The Eleventh International Conference on
Engineering Computational Technology
23–25 August, 2022 | Montpellier, France

Proceedings of the Eleventh International Conference on
Engineering Computational Technology
Edited by B.H.V. Topping and P. Iványi
Civil-Comp Conferences, Volume 2, Paper 2.12
Civil-Comp Press, Edinburgh, United Kingdom, 2022, doi: 10.4203/ccc.2.2.12


# Thermodynamic assessment on lng regasification process integrated with cryogenic distillation and organic rankine cycle system

**S. U. K. Suri[1,2], M. K. Majeed[1] and M. A. Qyyum[3]**
**[1]Department of Chemical Engineering, COMSATS University Islamabad (CUI) Lahore Campus, Pakistan**
**[2]Department of Chemical Engineering, Balochistan University of Information Technology and Management Sciences, Pakistan**
**[3]Department of Petroleum and Chemical Engineering, Sultan Qaboos University, Oman**

## Abstract

Recently, depleting the fossil fuel asset and frightful environmental influence because of burning fossil fuels spotlights the paramount significance of incorporating sustainable energy asset such as geothermal and solar energies. The unfolding of Organic Rankine cycle (ORC) as energy tool by the scientists has achieved notable demand for its commercialization. The singular ORC can generate high energy in comparison to other functioning cycles. For this purpose, Liquefied Natural gas (LNG) cold energy can be utilized through regasification to integrate ORC and cryogenic distillation. LNG cold energy recovery by regasification has supreme importance with aspect of energy economy and environment sustainability. LNG regasification from shell and tube heat exchanger makes minimal freezing risk and has high duty. Cryogenic distillation of bio gas is energy intensive process. It can made functional from LNG cold energy implementation through ORC by maintaining cryogenic temperature there. Into the bargain, greenhouse gases emission can be reduced. A state of the art thermodynamic assessment on discussed energy system proves viable to conduct by manipulating different working fluids. Furthermore, there is reported a business case with LNG regasification terminal capacity of 99.7764 million ton per year. It is contingent on consumption of LNG cold energy to make electricity and distilling bio gas. The environmental regulation governing bodies, industrialists, energy development boards and academic can avail benefit from this research work to configure environmental affable atmosphere and energy for contemporary society. It is an unprecedented and welcomed results declaration with precise evaluation.

**Keywords:** fluid, energy, exergy, orc, lng, regasification, manipulation.

## 1 Introduction

The worldwide population expansion has raised the energy demand [1]. The Natural gas (NG ) is a good source of energy for clean environment [2]. Recently, efforts are underway to develop some efficient techniques to tap Liquefied Natural gas (LNG) wasted cold energy (830 (kJ/kg) for running power cycles and cryogenic capture of carbon dioxide [3]. Due to this fact, a productive usage of LNG cold energy is beneficial, if it is tackled properly [4]. LNG regasification system aims to increase LNG cold energy recovery [5]. In particular, the retrieved energy by regasification works as heat sink for integrating power cycles and cryogenic processes [6]. LNG cold energy is usually wasted into air or sea water in a vaporization system [7]. LNG regasification takes place when LNG at -161°C and 1 atm is converted to natural gas (NG) at atmospheric temperature and pressure. These regasification plants are located on land and floating units. The typical regasification plant uses sea water to transform LNG into NG [8]. In total, there are nine functional regasification technologies including open-rack, ambient air, combustion heat, combustion heat intermediate fluid, shell and tube, submerged combustion, combined heat and power units with submerged combustion units, shell and tube heat vaporizer (STV) [9] and atmospheric evaporators. There are definite restraints of these techniques which are contingent to their regasification schemes.

The most-optimal regasification technique is shell and tube vaporizer for a distinction to have a large operating range (open-loop, closed-loop and combined mode). High-grade steel material allows it to function both at onshore and offshore [10]. Also, it has a minimum freezing risk at low temperature [11]. On the other hand, the various power cycles are scrutinized by contemporary scientists utilizing LNG cold energy. Their findings proved that singular Organic Rankine cycle (ORC) possesses greater energy efficiency around 67% as compared to other power cycles [12]. In present research work, LNG regasification process is integrated with an ORC and cryogenic distillation process merging bio-gas. The cryogenic distillation is more energy consuming and costly. From the obtained results, it is now established that incorporating LNG cold energy for cryogenic distillation upgrades the thermodynamic assessment i-e;(energy and exergy efficiencies) appreciably. The environmental regulation bodies, government authorities, industrialists and academic can take benefit the economy of this thermodynamic assessment to materialize integrated energy setup on commercial basis.

## 2 Methods

In this research article, a thermodynamic assessment is done on novel LNG regasification process integrated cryogenic distillation and ORC system. In detail, ORC energy cycle deals with manipulation of organic working fluid. It is broadly familiar that working fluids have to be integrated with energy system on account of their well-built linkage to find most-optimum working fluid. Organic working fluids substantially diverge by each other with respect to thermodynamic and physical traits. In figure 1, there are used 14 working fluids on ORC turbine inlet (pt. 8) at the same operating conditions. It constitutes 14 configurations. In Figure 2, there is reported precise methodology of LNG cold energy utilization at ORC. Hence, this work accords the selection of appropriate refrigerant or working fluid for this proposed energy system using latest computational techniques.

In ORC, the turbine/expander design is critical because of a working fluid thermodynamics properties. This strongly influences the proposed plant integrated structure and plot of accessories. The paired energy and exergy analyses are calculated from 1st and 2nd law of thermodynamic respectively [13]. The thermodynamic modeling of this configuration is performed in Aspen Hysis V11 [14]. The optimization is executed by the Particle Swarm Optimization (PSO) algorithm, developed in MATLAB R290a environment and interfaced or coupled with Aspen Hysys V11 [15].

*2.1. Optimization:*

With every working fluid and scheme, it is prerequisite to perform system optimization for acquiring better thermodynamic efficiencies. The optimization steps are reported as;

- Objective function;
- Optimizing variables required for optimization of LNG Regasification integrated ORC and cryogenic distillation;
- Understanding the chemical process plant components and the simulation softwares tools;
- Knowledge of optimization algorithm/optimizer/optimization approach [16];

*2.2. Assumptions:*

Assumptions are taken with description of mathematical model to simulate this combined energy system. These details are outlined as;

- Steady state conditions at integrated process;
- Constant values of adiabatic and isentropic efficiencies of turbomachineries;
- Constant pressure drop at heat devices;
- Each one of the devices are viewed as adiabatic;
- LNG composition: Pure- $CH_4$;
- Turbine/Expander in configuration is simulated incorporating the Aspen Hysis expander element, as reported in Aspen-Hysis operation guide 2004;
- Number of iterations: 1000;

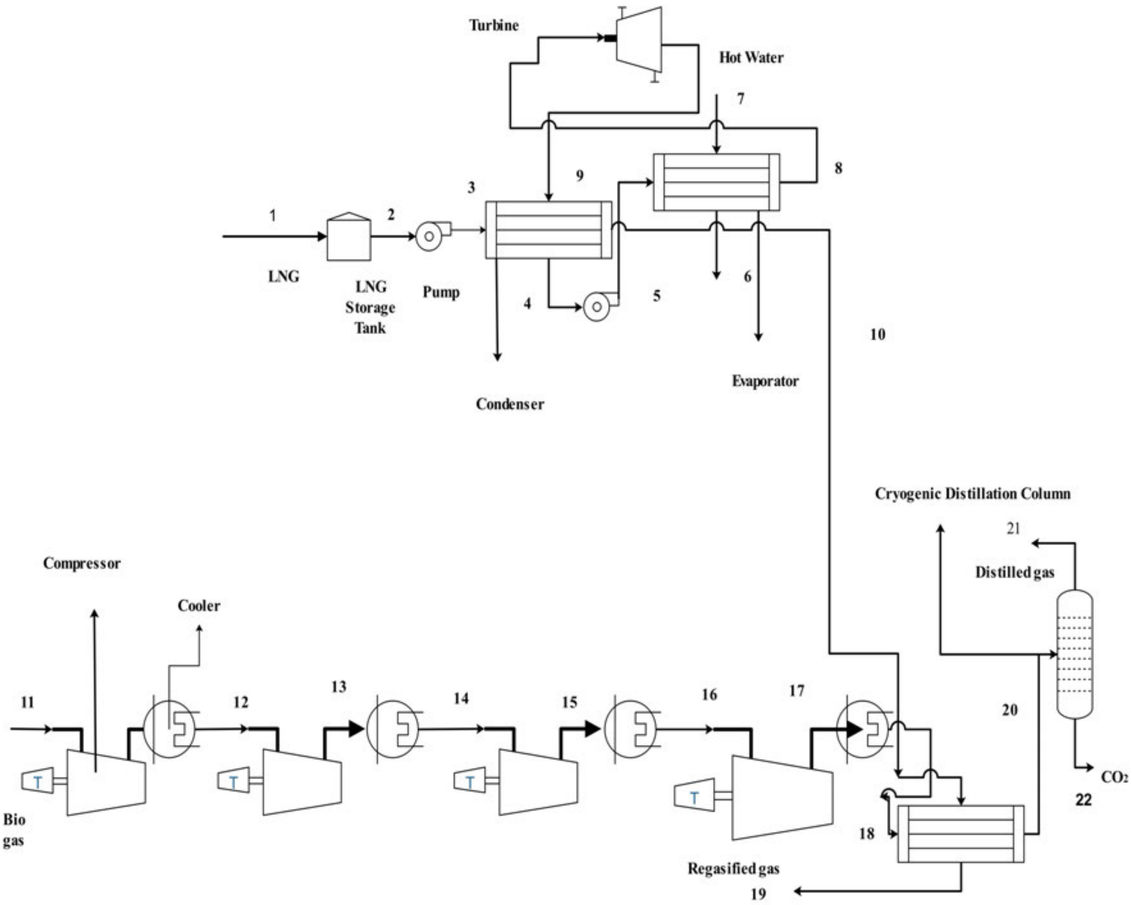


Figure 1: Process Flow diagram of LNG regasification process integrated with cryogenic distillation and ORC system.

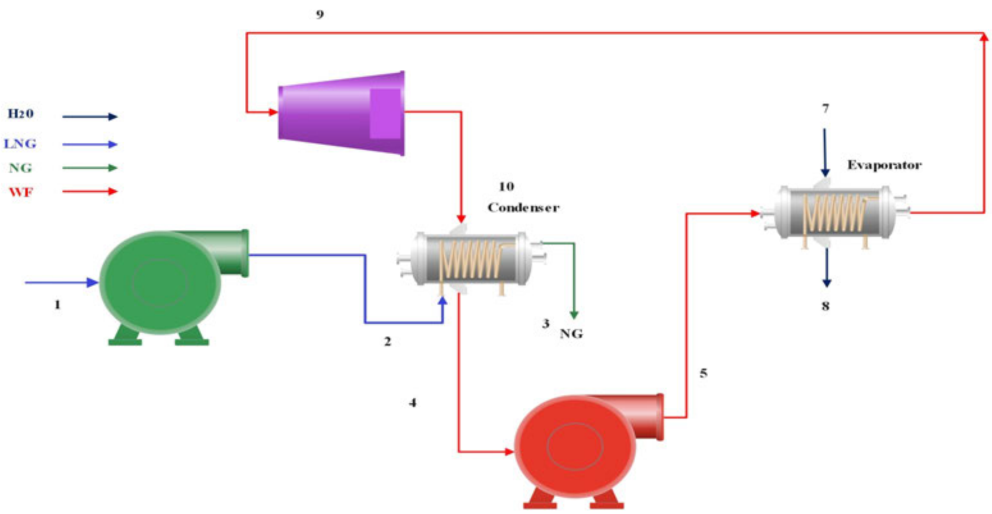


Figure 2: Methodology of LNG cold energy utilization at ORC.

## 3 Results

### *3.1. Power Generation*

In Figure 3, there is shown obtained power (MW) up-to 1948. 6, 1948, 1567, 1511, 1397, 1304 and 1010 by manipulating seven working fluids in single mode at this integrated energy system. While, in Figure 4, there is presented the achieved power output (MW) up-to 1552, 1500, 1329, 1286, 1230, 1218, and 1206 using seven working fluids in multiple mode. Pentane is found as a most suitable working fluid contributing power up-to 1948.6 MW slightly surpassing the Butane which secures power around 1948.6 MW. Table 1 delineates operating values of configuration I deploying Pentane as working fluid at ORC. These results show that power generation from turbine is dependent on working fluid thermodynamic properties [17].

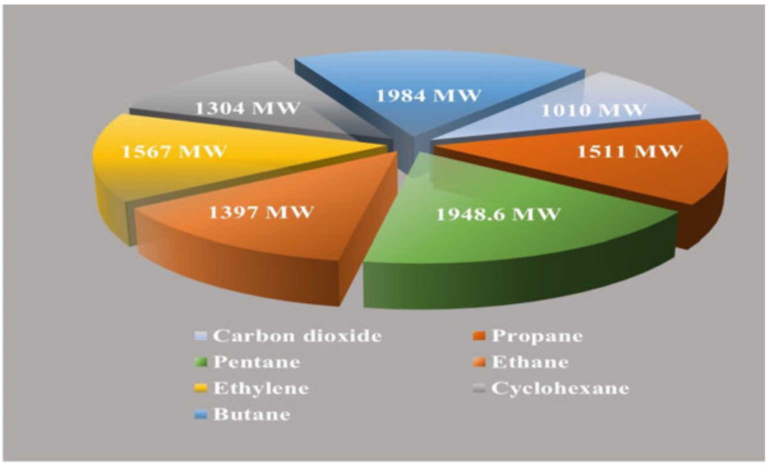


Figure 3: Illustration on net electricity produced by ORC placing working fluid in single mode.

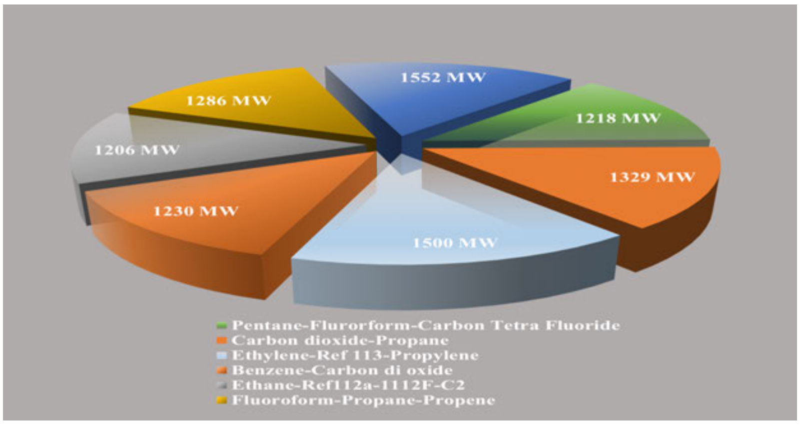


Figure 4: Illustration on net electricity produced by ORC placing working fluid in multiple mode.

| Thermodynamic point | Temperature [°C] | Pressure (kPa) | Mass Flow Rate [kg/h] | Fluid |
|---|---|---|---|---|
| 1 | -161 | 106.4 | $1.139 \times 10^7$ | LNG |
| 2 | -161 | 106.4 | $1.139 \times 10^7$ | LNG |
| 3 | -159.9 | 2000 | $1.139 \times 10^7$ | LNG |
| 4 | -30 | $1.3061 \times 10^{-7}$ | $1.236 \times 10^5$ | Pentane |
| 5 | -29.3 | 400 | $1.236 \times 10^5$ | Pentane |
| 6 | 21 | 15 | $7.206 \times 10^6$ | $H_2O$ |
| 7 | 30 | 4.177 | $7.206 \times 10^6$ | $H_2O$ |
| 8 | 400 | 3000 | $1.236 \times 10^5$ | Pentane |
| 9 | 80 | $1.071 \times 10^{-5}$ | $1.236 \times 10^5$ | Pentane |
| 10 | -35 | 2000 | $1.139 \times 10^7$ | NG |
| 11 | 20 | 50 | $1.033 \times 10^4$ | Bio gas |
| 12 | 140 | 1000 | $1.033 \times 10^4$ | Bio gas |
| 13 | 224.9 | 2100 | $1.033 \times 10^4$ | Bio gas |
| 14 | 140 | 2100 | $1.033 \times 10^4$ | Bio gas |
| 15 | 184.2 | 3100 | $1.033 \times 10^4$ | Bio gas |
| 16 | 140 | 3100 | $1.033 \times 10^4$ | Bio gas |
| 17 | 216.3 | 6000 | $1.033 \times 10^4$ | Bio gas |
| 18 | 80 | 6000 | $1.033 \times 10^4$ | Bio gas |
| 19 | -36.2 | 1800 | $1.139 \times 10^7$ | NG |
| 20 | -34.99 | 1000 | $1.033 \times 10^4$ | Bio gas |
| 21 | -81 | 4000 | 5932 | Distilled $CH_4$ |
| 22 | 0.554 | 3500 | 4401 | $CO_2$ |

Table 1: Operating values of Configuration I employing Pentane as working fluid.

*3.2. Energy Efficiency*

In Figure 5 and 6, there are shown obtained energy efficiencies (%) of integrated energy system manipulating working fluid in single and multiple modes respectively. It is calculated from first law of thermodynamic in Equation 1 [18].

$$\textit{Energy Efficiency}\ (\%) = \frac{\textit{Work Output-Energy Input}}{\textit{Energy Input}} \times 100 \quad (1)$$

Using Butane, Pentane, Ethylene, Propane, Ethane, $CO_2$ and Cyclohexane in single mode at ORC, the obtained energy efficiencies (%) are around 66.84, 63.86,31.20, 26.52, 16.80, 11.59 and 8.80 respectively. The obtained energy efficiencies (%) of working fluids $C_5H_{12}$-$CHF_3$-$CF_4$ (WFm-1), $CO_2$-$C_3H_8$ (WFm-2), $C_2H_4$ -R134a-$C_3H_6$ (WFm-3), $C_6H_6$-$CO_2$ (WFm-4), Ref-112a-C2H4-C3H6 (WFm-5), $CHF_3$- $C_3H_8$-$C_3H_6$ (WFm-6) and $C_6H_{12}$-$C_6H_6$-$CO_2$ (WFm-7) in multiple modes are found as 30.01, 25.55, 11, 7.33, 2.56, 1.54 and 0.59 simultaneously.

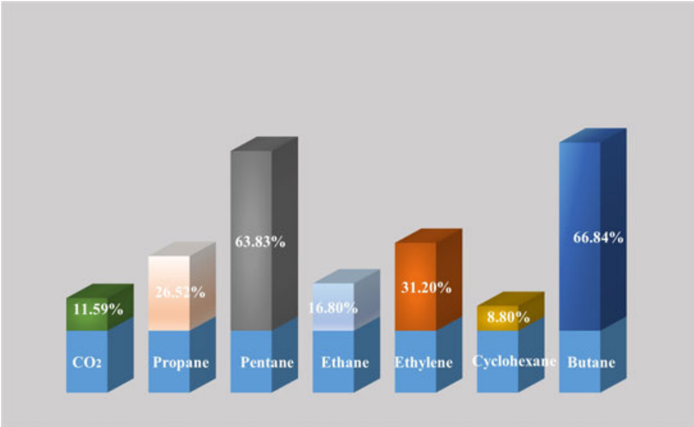


Figure 5. Illustration on attained energy efficiency percentage placing working fluid in single mode.

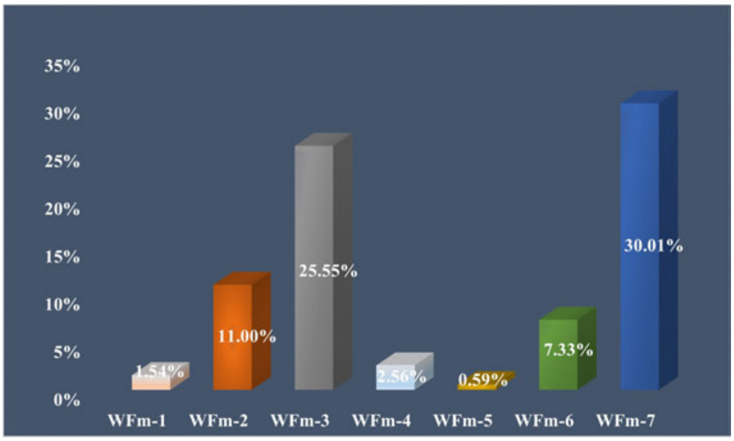


Figure 6. Illustration on attained energy efficiency percentage placing working fluid in multiple mode.

*3.3. Exergy Efficiency:*

Exergy efficiency was estimated using second law of thermodynamic in Equation 2 [19]. By placing working fluids Butane, Pentane, Ethylene, Propane, Ethane and $CO_2$ in single mode at ORC, secured exergy efficiencies (%) are found to be around 72.58, 71. 26, 57. 11, 55.03, 50.81, 47.36, 36.45 respectively. The multiple working fluids $C_5H_{12}$-$CHF_3$-$CF_4$(WFm-1), $CO_2$-$C_3H_8$ (WFm-2), $C_2H_4$ -R134a-$C_3H_6$ (WFm-3), $C_6H_6$-$CO_2$ (WFm-4), Ref-112a-C2H4-C3H6 (WFm-5), $CHF_3$- $C_3H_8$—$C_3H_6$ (WFm-6) and $C_6H_{12}$-$C_6H_6$-$CO_2$ (WFm-7) manipulation at ORC can generate exergy efficiencies (%) around 44.17, 48.28, 54.63,44.61, 43.72, 46.69 and 56.56 respectively.

$$Exergy\ Efficiency\ (\%) = \frac{Work\ produced\ -\ Energy\ conseumed\ by\ Turbomachinery}{Energy\ Input} \times 100 \tag{2}$$

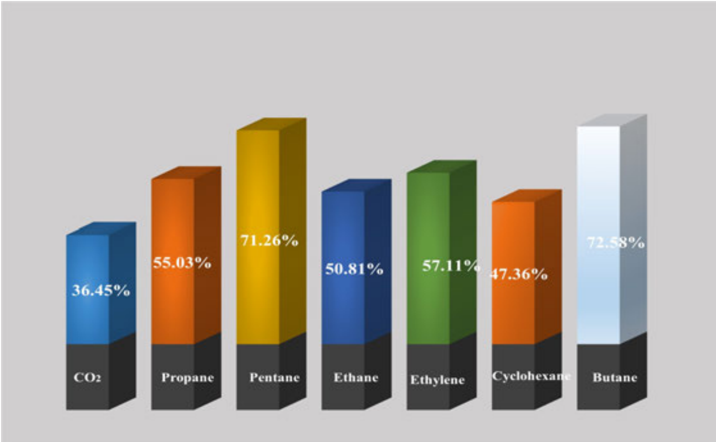


Figure 7: Representation of attained exergy efficiency percentage placing working fluid in single mode.

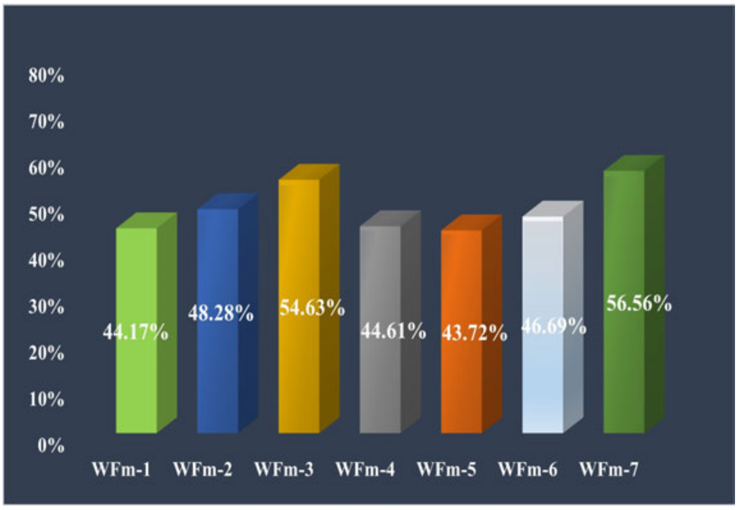


Figure 8: Representation of attained exergy efficiency percentage placing working fluid in multiple mode.

## 4 Conclusions and Contributions

It is proved that using single working fluid at ORC makes high power in contrast to working fluids of multiple mode. It is due to the fact that its thermodynamic properties i.e; (i)- Critical temperature, (ii)- Boiling temperature, (iii)-Specific heat, (iv)- Latent heat of evaporation, (v)- Heat transfer coefficient, (vi)- Enthalpy drop, (vii)- Thermal stability, (viii)- Viscosity, (ix)- Specific volume do not coincide each other.

- The ORC concept is identical to steam engine. Parallel to steam engine, this scheme is materialized into energy system by an impressive technological distinction at the moment. The main features of ORC appear to be good flexibility and efficacy at low energy span.

- ORC execution by LNG cold energy can coproduce energy and chilling. In conclusion, it is inherently valuable for given energy transformation with respect of their gross energy efficiency.
- It is also concluded that exergy efficiency is greater than energy efficiency of energy system, evident from acquired results.
- This paper discloses a business case that is now not available in scientific literature pinpointing usage of LNG cold energy for making electricity and running cryogenic distillation process. It formulates LNG regasification capacity of 99.7764 million tons per year at a port. It favorably portrays to produce electric energy and decreasing pollutants from bio gas setup. As, bio gas plants dispense high amount of $CO_2$ and there is required high energy for its cryogenic distillation or purification. It can be overcome from this proposed energy process. In this respect, the environmental regulation bodies, government authorities, industrialists and academic can take benefit from thermodynamic assessment of this proposed energy setup.
- The heat transfer equipments which are associated to this proposed energy integrated setup are categorized as condenser/regenerator, evaporators and preheater. It is concluded that shell and tube heat exchanger has come up with finer results. For practical implication, there is also recommendation to use that shell and tube heat exchanger as condenser and evaporator in ORC facility with respect of its facets comprising optimum heat transfer, minimum LNG freezing risk, on-shore/off-shore operation modes and maintenance.
- The present research work identifies to use hot sea water of port area in ORC evaporator with effects of its easy manipulation and no cost in summer.

### Acknowledgements

This work was supported by the Higher Education Commission (HEC), Pakistan grant (119-FEG2-012) funded by the Pakistan government.

## References

[1] B. Duldey, "BP Energy Outlook", London, United Kingdom, 2018.
[2] V. Smil, "Natural gas: fuel for the 21st century", John Wiley & Sons Publications, 2015. doi:
[3] T. He, Z. R. Chong, J. Zheng, Y. Ju, and P. Linga, "LNG cold energy utilization: Prospects and challenges", Energy, 170, 557-568, 2019. doi: 10.1016/j.energy.2018.12.170
[4] F. Xue, Y. Chen, and Y. Ju, "A review of cryogenic power generation cycles with liquefied natural gas cold energy utilization", Frontiers in Energy, 10, 363–374, 2016. doi: 10.1007/s11708-016-0397-7
[5] J. Bao, Y. Lin, R. Zhang, N. Zhang, and G. He, "Effects of stage number of condensing process on the power generation systems for LNG cold energy

recovery", Appied Thermal Engineering, 126, 566–582, 2017. doi: 10.1016/j.applthermaleng.2017.07.144

[6] Y. Liu and K. Guo, "A novel cryogenic power cycle for LNG cold energy recovery", *Energy*, 36, 2828–2833, 2011. doi: 10.1016/j.energy.2011.02.024

[7] G. Angelino and C. M. Invernizzi, "Carbon dioxide power cycles using liquid natural gas as heat sink", Appied Thermal Engineering, 29, 2935–2941, 2009. doi: 10.1016/j.applthermaleng.2009.03.003

[8] G. Oliveti, N. Arcuri, R. Bruno, and M. De Simone, "A rational thermodynamic use of liquefied natural gas in a waste incinerator plant", Appied Thermal Engineering, 35, 134–144, 2012. doi: 10.1016/j.applthermaleng.2011.10.015

[9] R. Agarwal, T. J. Rainey, S. M. Rahman, T. Steinberg, R. K. Perrons, and R. J. Brown, "LNG regasification terminals: the role of geography and meteorology on technology choices", Energies, 10, 2152, 2017. doi: 10.3390/en10122152

[10] G. Prasad and A. Das, "Design Approach of Shell and Tube Vaporizer for LNG Regasification", Jordan Journal of Mechanical and Industrial Engineering, 12, 109-116, 2018.

[11] A. Brenk, J. Kielar, Z. Malecha, and Z. Rogala, "The effect of geometrical modifications to a shell and tube heat exchanger on performance and freezing risk during LNG regasification", International Journal of Heatand Mass Transfer, 161, 120247, 2020. doi: 10.1016/j.ijheatmasstransfer.2020.120247

[12] M. Mehrpooya, M. M. M. Sharifzadeh, and M. H. Katooli, "Thermodynamic analysis of integrated LNG regasification process configurations", Progress in Energy and Combustion Science, 69, 1–27, 2018. doi: 10.1016/j.pecs.2018.06.001

[13] M. Astolfi, E. Martelli, and L. Pierobon, "Thermodynamic and technoeconomic optimization of Organic Rankine Cycle systems", E. Macchi and M. Astolfi (Editors) Organic Rankine Cycle (ORC) Power Systems Technologies and Applications, Woodhead Publications, Cambridge, United Kingdom, Chapter 7, 173–249, 2017. doi: 10.1016/B978-0-08-100510-1.00007-7

[14] 'Aspen HYSYS | Process Simulation Software | AspenTech'. [Online]. Available: https://www.aspentech.com/en/products/engineering/aspen-hysys. [Accessed: 07-Jan-2022]. doi:

[15] D. Fioriti, A. Baccioli, G. Pasini, A. Bischi, F. Migliarini, D. PoliLorenzo and L. Ferrari "LNG regasification and electricity production for port energy communities: Economic profitability and thermodynamic performance", Energy Conversion and Management, 238, 114128, 2021. doi: 10.1016/j.enconman.2021.114128

[16] M. Astolfi, M. Romano, P. Bombarda, and E. Macchi, "Binary ORC (Organic Rankine Cycles) power plants for the exploitation of medium–low temperature geothermal sources – Part B: Techno-economic optimization", Energy, 66, 435-446, 2014. doi: 10.1016/j.energy.2013.11.057

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

[18] P. C. E. & S. ER 100/200, ‘Thermodynamic law efficiency.’ [Online]. Available:https://nature.berkeley.edu/er100/sections/Week5_section_handout.pdf. [Accessed: 15-Jan-2022].
[19] V. Nikulshin, C. Wu, and V. Nikulshina, “Exergy efficiency calculation of energy intensive systems”, Exergy An International Journal, 2, 78–86, 2002. doi: 10.1016/S1164-0235(01)00042-5