CHEMICAL ENGINEERING TRANSACTIONS
VOL. 94, 2022

A publication of AIDIC
The Italian Association
of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Yee Van Fan, Jiří J. Klemeš, Sandro Nižetić

ISBN 978-88-95608-93-8 **ISSN** 2283-9216

DOI: 10.3303/CET2294021

An Innovative Polygeneration System Integrating Compressed Air Energy Storage (CAES) and Multi-effect Desalination for Efficient LNG Cold Energy Utilization

Seyed Mojtaba Alirahmi [a], Truls Gundersen [b], Haoshui Yu [a,]*

[a]Department of Chemistry and Bioscience, Aalborg University, Niels Bohrs Vej 8A, Esbjerg, 6700, Denmark
[b]Department of Energy and Process Engineering, Norwegian University of Science and Technology, Kolbjoern Hejes v. 1A, NO-7491 Trondheim, Norway
hayu@bio.aau.dk

Liquefied natural gas (LNG) contains a huge amount of cold energy, generally wasted during the regasification process. With the increasing penetration of renewable energy in the grid, the power generation profile does not match well with that of power demand, which causes power shortage during peak hours and surplus power during off-peak hours. Under this circumstance, a hybrid energy system integrating compressed air energy storage (CAES) system with LNG cold energy utilization process is proposed to address these issues. The integrated system consists of an organic Rankine cycle (ORC), a gas turbine, a multiple effect desalination unit, a CAES system, and a domestic cooling unit. A comprehensive analysis is carried out to assess the system's economic and thermodynamic performance. The study presents a parametric study to illustrate the impacts of critical parameters on the system performance. The energy efficiency of the integrated system is boosted significantly since the ORC can utilize the LNG cold energy and compression waste heat from the CAES system simultaneously. The proposed system can produce 29.8 MWh of electrical energy and 2.6 kg/s fresh water during peak hours. Also, results show that the value of CO_2 emission, exergetic round trip efficiency, and cost rate are 0.267 kg/kWh, 45.9 %, and 448.6 $/h.

1. Introduction

Global carbon emissions from fossil fuels have significantly increased since 1900 due to the huge amount of energy consumption in various industries (Bashiri Mousavi et al., 2022a). Energy transition from fossil fuel to sustainable and renewable energy is urgent, and the corresponding infrastructures should be built as soon as possible (Babaei et al., 2021). During energy transition, the most significant challenges include low efficiency, reliability, and economic concerns of the renewable energy systems. Solar and wind power plants have attracted much attention compared to other renewable energy sources because wind and solar energy are abundant, inexhaustible, and free (Bashiri Mousavi et al., 2022b). However, their unstable and unpredictable nature has limited their penetrations into the energy markets. On the other hand, there is a gap between the demand and supply of power plants and power distribution systems because of variations in energy demand at different times (Lashgari et al., 2022). In this regard, energy storage technologies become an effective way to reduce the gap between demand and supply.

There are different energy storage systems; however, the compressed air energy storage (CAES) systems have many advantages over other systems, including high power and energy capacity, long lifetime, rapid response time, and relatively low maintenance costs. The CAES system can be used for daily, weakly, and seasonally power storage (Yu et al., 2022).

Foley and Díaz Lobera (2013) investigated the effects of CAES on the power markets with an extensive portfolio of the renewable energy market. They concluded that a CAES power plant could successfully optimize the energy arbitrage opportunities, enhance electricity supplier income, and reduce the CO_2 emission. Alirahmi et al. (2021) have successfully achieved the simultaneous production of 226,782 m^3 fresh water and 27,551 MWh electrical energy in a year during consumption periods by integrating a CAES with a desalination unit.

Paper Received: 14 April 2022; Revised: 11 June 2022; Accepted: 20 June 2022
Please cite this article as: Alirahmi S.M., Gundersen T., Yu H., 2022, An Innovative Polygeneration System Integrating Compressed Air Energy Storage (CAES) and Multi-effect Desalination for Efficient LNG Cold Energy Utilization, Chemical Engineering Transactions, 94, 127-132 DOI:10.3303/CET2294021

Heat losses from turbines and compressors are significant in the CAES power plant. Consequently, waste heat recovery (WHR) plays a vital role in enhancing system efficiency. Organic Rankine cycle (ORC) is an effective technology to convert low and medium-temperature heat into power. The ORC has become a mature technology for waste heat recovery because of its moderate operational conditions, simple arrangement, low maintenance, and independent operation (Yu et al., 2016). On the other hand, the power output and efficiency of an ORC can be further increased by using a lower temperature heat sink such as liquified natural gas (LNG). Besides, the LNG gasification process is also done concurrently by using this method. In the conventional regasification process, the LNG enters an evaporator at -161 °C so that it can be vaporized into natural gas (NG) by seawater, and the high-quality LNG cold energy is destructed (Emadi et al., 2020). Therefore, many researchers have been working on the utilization of LNG as the heat sink for the ORC.

Zhang et al. (2016) have performed a thermoeconomic analysis of a hybrid system that integrates three ORCs and the LNG regasification process. Their results showed that this system can produce more electricity and has a lower total investment cost compared with the separated LNG and ORC systems. Yu et al. (2019) investigated the performance of ORCs operating below the ambient temperature for LNG cold energy utilization with 22 working fluids. R125, R143a, R290, and R1270 were the most energy-efficient working fluids. Ghaebi et al. (2018) have proposed a novel energy system based on geothermal as a heat source and LNG as a heat sink. It was found that the exergy efficiency and cost of the product of the proposed system were 18.52 % and 69.76 GJ/$.

Water and energy are crucial societal to sustain human life in the future. Desalination of seawater is a promising prospect to address water supply shortages. Among the various desalination methods, Multi-Effect Desalination unit with Thermal Vapor Compression (MED-TVC) is excellent option. Hybridizing desalination systems and CAES can provide a solution for handling both water and energy issues simultaneously.

The novelty of the proposed system can be highlighted by the integrated ORC system, which coupled LNG regasification process and the waste heat recovery process of the CAES system. Besides, the proposed system can not only produce multiple products, including electricity, fresh water, and cooling but also overcome the intermittency of solar and wind energy.

In this study, despite analysing the proposed system in terms of energy and exergy, economic relations are applied for system components to evaluate the total cost of the proposed system. Based on the proposed configuration, the problem of the highly fluctuating and periodic nature of renewable energies is solved, which can provide a base for further development and penetration of these resources into the energy markets.

2. Description of the proposed integrated system

The principle of a CAES is similar to a conventional gas turbine power plant, but the air is compressed by surplus electricity from renewable energy and stored during the off-peak hours. During peak hours, the compressed air is heated up and expanded through turbines to generate electricity. Since the air compression work is provided by surplus electricity from renewable energy, the CAES power plant has a much higher efficiency than conventional gas turbine power plants. A schematic of the proposed system is depicted in Figure 1. It should be noted that all settings of the proposed system are for 8 h charging and 4 h discharging periods.

During the charging process, the air is compressed by a compressor train. To reduce the exergy destruction, the compression heat is recovered and stored in a hot storage tank. Water is used both as the circulating medium to recover waste heat and as a heat source in the ORC system.

On the other side, LNG is pumped to the ORC condenser, where LNG is regasified (vaporized). After the regasification in the condenser, the temperature of the (partially) regasified LNG is still low. So, it is directed towards a cooling unit to produce cold water or other cooling fluids for domestic air conditioning. The gasification process is completed in this stage, and LNG is converted to NG. Due to the high pressure of NG, it can be expanded through a turbine to produce electricity. Eventually, a large part of NG is injected into the natural gas network after expansion, and a small part of the NG is burned in the CAES power plant.

During the discharge period, the recuperator recovers a portion of the high energy density exhaust gas. However, the exhaust gas still has a high heating value, so to improve system efficiency, the remaining heat is used as the heat source for a MED-TVC. Further information for analysing each element of the proposed system is available in Alirahmi et al. (2021).

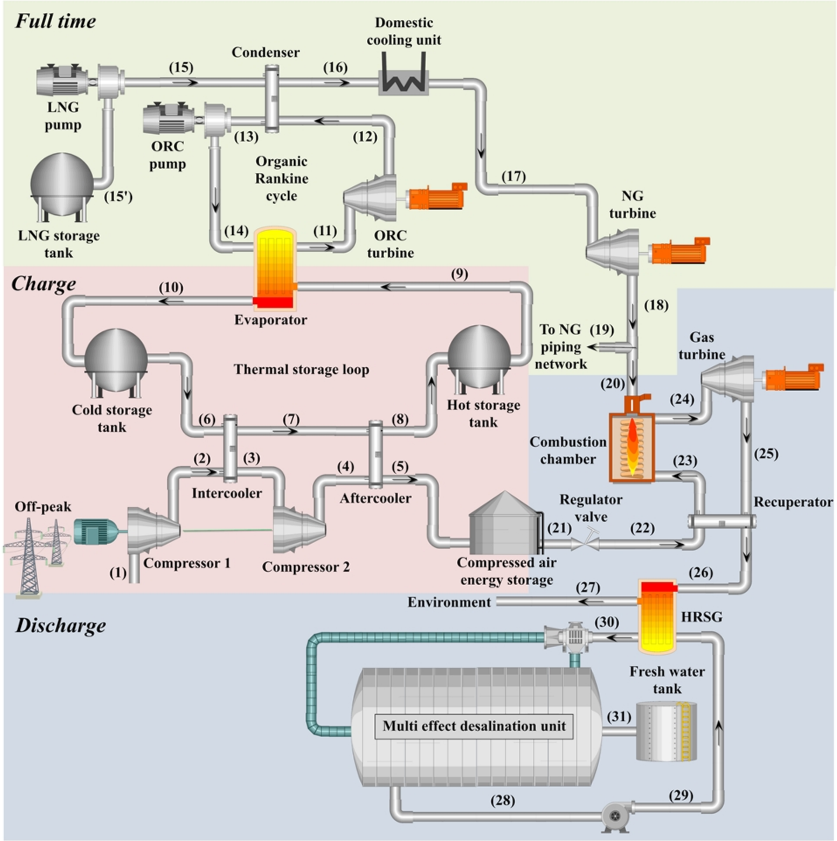

Figure 1: Schematic of the new hybrid system based on LNG-ORC-CAES-MED

3. System modeling and evaluation

Each component is considered a control volume to perform the thermodynamic analysis, and its energy and mass balance equations are evaluated. Matlab and Engineering Equation Solver (EES) software are used to simulate the integrated LNG-ORC-CAES-MED system. Due to space limitation of the paper, detailed equations to model each subsystem are not presented here. To reduce the complexity of the simulation, some assumptions must be taken into account before pointing out energy and exergy equations. The following assumptions are adopted in this study to simplify the modeling and simulation of the integrated system.

- Kinetic and potential energies and pressure drops in connecting pipelines and heat exchangers are negligible.
- All subsystems are in steady-state operation.
- Air is assumed to be a mixture of nitrogen and oxygen and is regarded as an ideal gas with no humidity.
- The fuel injected into the combustion chamber (CC) is NG.

Table 1 shows the assumed design conditions for a thermodynamic analysis of the LNG-ORC-CAES-MED system.

Table 1: Design values of the proposed system

Parameter	Value	Parameter	Value
Ambient pressure (kPa)	101.3	Inlet temperature of the gas turbine (°C)	1,050
Ambient temperature (°C)	25	Intercooler and aftercooler efficiency (-)	80 %
CC pressure drop (-)	3 %	LNG turbine inlet pressure (kPa)	6,500
Compressor isentropic efficiency (-)	86 %	MED-TVC number of effects (-)	6
Discharging mass flowrate of CAES (kg/s)	10	NG network pressure (kPa)	3,000
Gas turbine isentropic efficiency (-)	86 %	Outlet pressure of the CAES tank (kPa)	1,500
Inlet pressure to the CAES tank (kPa)	4,500	Pump isentropic efficiency (-)	85 %

3.1 Energy and exergy analysis

The energy balance for each control volume is as follows (Alirahmi et al., 2020):

$$\dot{Q}-\dot{W}=\sum_{out}\dot{m}h-\sum_{in}\dot{m}h \tag{1}$$

where $\dot{Q}$, $\dot{W}$, h, and $\dot{m}$, denote heat load, work, specific enthalpy, and mass flow rate. Subscripts “out” and “in” refer to outlets and inlets.

In order to calculate the exergy destruction rate ($\dot{E}x_D$), the exergy balance equation is applied to each component as follows:

$$\dot{E}x_{in}-\dot{E}x_{out}=\dot{E}x_D \tag{2}$$

here $\dot{E}x$ represents the exergy rate of a stream.

3.2 Economic analysis

To determine the financial profitability of the proposed LNG-ORC-CAES-MED system, an economic analysis is conducted. A crucial economic indicator is the investment cost rate, which also results in maintenance and operation of each component (Razmi et al., 2022).

$$\dot{Z}_k=\dot{Z}_k^{CI}+\dot{Z}_k^{OM} \tag{3}$$

Here, $\dot{Z}_k$ is the total investment of each component, and superscripts “OM” and “CI” denote the operating and maintenance expenditures and the capital investment. Finally, based on the sum of the total investment cost rate and the fuel cost, the economic indicator is as follows:

$$\dot{C}_{tot}=\sum_{k=1}^{n_k}\dot{Z}_k+\sum_{i=1}^{n_F}\dot{Z}_{F_i} \tag{4}$$

3.3 Environmental analysis

The CO_2 emission index is defined by Eq(5) as the ratio of CO_2 discharged into the atmosphere to the net output power:

$$\zeta_{CO_2}=\dot{m}_{CO_2}/\dot{W}_{net} \tag{5}$$

4. Results and discussions

Based on the design conditions, governing equations and assumptions, Table 2 shows the thermodynamic results of the hybrid LNG-ORC-CAES-MED system.

Table 2: Important results of the proposed LNG-ORC-CAES-MED system

Parameter	Symbol	Unit	Value
CO_2 emission	ζ_{CO_2}	kg/kWh	0.267
Cooling	$\dot{Q}_{cooling}$	MWh	22.3
Exergetic round trip efficiency	ERTE	%	45.9
Fresh water mass flow rate	$\dot{m}_{31}$	kg/s	2.6
Input power of LNG pump	$\dot{W}_{LNG,P}$	MWh	0.83
Input power of the compressors	$\dot{W}_{Comps}$	MWh	21.6
Output power of the gas turbine	$\dot{W}_{GT}$	MWh	29.8
Output power of the LNG turbine	$\dot{W}_{LNG,T}$	MWh	3.4
Output power of the ORC	$\dot{W}_{ORC}$	MWh	3.55
Total cost rate	$\dot{C}_{tot}$	\$/h	448.6

The maximum inlet pressure and pressure ratio of the CAES tank are two important indices for evaluating system performance. Figure 2 shows the analysis of design parameters in a contour form. This analysis provides valuable information about the effect of design parameters on the objective functions.

It is found that by increasing the pressure ratio between the CAES tank inlet and outlet, the pressure at state 22 in Figure 1, tank volume, and the turbine’s inlet pressure are reduced. In addition, by increasing the pressure ratio, the system’s produced power and total cost are decreased at constant power consumption. As a result, this would lead to a lower exergetic round trip efficiency (ERTE). Also, by increasing the pressure ratio, the CO_2 emission index increases, which is due to the reduction of the denominator of the fraction in Eq(5).

With an increase in the inlet pressure of the CAES tank, the output power of the gas turbine increases, which means the efficiency is enhanced and the CO_2 emission is reduced. According to Figure 2, there is a specific optimal value for efficiency at every pressure ratio. Also, by increasing the pressure, the capacities and sizes of the parts are increased, resulting in increased total cost rate.

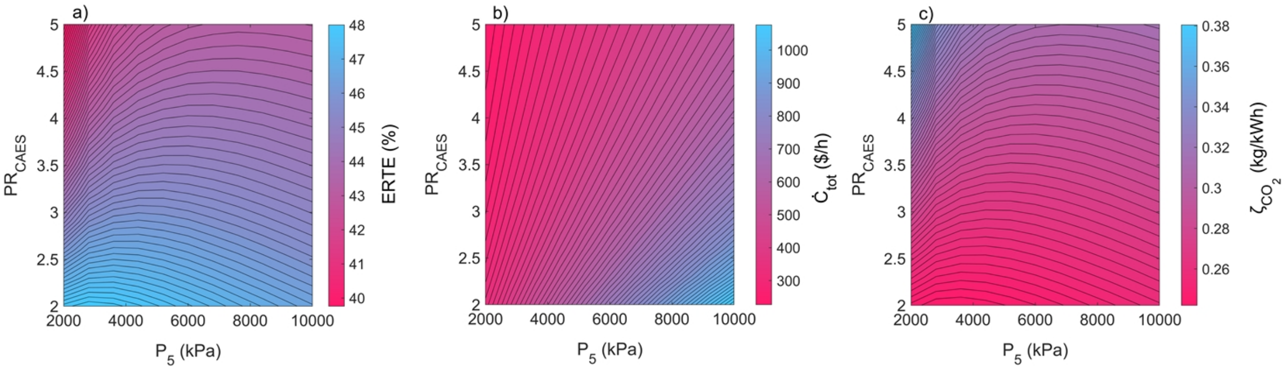

Figure 2: The effect of pressure ratio and maximum inlet pressure of the CAES tank on system performance

As for the MED system, Figure 3 shows the influence of the number of effects on the fresh water mass flow rate and cost rate. It can be seen that by increasing the number of effects, the water production is enhanced. The total thermal need of the MED is supplied in the first effect; besides, at constant thermal energy of the first effect, the fresh water mass flow rate is increased almost linearly by increasing the number of effects.

Also, the cost of the MED is increased with the higher number of effects. Also, the rate of the cost increases considerably beyond eight effects. It can be concluded that increasing the number of effects to produce more fresh water is not a good choice in terms of investment cost. However, the more the number of effects, the higher the annual profit and water production.

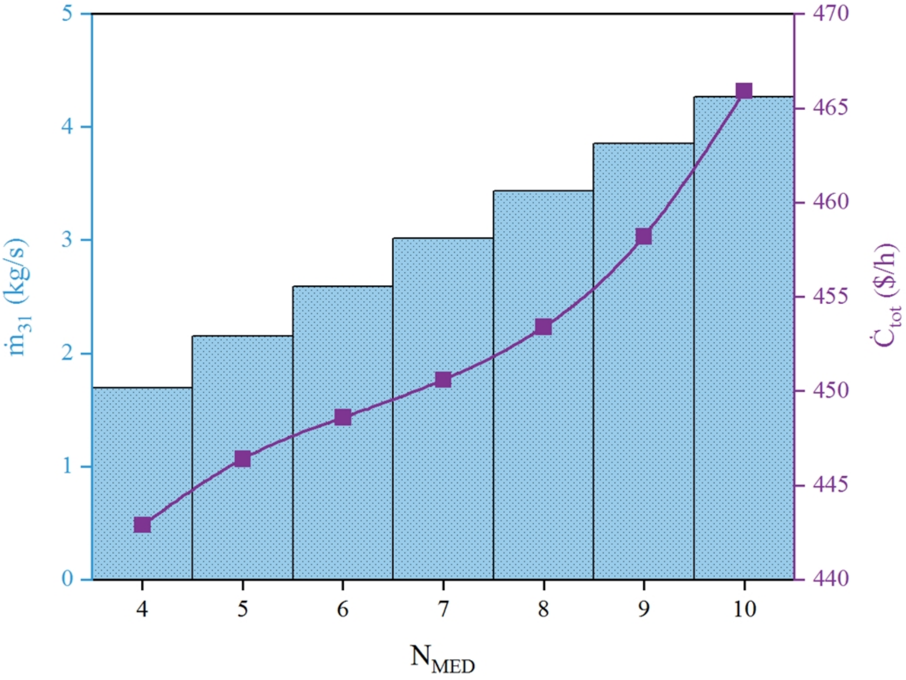

Figure 3: Impacts of the number of effects on fresh water mass flow rate and cost rate

5. Conclusions

In this study, the LNG-ORC-CAES-MED system was proposed and designed. The integrated energy system has three-fold benefits. Firstly, the waste heat from the compressed air energy storage (CAES) system is utilized efficiently, which can improve the energy efficiency of the CAES system. Secondly, the liquefied natural gas (LNG) cold energy is recovered to produce electricity in the ORC system and provide domestic cooling. Finally, the waste heat from the gas turbine is utilized in the multi-effect desalination (MED) unit to produce fresh water. The integrated system can be an energy-efficient and cost-effective technology at an industrial scale if optimization is performed in future work. The proposed system was analysed comprehensively in terms of energy, exergy, environmental impacts and economy (4E). The highlighted results are as follows:

- The proposed system consumes 21.6 MWh of grid electricity during the off-peak hours, while the integrated CAES system produces 29.8 MWh of electricity during peak hours. The thermodynamic analysis shows that the system exergy round trip efficiency (ERTE) is 45.9 %.
- The pressure ratio and inlet pressure of the CAES tank are the most important design parameters that significantly affect the objective functions.
- By increasing the number of MED effects from four to nine, the freshwater mass flow rate can be increased from 1.7 to 4.2 kg/s.

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