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COLD ENERGY RECOVERY IN LNG PLANTS WITH ORGANIC RANKINE CYCLE

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ABSTRACT

During the production phase, natural gas (NG) is compressed and chilled to liquid state (liquified natural gas, LNG) for sake of volume reduction, hence to ease transportation. Approximately, 500 kWh of electricity or mechanical power per ton of LNG is needed for LNG compression and refrigeration during the production phase, which makes cold energy exploitation interesting from a thermodynamics point of view. An effective way to harness the cold energy contained in LNG is through an Organic Rankine Cycle system. A Cold Energy Plant (CEP) is an efficient system based on ORC technology which regasifies liquified natural gas and converts the heat absorbed from sea water into electricity by recovering the valuable exergy content of LNG. This solution allows to produce electrical power on-site without any additional external fuel consumption and no emissions at stacks. The CEP is a low-maintenance and cost-effective solution that can be efficiently applied in the LNG industry to increase energy efficiency and sustainability of operations. The CEP system designed by Exergy achieves high efficiency thanks to the use of the proprietary Exergy Radial Outflow Turbine combined with the Multilevel Condensation Cycle, maximizing the revenue from electricity production. This paper will outline the technical features of a CEP power plant and will present a case study based on a Liquified Natural Gas regassification system engineered to produce Nominal 4 MWe (4000 kWe) net electric power while simultaneously fulfilling the regasification of 180 ton/h (~1 MTPA) of LNG. 626

1 INTRODUCTION

Among fossil fuels, Natural Gas (NG) is the one having the lowest pollutant content, the highest calorific value and the lower specific CO_2 emission. Moreover, its production is spread among all continents making it a fundamental asset during the energy transition towards renewables. Liquefied Natural Gas (LNG) is gaining more and more attention thanks to the growth in interest from importing countries, mainly Europe and Japan, which aims to increase energy security through suppliers diversification: Natural gas, in its liquefied form, has a density of 430-470 kg/m^3, and can be easily transported worldwide by sea, from many different producing countries, with great geographical & market flexibility. The global LNG trade in 2020-2021 was around 28billion of cubic meters (IEA, 2022). During the production phase, natural gas (NG) is liquefied by cooling at cryogenic temperature, roughly -160 °C, at 1 atm pressure, for sake of volume reduction and ease of transportation and storage. Natural gas refrigeration is an energy intensive process: energy consumption for liquefaction is on average 500 kWh of electricity consumed per ton of LNG produced (Agarwal R., 2017) which correspond to roughly 3.6% of the natural gas LHV.

LNG transportation occurs in insulated cryogenic ship tanks at atmospheric pressure. Before being provided to a transportation and distribution network, LNG must be pressurized, usually at 80 to 120 barg (Mokhatab, 2014), and returned to gaseous state. The latter is performed at LNG import terminals in vaporizers. Conventional vaporizers are submerged combustion (SCV), open-rack (ORV) and intermediate-fluid (IFV) type. For the latter two the heat source is seawater, while in SCV a fraction of NG is combusted and the flue gases heat a pool of water which later provides heat to LNG. In ORV sea water is flowing in counterflow outside LNG tubes, while the IFV consists in a shell and tube heat exchanger in which an intermediate fluid, in the shell, absorbs heat by vaporizing in contact with sea water and then condenses releasing latent heat to LNG, both LNG and sea water flows in the tubes. In all these vaporization processes a considerable amount of the energy used in the liquefaction phase (around 28%) is wasted to the environment and, additionally, they require the consumption of electrical energy (for LNG pumps and water pumps in ORV) and/or regasified gas in case of SCV.

1.1 Harvesting the Cold Energy Potential

An interesting use of cryogenic LNG, to increase the efficiency of regasification terminals, is electric power generation through the introduction of a power cycle between the environment and the vaporization process. In fact, a thermal engine can convert any meaningful temperature difference into mechanical energy and then into electrical energy in a turbogenerator. Power can be produced in a thermodynamic cycle in which LNG acts as the cold heat sink, and the ambient (e.g. seawater) at higher temperature as hot resource. Generated electrical power becomes a valuable "sub-product" of regasification and can be used for internal LNG terminal consumption and the excess fed to national grid. LNG contains an enormous potential for power generation, the "cold energy potential". The available heat is about 725 kJ_{th}/kg_{LNG} (from -160°C to 15°C @ 80 bara), and the available mechanical exergy from the gasification process alone about 348 kJ_{ex}/kg (Invernizzi M. C., 2016).

The ORC technology is an efficient and market-available way to harness the cold energy potential from LNG and will be the object of this paper. It has been developed since 1980, particularly in Japan by Osaka Gas, but few and sparse information about the pilot plants are available (Astolfi M., 2017). Referring to the schematic in **Figure 1**, in analogy with IFV, in ORC seawater is fed into a series of heat exchanger and vaporizes a low-boiling working fluid. In ORC the high pressure fluid vapor expands in the turbine and is then discharged in the condensers, where the heat is released to LNG to vaporize it until is returned in gaseous form. Similar to traditional IFV, the LNG is vaporized through an intermediate fluid, but with ORC the cold energy potential is not wasted, is converted in a turbo-expander. As a strategy for even higher cold energy conversion efficiency, ORC can be integrated with other technologies, as Direct Expansion (DE) in combined cycle cold energy plants (Invernizzi M. C., 2016) (Sugiyama). Currently, cold energy utilization accounts for less than 1% of its total potential, although around 12 GWe could be produced from its exploitation, which could be further boosted by climate change policies (Agarwal R., 2017). The aim of this paper is to present Exergy International's studies and patented Cold Energy Plant (CEP) for efficient utilization of cold energy potential through internally developed ORC technology and proprietary turbine design.

2 COLD ENERGY ORC PLANT

2.1 Exergy International Patented Multi-Level Condensation ORC

Conventional ORC systems are characterized by a single level of condensation and the use of propane, R13, R22 or R23 as working fluid. The typical size ranges from few hundreds kWs to 5 MW (Astolfi M., 2017). The Temperature-Heat Exchanged diagram for the working fluid condensation process (**Figure 5**) demonstrates that this single-condensation plant configuration is characterized by a condensation curve which does not match the LNG vaporization and strongly limits the turbine expansion, thus the ORC plant power production.

To overcome single level ORC performance limitation Exergy International S.r.l. developed and patented (Patent No. EP 3 642 458 B1, 2021) a multi-level condensation ORC CEP, with the final aim to utilize at its maximum the LNG heat sink along the vaporization curve, increase the cycle efficiency thus maximizing the electrical power production at requested regasification rate. The patent allows up to four levels of condensation, with the use of a single feed pump in ORC circuit and Exergy's radial outflow turbine. The advantages of Exergy's multi-level condensation with single feed pump are:

- Higher cycle efficiency, Higher specific power production (SPP), and higher cold-energy-recovery factor than single level: see performance parameter definition in section 2.2.1 and comparison of single vs. two-pressure condensation level-based ORC plants in section 2.2.2.

- Single pump configuration is enabled by the use of a throttling valve at high pressure condensers outlet. At valve outlet the fluid will be de-pressurized and in two-phase, liquid and vapor. The two-phase flow is routed to the lower-pressure condensers where the liquid mixes with the low pressure condensate and the vapor is condensed along with the low-pressure vapor from turbine discharge. Single, low suction pressure, pump means: lower ORC plant complexity and lower plant CAPEX, lower number of critical equipment exposed to cryogenic temperatures, expected lower stops for maintenance and higher plant annual availability.
- Integration with Exergy International's patented high efficiency ROT (Radial Outflow Turbine), see section 3 below, which naturally allow spillages between stages. High pressure and low-pressure expansion both in a single turbomachine unit.
- Suitable for the use of propane as working fluid, which is indicated by literature as one of best performing among hydrocarbons (Astolfi M., 2017) and has high market availability at low cost: in fact propane has already been successfully employed in conventional IFV and many cryogenic applications. Other advantages of propane are: low Global Warming Potential (GWP < 10), moderate vacuum in low pressure condenser (> 0.1 bara)

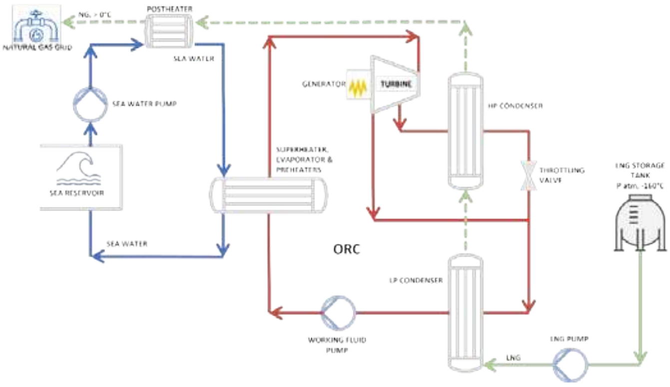

Figure 1 Exergy's Multi-Level Condensation ORC CEP in two-pressure level configuration

The schematic above (**Figure 1**) shows the patented multiple condensation levels ORC plant in two-condensation pressure levels configuration. The main ORC equipment are: preheaters, evaporator and superheater, exchanging heat with sea-water, ROT turbine and generator, high pressure (HP) and low pressure (LP) condensers, exchanging heat and achieving the regasification of LNG, single feed pump, condensate throttling valve at HP condenser outlet (ORC side). A LNG post-heater is designed in order to heat up LNG from HP condenser outlet with seawater: the final aim is to guarantee the NG temperature is always higher than the minimum required by NG distribution network.

Even though the patent allows up to four levels of condensation, the two-pressure levels configuration has been selected as the object of this paper and its performance improvements with respect to conventional single-level ORC will be further discussed in next sections. Currently, two-levels of condensation has resulted, by Exergy's internal analysis, as an optimum compromise among efficiency, plant complexity and overall CAPEX.

2.2 Comparison Two-Level Vs. Single-Level Condensation Plants

2.2.1 Performance Parameters, Definitions, Case Description: First law efficiency as usually defined as net power output over heat input is not a suitable parameter for cold energy plants comparison, since it does not directly show the efficiency in utilizing the cold energy potential from LNG. Thermal efficiency could be more effectively defined considering the total heat output, which is discharged at ORC condenser for LNG vaporization:

$$\eta_{Th,net}\,[\%] = \frac{W_{e,net}}{Q_{cond}} \qquad (1)$$

Where: $Q_{cond} = \sum_{i=1}^{N} Q_{cond,i}$ with N = total number of condensation steps.

The capability to utilize at its maximum the available heat sink provided by LNG regasification process from cryogenic temperature (about -160°C) up to the required temperature at interface outlet (generally ≥ 0°C), is shown by the cold-energy recovery factor value, as defined below:

$$f_{CE,REC}\ [\%] = \frac{Q_{cond}}{Q_{LNG}} = \frac{Q_{cond}}{\dot{m}_{LNG} \cdot (h_{NG,out} - h_{LNG,in})} \quad (2)$$

Multiplying the recovery factor with the thermal efficiency, the result is the net cold energy efficiency, representing the net electrical power output per unit of heat that could theoretically be transferred to LNG:

$$\eta_{CE,net}\ [\%] = \frac{W_{e,net}}{Q_{cond}} \cdot f_{CE,REC} = \frac{W_{e,net}}{Q_{LNG}} \quad (3)$$

Literature (Invernizzi M. C., 2016) indicates the SPP (Specific Power Production) parameter as the best index for performance evaluation. SPP is defined as ORC plant net electrical energy production per unit mass of LNG vaporized:

$$SPP\ \left[\frac{MJ_e}{kg_{LNG}}\right] = \frac{EE_{net}}{M_{LNG}} \quad (4)$$

SPP allows to compare perforce of different cold energy recovery technologies in different configurations and correctly represent the effectiveness in generating electrical energy from the required LNG regasification process.

Table 1 Case Description: Input & Design Data, Constraints

LNG regasification plant size	**1 MTPA**	**NG temperature @ Post-heater Outlet**	**10°C**
(Peak) LNG flow to ORC	180 t/h	**Sea Water Temperature**	18°C
LNG pressure @ ORC inlet	94 bara	**Sea Water Allowed ΔT**	4°C
LNG temperature @ ORC inlet	-157 °C	**ORC Working Fluid (WF)**	Propane
ΔP **ORC Vapor Phase (Evaporator, Superheater, Turbine inlet line)**	0.60 bar	ΔP **ORC Condensers (WF side) HP / LP**	0.05 bar / 0.05 bar
ΔP **ORC Turbine Discharge Line**	0.02 bar	ΔP **ORC Condensers (LNG side) HP / LP**	0.25 bar / 0.25 bar
ΔP **ORC Liquid Phase (Preheater, Liquid Lines)**	0.80 bar	**ORC Auxiliaries Consumption (other than WF Pump)**	67 kW
$\eta_{T,el-mec}$	97.5%	$\eta_{P,hyd}$	65%
$\eta_{T,is}$	89%	$\eta_{P,el-mec}$	93%
ΔT_{pp} **in ORC Condensers**	5°C	ΔT_{pp} **in ORC Evaporator**	≥ 3°C
ΔT_{sc} **@ ORC Condensers Outlet**	1°C	ΔT_{pp} **in ORC Superheater**	≥ 3°C
Turbine Discharge Vapor ΔT Superheating	≥ 2°C	**Fluid Properties Database**	NIST REFPROP 9

Reported in sections below are the results from the energy balances and sensitivity analysis for the two cold energy ORC configurations: single level and two-level condensation pressure. In **Table 1** the main input data and constraints for the calculations are collected. The cycle constraints are on pinch-point temperature differences in heat exchangers and on turbine outlet temperature, the latter shall always be above saturation to guarantee dry expansion and no liquid droplets in last turbine stages. Simulations have been performed in internally developed Microsoft Excel + VBA code environment with thermodynamic fluid properties from NIST REFROP V9.1 (Lemmon, 2013) database. The optimization algorithm uses the Generalized Reduced Gradient (GRG) non linear code, built-in Excel solver tool (Leon S. Lasdon, 1975). The ORC optimization target, both in single and in two-pressure level configuration, is to maximize the SPP parameter by acting on the following variables: turbine spillage flow rate, ORC evaporation pressure, ORC condensation pressure (both HP and LP for two-pressure levels cycle), degrees of superheating at turbine inlet.

2.2.2 Thermodynamic Results: Reported in **Figure 2** below is the comparison between two and one-pressure level for all the performance parameters defined above. The plot has on the horizontal axis the

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LNG temperature at post-heater inlet, i.e. at ORC condensers outlet, which is the HP Condenser outlet for the two pressure levels cycle. This temperature is an indication of the cold energy utilization in the ORC system. Higher LNG post-heater inlet temperature always means higher cold energy recovery for both single and two pressure level configurations. Lower LNG inlet temperatures are associated with lower condensation pressure and therefore to higher ORC thermal efficiency, as defined above by equation (1). There is, therefore, a trade-off between achievable thermal efficiency and cold energy utilization. The optimum SPP and cold energy efficiency are in an intermediate LNG outlet temperature region, where the recovery factor is still adequate and the cycle thermal efficiency is not excessively limited by the LNG condenser outlet temperature, which directly affect the turbine discharge pressure. It can be observed from **Table 2** that the single pressure level cycle optimum SPP point is located at lower temperatures than the two pressure level cycle (-55°C vs -44°C).

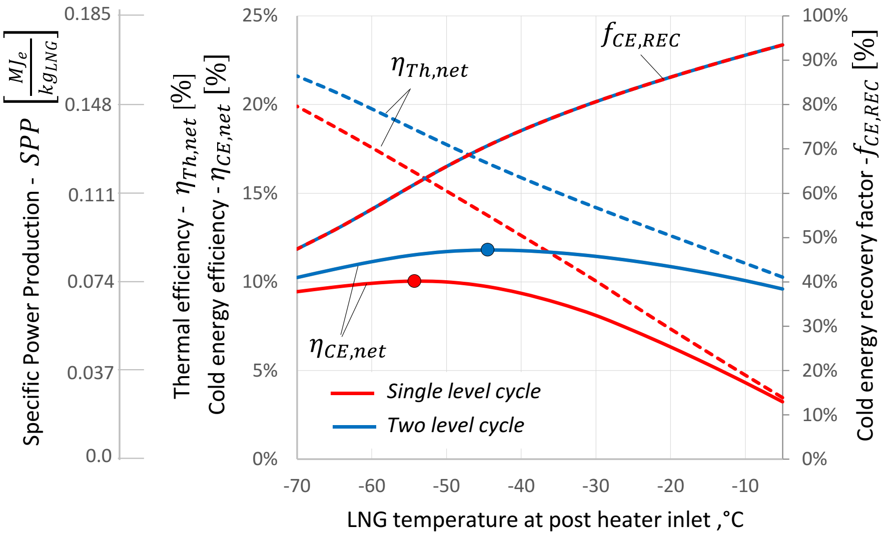

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Figure 2 Comparison of performance parameters for single and two-condensation pressure level configurations as function of NG temperature at ORC condenser outlet (post-heater inlet).

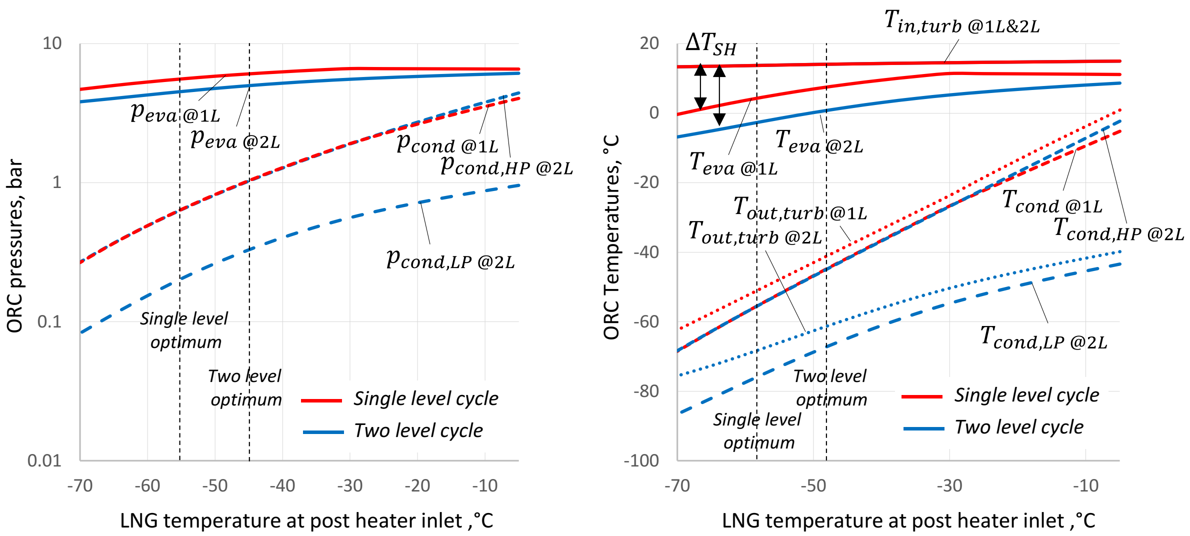

Figure 3 Optimization Variables as function of LNG post-heater inlet temperature

The optimization variables trends are shown in **Figure 3**, again as a function of LNG temperature at post-heater inlet. The power output optimization algorithm slightly increases the evaporation pressure and decreases the superheating as the LNG temperature increases, for both single and two-pressure level cycles, while satisfying the constraint on turbine outlet minimum 2°C superheating to guarantee dry expansion. The superheater pinch point temperature difference is always kept by the algorithm at the minimum allowed value of 3°C. For single level cycle the trend changes at LNG post-heater inlet temperature greater than -30°C: above this temperature the cycle performance limiting factor shifts from the limitation due to mandatory dry turbine expansion to minimum pinch-point temperature difference inside the ORC evaporator, and the optimization algorithm starts decreasing the evaporation pressure while increasing again the turbine inlet superheating to satisfy the requirement: this behavior is expected since in low temperature region the propane vapor saturation curve is slightly bell-shaped, see Ts-diagram in **Figure 5**, while from -30°C the curve becomes almost vertical, or "isentropic".

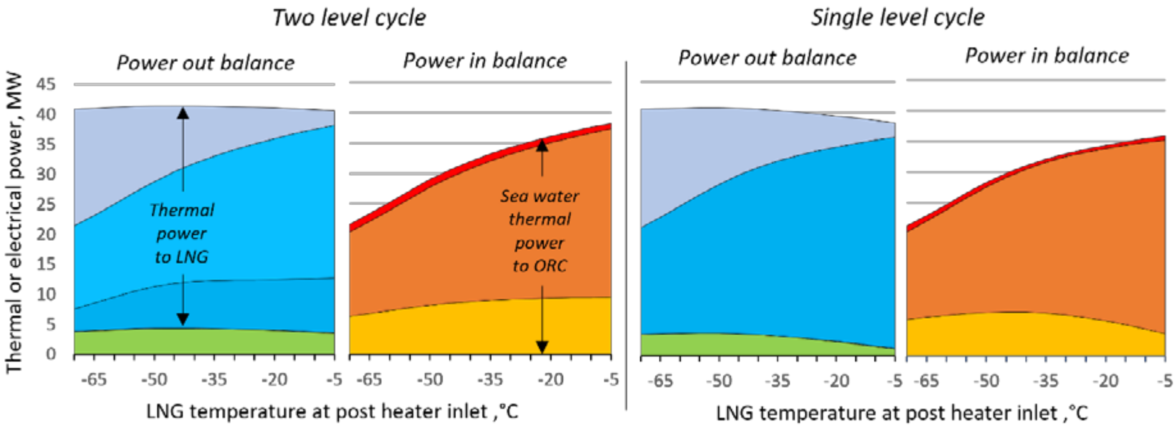

Figure 4 First Law Energy Balance as function of LNG temperature at post-heater inlet. Legend: ☐ LNG post-heater; ☐ LP condenser in two level cycle; ☐ HP condenser in two level cycle / condenser in single level cycle; ☐ Energy Losses; ☐ Electrical Power output; ☐ Superheater; ☐ Evaporator; ☐ Preheater

The first law balances results are presented in **Figure 4**. It is evident that the higher the LNG temperature at post-heater inlet, the higher the seawater thermal power required entering the ORC. Most of the thermal duty on seawater-propane side is processed by evaporator, while superheater thermal power is relatively small, hinting on the possibility of integration of these two units in a single exchanger for possible capital cost reduction. Superheater duty in two level cycle is higher than in single level, showing the necessity to increase more the turbine inlet temperature in the first configuration. On LNG side the majority of ORC wasted heat to LNG is discharged by low pressure condenser in the two-level cycle. In both configurations post-heater duty, and therefore necessary exchanger area and costs, increases as the LNG temperature at its inlet decreases. 631

Table 2 Best SPP Point Comparison: Two-level vs. Single Level

Case:	**Two Level**	**Single Level**
LNG Temperature @ Post-Heater Inlet	-44°C	-55°C
Propane Temperature @ ORC Turbine Outlet	-59°C	-48°C
Evaporation Pressure	5.0 bara	5.6 bara
Turbine Inlet Superheating	12.5°C	8.4°C
Condensation Pressure (HP / LP)	1.0 / 0.3 bara	0.6 bara
Net Electric Power	4.3 MWe	3.7 MWe
SPP [MJ/kg] (4)	0.087	0.074
Recovery Factor [-] (2)	70.3%	61.3%
Thermal Efficiency [-] (1)	16.8%	16.4%
Cold Energy ORC Efficiency [-] (3)	11.8%	10.0%

The two best SPP operating points have been selected for both cycles and the major results from the calculations are reported in **Table 2**. The two-pressure level cycle configuration alone allows an increase in SPP of around +18% and achieve the optimum performance at +9°C LNG temperature at condenser outlet, or post-heater inlet, thus at less critical cryogenic temperatures (above -50°C), this is thanks to the much higher cold energy recovery factor.

In **Figure 5**, for the two best SPP cases, the temperature-heat exchanged diagram and temperature-entropy diagram are plotted. The advantage of more than one single condensation pressure is evident: in two level case the condensation curve better match the LNG heating and regasification process, while achieving lower turbine discharge pressure and therefore higher electrical power production. In temperature-entropy diagram for the two-level cycle is shown the spillage from an intermediate turbine stage. The spilled flow is routed to the HP condenser for full condensation (marked points x-y), then the HP condensate is throttled by a valve (y-y') down to LP condenser pressure. The low pressure condensate is, in both cases, pressurized and sent to primary heat exchangers by a single feed pump.

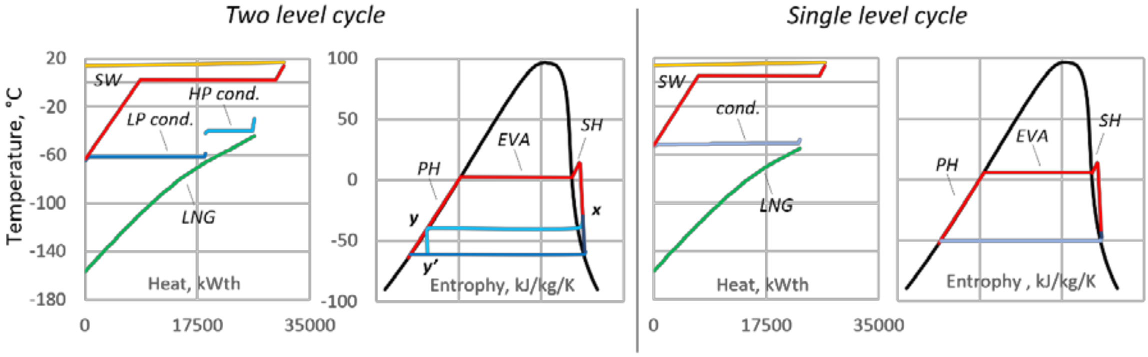

Figure 5 Temperature-Heat Exchanged diagrams and Temperature-Entropy Diagrams for the two configurations in best SPP point. Note: Thermal duty in LNG post-heater is not here represented.

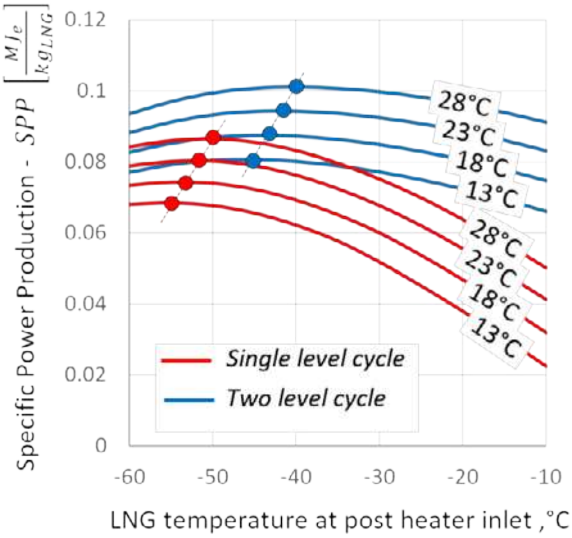

Figure 6 Effects of Sea Water temperature on ORC SPP performance parameter. For all the cases the maximum allowed water cooling is 4°C

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2.2.3 Effect of Sea Water Temperature: Seawater temperatures vary during the year and by geographical region, and the above study has been performed at an average seawater temperature of 18°C. Nevertheless, the maximum seawater temperatures are between 21.5 ◦C and 29.1 ◦C and are consistent across the globe, while the minimum mean seawater temperature range between 8.1°C and 24.1°C, reaching below 5°C only in few countries during winter (Agarwal R., 2017). A dependency study highlights the effect of seawater temperature on the ORC performance. In **Figure 6** are reported the results for seawater temperature ranging from 13°C to 28°C, which is a representative interval, both for two and single-pressure level cycle configuration. As expected, ORC always benefits from an increase in seawater temperature: higher temperature means higher ORC evaporator pressure, thus higher power production and SPP. The optimum SPP point shifts at higher post heater inlet temperature, meaning higher recovery factor is achieved. For the two level cycle optimum SPP increases +25% passing from 13 to 28°C.

2.3 ORC Configuration: Effects on Turbomachinery

The selection and design of the ORC turboexpander is clearly affected by the thermodynamic properties at its inlet and outlet interfaces and, in the case of multi-pressure condensation cycles, also at the intermediate spillage point.

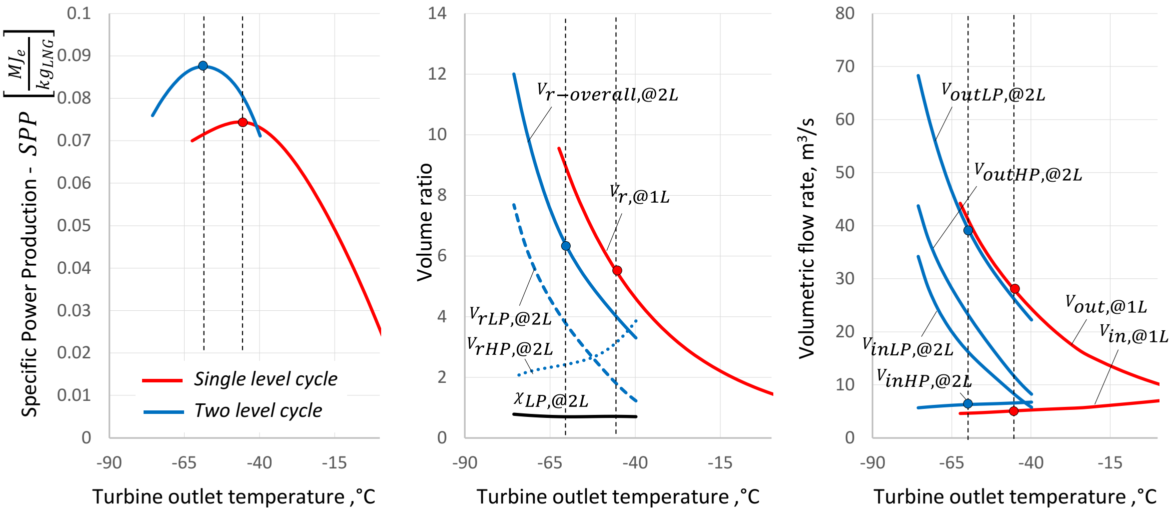

Figure 7 ORC Results for Turbomachinery: SPP vs. turbine outlet temperature, volume ratio and volume flow rate for two and single pressure level cycles.

The main parameters that give the first direction to be taken for the turbomachinery design, and which roughly determine the overall dimensions (outside diameter, stages radius) and the total number of stages, are the volume ratio and outlet volume flow rate. For cold energy applications, the turbine outlet temperature also has a major impact: as cryogenic it determines the proper material selection. For this reason, the plots presented in this section (**Figure 7**) are as function of turbine outlet temperature (LP turbine outlet for multi-level cycle). The optimum SPP point for two level cycle is located at lower temperature, thus pressure, than for the single-level cycle. The lower pressure results in a higher volumetric flow rate at turbine discharge than in the single-pressure case, but the two level is not excessively higher (approximately 40 m^3/s vs. slightly under 30). Nevertheless, the volume ratio processed by the machines, at the optimum SPP points, is close to 6 for both configurations. All of the above indicates that the two turbo-machines for the two optimal SPP cycles will be very similar in terms of sizing, and therefore it can be reasonably predicted that a two-pressure level turbine will have a comparable manufacturing cost of a single-pressure level turbine for cold energy applications. A precise cost analysis and comparison may be the object of future study. **633**

3 RADIAL OUTFLOW TURBINE FOR COLD ENERGY PLANT

The patented multi-level condensation CEP, as described in the previous section, involves the use of the Radial Outflow Turbine (ROT) as turbo-expander. Radial Outflow Turbine architecture can process high volumetric flow ratio and important enthalpy drops, typical of organic working fluid, while achieving very high efficiency: this thanks to the possibility to have multiple stages, limiting the load on each stage and, therefore, subsonic flows (Spadacini C., 2015).

The ROT has been conceptualized and produced by Exergy based on Ljungstrom turbine and launched in the market in 2009. In this particular application the ROT, keeping the standard single rotor disk architecture, is conceptually re-designed to meet the Multi-level Condensation Cycle needs:

- Both turbine sections, high pressure and low-pressure level, have been optimized using an internally developed Excel-based simulation tool, which output is the preliminary 1D turbine sizing. Then, the geometry is designed tridimensionally with Ansys CFX, and several geometric parameters are tuned to extract the best possible performance.

- The ROT mechanical group have been designed to be extracted for easy maintenance, minimizing service effort. Bearing and shaft of the turbine are located in the non-cryogenic process area (see **Figure 8**), far from the low temperature discharge of the working fluid: mechanical group is never exposed to cryogenic temperatures minimizing the use of valuable materials, making possible to employ well-known and robust technology and reducing the overall thermal effects on the machine.
- The CEP ROT presents nitrogen seal system with double mechanical arrangement that allows the sealing of the turbine shaft thus minimizing propane leakages to the environment. In normal operating conditions, may happen that the sealing fluid leaks from both side, atmospheric and process side. The use of nitrogen (instead of seal oil) as barrier fluid prevents the problem of solidification of mineral oil in cryogenic conditions due to leakage on the process side.
- The control unit comprises dedicated fin fan coolers as well as a vacuum pump to guarantee turbine sealing even in case of failures, hence enhancing the turbine lifetime.

The Radial Outflow Turbine ensures different advantages in cryogenic applications compared to other solutions. The isentropic efficiency is high both in on and off-design conditions thanks to: optimization of velocity triangles, multiple reaction and action stages, the natural radial increase of passage area, that allows to expand high volumetric flow ratio. The ROT configuration naturally allows spillages between stages in single-disc turbine, therefore can enable the multi-level condensation pressure level ORC in a single machine: no need for multiple turbines at different pressure levels. The ROT shaft length, unlike the axial turbines, does not need to be increased to make room for the spillages point clearance, avoiding several rotor dynamic problems for overhung configuration. In addition, the low rotational speed makes possible the direct drive avoiding the need for additional gearbox.

Table 3 Turbine sizing for the two level ORC CEP at best SPP point (see Section 2, Table 2); “R out” is the outer radius for the last stage for each pressure level. Selected rotational speed is 1500 rpm. **634**

		HP	LP
N°stages	[-]	3	2
R out	[mm]	751	897

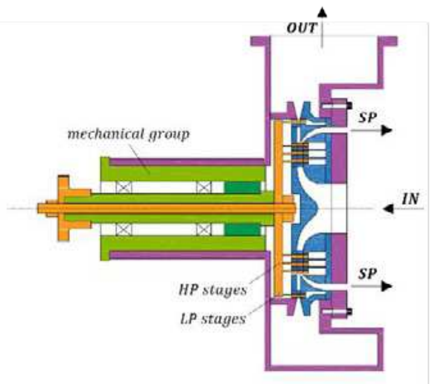

Figure 8 ROT sectional drawing for two-pressure level CEP. IN = Working fluid inlet; SP = Spillage point, to HP condenser; OUT = Turbine discharge, working fluid outlet to LP condenser.

4 CONCLUSIONS

Cold Energy Plant (CEP) based on Exergy International’s patented multi-level condensation, single pump, and ROT turbine ORC is a market-available solution for the cold energy recovery from the LNG vaporization process. The calculations and the results demonstrated that the single-pump two-pressure level cycle has better performance than conventional single-level cycle, about +18% in net Specific Power Production (SPP). Performance is, in both cases, strongly dependent on seawater temperature:

ORC efficiency in power production from LNG strongly benefits from warm climates. The analysis on the process parameters for turbine sizing demonstrated that no significant differences in size and cost compared to a single pressure level turbine are to be expected. The multi-level ORC patent involves the use of Radial Outflow Turbine (ROT), which enables the multi-level CEP since naturally allows spillages between stages and accommodates the large volumetric expansion while achieving high efficiency. Furthermore, the ROT mechanical group is located far from turbine cryogenic region.

NOMENCLATURE

Nomenclature and Acronyms

LNG	Liquefied Natural Gas
LHV	Lower Heating Value (MJ/kg)
SCV	Submerged Combustion Vaporizer
ORV	Open Rack Vaporizer
IFV	Intermediate Fluid Vaporizer
DE	Direct Expansion
ORC	Orgnic Rankine Cycle
CEP	Cold Energy Plant
ROT	Radial Outflow Turbine
GWP	Global Warming Potential
HP	High Pressure
LP	Low Pressure
η	Efficiency (%)
f	Recovery Factor (%)
SPP	Specific Power Production (MJe/kg-LNG)
EE	Electric Energy (MJe)
M	Mass (kg of LNG)
MTPA	Million Tons Per Annum of LNG (1000 kg LNG/year)
WF	Working (Organic) Fluid
SW	Seawater
T	Temperature (°C)
P	Pressure (bara)
PH	Preheater or Economizer
EVA	Evaporator, Evaporation
SH	Superheater
COND	Condenser, Condensation
V	Volume
L	Levels, of condensation pressure
R	Radius (mm)

Subscripts

th	Thermal
e, el	Electrical
CE	Cold Energy
REC	Recovery
net	Net
T, turb	Turbine
P	Pump
is	Isentropic
el-mec	Electro-mechanical
hyd	Hydraulic
pp	Pinch Point
SH	Superheating
r	Ratio

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This book contains the compilation of works contributed to the *7th International Seminar on Organic Rankine Cycle Power Systems* (ORC 2023), held in Seville between the 4th and 6th of September 2023. The event was hosted by Universidad de Sevilla on behalf of the Knowledge Centre on Organic Rankine Cycle Technology (KCORC), incorporated in The Netherlands.

The ORC conference, organized biennially, stems as the only conference that is specific to ORC technology, therefore gathering a diverse community whose affiliation spans across all the interested stakeholders, not only in this particular technology but also and in a broader context, in the energy transition. Original equipment manufacturers, professional associations, end-users, investors, policy makers, academics, scientists feel at home at ORC 2023.

The almost 100 proceedings in this book cover a wide variety of topics, from fundamentals to system integration through component design, accounting for thermodynamic performance as well as component design. In addition to this, and as a new track in 2023, works on heat pump technology were also accepted in order to raise awareness of the strong ties between both technologies, specifically in energy storage applications.

This book provides an excellent overview of the current maturity of power systems based on Organic Rankine Cycle technology for applications as diverse as geothermal and waste heat recovery in industry or downstream of other prime movers (e.g., marine applications). It is also an excellent source of information to understand the current challenges faced by the technology, stemming from a very competitive market and increasingly stringent environmental regulations.

The organizers of ORC 2023 hope that the reader finds this work as exciting as the attendees to the conference and, maybe, make the decision to join the 8th edition to the conference in 2025.

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