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Finite sum based thermoeconomic and sustainable analyses of the small scale LNG cold utilized power generation systems☆

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HIGHLIGHTS

- An original finite sum approach is applied in three LNG importing countries.
- Two different LNG cold utilized micro cogeneration systems are analyzed.
- The morning session provides the best yearly performance results.
- The combined system is more feasible and sustainable than the single system.

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ABSTRACT

Liquefied natural gas (LNG) cold utilized micro cogeneration systems are the feasible and sustainable solutions for the inland regions where the large scale LNG cold utilization or the conventional pipeline systems are not economically applicable. The present study investigates the single and combined systems in three LNG importing countries by using the finite sum modeling which is firstly performed for the LNG cold utilization systems with the sustainability index assessment. To generate electricity, the microturbine is integrated with an LNG vaporizer and an LNG pump in the single system while the combined system includes a Stirling engine and a thermal energy storage tank in addition to the microturbine and LNG cold utilization components. Thermodynamic, environmental, thermoeconomic and sustainable analyses are performed to obtain their yearly performance maps that are extremely difficult to obtain with the conventional dynamic modeling. The yearly performance trends of the net power generation rate, exergetic efficiency, and the levelized product cost are found similar to each other while they have contrary yearly trends with the overall energetic efficiency and the Stirling engine performance parameters. The net generated power rate, the Stirling engine performance parameters, the levelized product cost, the emission rate and the sustainability index have significant changes which must be considered for the real applications while the other factors are able to be neglected during the dynamic analysis since their fluctuations are small. The most convenient time are found at 08:00 am in all the case countries though the corresponding months change for each case country. The combined system is found more feasible than the single system from the thermodynamic, thermoeconomic, environmental and sustainable viewpoints.

1. Introduction

The regasification step of liquefied natural gas (LNG) trade is one of the main steps for the natural gas-utilized power generation applications in the LNG importing countries. It shares 20% [1] and nearly 70% [2] of the LNG value and greenhouse gas emission (GHG) chains with the relevant power generation part. To achieve sustainable LNG regasification, the LNG vaporizer can be used as heat sink in the combined thermal or power plants which are called as LNG cold utilization systems [3,4] that are widely used in the large scale regasification processes as real engineering applications [5]. In addition to the large scale LNG regasification and cold utilization systems, the recent studies pointed out the small scale LNG regasification and cold utilization systems may be more sustainable solution in the LNG trade [6,7] especially for the inland and stranded markets where the pipeline natural gas method or the large scale LNG regasification plants are not

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Nomenclature

c	unit cost, \$/kJ
$\dot{C}$	cost, \$
CRF	Capital Recovery Factor, –
$\bar{e}$	specific exergy, kJ/kmol
ER	emission reduction, %
$\dot{E}$	exergy rate, kJ/s
f	exergoeconomic factor, %
F	fuel flow rate of microturbine, kJ/s
$\bar{h}$	specific enthalpy, kJ/kmol
$\dot{H}$	energy rate, kJ/s
i	interest rate, %
L	heat loss ratio from combustion chamber, %
LHV	lower heating value, kJ/kg
	molar mass, kg/kmol
$\dot{m}$	mass flow rate, kg/s
n	system lifetime, years
$\dot{n}$	molar flow rate, kmol/s
p	pressure, bar
PEC	purchased equipment cost, \$
r	relative cost difference, %
RV	reversibility factor
$\bar{R}$	universal gas constant, kJ/kmol K
$\bar{s}$	specific entropy, kJ/kmol K
SI	sustainability index, –
T	temperature, K
$\dot{W}$	work rate, kJ/s
$\dot{Q}$	heat rate, kJ/s
x	molar fraction
$\dot{Z}$	levelized component cost, \$/s

Greek letters

γ	constant for polytropic state
$\bar{\lambda}$	fuel-air ratio
ζ	ratio of cold gas inlet to hot gas inlet
ϵ	effectiveness
η	energetic efficiency
ε	exergetic efficiency
ς	carbon dioxide emission rate
τ	annual operation time, hours
ω	heat exchanger effectiveness

Superscripts

a	air
CH	chemical exergy
$comb$	combined
	mechanical component of physical exergy
T	thermal component of physical exergy
p	product
PH	physical exergy

Subscripts

0	dead state
a	air
abs	absolute
C	compressor
CC	combustion chamber
d	destruction
for	formation
GT	gas turbine
gen	generated
HE	heat exchanger
in	inlet
f	fuel
L	loss
$O\,\&\,M$	operation and maintenance
p	product
pcy	polytropic
REC	recuperator
ref	reference state
ST	Stirling engine
tab	tabular source
th	thermal energy

Abbreviations

ANN	artificial neural network
CHE	cold heat exchanger
HHE	hot heat exchanger
NIST	National Institute of Standards and Technology
LNG	liquefied natural gas
LNGVap	liquefied natural gas vaporizer
PCM	phase change material

economically feasible [8]. Our research group has been focusing the thermodynamic, thermoeconomic and environmental assessments [7,9–13] to present more efficient and sustainable small scale LNG cold utilization applications for the real engineering applications in the mentioned areas.

All the assessment methods have been conducted for the steady-state power generation systems like many other energy conversion systems. Beside our previous small scale studies, there are different works that performed the LNG cold utilization systems in the large scale. Gomez et al. [14,15] combined the Brayton and Rankine cycles for the cold utilization, and investigated the system with the thermodynamic perspective. The thermodynamic perspective was also used by Garcia et al. [16,17] in order to assess the combined Rankine and direct expansion cycles during the LNG regasification. Apart from the combined systems which included the Rankine cycle, Morosuk and Tsatsaronis presented a combined cycle that had three different sub-cycles with a direct expansion cycle and two Brayton cycles [18]. Furthermore, the alternative system schematics were shown. For the similar system schematics, various parametric advanced exergy analyses were performed in different studies [19–22]. In addition to the exergetic and advanced exergetic analyses, the exergoeconomic and exergoenvironmental performances were mentioned in Ref. [23]. Mehrpooya et al. [24] applied the air separation process with the LNG cryogenic energy, and evaluated the results from the thermodynamic perspective. The similar approach was carried out for the carbon dioxide capture with the LNG cold energy in Ref. [25]. Also, the thermoeconomic studies were conducted for the combined air separation-LNG cryogenic energy system [26] and combined organic Rankine cycle-LNG cryogenic energy-solar energy system [27], respectively. Like the highlighted studies, many other significant large scale LNG regasification studies [28–35] performed the LNG cold utilization systems under the steady-state conditions, in which the studies investigated the energy conversion systems independently from the time constraint. Although there are many useful outputs obtained from the steady-state analysis, it is possible to miss some significant points for the real engineering applications since the real engineering applications are usually under the dynamic conditions. Several dynamic studies have been conducted for the energy conversion systems such as combined heat and power systems [36–39] and solar thermal systems [40,41]. The dynamic simulations provide trustful data for the real operations, but the accurate