Thermoeconomic Analysis of an Organic Rankine Cycle for LNG Cold Energy Utilization

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Abstract: *Liquefied natural gas (LNG) has become a crucial source of energy supply security amid growing geopolitical tensions in recent years. During LNG regasification, a substantial amount of cold energy is released, and typically wasted into seawater. The cold-energy potential of LNG during regasification and warming from −161 °C to +15 °C at 80 bar is 750 kJ/kg, while the associated exergy potential is 400 kJ/kg. This paper investigates the potential for converting LNG cold energy into electricity through a cryogenic binary cycle. The results indicate that integrating an ORC system into the LNG regasification process can yield substantial energy and economic benefits while reducing the thermal waste at regasification terminals. The recoverable power per 1 kg/s of LNG is 90 kW/(kg/s) for a single-pressure ORC configuration using ammonia as the working fluid. The levelized cost of electricity (LCOE) is 45 €/MWh while specific installation costs (SIC) are 2225 €/kW for a brownfield retrofit project on an existing regasification unit. This research confirms that the application of innovative cryogenic cycles enables a more sustainable and efficient use of the LNG supply chain, contributing to the decarbonization of the energy sector.*

Keywords*: LIQUEFIED NATURAL GAS (LNG); COLD ENERGY UTILIZATION; THERMOECONOMIC ANALYSIS; ORGANIC RANKINE CYCLE (ORC).*

1. Introduction

Liquefied natural gas (LNG) is expected to play a crucial role in facilitating the global transition towards renewable energy systems. LNG can be transported via sea routes between producers and consumers, enabling flexible worldwide energy supply. The current global LNG liquefaction capacity stands at 670 billion cubic meters (bcm) per year, equivalent to approximately 490 million tonnes annually (MTPA), by the end of 2024. This capacity is expected to expand significantly as new projects become operational. Between 2025 and 2030, more than 300 bcm (220 MTPA) of new export capacity is anticipated to commence operations [1]. From January to October 2025, final investment decisions (FIDs) for LNG reached record levels, totaling 96 bcm/year of new liquefaction capacity worldwide, with the United States accounting for 83 bcm/year of this growth [2].

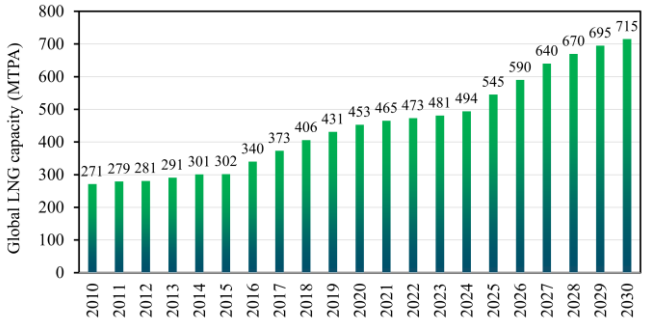

Fig. 1. *Global LNG capacity: recorded data (2010-2024) and forecasted data (2025-2030)*

Natural gas liquefaction is a highly energy-intensive process, requiring 0.3–0.4 kWh of compression or turbine power to produce 1 kg of LNG [3]. The cooling energy required to liquefy natural gas from +15 °C to −161 °C at 1 atm amounts to 850 kJ/kg [4]. Prior to regasification, LNG is generally pressurized to 60–80 bar, matching the inlet pressure of natural gas transmission networks. During warming from −161 °C to +15 °C at 80 bar, LNG possesses a cold-energy potential of 750 kJ□ □ /kg_{LNG}, corresponding to an exergy potential of 400 kJ/kg_{LNG}. Assuming an average cryogenic power plant exergy efficiency of 40% [5], the current global LNG regasification capacity (490 Mt_{LNG}/year) represents a theoretical electricity generation potential of approximately 2.5 GW.

LNG cold energy can be harnessed for multiple applications, including power generation, air separation, seawater desalination, refrigeration and cooling, and cryogenic CO_2 capture [6]. Other uses involve district cooling, food preservation, and data center cooling, or as an auxiliary cooling source in air separation, hydrogen, and ammonia liquefaction processes. Hybrid systems integrating several cold-energy applications can substantially reduce the overall power and cooling requirements at LNG regasification terminals [7].

Among these applications, power generation is the most extensively studied. Commonly investigated cycles include direct expansion (DE) [8–9], the Kalina cycle [10], the Brayton cycle [11], and the Organic Rankine Cycle (ORC) [12–13]. The ORC is generally preferred due to its technological maturity, ease of integration, and proven effectiveness in converting low-temperature heat sources such as geothermal [14], solar [15], and seawater energy [16]. LNG cold-energy utilization through ORC systems is analogous to Intermediate Fluid Vaporizer (IFV) configurations, both employing seawater as a heat source to vaporize an intermediate fluid. However, unlike IFVs that discharge LNG cold energy into the ambient, ORCs recover part of this energy as useful work. The research on systems and components for cold energy and waste heat utilization is gaining growing attention [17–20], as they recover valuable energy that would be otherwise wasted into the ambient, increasing the overall energy efficiency and reducing greenhouse gas emissions from the industry.

The vaporization pressure of LNG affects the selection of the working fluid and ORC configuration. The recoverable power per 1 kg/s of LNG is 100–120 kW/(kg/s) for single-stage, 130–150 kW/(kg/s) for two-stage, and up to 225 kW/(kg/s) for double two-stage parallel ORC systems [21]. Direct expansion and cryogenic turboexpanders achieve 150–165 kW/(kg/s) [22]. The recoverable power increases with the heat source temperature, ranging from 158 kW/(kg/s) at 25 °C to 249 kW/(kg/s) at 85 °C [23]. Daniarta et al. [24] reviewed cryogenic power systems including ORC, Brayton, Kalina, DE, and supercritical CO_2 cycles, reporting efficiencies of 6.5–48% for ORC, 30–73% for Brayton, 24–48% for DE, and 32–45% for Kalina and SCO_2 cycles, depending on the working conditions.

ORC systems cover a wide range of power outputs: micro-ORC units (1–50 kW) are used for small-scale waste-heat recovery; small-scale units (50–500 kW) are applied to geothermal, biomass, and solar-thermal sources; medium-scale systems (0.5–5 MW) serve industrial and CHP applications [25]; while large-scale ORCs can reach 50 MW, particularly in geothermal power plants [26].

Recent advances in LNG cold-energy power generation have aimed to enhance the performance of the traditional Rankine cycle. Several studies [27] improved thermal efficiency using internal heat recuperators, which preheat the working fluid via turbine outlet vapor. Others [28] employed flash tanks or fluid mixtures to better match the temperature profile of the heat source. Further efficiency

gains have been demonstrated by combining multiple Rankine loops in series or parallel, as well as through cascade and multi-stage cycle configurations [29].

Previous studies have mostly focused on the thermodynamic optimization, while fewer studies have addressed the economic performance of ORC systems for LNG cold energy utilization.

Tsougranis and Wu [30] examined a two-stage cryogenic ORC integrated into an LNG-powered vessel. Using ethylene (C_2H_4) as the working fluid, the study reported a specific investment cost (SIC) in the range of 4300-4900 US$/kW. The corresponding LCOE was calculated as 42-48 US$/MWh, assuming a 5% discount rate, 20-year lifetime, and 8,000 operating hours per year. Other studies of LNG cold-energy utilization found higher cost levels when additional subsystems or storage components are integrated. For instance, Zheng et al. [31] assessed small-scale LNG cold-energy power generation systems and reported LCOEs in the range of 90-110 US$/MWh along with an exergy efficiency of 48-55%. Similarly, Wang et al. [32] evaluated a 10 MW LNG cold energy power plant with liquid air energy storage and calculated an LCOE of 100 US$/MWh at an exergy efficiency of 63%. Other studies report LCOE values in the range of 100-300 US$/MWh [33] for more complex ORC configurations and partial-load operation.

The literature overview revealed that the economic performance of ORC systems for LNG cold energy utilization is still lacking. To fill this research gap, the present study carries a thermo-economic assessment that evaluates both the energy and economic performance of ORC systems for LNG cold energy utilization.

2. Methodology

The ORC system for LNG cold energy utilization is modelled as a single-pressure configuration with ammonia as the working fluid, as shown in Figure 2. The system integrates three main circuits: the ORC working-fluid loop (purple line), the LNG circuit (green line), and the seawater circuit (blue line). This system simultaneously generates power through the ORC turbine by utilizing the temperature difference between warm seawater and cold LNG, and regasifies LNG, using the ORC condenser and the afterheater as heat sources [34]. The integration maximizes exergy utilization by recovering LNG cold energy while minimizing environmental impact and improving overall thermal efficiency.

The ORC loop converts low-temperature thermal energy into mechanical power, which is then converted to electricity via a generator. LNG acts as the cold source for condensation, while seawater provides the heat source for evaporation and preheating of the ORC working fluid.

Seawater, driven by a seawater pump, transfers heat to the ORC working fluid in the preheater, ④ → ⑤. The preheated ORC fluid continues to the evaporator, where it absorbs additional heat from seawater and becomes dry or superheated vapor, ⑤ → ①. The ORC vapor expands through a turbine, ① → ②, producing mechanical work that drives a generator to produce electricity. The exhaust vapor from the turbine is condensed using LNG as the cooling medium. Here, the LNG absorbs heat and is vaporized, while the ORC working fluid is condensed into liquid, ② → ③. The condensed ORC fluid is pressurized by a feed pump, ③ → ④, and sent back to the preheater, completing the closed cycle.

On the LNG side, a cryo pump pressurizes the LNG from the LNG tank pressure (1 bar) to the pressure at the inlet of the natural gas transmission network (70 bar), ⑥ → ⑦. The LNG passes through the condenser, ⑦ → ⑧, absorbing heat from the ORC fluid and vaporizing. The partially vaporized LNG then flows through an LNG afterheater, ⑧ → ⑨, where it is further warmed by seawater to meet delivery conditions.

The physical properties of LNG are assumed to be equivalent to those of pure methane (CH_4), while the effects of heavier hydrocarbon components are neglected. The physical properties of seawater were approximated by those of freshwater for simplification, and all thermophysical calculations were performed using the REFPROP v10.0 database. The heat balance equations for the evaporator, the preheater and the condenser are:

$$\dot{Q}_{EV} = \dot{m}_{sw} \cdot c_{sw} \cdot \Delta T_{sw} = \dot{m}_{ORC}\left(h_1 - h_5\right) \quad (1)$$

$$\dot{Q}_{PH} = \dot{m}_{sw} \cdot c_{sw} \cdot \Delta T_{sw} = \dot{m}_{ORC}\left(h_5 - h_4\right) \quad (2)$$

$$\dot{Q}_{C} = \dot{m}_{ORC}\left(h_2 - h_3\right) = \dot{m}_{LNG}\left(h_8 - h_7\right) \quad (3)$$

The turbine and the feed pump power are calculated as follows:

$$\dot{W}_{T} = \dot{m}_{ORC}\left(h_1 - h_2\right) = \dot{m}_{ORC}\left(h_1 - h_{2s}\right)\eta_{T} \quad (4)$$

$$\dot{W}_{FP} = \dot{m}_{ORC}\left(h_4 - h_3\right) = \frac{\dot{m}_{ORC}\left(h_{4s} - h_3\right)}{\eta_{FP}} \quad (5)$$

The net thermal efficiency of ORC system is determined as the ratio between the net power output and the total heat flow to the preheater and evaporator:

$$\eta_{th,net} = \frac{\dot{W}_{net}}{\dot{Q}_{EV} + \dot{Q}_{PH}} = \frac{\dot{W}_{T} - \dot{W}_{FP}}{\dot{m}_{ORC} \cdot (h_1 - h_4)} \quad (6)$$

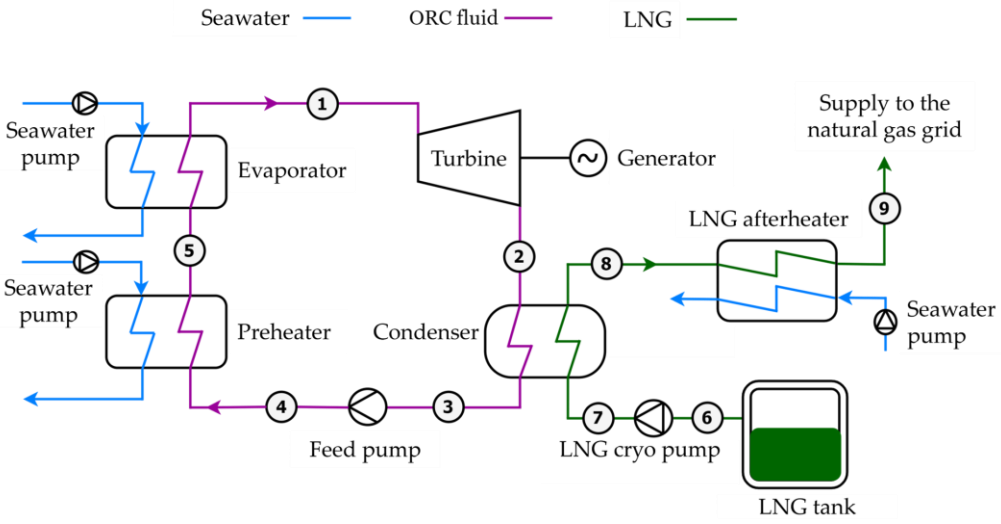

Fig. 2. *Configuration of the single-pressure ORC power plant for LNG cold energy utilization*

The levelized cost of electricity (LCOE) is the net present value of all the power plant lifetime costs divided by the net present value of all the electricity produced. It is the ratio between the total discounted costs, including capital investment, operation and maintenance, and the total discounted electricity generation. The LCOE indicates the minimum electricity price at which the project breaks even economically.

$$LCOE = \frac{C_{CAP} + \sum_{t=1}^{t=N} C_{O\&M,t}\left(1+e\right)^t \Big/ \left(1+r\right)^t}{\sum_{t=1}^{t=N} E_{net}(1-d)^t} \quad (7)$$

The present value of the project capital cost is the product of the annuity and the project lifetime:

$$C_{CAP} = A \cdot T = C_{project} \frac{r \cdot (1+r)^T}{(1+r)^T - 1} \cdot T \quad (8)$$

Table 1. lists the assumed values of the economic parameters necessary for calculating the LCOE. Total project costs are estimated from the major equipment costs (turbines, pumps, heat exchangers, compressors, tanks). The equipment costs are increased using multiplication factors, which account for direct (site preparation, assembly, piping, insulation, electrical, sensors, controls, etc.) and indirect costs (transport, contingencies, fees).

$$C_{project} = \sum_{i}^{N} \underbrace{C_{EQ}\left[1 + f_{TM} + f_{aux}\right]}_{\text{referent equipment costs}} \underbrace{\left(\frac{CEPCI_{2024}}{CEPCI_{ref}}\right)}_{\text{cost index correction}} \quad (9)$$

Table 1: *Assumed values for the economic analysis of the ORC system*

Economic parameter	Value
Discount rate (real value), *r*	7%
Price escalation rate, *e*	4%
Capacity degradation rate, *d*	1%
Project lifetime, *T*	25 years
Contingencies and fees, f_{TM}	+20% (f_{TM} = 0,20)
Auxiliary costs, f_{AUX}	+60% (f_{AUX} = 0,60)
Annual O&M costs	130 €/kW
Annual operating hours	7000 h

The equipment costs (C_{EO}) are estimated using cost correlations available in the literature [35]. Because these correlations were derived from historical cost data, the calculated equipment costs are updated to present-day values by applying the appropriate cost index adjustment ($CEPCI_{2024}/CEPCI_{ref}$). The Chemical Engineering Plant Cost Index (CEPCI) is published monthly by the Chemical Engineering magazine [36] and tracks the cost of equipment, materials, labor, and construction in chemical process plants.

Specific installation cost (SIC) indicates how much is the capital investment per unit of net power output:

$$SIC = \frac{C_{project}}{\dot{W}_{net}} \quad (10)$$

3. Results and discussion

The LNG cold energy power plant achieves a net power output of 6.7 MW using ammonia as the working fluid and for an LNG regasification capacity of 400,000 m^3/h (75.5 kg/s). The specific net power output is 90 kW/(kg/s) net power output is achieved for a condensation pressure of 0.156 bar, equivalent to a condenser temperature of -65 °C, as shown in figure 3. The seawater temperature is 20 °C while the minimum pinch point temperature difference in the evaporator and condenser is 10 °C. The LNG enters the condenser at -161 °C and leaves with a temperature of -75 °C. The LNG is heated up to +15 °C in the afterheater, which is the temperature at the inlet of the natural gas transmission network.

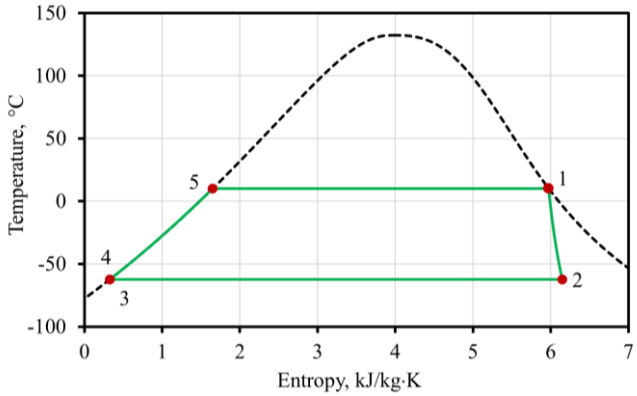

Fig. 3. *Temperature-entropy chart of LNG cold energy power plant using ammonia as the working fluid*

The net power output exhibits a characteristic peak for all fluids (ethane, propane, pentane, ammonia and carbon dioxide), as shown in figure 4. As the saturation temperature in the condenser decreases from −30 °C toward cryogenic temperatures, the net power initially increases, reaches a maximum at −65 °C, and then declines. In general, lowering the condenser saturation temperature increases the enthalpy drop in the turbine, however, this also reduces the mass flow rate of the ORC working fluid. The net thermal efficiency of the ORC system ranges between 21% for ammonia and 15% for carbon dioxide.

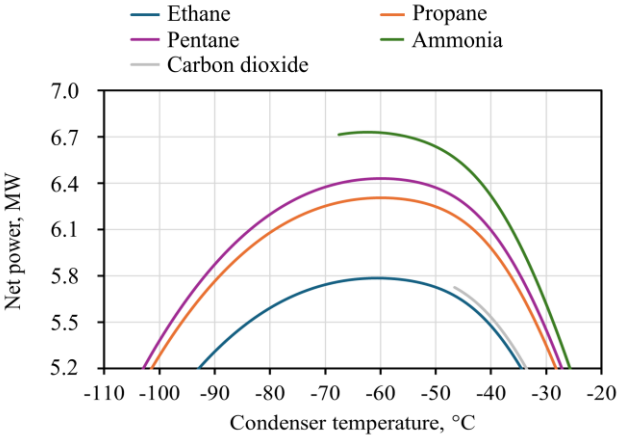

Fig. 4. *Power output as function of the condensation temperature, regasification capacity of 400,000 m^3/h*

The SIC are estimated at 2225 €/kW for a brownfield project, i.e., an LNG cold-energy power plant integrated into an existing regasification terminal. The LCOE is estimated at 45 €/MWh, which is comparable to the most recent economic indicators of other renewable energy power plants [37], as reported in table 2.

Table 2: *Comparison of the ORC power plant for LNG cold energy utilization with other renewable power plants*

Power plant type	**SIC (€/kW)**	**LCOE (€/MWh)**
Biofuels	3016	80
Geothermal	3734	55
Hydro	2108	52
Solar PV	642	40
CSP	3422	85
Wind onshore	967	31
Wind offshore	2652	73
LNG cold energy	2225	45

4. Conclusions

The present study evaluated a single-pressure ORC integrated with LNG regasification and demonstrated that significant power can be recovered from LNG cold energy. Using ammonia as the working fluid, the system achieves a net power output of 6.7 MW at an LNG flow rate of 75.5 kg/s, corresponding to a specific power output of 90 kW/(kg/s). Maximum performance occurs at a condenser saturation temperature of approximately −65 °C, with a thermal efficiency of about 21%. Economically, the specific installation cost is estimated at 2225 €/kW for a brownfield installation, while the LCOE of 45 €/MWh positions LNG cold-energy recovery as cost-competitive against other mature renewable energy power generation options.

Future research should investigate multi-stage and recuperated ORC configurations, different working fluids and their mixtures, and integrated systems combining power, desalination, and cold-storage functions. Broader economic analyses including carbon pricing and market uncertainties could further support the transition of LNG terminals toward efficient and low-carbon operation.

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