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## A micro cogeneration system with LNG cold utilization-part 1: energetic, economic and environmental analyses

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### Abstract

Few studies have been studied on the LNG cold utilization with micro-cogeneration systems while many studies were related to large scale power generation systems. This study proposes a combined LNG cold utilized micro-cogeneration system which includes an LNG pump, an LNG vaporizer, a combustion chamber, a recuperator, a compressor, a gas turbine and a heat exchanger. Economic, energetic and environmental analyses are conducted according to various ambient air temperatures and the results are compared with overall performance of the conventional micro c-generation system. The generated electricity rate and the thermal efficiency are found the same for both investigated cycles. However, the payback period is approximately 6% higher than the conventional cycle. The mean environmental payback period was found approximately 4.8 years.

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**Keywords:** LNG cold energy, Cogeneration, Combined heat and power, Economic analysis, Environmental analysis, Thermodynamic analysis.

### Nomenclature

$c$	Unit cost, (\$/kJ)
$EPC$	Environmental pollution cost, (\$/kJ)
$F$	Fuel flow rate of turbine, (kJ/s)
$\bar{h}$	Specific enthalpy, (kJ/kg)
$L$	Heat loss ratio from the combustion chamber, (%)
$LHV$	Lower heating value of the fuel, (kJ/kmolK or kJ/kgK)
$\dot{m}$	Mass flow rate, (kg/s)

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$M$	Molar mass, (kg/kmol)
$n$	System lifetime, (years)
$\dot{n}$	Molar flow rate, (kmol/s)
$OM$	Operation and maintenance cost, (\$)
$PEC$	Purchased equipment cost, (\$)
$PP$	Payback period, (years)
$TEP$	Total environmental price, (\$)
$\dot{W}$	Work rate, (kJ/s)
$\dot{Q}$	Thermal energy rate, (kJ/s)
$x$	Molar fraction, (- or %)
<i>Greek letters</i>	
$\bar{\lambda}$	Fuel to air ratio, (- or %)
$\eta$	Energetic efficiency, (%)
$\tau$	Annual operation time, (hours)
<i>Superscripts</i>	
$a$	Air
$p$	Product
<i>Subscripts</i>	
$a$	Air
$env$	Environmental
$el$	Electric
$f$	Fuel
$in$	Input
$mt$	Micro turbine
$net$	Net generated
$p$	Product
<i>Abbreviations</i>	
LNG	Liquefied natural gas

## 1. Introduction

LNG is a mature transportation method for natural gas with conventional pipeline technology [1]. It is commercially feasible for long distance which above 3500 km while the pipeline method is feasible for less than 1000 km distances [2]. LNG is safe, non-corrosive, non-toxic, and odorless gas and its density range is between 400 and 500 kg/m<sup>3</sup> [3-5]. Owing to developing technologies in LNG processing, the cost of LNG supply chain that includes production, liquefaction, transportation, and regasification processes [6] has decreased. It has been closed to the cost of conventional technology. Regasification process provides transformation of the liquid phase to gas phase owing to external thermal sources.

LNG cold utilization systems provide to use of required thermal energy as additional thermal or electricity energy in many areas such as cold storage, power generation, seawater desalination, incinerator plants, district cooling systems, etc. [7,8]. Power generation sector is the main sector for LNG cold utilization systems. Rankine, Brayton, and direct expansion cycles are three commonly used cycles that are being used in LNG cold utilization system design in the literature [2]. There are many LNG cold utilization systems in today's world and all the existing plants are combined plants which include Rankine and direct expansion cycles [9]. Gas turbine based LNG cold utilization systems are generally designed for low capacities. This study aims to investigate the micro-cogeneration system with 30 kW power capacity in two cases; with LNG cold utilization and without LNG cold utilization according to energetic,

economic and environmental aspects respectively to see the feasibility of LNG cold utilization systems for small scale applications.

## 2. Modeling

System schematics of the conventional micro-cogeneration system and the LNG cold utilized micro-cogeneration system are illustrated in Fig. 1(a, b). The conventional micro-cogeneration system includes a compressor, a recuperator, a combustion chamber, a gas turbine/generator couple, and a heat exchanger. The system capacity is 30 kW and Capstone C30 micro turbine system is used for this system. The heat exchanger is used to producing hot water instead of steam generation. Thermal energy capacity for the heat exchanger is assumed as 50 kW at 298.15 K ambient air temperature that is an average value of some industrial applications of the Capstone C30 micro turbine system [10,11].

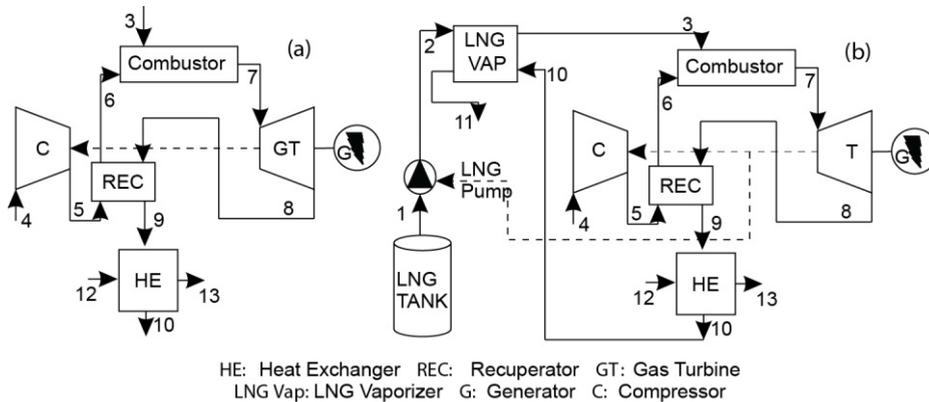


Fig.1: Simplified schematic of (a) the conventional micro-cogeneration system and (b) the LNG cold utilized micro-cogeneration system.

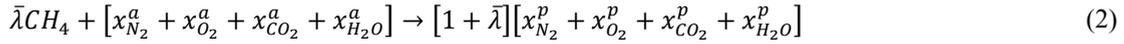
LNG cold utilization system is integrated to the micro-cogeneration system as shown in Fig. 1b. LNG is sent to the LNG pump and it is pressurized from the atmospheric conditions ( $-162^{\circ}\text{C}$ , 1 atm). LNG changes its phase from liquid to gas by heat transfer in the LNG vaporizer. The exhausted gas of heat exchanger is recovered in the LNG vaporizer. Stream 3 is assumed 100% natural gas and there is no multiphase flow. After vaporization of natural gas, it is sent to the micro-cogeneration system. Isentropic efficiencies of the compressor, gas turbine, and LNG pump are assumed as 79% [12], 84.38% [12] and 75%, respectively. Generator efficiency is 96% [12]. System lifetime is 20 years and annual operating hour is determined as 8000 hours. The relative humidity is assumed 60% for all different ambient temperatures. Lastly, Lower Heating Value (LHV) of the natural gas and the LNG are assumed as the same.

Thermodynamic modeling is based on the first law analysis for this paper. The exhausted mass flow rate from the micro-cogeneration system was received from manufacturer data [13]. The required mass flow rate for the fuel is calculated by dividing the fuel flow rate of micro turbine [13] to LHV [14] of the fuel and then the molar flow rate of fuel is calculated in Eq.(1).

$$\dot{n}_f = (F/LHV)/M_f = \dot{m}_f/M_f \quad (1)$$

where  $\dot{n}_f$  and  $\dot{m}_f$  are molar and mass flow rates of the fuel, respectively, and  $F$  is the fuel flow rate of micro gas turbine whereas  $M_f$  is the molar mass of the fuel. Natural gas is the fuel of this study and

methane is assumed 100% of natural gas. The difference between mass flow rates of the exhausted gas ( $\dot{m}_p$ ) and the fuel ( $\dot{m}_f$ ) presents the mass flow rate of the required air ( $\dot{m}_a$ ) for the micro-cogeneration system. Nitrogen, oxygen, carbon dioxide, and water vapor are assumed as chemical contents of the air and molar mass of the air ( $M_a$ ) is calculated by using these chemical contents. Molar flow rate of the air ( $\dot{n}_a$ ) can be found by dividing  $\dot{m}_a$  to  $M_a$ . The ratio of molar flow rate of the fuel to the air is called as fuel to air ratio ( $\bar{\lambda}$ ) and it is significant parameter in the calculation of combustion equation as shown in Eq.(2).



where  $x^a$  and  $x^p$  are molar fractions of chemical contents, and  $[1 + \bar{\lambda}]$  is equal to ratio of molar flow rate of the exhausted gas ( $\dot{n}_p$ ) to the air ( $\dot{n}_a$ ) that means the molar flow rate of the exhausted product is found by solving the combustion equation. Enthalpy calculations of the air and the exhausted gas are another crucial criteria for the first law analyses. In addition to the molar fractions, enthalpy values of the chemical contents are also required. Eqs. (3) and (4) present the specific enthalpy calculations of the air and product gas, respectively.

$$\bar{h}_a = [x_{N_2}^a \bar{h}_{N_2} + x_{O_2}^a \bar{h}_{O_2} + x_{CO_2}^a \bar{h}_{CO_2} + x_{H_2O}^a \bar{h}_{H_2O}] \quad (3)$$

$$\bar{h}_p = [x_{N_2}^p \bar{h}_{N_2} + x_{O_2}^p \bar{h}_{O_2} + x_{CO_2}^p \bar{h}_{CO_2} + x_{H_2O}^p \bar{h}_{H_2O}] \quad (4)$$

where  $\bar{h}_a$  and  $\bar{h}_p$  are the molar specific enthalpy values of the air and the product gas, respectively. Specific enthalpy values of the chemical contents can be found from the thermodynamic tables. By multiplying the specific enthalpy of air and product gas with the molar flow rate of air and product gas, enthalpy values of the air and the product are found, respectively. More details on thermodynamic calculations of LNG cold utilization and gas turbine systems can be found from Morosuk and Tsatsaronis' work [15] and Bejan et al. [16], respectively. The net generated work and the energetic efficiency of the micro-cogeneration system are shown in Eqs. (5) and (6), respectively.

$$\dot{W}_{net} = \dot{W}_{mt} - \dot{W}_{LNG\ Pump} \quad (5)$$

$$\eta = \dot{W}_{net} + \dot{Q}_{HE} / \dot{Q}_{in} \quad (6)$$

where  $\dot{W}_{net}$ ,  $\dot{W}_{mt}$ , and  $\dot{W}_{LNG\ Pump}$  are the net generated work rate, the micro-turbine work rate and the LNG pump work rate, respectively, and  $\dot{Q}_{HE}$  is the produced thermal energy from the heat exchanger and it is also considered during the calculation of energetic efficiency ( $\eta$ ). However, when the single generation system is considered, thermal energy production is not considered.  $\dot{Q}_{in}$  is the total heat input of the micro-cogeneration system and both systems have the same  $\dot{Q}_{in}$  rates due to fact that LHV values of the natural gas and the LNG are assumed as the same. The calculation of  $\dot{Q}_{in}$  is shown in Eq. (7).

$$\dot{Q}_{in} = \dot{n}_f \cdot LHV \cdot (1 - L) \quad (7)$$

where  $L$  is the heat loss ratio from the combustion chamber to the environment.

Payback period is main aspect of the economic analysis and it consists of equipment costs, operation and maintenance costs, operation time, and the generated energy rate with its price. CO<sub>2</sub> emissions have also impact on the economic analyses of thermal systems and the relationship between emissions and the

economics is defined with Environmental Payback Period ( $PP_{env}$ ) in this study. To calculate the  $PP_{env}$ , Total Environmental Price ( $TEP$ ) must be known that can be calculated in Eq.(8).

$$TEP = EPC \cdot \dot{m}_{pCO_2} \cdot \tau \cdot n \tag{8}$$

where  $EPC$  is the Environmental Pollution Cost of  $CO_2$ , 0.0327 \$/kg $CO_2$  that is received from Rosen and Dincer [17] by using related inflation and exchange rates [18],  $\dot{m}_{pCO_2}$  (kg/h) is mass flow rate of the exhausted  $CO_2$  from the cogeneration system. Annual operation time and the system lifetime are denoted by  $\tau$  and  $n$ , respectively. The calculation of  $PP$  and  $PP_{env}$  can be seen in Eqs. (9) and (10), respectively. More details on the payback period calculation can be found from Bejan et al. [16]. For the  $PP_{env}$  calculation, the produced thermal energy rate is not considered.

$$PP = [(PEC + OM) \cdot 4.3] / [(\dot{W}_{net} \cdot c_{el} \cdot 3600 + (\dot{Q}_{HE} \cdot c_{LNG} \cdot 3600) \cdot \tau)] \tag{9}$$

$$PP_{env} = TEP / (\dot{W}_{net} \cdot c_{el} \cdot 3600 \cdot \tau) \tag{10}$$

where  $PEC$  is the purchased equipment cost. The  $PEC$  values are 700 \$/kW, 2000 \$ and 1130 \$/kW for the LNG pump, the LNG vaporizer and the micro turbine system, respectively.  $c_{el}$  and  $c_{LNG}$  are the electricity price and the LNG price which are equal to  $3.49 \times 10^{-5}$  (\$/kJ) [19] and  $6.98 \times 10^{-6}$  (\$/kJ) [20]. Moreover, the natural gas price is used instead of the LNG price for the calculation of conventional micro-cogeneration system and it is  $6.49 \times 10^{-6}$  (\$/kJ) [21].  $OM$  is the operation and maintenance cost and it is assumed as 1.092% of purchased equipment cost for each system component [22].

### 3. Results and Discussions

Results show that the required LNG pump rates are between  $2.20 \times 10^{-3}$  and  $2.24 \times 10^{-3}$  kW in the range between 288.15 K and 313.15 K at compressor pressure ratio of 3.64 as they can be seen from Fig. 2a. These values show that the LNG pump work does not have a significant effect on power generation performance. Therefore, the first law efficiency and the net generated work rates of the LNG cold utilized micro-cogeneration system are very close to the energetic efficiency and the net generated work rate of the conventional micro-cogeneration system. Fig. 2b presents the thermal efficiency and generated work rate for the LNG cold utilized micro-cogeneration system.

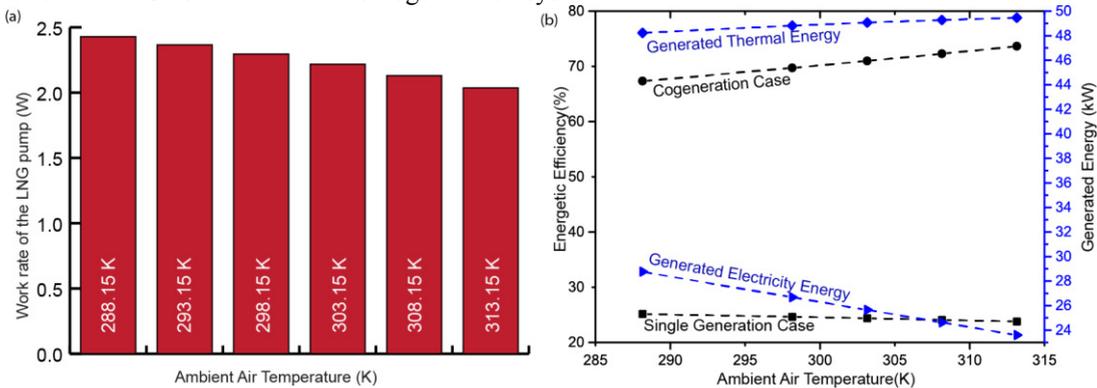


Fig.2: (a) Work rate of the LNG pump, (b) Energetic efficiency and generated power/thermal energy rates of the LNG cold utilized micro-cogeneration system.

The generated work rate drops and it causes a decrement in the energetic efficiency for the single power generation case. In contrast to work generation, the produced thermal energy increases so that is the main reason why the energetic efficiency decreases for the single power generation case while it rises for the cogeneration case by the rising of ambient air temperature. For the work generation, the decrement is nearly 18% while the thermal energy increases 2.5% for the ambient air temperature increment from 288.15 K to 318.15 K.

After the first law analyses, economic analyses are performed and payback periods are calculated for the conventional micro-cogeneration system and the LNG cold utilized micro-cogeneration system, respectively. In both cases, two configurations are considered as power based configuration and cogeneration based configuration which means the power based configuration only focuses on the electricity generation while the cogeneration based configuration considers both electricity and thermal energy productions as illustrated in Fig. 3 with environmental payback period results for the conventional and LNG cold utilized micro-cogeneration systems

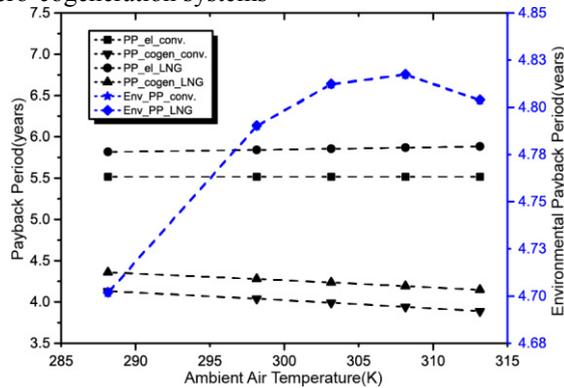


Fig.3: Payback and environmental payback periods for conventional micro-cogeneration and LNG cold utilized micro-cogeneration cases.

Results show that the conventional micro cogeneration case has average 5.5 and 3.99 years payback periods for power based and cogeneration based configurations, respectively. The LNG cold utilization application increases the payback periods nearly 6% and reaches 5.85 and 4.24 years for power and cogeneration based configurations, respectively. When environmental payback periods are investigated it is seen that both systems have the same  $PP_{env}$  trends due to fact that both systems have similar generated work rates. Environmental payback period finds its maximum point at 308.15K. This shows that there must be a maximum point for produced the CO<sub>2</sub> emissions. The calculated CO<sub>2</sub> emission rates are shown in Fig. 4.

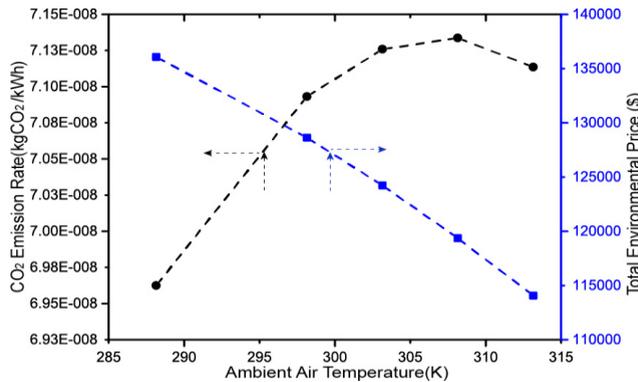


Fig.4: The total environmental price and CO<sub>2</sub> emission rates for the LNG cold utilized micro-cogeneration system

Emission rates show that there is a peak point which is near to 308.15K. However, when the emission rate is investigated it is seen that the emission rate does not have a significant effect due to the very small difference between emission rates. Moreover, the total environmental price is investigated and it is deduced that the *TEP* decreases more than 17% by the rising of ambient air temperature from 288.15 K to 313.15 K.

#### **4. Conclusions**

Energetic, economic and environmental analyses were investigated for the small scale LNG cold utilization system which was operated by the LNG pump, the LNG vaporizer and the gas turbine based micro-cogeneration system with 30 kW electricity capacity. The generated work rate of the LNG pump had no significant effect on the general power generation so that there was no difference between conventional micro-cogeneration and LNG cold utilized micro cogeneration cases from the point of electricity generation and energetic efficiency. Generated electricity work rates decreased by the rising of ambient air temperature while thermal energy increased. The energetic efficiency decreased for the power based case while it increased for the cogeneration case. LNG cold utilization components rose payback periods nearly 6%. Environmental payback periods increased by the growing of ambient air temperature. The total environmental price decreased while ambient air temperature rose. It is deduced that there is still significant gaps to increase the feasibility of LNG cold utilization system for micro-cogeneration cases. Exergy analysis should be applied to the LNG cold utilization system to see the convenient points to increase the overall efficiency. Also, exergy destruction and loss rates can present ideas to develop the proposed model efficiently.

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## References

- [1] British Petrol. *BP energy outlook 2035*. 2015
- [2] Mokhatab S, Mak JY, Valappil JV, Wood DA. *Handbook of liquefied natural gas*. Burlington:Elsevier Science; 2013.
- [3] Kumar S, Kwon HT, Choi KH, Lim W, Cho JH, Tak K, et al. LNG: an eco-friendly cryogenic fuel for sustainable development. *Appl Energ* 2011;**88**:4264-73.
- [4] Shi GH, Jing YY, Wang SL, Zhang XT. Development status of liquefied natural gas industry in China. *Energy Policy* 2010;**38**:7457-65.
- [5] Won W, Lee S, Choi K, Kwon Y. Current trends for the floating natural gas (FLNG) technologies. *Korean J Chem Eng* 2014;**31**:732-43.
- [6] Total. *Liquefied natural gas*. 2009.
- [7] Messieno A, Panno D. Potential applications using LNG cold energy in Sicily. *Int J Energ Res* 2008;**32**:1058-64.
- [8] Hirakawa S, Kosugi K. Utilization of LNG cold. *Int J Refrig* 1981;**4**:17-21.
- [9] Romero Gomez M, Ferreiro Garcia R, Romero Gomez J, Carbia Carril J. Review of thermal cycles exploiting the exergy of liquefied natural gas in the regasification process. *Renew Sust Energ Rev* 2014;**38**:781-95.
- [10] Capstone Turbine Corporation. *den Dulk Dairy case study*. 2008.
- [11] Capstone Turbine Corporation. *MTS Argonon case study*. 2011.
- [12] Capstone Turbine Corporation. *Final Technical Report*. 2008.
- [13] Capstone Turbine Corporation. *Capstone model C30 technical reference*. 2006.
- [14] Boundy B, Diegel SW, Wright L, Davis SC. *Biomass energy data book*. 4<sup>th</sup> ed. Oak Ridge (TN):Oak Ridge National Laboratory; 2011.
- [15] Tsatsaronis G, Morosuk T. Advanced exergetic analysis of a novel system for generating electricity and vaporizing liquefied natural gas. *Energy* 2010;**35**:820-9.
- [16] Bejan A, Tsatsaronis G, Moran MJ. *Thermal design and optimization*. NY:Wiley;1996.
- [17] Rosen MA, Dincer I. Exergy analysis of waste emissions. *Int J Energ Res* 1999;**23**:1153-63.
- [18] Bank of Canada. *Historical data-inflation*, <http://www.bankofcanada.ca/rates/indicators/capacity-and-inflation-pressures/inflation/historical-data/>; 2016 [accessed 31.05.16].
- [19] US Energy Information Administration. *Electric power monthly*, [https://www.eia.gov/electricity/monthly/epm\\_table\\_grapher.cfm?t=epmt\\_5\\_6\\_a](https://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_5_6_a); 2016 [accessed 31.05.16].
- [20] US Energy Information Administration. *Price of US natural gas LNG imports*, <https://www.eia.gov/dnav/ng/hist/n9103us3m.htm>; 2016 [accessed 31.05.16].
- [21] US Energy Information Administration. *Natural gas prices*, [https://www.eia.gov/dnav/ng/ng\\_pri\\_sum\\_dcu\\_nus\\_m.htm](https://www.eia.gov/dnav/ng/ng_pri_sum_dcu_nus_m.htm); 2016 [accessed 31.05.16].
- [22] Tsatsaronis G, Pisa J. Exergoeconomic evaluation and optimization of energy systems- application to the CGAM problem. *Energy* 1994;**19**:287-321.



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