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Storage system for distributed-energy generation using liquid air combined with liquefied natural gas

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HIGHLIGHTS

- A storage-generation system using liquid air and liquefied natural gas is proposed.
- Round-trip and storage efficiencies of the system are 64.2% and 73.4% respectively.
- Exergy efficiencies of the storage and the system are 70.2% and 62.1% respectively.
- LCOE ranges from 142.5 to 190.0 $/MWh, depending on the sizes and the storage time.
- The proposed system is an economic option without geographical limitations.

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ABSTRACT

This study proposed a storage-generation system for a distributed-energy generation using liquid air combined with liquefied natural gas (LNG). The system comprised three main sites: the renewable-electricity sources (RESs), liquid-air energy storage (LAES), and natural-gas combustion. The low-priced off-peak electricity generated by the RESs was supplied to the LAES. The supplied electricity and previously stored cold energies liquefied the air. At the on-peak time, the liquid air and LNG were pressurized, re-gasified, and burnt immediately after mixing to generate the high-priced electricity while their cold energy was stored in thermal media. The proposed system was evaluated in terms of the thermodynamic, environmental, and economic performances. Its round-trip and storage efficiencies were 64.2% and 73.4%, respectively. The exergy efficiency of the storage-site, the generation-site, and the system was 70.2%, 75.1%, and 62.1%, respectively. The levelized cost of energy (LCOE) ranged from 142.5 to 190.0 $/MWh depending on the sizes and the storage time. The proposed system was compared to the diabatic compressed air-energy storage (CAES) systems and the adiabatic LAES system. The sensitivity analyses compared the systems for the fixed power output and storage time, and for the option to use natural gas. The proposed system showed better storage and round-trip efficiencies than those of comparison systems. Its LCOE was competitive with those of the compared systems except for the under-ground CAES system. The proposed system was an economic and viable option considering the geographical limitations and the environment impacts of the CAES system.

1. Introduction

Natural gas (NG) and renewable-energy sources (RESs) are rapidly emerging as solutions to the challenging climate-change problem. The supply and demand of natural gas are driven by the development of shale gas, which has recently been introduced. Moreover, natural gas can be converted into liquefied natural gas (LNG), and subsequently, transported to micro-grids using distributed-generation systems. The use of RESs is rapidly increasing because of the need to reduce greenhouse gas emissions. According to the U.S. Energy Information Administration (EIA), the total energy generated from RESs is annually increasing at a rate of 2.9%. In 2040, the electricity generated through RESs will account for 29% of the net electricity generation worldwide [1].

With the development of RESs, many challenges have been introduced in the conventional storage systems. Various RESs such as wind, solar, or geothermal power cannot be easily controlled; moreover, the output power is unpredictable. Accordingly, these sources are referred to as variable RESs. Energy-storage systems (ESSs) have played a significant role in alleviating many challenges. The roles of ESSs vary with the size, duration of storage, charge/discharge rates, and many other parameters. The representative functions of ESSs are time shifting

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Nomenclature

Scripts

T_{min}	minimum-approach temperature (°C)
η_{comp}	isentropic efficiency of compressor (%)
η_{turb}	isentropic efficiency of turbine (%)
η_{pump}	isentropic efficiency of cryogenic pump (%)
η_{RTE}	round-trip efficiency (–)
$\eta_{storage}$	energy-storage efficiency (–)
η_{CC}	combined cycle efficiency (–)
η_{ex}	exergy efficiency (–)
r_d	exergy destruction ratio (–)
h	storage time per day (hours)
e	inflation or escalation (%)
$E_{generation}$	amount of energy generation (MWh)
E_{charge}	amount of energy charged (MWh)
E_{fuel}	amount of energy fueled (MWh)
$E_{renewable}$	amount of energy based on renewable (or grid) (MWh)
γ_{RES}	renewable (or grid) energy-source penetration ratio (–)
$\dot{Ex}$	exergy flow of a stream (kW)
$\dot{ex}$	molar exergy flow of a stream (kJ/kg)
x	molar fraction (–)
$\dot{n}$	molar flow (kg mole/s)
th	thermal (–)
i	ith component (–)
o	reference state (–)
	work flow (kW)
T	temperature (K)
P	pressure (bar)
h	molar enthalpy (kJ/kg mole)
s	molar entropy (kJ/kg mole K)

Abbreviation

BOP	balance of plant (–)
CAES	compressed air-energy storage (–)
CH	chemical (–)
CR	CO_2 ratio (ton/kWh)
CRF	capital recovery factor (–)
EC	electricity cost ($/MWh)
ER	energy ratio (kWh_{in}/kWh_{out})
ESPWF	escalating series present worth factor (–)
ESS	energy storage system (–)
FC	fuel cost ($\$/kWh_{th}$)
FOM	fixed operating and maintenance ($/kW yr.)
HR	heat rate (kWh_{th}/kWh_{out})
HX	heat exchanger (–)
KN	kinetic (–)
LAES	liquid-air energy storage (–)
LCOC	levelized cost of capacity ($/kW yr.)
LCOE	levelized cost of energy ($/MWh)
LNG	liquefied natural gas (–)
NA	not applicable (–)
NG	natural gas (–)
O&M	operating and maintenance (–)
PH	physical (–)
PHES	pumped hydro-energy storage (–)
PT	potential (–)
RES	renewable-energy source (–)
SW	sea water (–)
TIT	turbine inlet temperature (°C)
TPC	total plant cost ($)
VOM	variable operating and maintenance ($/MWh)
WACC	weighted average cost of capital (%)

in terms of arbitrage (annual, seasonal, weekly, or daily smoothing of loads), improving energy security, and smooth wind/solar power and control of voltage and frequency [2].

Various types of ESSs have been presented and analyzed. They are either well developed, demonstrated, or in a conceptual stage, including hydro energy, hydrogen, biomass, compressed/liquefied air, flywheel, and superconducting magnetic-energy storage. The surplus energy generated by the RESs or grid is converted into electrical, gravitational, mechanical, thermomechanical, chemical, or two or more integrated forms of energies [3–6]. The RESs, ESSs, and micro-grids should be developed holistically because they are closely related to each other.

The pumped hydro-energy systems (PHESs) are most widely used to store energy. This technology accounts for 99% of the bulk storage systems used worldwide [7]. The PHESs are of three types: closed-loop, semi-open, and open systems. In these systems, natural reservoirs or mountains are utilized to create a system of the required capacity. Thus, the systems have geographical limitations. Furthermore, these technologies require long development-time frames, large-scale civil projects; and may have a significant impact on the environment in terms of soil, biodiversity, and water quality [8,9]. Generally, these disadvantages are neglected while performing the cost analysis.

The compressed air-energy storage (CAES) is the second-most developed technology after the PHES. The CAES can be categorized into three types depending on the heat sources and processes: diabatic, adiabatic, and isothermal [10]. The diabatic-type CAES is a hybrid electricity generation and storage technology. In this system, the heat generated by compressing the air is released to the ambient atmosphere, which generates irreversibility. In the adiabatic-type CAES system, the heat released from the system is negligible because the compressed heat is recovered before the expansion process. The adiabatic CAES does not use fossil fuels and combustion. In addition, the heat generated in the compression process is minimized in the isothermal-type CAES. In the isothermal-type CAES, a pump–turbine system is used wherein a hydraulic oil is employed to compress the air [11]. The compressed air is stored in a steel pressure vessel for above-ground storage, or in a salt cavern (large scale) for below-ground storage. Moreover, the salt caverns are manufactured by employing natural resources, which may raise environmental concerns.

The liquid–air energy storage (LAES) systems are quite similar to the CAES technology, except for the thermal and cryogenic energy storage. The density of liquid air is 80 times higher than that of compressed air, which is stored at 80 bar [12]. In addition, the LAES is irreplaceable for bulk energy storage and can be arbitraged in situations where geographical conditions limit the PHES and CAES technologies [6]. In addition to these advantages, liquid air can be transported to other energy-demand grids. Hence, bulk LAES systems have great potential and opportunity to play a significant role in distributed energy and micro-grids systems [13].

Many researchers have studied in LAES systems. Kishimoto et al. proposed the first-generation LAES system [14]. Chino and Araki improved the LAES system using a regenerator and a conventional combined-cycle power plant [12]. Many thermodynamic analyses have been conducted on various configured LAES systems. Guizzi et al. conducted a thermodynamic analysis of a stand-alone LAES system [15]. Ameel et al. investigated an LAES system combined with a Rankine cycle and improved the efficiencies from those obtained via a simple Rankine cycle [16]. Sciacovelli et al. analyzed an LAES system with packed bed through dynamic modelling and the round-trip efficiency of the plant reached 50% [17]. Morgan et al. demonstrated the first pilot-scale plant by employing the conventional Claude cycle process [18]. Antonelli et al. proposed several processes that utilized