International Journal of Advanced Research in Engineering Technology & Science
ISSN: 2349-2819
Impact Factor: 7.10
(Peer-Reviewed, Open Access, Fully Refereed International Journal)
Email: editor@ijarets.org Volume-11 Issue-7 July-2024 www.ijarets.org

Exergy Efficiency Improvement of Combined Cryogenic Power Cycle Utilizing LNG Cold Energy

Zeinab A. M. Khalel[1], Abdelgadir Bashir Banaga[2]

[1]*Department of Transportation & Refining Engineering, College of Petroleum & Mining Engineering, Sudan University of Science & Technology, P.O. Box 72, Khartoum 11111, Sudan*

Corresponding author. Tel: +9966561409079

E-mail: zeinabkhaleel@yahoo.com

Abstract:

The cold energy released from liquefied natural gas regasification can be utilized in cryogenic power generation cycles, the combined power cycle is one of the most commonly used cycles, and a simple modification is proposed by drawing a bypass stream from the evaporated working fluid to work as the heating medium for the natural gas before expanded it in the turbine, the exhausted working fluid stream fed back to the evaporator after mixing it with the liquid working fluid out of the pump, this modification reduced the exergy destruction in the evaporator by 20.6%, in the heat exchanger by 27.1%, and in the overall cycle by 4%, also the exergy efficiency of the cycle reduced by 14.4% and lowered the amount of water used for heating by 50%.

Keywords:

Cold Energy, Combined Cryogenic Power Cycle, Exergy efficiency, Destroyed Exergy,

Liquefied Natural Gas.

1. INTRODUCTION

Natural gas (NG), a traditional fossil fuel, is extensively used due to its high calorific value and minimal greenhouse gas emissions. Natural gas (NG) is typically in a gaseous form at normal temperature and pressure. To transport and store it over long distances, it needs to be converted into liquefied natural gas (LNG) by a process called liquefaction. This process significantly enhances the energy density of LNG, making it approximately 600 times more dense than NG. [1], and one ton of LNG consumes about 850 kWh of electric energy [2]. At the receiving terminal, LNG is slightly above the atmospheric pressure and at a temperature of around -160^{o}C, and it must be regasified before being fed to the final users at the ambient temperature and a suitably elevated pressure [3]. LNG possesses a significant amount of cryogenic exergy, which is usually known as cold energy. A portion of this energy can be reclaimed to generate power in LNG regasification plants. Nevertheless, traditional regasification techniques that utilize vaporizers do not effectively harness the cold energy contained in LNG [4].

There are different techniques to utilize the cold exergy produced during the LNG regasification process, including air separation, seawater desalination, food processing, household air conditioning, and power generation [5]. Previously, seawater was used as the heat source to vaporize LNG but this wastes a great amount of cold energy besides the power consumption of the pump that is used to drive the seawater. Recently, LNG cold energy can be utilized in many ways, such as in the food industry for storing and freezing foods and in seawater desalination, and also in the process of air liquefaction and separation [6]. Over the past few years, there has been extensive research conducted on utilizing LNG cold energy to enhance the efficiency of thermal power plants. LNG is primarily employed as low-temperature heat sink in various power generation cycles. One of the most widely-used applications of LNG cold energy is to improve the cryogenic power cycle efficiency as it works as a cold sink [5].

The rankine cryogenic power cycle is commonly used in utilizing LNG cold energy. Some studies have used a zeotropic mixture such as ammonia-water mixture as a working fluid instead of a pure substance fluid because it evaporates at variable temperatures at a constant pressure, which reduces the exergy destruction in the heat exchanger. Wang et al. [7] Examined the most efficient operation of a Rankine cycle using ammonia-water as the working fluid and LNG as the source of heat absorption. Lu and Wang [8] Proposed a power cycle design that utilizes a cascade approach, where LNG is directly expanded. This design includes an ammonia-water Rankine cycle and a combustion gas power cycle, both of which aim to recover the cryogenic energy from LNG. Miyazaki et al. [9] The standard trash incineration power cycle was compared to a composite power cycle that included ammonia-water and LNG Rankine cycles.

On the other hand, the organic Rankine cycle (ORC) is a different copy of the Rankine cycle that replaces water with an organic working fluid [10]. The organic Rankine cycle has high efficiency in low-grade heat recovery and is one of the hot topics of researchers in recent years, Bao and Zhao [11] reported a review of working fluid and expander selections for the organic Rankine cycle, and Lecompte et al. [12] reviewed the

ORC architectures for waste heat recovery. Szargut and Szczygiel [13] Examined the potential use of the cryogenic exergy of LNG for generating power without any extra combustion of LNG components, using three different plant configurations. Choi et al. [14] Explored a cascade Rankine cycle comprising many stages of ORC to utilize the cold energy from LNG for power generation. The study by Choi et al. This study proposed an optimization method to assess the feasibility of utilizing an ORC in conjunction with a regasification facility for LNG in order to harness cold energy. The optimization primarily aimed to determine the most efficient allocation of resources, including thermal energy and equipment size, while facing constraints in both LNG cryogenic energy and the overall heat transfer capacity of heat exchangers [15].

Other researchers use propane as a working fluid in the power cycles, Bai has adjusted the pressure and temperature of LNG and the concentration of methane in LNG respectively, in the proposed Rankine cycle using propane as the working fluid [16], Zhu et al. have compared the performance of propane and ternary mixed fluids consisting of propane, ethylene, and isobutane at a mole fraction ratio of 0.39:0.16:0.45 in LNG-air Rankine cycle [17]. Chen has adopted the mixture of propane and butane as a working fluid in the Rankine cycle using LNG as its heat sink. The study states the variation trend of the exergetic efficiency of the vaporizer and condenser along with the change in mixing ratio and mixture flow rate [18]. The study by António Domingues et al, studied the compact system of liquefied natural gas (LNG) regasification/electricity generation, with a two-stage cascade Rankine cycle, using the ternary mixtures methane-ethylene-propane and ethane-propane-butane in the first and second stages, respectively, with seawater as the hot utility and LNG as the heat sink. After optimization, the system achieves a thermal efficiency of 23.7% and an exergy efficiency of 79.18%. Performance was found to increase when compared to a conventional system with a simple Rankine cycle [19]

The basic and conventional methods to utilize the cold energy of LNG are direct expansion of the LNG cycle, the Rankine cycle using the intermediate cooling medium, and the combination of the aforementioned cycles, the direct expansion cycle converts the pressure exergy of LNG into power, as shown in Figure 1 LNG from the storage tank is pumped up and vaporized into NG with a high temperature and pressure, then this high-pressure NG expanded in turbine where electric energy is produced by a generator linked to a rotating shaft. Although the direct expansion cycle is very simple, its efficiency is low as the cold energy of LNG is not utilized [20].

In the Rankine cycle as shown in Figure 2 an intermediate cooling medium with low boiling temperature is used, the cycle goes through four stages of condensation, compression, vaporization, and expansion to generate power, and LNG is used as a heat sink, and low-quality heat (including solar energy, air, water, industrial waste heat, etc.) is used as heat source. The efficiency of the Rankine cycle is higher than the direct expansion cycle as the cold energy of LNG is used, but there is still an opportunity to increase the efficiency as the pressure energy is not utilized [20]

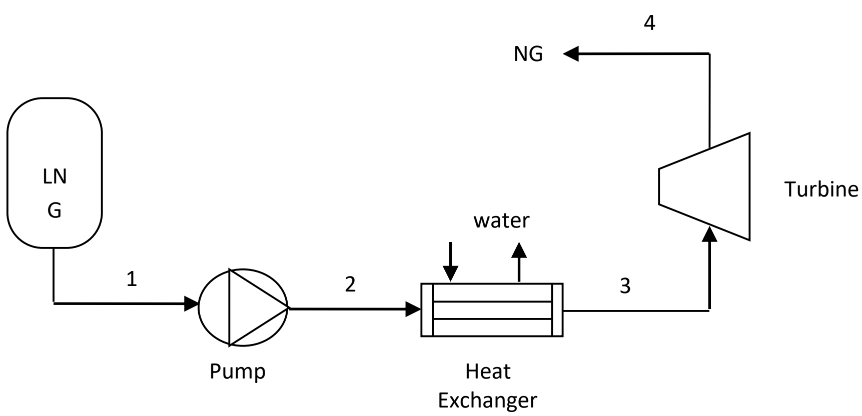

Figure 1. LNG Direct Expansion

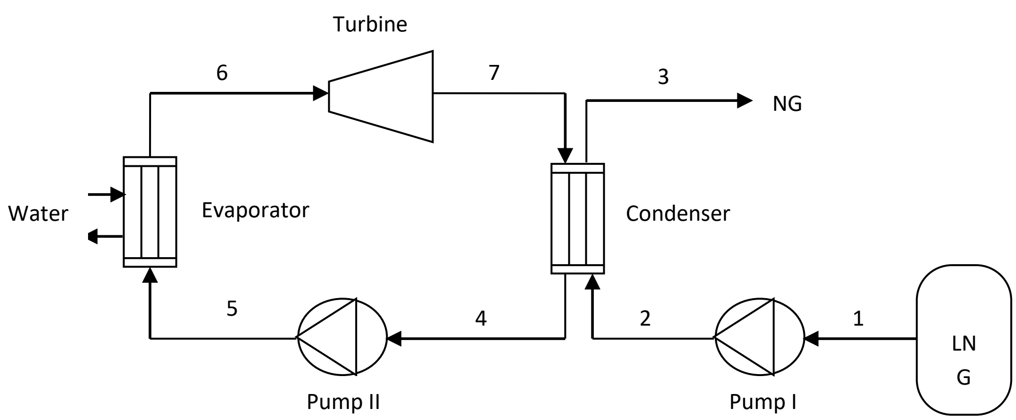

Figure 2. Rankine Cycle

The combined cycle is a combination of the direct expansion cycle and the Rankine cycle as illustrated in Figure 3. The direct expansion cycle is represented by streams, whereas the Rankine cycle is represented by streams. The efficiency of this cycle is higher than both the direct expansion cycle and the Rankine cycle as both temperature and pressure energies of LNG are utilized [21].

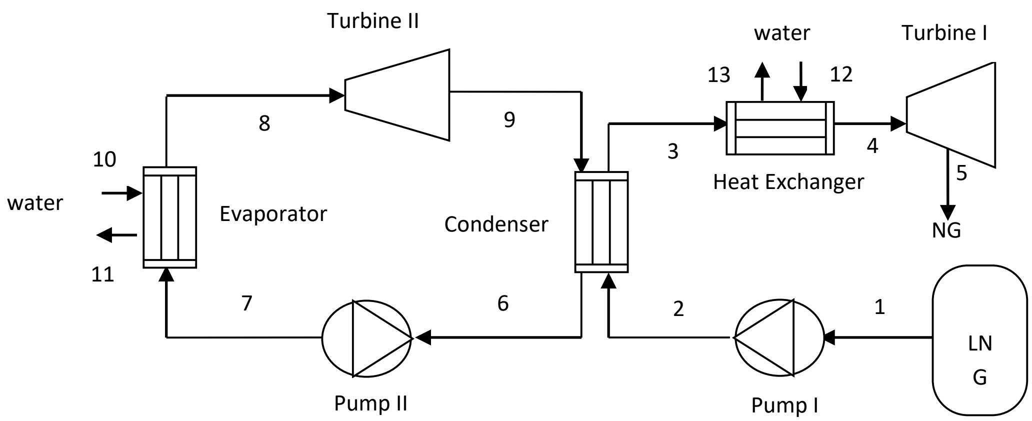

Figure 3. Combine Cycle

This research aims to propose a new modification in the combined Rankine cryogenic power cycle utilizing the cold energy of the LNG regasification process, with propane as a working fluid, and then calculate the exergy destruction to investigate the usefulness of this modification. In this study, the cryogenic combined cycle with propane as a working fluid is modified, and the effect of this modification is analyzed from an exegetic point of view. The modification was applied by using Aspen Plus.

2. METHODOLOGY

2.1. Calculation assumptions

Some general assumptions during calculation are made as follows:

(1) The simulation and analyses of the system are performed in a steady state.

(2) The changes in the kinetic and potential energies are neglected.

(3) The heat transfer between the system components and the environment is neglected.

(4) The pressure drop in the pipes of the system is neglected.

2.2. Proposed combined cycle

In this study, the conventional combined Rankine cycle with propane as a working fluid has been modified. The modification is to draw a bypass stream from the propane stream before being fed to turbine II. This stream works as a heat source for the heat exchanger of the NG before being expanded in turbine I. The exhausted propane stream is fed back to the propane evaporator after mixing it with the liquid propane out of the pump. The proposed cycle is shown in Figure 4.

Both conventional combined cycles, as shown in Figure 3 and the proposed cycle in Figure 4 have been simulated by Aspen Plus software.

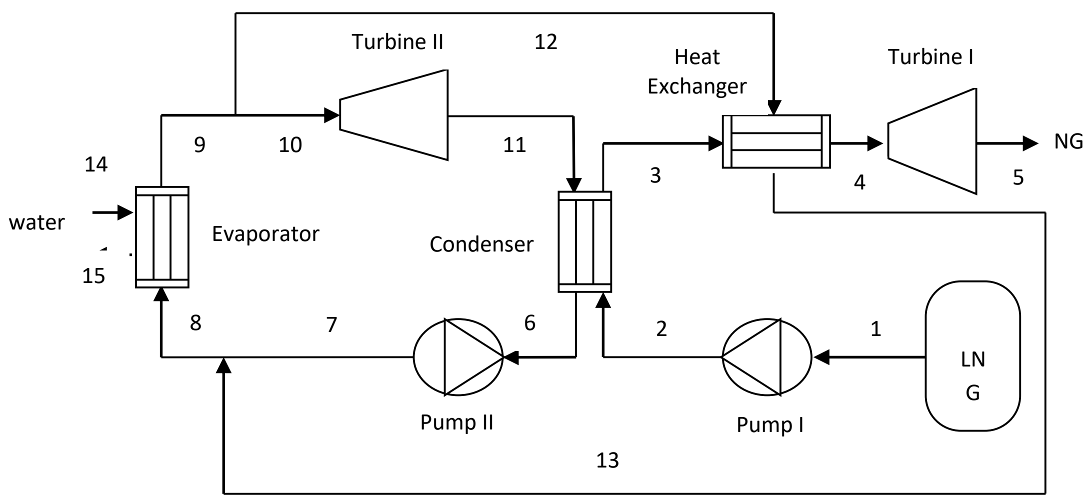

Figure 4 Proposed Combined Cycle

The Peng-Robinson property method is selected to calculate the fluid properties in this system. The simulation was carried out at a reference temperature (T_o) of 298 K and pressure (P_o) of 1 atm. LNG is available at 111.67 K and 0.1013 kPa [3]. Meanwhile, the natural gas component is assumed as methane only for the sake of simplicity.

2.3. Network production

The conventional combined cycle and the proposed combined cycle aim to produce work, which is given by the following equation:

$$\text{Network} = \text{NW} = W_{LNG} + W_p = (W_{TI} - W_{PI}) + (W_{TII} - W_{PII}) \quad (1)$$

where $W_{LNG,}$ W_p, W_{TI}, W_{PI}, and W_{PII} are the network from the LNG cycle, the network from the propane cycle, work generated from the NG turbine, work generated from the NG turbine, work consumed in the LNG pump, and work consumed in the propane pump, respectively.

2.3 Thermodynamic analysis

The exergy of a system is the most useful work possible as it proceeds to a specified final state in equilibrium with its surroundings. Exergy analysis is an effective tool to help analyze and optimize complex power generation systems [22]. Exergy is a co-property of the considered system and the environment in which it operates: if a system and a reference environment are given, the exergy is defined as the maximum amount of work obtainable from the system by bringing it into equilibrium with the reference environment [4]. The exergy destruction, also called irreversibility or exergy loss, is calculated by setting up the exergy balance as:

$$E_{destruction} = \sum_{in}(E_{work} + E_{haet} + E_{material}) - \sum_{out}((E_{work} + E_{haet} + E_{material})(2)$$

where E_{work} is the exergy transfer with work, and E_{heat} is the exergy transfer with heat.

The exergy transfer with work interaction is equivalent to work, and the exergy of heat flow is:

$$E_{heat} = Q\left(1 - \frac{T_0}{T}\right) \quad (3)$$

where Q is the heat transfer rate, T_0 is the ambient temperature, and T is the temperature at which the heat transfer takes place.

The exergy associated with the material stream $E_{material}$ is given by the sum of physical exergy, chemical exergy, kinetic exergy, and potential exergy, the kinetic and potential exergies are usually neglected, and the chemical exergy is not considered in this study as there is neither chemical reaction nor chemical separation. The exergy transfer with the material stream in this study is only the physical exergy, Physical exergy is the work obtainable by taking the substance through reversible processes from its initial state temperature (T), and pressure (P), to the reference or standard state at which the free enthalpy and entropy of formation are calculated [23]. The physical exergy is calculated as:

$$E_{ph} = me = m[h - h_0 - T_0(s - s_0)] \quad (4)$$

To perform an overall exergy balance, the total exergy input (E_{in}) to the system by the summation of the exergy of the heating source stream input (E_{hin}) and the LNG exergy input (E_{LNGin}) and it is equal to the summation of of heating source streams exergy output (E_{hout}) and the LNG exergy output (E_{LNGout}) and of the total network (NW) and the total exergy destruction (D_{tot}) of all units in the cycle as follows:

$$E_{in} = \sum E_{hin} + E_{LNGin} = \sum E_{hout} + E_{LNGout} + W_{LNG} + W_p + D_{tot} = NW + D_{tot} \quad (5)$$

From the definition of any efficiency which is the ratio of desired output to the required input, then:

$$\text{Exergy efficiency of LNG cycle } (\eta_{LNG}) = \frac{W_{LNG}}{E_{in}} \quad (6)$$

$$\text{Exergy efficiency of propane cycle } (\eta_p) = \frac{W_p}{E_{in}} \quad (7)$$

$$\text{Exergy efficiency of the combine cycle } (\eta_{tot}) = \eta_{LNG} + \eta_p = \frac{W_{tot}}{E_{in}} \quad (8)$$

4. RESULTS AND DISCUSSION

In this section, the simulation results and comprehensive discussion about the proposed combined cycle have been studied, and compared with the conventional cycle. Firstly, the results of the energy, exergy, and performance of the basic design case are reported. Secondly, parametric analyses are conducted to investigate the effects of key variables on the performance of the proposed system. Thirdly, the optimization is performed to maximize the exergy efficiency.

In this study, the effect of the modification in the proposed combined cycle has been studied and compared with the conventional cycle. The basic simulation conditions have the same values in both cycles for an accurate comparison, the flow rate of LNG (0.2 kg/s) and the propane flow rate in the Rankine cycle (0.3 kg/s), as the turbines and pumps inlet and outlet pressure and temperature are the same in both cycles, therefore the turbines delivered and pumps consumed the same work as shown in Table 1.

Table 1 Work Delivered and Consumed in Conventional and Proposed Combine Cycles

Unit	Work (kW)
Pump I	-1.43
Pump II	-1.54
Turbine I	35.72
Turbine II	23.22
Sum	55.97

Tables 2 and 3 show the thermodynamic properties of streams in the conventional and proposed combined cycles, respectively. The exergy of each stream is calculated by equation 4.

Table 2 Thermodynamic Properties of the Streams in Conventional Combine Cycles

No	Fluid	m (kg/s)	T (K)	P (kPa)	h (kJ/kg)	s (kJ/kg.K)	E (KW)
1	LNG	0.2	111.0	101.3	-5556.4	-11.71	216.49
2	LNG	0.2	112.8	1000.0	-5549.2	-11.67	215.12
3	NG	0.2	212.4	1000.0	-4848.8	-7.00	76.95
4	NG	0.2	280.0	1000.0	-4697.6	-6.38	70.36
5	NG	0.2	191.0	101.3	-4876.2	-5.98	10.85
6	propane	0.3	225.0	101.3	-2915.9	-8.39	42.07
7	propane	0.3	227.1	1000.0	-2910.8	-8.38	42.15
8	propane	0.3	315.0	1000.0	-2371.6	-6.50	36.19
9	propane	0.3	252.1	101.3	-2449.0	-6.38	1.82
10	water	5.0	330.0	101.3	-15827.7	-8.86	36.31
11	water	5.0	322.9	101.3	-15860.1	-8.96	22.23
12	water	5.0	330.0	101.3	-15827.7	-8.86	36.31
13	water	5.0	328.7	101.3	-15833.8	-8.88	33.43

Table 3 Thermodynamic Properties of the Streams in Proposed Combine Cycles

	Fluid	m (kg/s)	T (K)	P (kPa)	h (kJ/kg)	s (kJ/kg.K)	E (KW)
1	LNG	0.20	111.0	101.3	-5556.4	-11.71	216.49
2	LNG	0.20	112.8	1000.0	-5549.2	-11.67	215.12
3	NG	0.20	212.4	1000.0	-4848.8	-7.00	76.95
4	NG	0.20	280.0	1000.0	-4697.6	-6.38	70.36
5	NG	0.20	191.0	101.3	-4876.2	-5.98	10.85
6	propane	0.30	225.0	101.3	-2915.9	-8.39	42.07
7	Propane	0.30	227.1	1000.0	-2910.8	-8.38	42.15
8	propane	0.45	276.1	1000.0	-2798.2	-7.93	53.84
9	propane	0.45	315.0	1000.0	-2371.6	-6.50	54.28
10	propane	0.30	315.0	1000.0	-2371.6	-6.50	36.19
11	propane	0.30	252.1	101.3	-2449.0	-6.38	1.82
12	propane	0.15	315.0	1000.0	-2371.6	-6.50	18.09
13	propane	0.15	300.0	1000.0	-2573.1	-7.17	17.78
14	Water	5.00	330.0	101.3	-15827.7	-8.86	36.31
15	water	5.00	321.5	101.3	-15866.1	-8.98	19.96

The calculated exergy of each stream in the conventional and the proposed cycle are used to calculate the exergy destruction for each unit by using equation 2 and the results are shown in Table 5, the exergy efficiency of both conventional and proposed combined cycles are calculated using equation 8 and it is 19.4% and 22.1%, respectively.

The heating source utility in the conventional cycle is in the evaporator of the propane and the heat exchanger to increase the NG temperature before expanding in the turbine, but in the proposed cycle, the modification canceled the need for the heating source in the NG heat exchanger, and as a result, the amount of heating source water decreased.

Table 5 Exergy Destruction of Combine and Proposed Combine Cycles

Unit	Exergy Destruction	
	Combine Cycle	**Proposed Cycle**
Pump I	2.80 kW	2.80 kW
Pump II	1.47 kW	1.47 kW
Turbine I	23.80 kW	23.80 kW
Turbine II	11.14 kW	11.14 kW
Condenser	97.92 kW	97.92 kW
Evaporator	20.04 kW	15.91 kW
Heat Exchanger	9.47 kW	6.90 kW
Sum	166.63 kW	159.94 kW
Exergy Efficiency	19.4%	22.1%

Despite that, the conventional and proposed cycles produced the same amount of work, but they had different exergy destruction, from the results in Table 5 the exergy destruction is the same in all units except the evaporator and heat exchanger, which showed a reduction of destroyed exergy in the proposed cycle, the bypass stream simply reduced the temperature difference across the evaporator and the heat exchanger, and the high-temperature difference is one of the major causes of entropy generation, moreover over this modification increase the overall exergy efficiency of the cycle, and eliminated the water used for heating.

5. CONCLUSION

A novel modification is proposed by drawing a bypass stream from the evaporated working fluid to work as the heating medium for the natural gas before expanding it in the turbine. Comprehensive thermodynamic and exergy analyses were conducted for the modified cycle. Then, detailed parametric analyses were performed to investigate the effects of key variables on the thermodynamic and exergy efficiency. The results show that the modification reduced exergy destruction in the evaporator heat exchanger by 20.6%, and 27.1 %, respectively. Furthermore, the exergy destruction in the overall cycle decreased by 4 %. This modification successfully reduces the overall exergy efficiency by 14.4 %, and the total heating source is reduced by 50 %.

Conflict of interest

The authors declare that they have no conflict of interest.

Funding Statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References:

[1] Kim, H., Y., L. and K. H. Kim. 2015. Energy and Exergy Analyses of a Combined Power Cycle Using the Organic Rankine Cycle and the Cold Energy of Liquefied Natural Gas. *Entropy.* 17(9): 6412-6432. doi.org/10.3390/e17096412

[2] Hongtan, L., and L. You**.** 1999. Characteristics and applications of the cold heat exergy of liquefied natural gas*. Energy Conversion & Management*. 40(3): 1515–25. doi.org/10.1016/S0196-8904(99)00046-1

[3] Xiaojun Shi, Defu Che. 2009. A combined power cycle utilizing low-temperature waste heat and LNG cold energy. *Energy Conversion and Management.* 50(3): 567–575. /doi.org/10.1016/j.enconman.2008.10.015

[4] Alessandro, F., and C. Giovannini. 2023. Optimal design of direct expansion systems for electricity production by LNG cold energy recovery*.* Energy. 280(1): 128173. doi.org/10.1016/j.energy.2023.128173

[5] Wen, C., H. Li, X. Li, F. Chang, L. Wang, and Z. Feng. 2021. Exergoeconomic analysis and optimization of the Allam cycle with liquefied natural gas cold exergy utilization . Energy Conversion and Management. 235(1): 113972. org/10.1016/j.enconman.2021.113972

[6] Muhammad, H. N. A., N. E. M. Rozali, S. Mahadzir, P. Y. Liew. 2023. *Utilization of Cold Energy from LNG Regasification Process: A Review of Current Trends.* Processes. 11(2): 517. doi.org/10.3390/pr11020517

[7] Wang, J., Z. Yan, and M. Wang. 2013. Thermodynamic analysis and optimization of an ammonia-water power system with LNG (liquefied natural gas) as its heat sink*. Energy.* 50(1): 513–522. doi.org/10.1016/j.energy.2012.11.034

[8] Lu, T., and K. S. Wang. 2009. Analysis and optimization of a cascading power cycle with liquefied natural gas (LNG) cold energy recovery. *Applied Thermal Engineering*. 29(8-9): 1478–1484. doi.org/10.1016/j.applthermaleng.2008.06.028

[9] Miyazaki, T., Y.T Kang, A. Akisawa, and T. Kashiwagi. 2000. A combined power cycle using refuse incineration and LNG cold energy. *Energy*.25(7): 639–655. doi.org/10.1016/S0360-5442(00)00002-5

[10]Muhammad, H. N. A, N. E. M. R, S. Mahadzir, and P. Y. Liew. 2023. Utilization of Cold Energy from LNG Regasification Process: A Review of Current Trends. *processes*. 11(2): 517. doi.org/10.3390/pr11020517

[11]Bao, J. and L. Zhao. 2013. A review of working fluid and expander selections for organic Rankine cycle. *Renewable and Sustainable Energy Reviews.* 24: 325–342. org/10.1016/j.rser.2013.03.040

[12]Steven L., H. Huisseune, M. v. d. Broek, B. Vanslambrouck , and M. D. Paepe. 2015. Review of organic Rankine cycle (ORC) architectures for waste heat recovery. *Renewable and Sustainable Energy Reviews*. 47: 448–461. doi.org/10.1016/j.rser.2015.03.089

[13]Szargut, J. and I. Szczygiel. 2009. Utilization of the cryogenic exergy of liquid natural gas (LNG) for the production of electricity. *Energy*. 34(7): 827–837. doi.org/10.1016/j.energy.2009.02.015

[14] Choi, I.H., S. I. Lee, and Y. T. 2013. Analysis and optimization of cascade Rankine cycle for liquefied natural gas cold energy recovery. *Energy*. 61(1): 827–837. org/10.1016/j.energy.2013.08.047

[15]Hong, W. C., N. Sun-Ik, S. B. Hong, Y. Chung, D. K. Kim, and M. S. Kim. 15, 2020. Optimal design of organic Rankine cycle recovering LNG cold energy with finite heat exchanger size. *Energy*. 217: 119268. doi.org/10.1016/j.energy.2020.119268

[16]Bai, F. s. l. 2011. *Integrated and cost-effective design utilizes LNG cryogenic energy for power generation.* China: South China University of Technology, Dissertation for the Master Degree.

[17]Zhu, H. M., H. Sun, and D. Shu. 2010. Simulation of Rankine power cycle to recovery the cooling nature gas. *Cryogenics and Superconductivity.*12–14.

[18]Chen, M s.l. 2013. *Development and optimization of power generation airconditioning utilizes LNG cryogenic energy*. Guangzhou: South China University of Technology. Dissertation for the Master Degree .

[19]António, D., H. A. Matos, and P. M. Pereira. 2022. Novel integrated system of LNG regasification / electricity generation based on a cascaded two-stage Rankine cycle, with ternary mixtures as working fluids. *Energy*. 238: 121972. doi.org/10.1016/j.energy.2021.121972

[20]Feier, X., Y. CHEN, and Y. JU. 2016. A review of cryogenic power generation cycles with liquefied natural gas cold energy utilization. *Frontiers in Energy*. 10: 363–374. doi.org/10.1007/s11708-016-0397-7

[21]Guojun, Y., S. Jia, and B. Dai. 2018. Review on recent liquefied natural gas cold energy utilization in power generation cycles. *Advances in Geo-Energy Research.* 2(1): 86-102. doi.org/10.26804/ager.2018.01.08

[22]Kyung, C. K., J. M. Ha, and K. H. Kim. 2015. Exergy analysis of a combined power cycle using low-grade heat source and LNG cold energy. *International Journal of Exergy*. 17(3): 374-400 doi.org/10.1504/IJEX.2015.070504.

[23]Van, d. H. L, and S. Kjelstrup. 2010. Exergy analysis of two cryogenic air separation processes. *Energy*. 35(12): 4731-4739. doi.org/10.1016/j.energy.2010.09.019

Nomenclature

m	The mass flow rate.
e	The specific exergy.
h	The specific enthalpy.
s	The specific entropy
kW	Kilowatt
E	Exergy transfer
e	Specific exergy transfer