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Full Length Article

Technical performance analysis and economic evaluation of a compressed air energy storage system integrated with an organic Rankine cycle

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ABSTRACT

Energy storage becomes increasingly important in balancing electricity supply and demand due to the rise of intermittent power generation from renewable sources. The compressed air energy storage (CAES) system as one of the large scale (> 100 MW) energy storage technologies has been commercially deployed in Germany and the USA. However, the efficiency of current commercial CAES plants still needs to be improved. In this study, an integrated system consisting of a CAES system and an organic Rankine cycle (ORC) was proposed to recover the waste heat from intercoolers and aftercooler in the charging process and exhaust stream of the recuperator in discharging process of the CAES system. Steady state process models of the CAES system and ORC were developed in Aspen Plus®. These models were validated using data from the literature and the results appear in a good agreement. Process analysis was carried out using the validated models regarding the impact of different organic working fluids (R123, R134a, R152a, R245fa, R600a) of ORC and expander inlet pressures of the ORC on system performance. It was found that integrating ORC with the CAES system as well as selecting appropriate working fluid was a reasonable approach for improving performance of the CAES system. The round-trip efficiency was improved by 3.32–3.95% using five working fluids, compared to that of the CAES system without ORC. Economic evaluation on levelized cost of electricity (LCOE) was performed using Aspen Process Economic Analyser® (APEA). Different working fluids in ORC and different power sources (e.g. wind and solar) associated with the integrated system were considered to estimate the LCOEs. It was found that the LCOEs for the integrated system were competitive with fossil-fuel fired power and even lower than offshore wind power and solar power. The proposed research presented in this paper hopes to shed light on how to improve efficiency and reduce cost when implementing CAES.

1. Introduction

1.1. Background

With the increase in global electrical energy demand, the annual amount of electricity generation reached more than 22,000 TWh in 2012. Power generation from fossil fuels contributes to approximately 70% worldwide electricity energy supply [1,2]. As a result, massive CO_2 emission released to the atmosphere has led to the problem of greenhouse effect [3]. To reduce the CO_2 emission and also the dependence on fossil fuels, renewable energies have been considered as alternative sources such as solar, wind and tide power [1,4]. However, the majority of renewable energies have a common problem of intermittence, which brings a great challenge to ensure the stability and reliability of the electricity grid [2,4,5]. Electrical energy storage as one of the most promising methods to address the problem has become increasingly important in balancing supply and demand of electricity [4,6].

Electrical energy storage refers to a process of transforming energy from electrical energy into a form which can be stored and converted back into electrical energy when needed [2,7]. Many energy storage technologies have been developed such as pumped hydroelectric storage (PHS), compressed air energy storage (CAES), batteries, fuel cells, superconducting magnetic energy systems, flywheel, capacitors and supercapacitors [2,4–9]. Presently, only PHS and CAES technologies can be applied in large (e.g. grid) scale (> 100 MW) application. The PHS technology is mature and has been implemented widely [2,4,10,11]. Nevertheless, geographical constrains for PHS plants requiring two large reservoirs at different elevations limit its commercial deployment [7,9,12,13]. Thus, CAES technology could become an attractive alternative for large or grid scale energy storage.

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Nomenclature

W_t	output power of Turbine (kWh)
W_e	electrical energy taken from grid for driving the compressors (kWh)
E_f	thermal energy of fuel consumed (kWh)
η_{sys}	system electric efficiency
$\eta_{eff\,1}$	round-trip efficiency of the CAES system
$\eta_{eff\,2}$	round-trip efficiency of the CAES system with system electric efficiency
$W_{ORC\,1}$	power output of ORC during charging period of the CAES system (kWh)
$W_{ORC\,2}$	power output of ORC during discharging period (kWh)
W_{p1}	power consumption of ORC pump during charging period (kWh)
W_{p2}	power consumption of ORC pump during discharging period (kWh)
$\eta_{CAES+ORC}$	round-trip efficiency of the integrated system based on reducing the electricity taken from grid
$\eta'_{CAES+ORC}$	round-trip efficiency of the integrated system based on the round-trip efficiency of the CAES system
P_{EIP}	ORC expander inlet pressure (bar)
E_{output}	net power output annually of the integrated system
CAES	compressed air energy storage
ORC	organic Rankine cycle
LCOE	levelized cost of electricity
PHS	pumped hydroelectric storage
LPC	low pressure compressor
HPC	high pressure compressor
LPT	low pressure turbine
HPT	high pressure turbine
V	valve
TAC	total annual cost
ACAPEX	annualised capital expenditure
FOPEX	fixed operation expenditure
VOPEX	variable operational expenditure
CRF	capital recovery factor
CAPEX	capital expenditure
n	CAES plant life time
i	discount rate

1.2. Literature review

CAES technology began to be attractive by the mid-1970s [14]. The CAES system can be implemented at different scales of capacities. The advantages of large-scale CAES systems integrated with the grid network include peak shaving, load shifting, frequency and voltage control [10,11]. CAES plants also can be integrated with intermittent renewable energy, such as wind and solar power, to smooth the output power [10]. In addition, Bouman presented that the environmental impacts of CAES plants are lower than that of natural gas power plants [15]. However, the major constraints of the CAES system are the geographical requirement of the proper cavern and combustion of fossil fuel in the discharging process [7,10].

The Huntorf CAES plant in Germany, as the first commercial plant in the world, has been operated since 1978 [11,16]. The Huntorf CAES plant has 290 MW output power for ∼2-h discharging duration. Compressed air is stored in two caverns (with total volume around 310,000 m^3) with about 43–70 bar operating pressure and a depth of around 600 m [7,17,18]. It is reported that the Huntorf CAES plant has operated with remarkable performance with ∼90% availability and ∼99% starting reliability [7,10]. The round-trip efficiency of the plant is around 42% [10,19]. The second CAES plant has been operated since 1991 in McIntosh, Alabama, USA. The McIntosh CAES plant can generate 110 MW output power for around 26-h discharging duration. The storage capacity of the cavern is over 500,000 m^3 with operating pressure of 45–74 bar and a depth of around 450 m [7,10,18]. Comparing the two commercial CAES plants, the major improvement of the McIntosh CAES plant is the use of a recuperator to recover waste heat from turbine exhaust to preheat compressed air, which can increase round-trip efficiency from 42% to 54% and also reduce fuel consumption by 22–25% [10]. In 2016, a 10 MW advanced CAES system was implemented by the Energy Storage R & D Centre, Chinese Academy of Science in Bijie, Guizhou Province, China [20]. The aim of this project is scientific research and demonstration. The main components of the demonstration plant include wide-load compressor, high-load turbine and heat exchangers [20].

The round-trip efficiencies of current commercial plants are still insufficient and need to be improved. As for the further development of CAES technology, adiabatic CAES (A-CAES) technology was initiated in 2003 [14]. A-CAES aims for around 70% round-trip efficiency of A-CAES [10,14]. The strength of A-CAES technology can be high round-trip efficiency and emission-free (no fuels used in the discharging process); thermal energy storage (TES) is implemented for storing the heat from the charging process and reusing it during the discharging process in A-CAES system [14,21,22]. However, the technical cases and commercialised A-CAES plants about specific operating conditions have not been deployed so far; because the major challenges are the complex system engineering and adiabatic compressor combined with high-temperature TES, special materials could be required to overcome the thermal and mechanical stress [14,21,22]. Currently, some CAES systems are under research and development such as Norton 2,700 MW (3 × 900 MW) CAES project [7,14], Iowa 270 MW CAES project [23], Texas 317 MW CAES project [14], UK Larne 330 MW (2 × 165 MW) CAES project [14,24]. Some studies investigated process performance, components and the integrated system of the CAES system using different simulation tools such as CFD (computational fluid dynamics) [25–28], Aspen Plus [29,30], Matlab/Simulink [31–35]. In the literatures, the approaches used to improve round-trip efficiencies of CAES systems emphasise the waste heat recovery from compressors in charging process and turbine in discharging process of the CAES system. A detailed process description of the CAES system is given in Section 2.1.

Organic Rankine Cycle (ORC) has beneficial impacts on the energy efficiency through waste heat recovery [34,36]. Integrating an ORC with a system to convert waste heat into electrical energy could enable this system to achieve better performance [34,37–39]. The major advantages of the ORC include low mechanical stress, high efficiency of turbine, low operation cost and long plant life [40]. Also, Liu et al. investigated that the payback time of some pollutant gases CO_2, CH_4 and NO_x in the ORC for waste heat recovery life cycle can be shorter, compared with the grid emission of other five types of power generation modes [41]. ORC technology has been investigated since the 1880s, it could be implemented to recover low grade energy from different power systems, such as industrial waste heat solar energy, biomass, geothermal energy, fuel cells and ocean thermal energy [34,36,42–45]. ORC application with 0.2–2 MW output power has been validated in several industrial plants installed in the USA, Germany, Italy, Netherlands, Austria and Sweden [36,42]. Several commercial ORC projects have been established in the world with the power output range from kW to 10 MW using different working fluids and operating temperatures [36,46]. The selection of appropriate working fluids in ORC is crucial because it can have significant effects on the system performance [42]. A number of studies has reported that the selection of working fluids of ORC depends on the heat recovery applications and multiple criteria, such as low-toxicity, low-flammability, high flash