluid)
CU	Industrial use (Ethylene preheater): cold -90°C, -35°C
CU1, CU2	Industrial use [cold utilities working with LNG to be regasified (-100°C, 1°C)]
EP	Ethylene Pump
GTEP	Low pressure Expander (drives EP)
GT	Power Expander (Pel 3 MW)
EG	Electric generator
SWP	Sea Water Pump





Enthalpy-Pressure diagram by "Thermophysical properties R744 Carbon dioxide" IIR, Paris, France 2003 - ISBN 2-913149-30-8





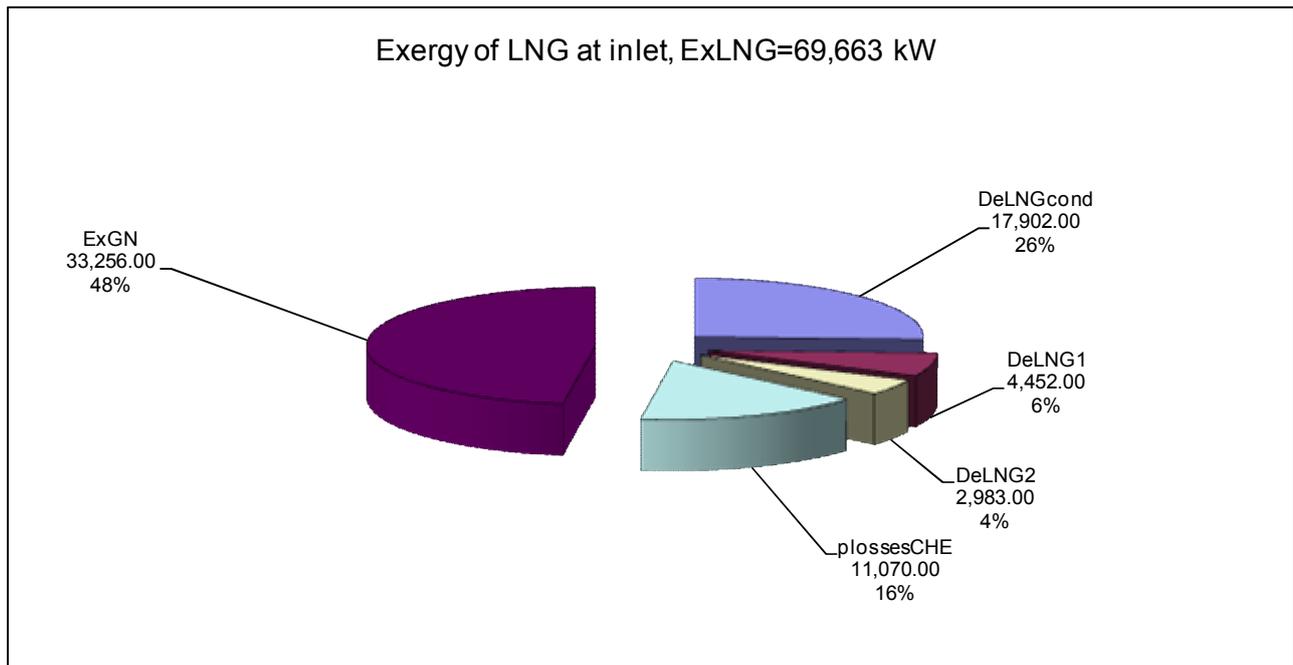


Fig 10

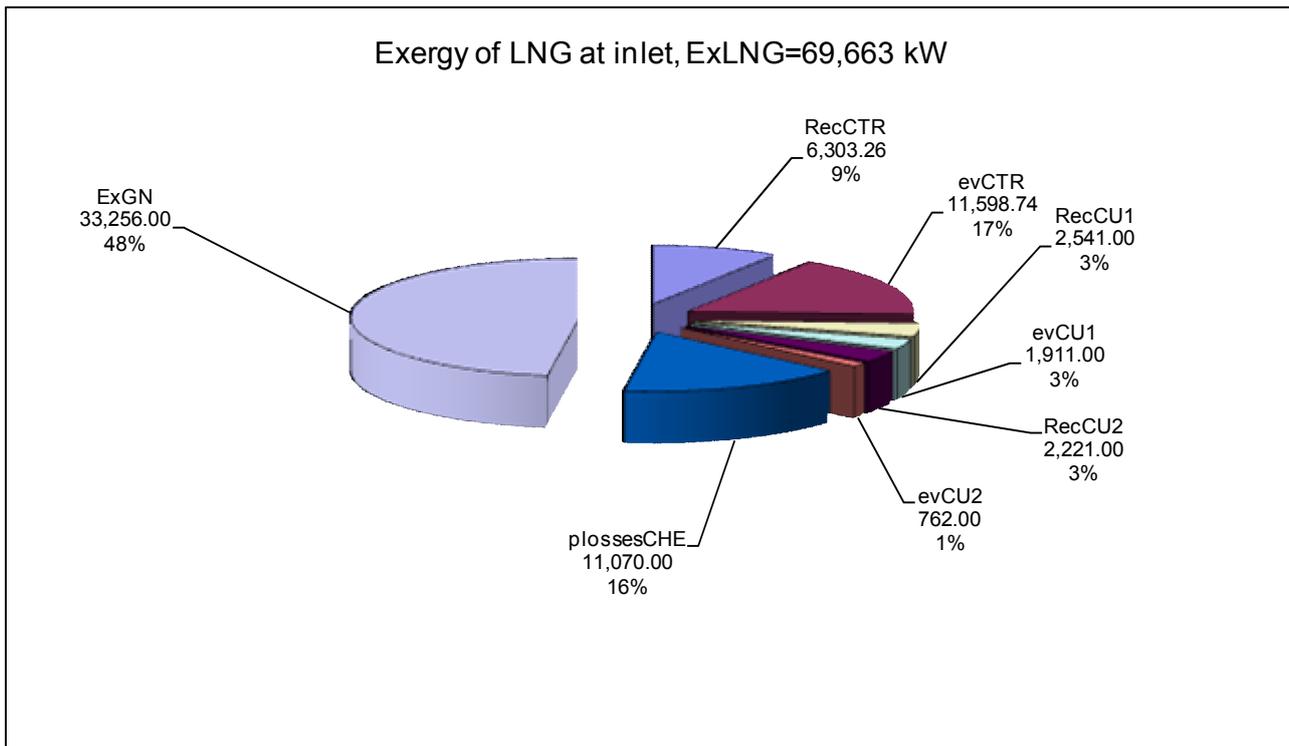


Fig 11

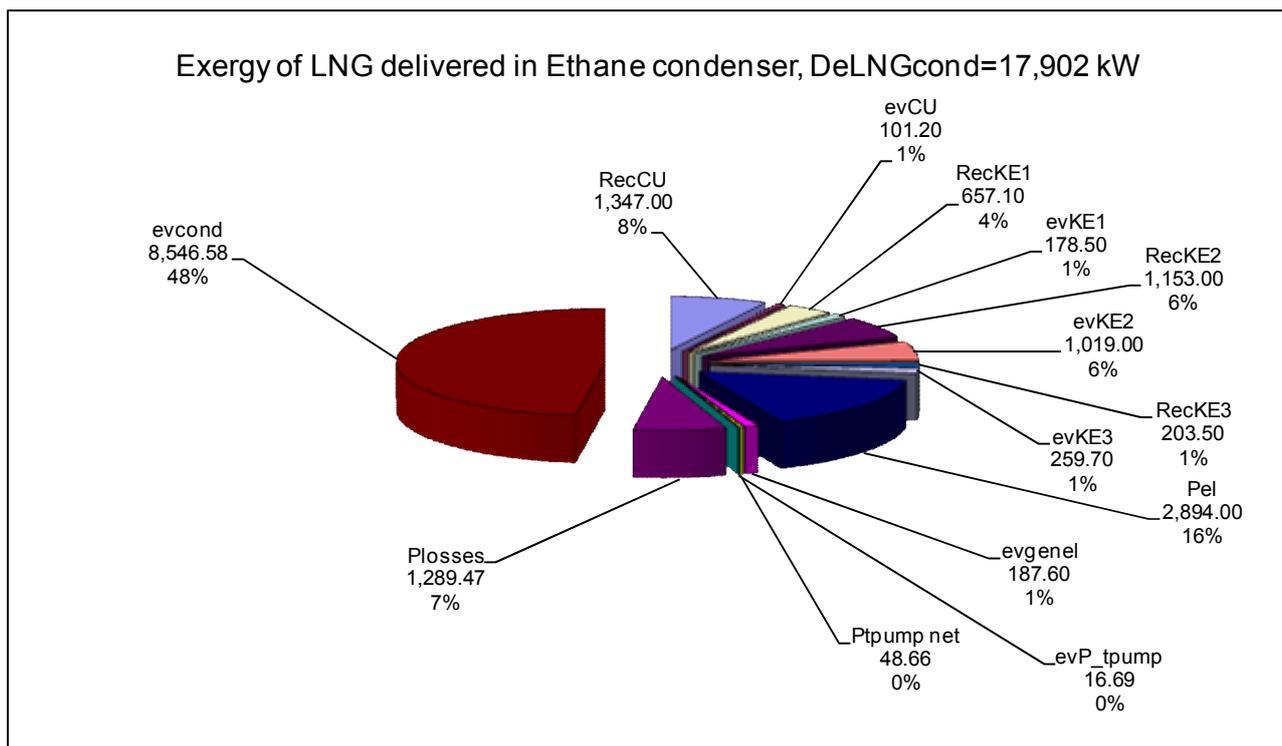


Fig 12

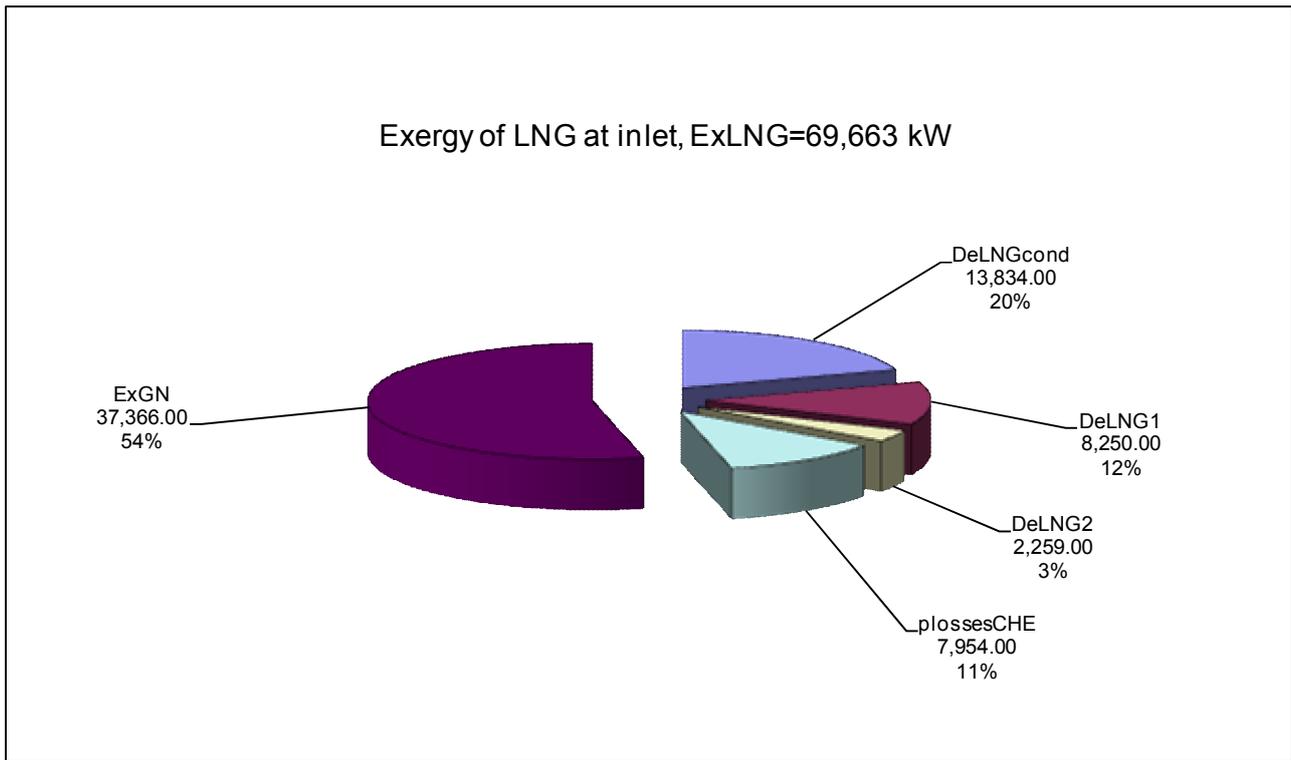


Fig 13

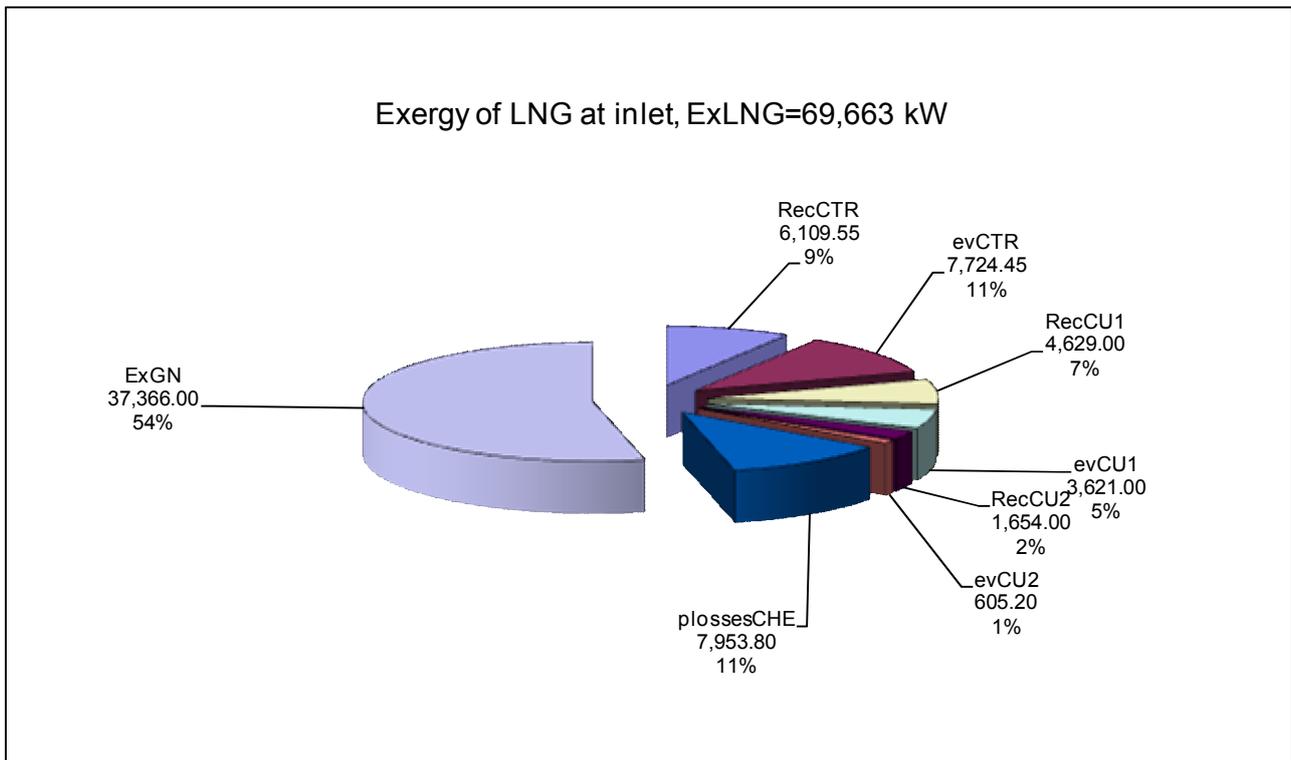


Fig 14

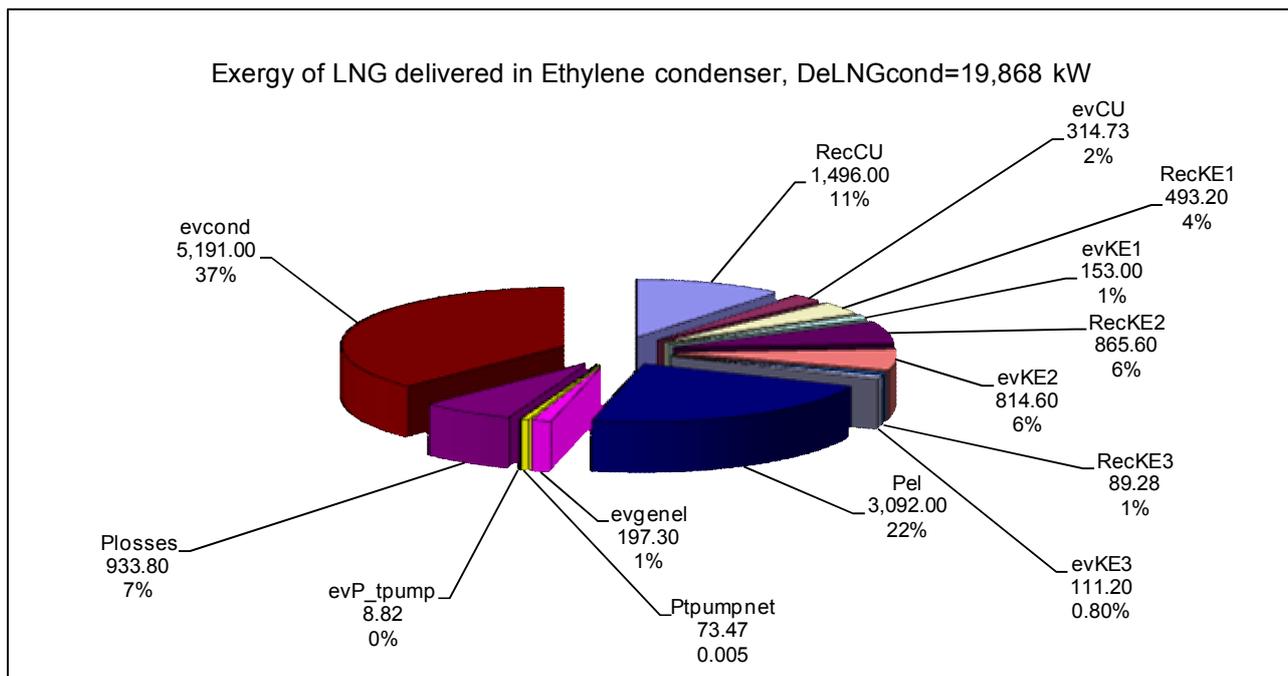


Fig 15

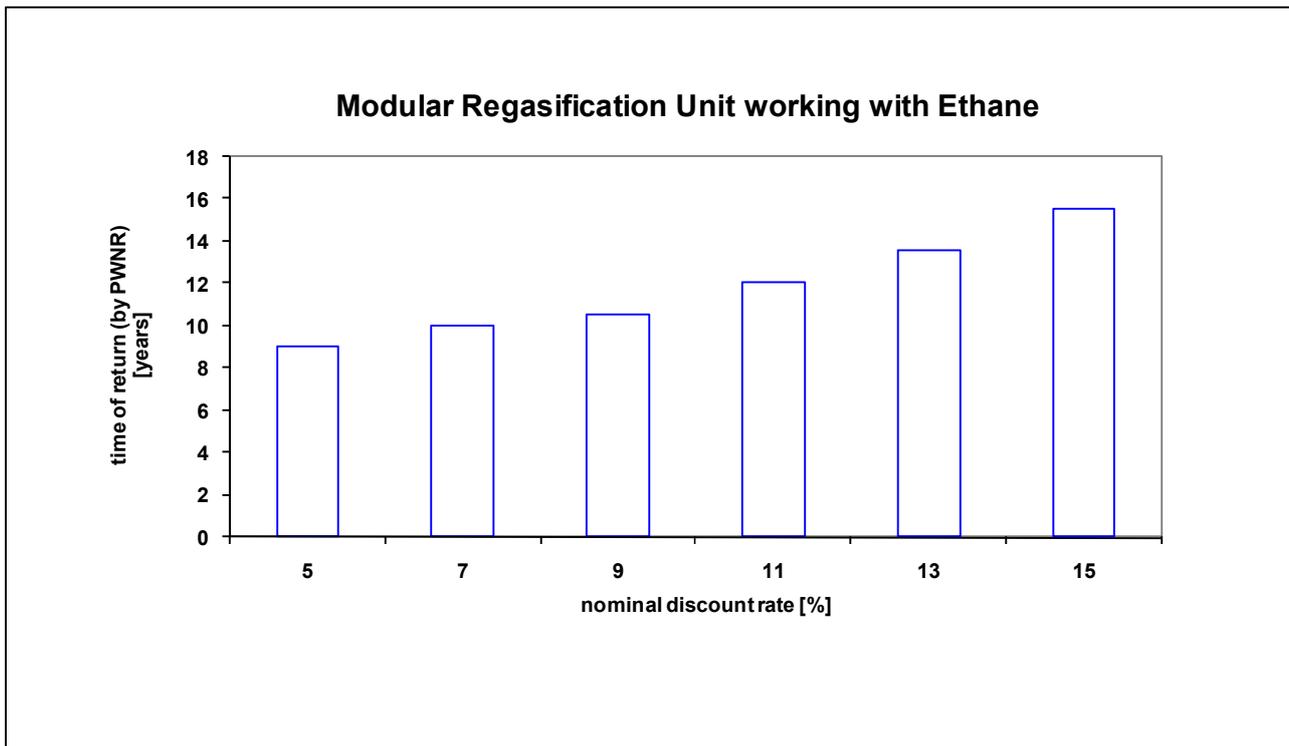


Fig. 16

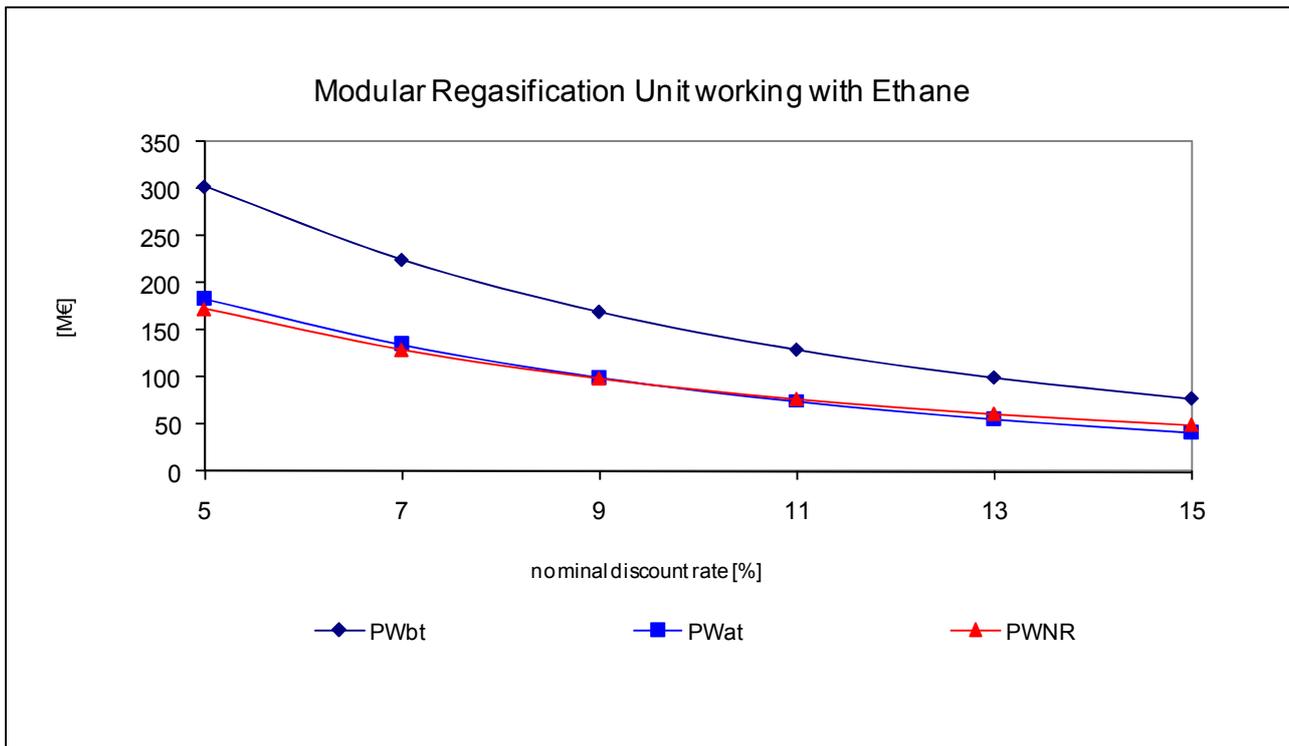


Fig. 17

Table 1 - A typical composition of LNG considered in the feasibility analysis of DREAM
University of Palermo

Composition		M	Tcr K	Pcr bar	Teb K
Component	% mol.				
Nitrogen	0.070	28.02	126	37.78	77.0
Methane	95.850	16.04	191	46.22	161.5
Ethane	3.100	30.07	305	48.64	184.4
Propane	0.850	44.09	370	42.40	231.0
i-Butane	0.050	58.12	408	33.70	261.0
n-Butane	0.070	58.12	425	36.33	272.8
i-Pentane	0.006	72.15	461	33.17	302.8
n-Pentane	0.004	72.15	470	33.61	309.4
LNG	100	16.78	196.31	46.24	162.88

Heating values (Calorific values): higher $\text{kJ/Stm}^3 = 9,600.00$; lower $\text{kJ/Stm}^3 = 8,650.00$
a Stm^3 has a pressure of 1 atm and a temperature of 15°C

Table 2 - Results of sensitivity analysis varying the nominal discount rate

r	PWbt	PWat	PWNR	TR
%	M Euro	M Euro	M Euro	anni
5	302.48	183.49	172.16	9.0
7	224.77	134.67	128.63	10.0
9	169.47	99.74	98.07	10.5
11	129.38	74.27	76.24	12.0
13	99.77	55.35	60.39	13.5
15	77.52	41.02	48.68	15.5

Table 3 - Unit prices used in economic analysis and Time of return

Electric energy c€/kWh	Cold c€/kWh	Modular unit T.r.y ^a
7.00	1.00	15.5
7.00	1.50	10.5
7.00	2.00	8.0
7.00	2.50	6.9
7.00	3.00	5.7
7.00	3.50	4.5

Loan mortgage time 15 years - Nominal discount rate fixed at 10% - ^a Time of return (by PWat) years