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Conventional and advanced exergy analyses of an underwater compressed air energy storage system

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HIGHLIGHTS

- Advanced exergy analysis is conducted on UWCAES for the first time.
- Detailed exergy destruction information is delineated.
- The analysis shows that UWCAES has great potential for performance improvement.
- The interactions among the components are found to be weak but interwoven.
- The advanced exergy analysis presents different and more pragmatic results.

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ABSTRACT

A 2 MW underwater compressed air energy storage (UWCAES) system is studied using both conventional and advanced exergy analyses. The exergy efficiency of the proposed UWCAES system is found to be 53.6% under the real conditions. While the theoretical maximum under the unavoidable condition is 84.3%; showing a great potential for performance improvement. Even though there are quantitative differences between conventional and advanced results, both show that the final compressor stage has the highest potential for improvement. The advanced exergy analysis reveals the real improvement potential of the UWCAES system. Further, it is revealed that the interactions between system components are complex but not very strong. Subsequently, the total exergy efficiency may not necessarily increase by improving the performance of the components individually.

1. Introduction

Today, energy storage technologies play an important role in distributed energy systems, smart grids, and renewable energy systems [1,2]. A flexible, scaleable energy storage technology, underwater compressed air energy storage (UWCAES) has been rapidly developing in recent years [3]. By taking advantage of the hydrostatic pressure in deep water, UWCAES can achieve isobaric compressed air storage, thereby mitigating many deficiencies of conventional isochoric compressed air energy storage systems [4–8]. Firstly, the isobaric storage system can operate essentially at rated steady state within the designed optimum performance envelope, thereby achieving higher efficiency than isochoric storage system under the identical conditions. Secondly, less storage volume is required in the isobaric storage system for the amount of electricity generation. UWCAES is a promising energy storage technology which can be utilized in coastal cities, islands, and offshore platforms where deep water is available. The world's first utility-scale underwater compressed air energy storage system located in Lake Ontario was realized by Hydrostor Corp. at the end of 2015 [9]. Brayton Energy LLC. is also developing a pilot UWCAES system on the Hawaiian Islands [10]. Other companies with plans to develop UWCAES systems include Lightsail Energy and Moffatt & Nichol, Arothron, and Bright Energy Storage Technologies. In terms of theoretical research, Cheung et al. [4,11] designed and analyzed a UWCAES system using conventional exergy-based methods, performed a sensitivity analysis, and subsequent optimization via genetic algorithm. The results showed that the pipe diameter, turbine, air compressor and air storage depth had the greatest influence on the system performance. The improvement priority was recommended to be given to turbo-

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Nomenclature

a	the total pressure recovery coefficient
A	the cross sectional wall area of heat transfer (m^2)
c_p	the specific heat at constant pressure ($J/(kg \cdot K)$)
d	the diameter of pipelines (m)
E	the energy (J)
e_x	the specific exergy (J/kg)
E_x	the total exergy (J)
g	acceleration of gravity (m/s^2)
h	the specific enthalpy (J/kg)
H	the enthalpy of fluids (J)
k	the total heat transfer coefficient of the insulating materials ($W/(m^2 \cdot K)$)
L	the length of pipelines (m)
$\dot{m}$	the mass flow rate (kg/s)
p	the pressure (Pa)
Q	heat (J)
R_g	the gas constant ($J/(kg \cdot K)$)
s	the specific entropy ($J/(kg \cdot K)$)
T	temperature (K)
W	work (J)
x	the relative exergy destruction
y	the exergy destruction ratio
z	the underwater depth of the air accumulators (m)

Greek letters

γ	the specific heat ratio
β_{exp}	the pressure ratio of expanders
η	the exergy efficiency (%)
η_M	the mechanical efficiency of pumps (%)
Ω	the effectiveness of the heat exchanger
ξ	the pressure loss ratio
μ	the heat loss ratio
ω	the air leak ratio of air accumulators
λ	the friction factor
φ	the local loss coefficient
ρ	the density (kg/m^3)
v	the mean velocity of the fluid (m/s)
ε	the exergy efficiency (%)

subscripts

0	the reference state
actual, comp	the actual process of the compressor
actual, exp	the actual process of the expander
atm	the atmosphere state
D	destruction
f	the final state of working fluids
f, actual	the final state of an actual process
f, isen	the final state of an isentropic process
F	fuel
i	the inlet state of working fluids
isen, comp	the isentropic process of the compressor
isen, exp	the isentropic process of the expander
K	the K-th component
P	product
RU	the value under real condition minus the value of unavoidable condition
sys	system
TES	thermal energy storage

superscripts

AV	avoidable
CH	chemical
EN	endogenous
EX	exogenous
KN	kinetic
PH	physical
PT	potential
Real	the real condition
UN	unavoidable
Unavoidable	the unavoidable condition

expanders and air compressors, and then to the heat recovery portion. Fiaschi et al. [12] proposed a versatile system for offshore renewable energy conversion including UWCAES, thermal energy storage, and battery pack electricity storage. It was determined that the thermodynamic efficiency of the versatile system could only reach a yearly average of 47.6% because of the fluctuating energy supply. In order to improve the efficiency of the UWCAES system when handling fluctuating energy supply and demand, Wang et al. [13] proposed a multi-level UWCAES system and evaluated the round-trip efficiency based on a conventional exergy analysis. The results showed that the exergy efficiency of the multi-level UWCAES system varied from 62% to 81% in different working modes. Vasel-Be-Hagh et al. [14] proposed a hybrid system of UWCAES and VIVACE (Vortex Induced Vibration Aquatic Clean Energy) converter to improve the efficiency of conventional UWCAES systems. Other research about UWCAES can be found in [3,6,7,15–17]. Improving energy efficiency has become a critical issue in all energy-related domains [18–21], and the UWCAES system is no exception. Thus, it is important to understand the distribution of exergy destruction and the improvement potential of the system.

In recent years, exergy-based analyses have been utilized widely. Compared to the first law energy analysis, exergy-based analyses take both the quantity and quality of energy into consideration. Consequently, the results from exergy-based analyses can be more insightful and reliable [22–26]. Conventional exergy-based analyses can quantify the exergy destruction of an energy system; however, it cannot uncover the real improvement potential because the unavoidable exergy destruction caused by technical and economic limitations is not considered. Furthermore, conventional exergy analyses do not provide information about the interactions between components within a system. Thus, advanced exergy-based analyses are proposed to overcome the deficiencies of conventional exergy-based analyses by splitting exergy destruction into avoidable, unavoidable, endogenous, and exogenous. The idea of splitting the exergy destruction into endogenous/exogenous parts was first proposed by Tsatsaronis for exploring the interactions between components [27]. And then Tsatsaronis and Moung-Ho defined the avoidable/unavoidable exergy destruction concepts by considering the unavoidable limitations of technologies and economy [28]. Today, these basic concepts in advanced exergy analysis have been extended to advanced exergoeconomic analysis and exergoenvironmental analysis [29–31]. More recently, Fallah et al. [32] analyzed a Kalina cycle applied for low temperature enhanced geothermal applications using both conventional and advanced exergy analyses. The results of advanced exergy analysis showed that the improvement priority should be given to the condenser, and then to the turbine, followed by the evaporator; while the results of conventional exergy analysis revealed that the exergy destruction of the evaporator was