Energy Proceedings
Vol 37, 2023
ISSN 2004-2965

The economic performance of a compressed CO_2 energy storage system for load shifting

Qingxi Huang[1], Biao Feng[2], Jun Gao[2], Miaoxun Zhou[2], Cuiping Ma[1*], Qie Sun[1,3*]

1 Institute for Advanced Technology, Shandong University, Jinan 250061, China

2 PowerChina HuaDong Engineering Corporation Limited, Hangzhou 311122, China
3 Institute of Thermal Science and Technology, Shandong University, Jinan 250061, China
(*Corresponding Author: Cuiping Ma, Email: macp@sdu.edu.cn; Qie Sun, E-mail: qie@sdu.edu.cn)

ABSTRACT

With the features of large-scale and long-term energy storage, compressed CO_2 energy storage (CCES) represents an efficient way to achieve load shifting and reduce fluctuations of electricity load. Therefore, the economic performance of a CCES system for load shifting was assessed in this paper. The two optimization modes, i.e., single-objective and multi-objective optimization, were proposed to determine the CCES operation. The reduction of load variance is the sole objective of single-objective optimization. In the case of multi-objective optimization, the objective is to maximize CCES system income while minimizing load variation. According to the simulation findings, the load variance can be decreased from its original value of 8725.4 to 678.5 in the single-optimization outcome, and the CCES system can generate an income of 49.6 kUSD. The Pareto optimality in the multi-objective optimization demonstrates a negative correlation between the variation of the load and the income of the CCES system.

Keywords: Compressed carbon dioxide energy storage; load shifting; multi-objective optimization; mixed inter linear programming

NONMENCLATURE

Abbreviations	
CCES	Compressed carbon dioxide energy storage system
LPT	Low-pressure gas tank
HPT	High-pressure gas tank
Symbols	
t	Scheduling time

1. INTRODUCTION

The intermittent and erratic nature of renewable energy will result in grid instability when there is a substantial penetration of renewable energy in the electricity system [1]. The output of renewable energy sources can be smoothed using an energy storage device to improve the stability of the electricity grid [2, 3]. The compressed CO_2 energy storage (CCES) is a novel and promising energy storage technology because of the advantages listed below. On the one hand, CO_2 is easier to condense to liquid since it has a higher dew point [4]. As a result, the pump can be utilized to compress CO_2 into greater pressure rather than a compressor, saving some electricity energy throughout the charging process [5]. On the other hand, the CCES system can offer the potential for extensive CO_2 usage, which is conducive to reducing CO_2 emissions.

The energy storage system can be used to reduce the valley-peak difference of the load in the electricity grid, which will smooth out the load and provide a solution for the investment in electricity transition and distribution lines during peak demand [6]. Both grid operators and users profit from the load shifting. The advantages for grid operators include raising facility utilization rates, delaying facility upgrades, and saving money on renewal costs. The electricity price difference between peak and valley can be used by users to conduct energy arbitrage [7].

The use of energy storage technologies, such as battery energy storage, to shift load has lately been the subject of several research. The battery's quick charging and discharging characteristics provide excellent load fluctuation management. Han et al. [8] selected the type of battery and optimized capacity of the batteries using

This is a paper for the international conference on energy, ecology and environment 2023 (ICEEE2023), Aug. 14-18, 2023, London, UK.

the cooperative game model to maximize the performance of the load-shifting. David Parra et al. [9] also optimize the size of the battery to maximize the equivale full cycles and the RTE as well as performing load shifting. The load shifting can be achieved with battery, but its large-scale commercialization is constrained by their life span, the specific application scenarios, and the application scale.

This study implements load shifting using the CCES system, which is inspired by the concept of load shifting with energy storage. The mechanical energy storage category includes the CCES system, which has the benefit of a long lifespan and greater installation capacity. Meanwhile, the CCES system can be located in the transmission to provide the service according to the grid needs [10]. As a result, the CCES system is perfectly suited to the load shifting and can potentially achieve a better techno-economic outlook.

Therefore, this paper aims to evaluate the performance of the CCES system for load shifting. For this purpose, this paper developed single-objective and multi-objective optimization to decide the operation strategy of the CCES system. Deeper understanding of the CCES system's applicability will be provided by the results.

2. PROBLEM FORMULATION

2.1 Single -objective optimization

In order to avoid repeatedly starting and stopping conventional generators and to decrease the spinning reserve's capacity, grid operators anticipate that the load will be as flat as feasible. The load's variance can be used to indicate the load's volatility. Therefore, the objective function of the single-objective optimization is shown in Eq. (1) [7].

$$minimize\ \sigma_D^2 = \frac{\sum_{t=1}^{N}(D^t - \overline{D})^2}{N} \quad (1)$$

Subjected to:

$$v_c^t + v_d^t \leq 1 \quad (2)$$

$$v_c^t \in \{0,1\} \quad (3)$$

$$v_d^t \in \{0,1\} \quad (4)$$

$$W_{Expa,min} \leq W_{Expa}^t \leq W_{Expa,max} \quad (5)$$

$$W_{Comp,min} \leq W_{Comp}^t \leq W_{Comp,max} \quad (6)$$

where the D^t is the load; the $\overline{D}$ is the average value of the load; the v_c^t and v_d^t are the unit state indicators for charging ang discharging modes respectively; the $W_{Expa,min}$ and $W_{Expa,max}$ are the minimum and maximum electric capacity of the expander; the $W_{Comp,min}$ and $W_{Comp,max}$ are the minimum and maximum electric capacity of the compressor; the superscript t denotes the scheduling time; N is sample number, and the Eq. (1) denotes that the CCES system can only perform one operation mode from charging, discharging, and idle modes.

2.2 Multi-objective optimization

The grid operators anticipate a load that is as flat as feasible, while the users are interested in increasing their profit. In order to serve the needs of both the grid operator and the users, a multi-objective optimization should be used. Eq. (7) illustrates the multi-objective function.

$$F = (\max profit, \min \sigma_D^2) \quad (7)$$

where the profit presents the income of the CCES system, which is shown in Eq. (8).

$$profit = \sum_{i=1}^{N}\left(v_d^t W_{Expa}^t p^t - v_c^t W_{Comp}^t p^t\right) \quad (8)$$

The restrictions for single-objective optimization and multi-objective optimization are identical.

2.3 Solving method

The optimization problem is a Mixed Inter Linear Programming (MILP) problem, which can be solved by conventional solvers efficiently. This paper uses the optimizer of Gurobi to solve he MILP problem.

2.4 Key performance indicator

The key performance indicators (KPIs) used to assess the performance of the CCES system for load-shifting include variance and income.

The degree to which a stochastic variable deviate from its mean value is reflected in its variance, and the variance of load data thus represents the demand curve's flatness. The variance is calculated as Eq. (9).

$$\sigma_D^2 = \frac{\sum(D(t) - \overline{D})^2}{N} \quad (9)$$

The income of the CCES system includes two parts: the energy arbitrage from electricity price difference between peak and valley, and the coal consumption reduction in thermal power plants due to load shifting. The energy arbitrage is reordered as direct income, which is shown as Eq. (10).

$$Inc_{dir} = \sum_{t=1}^{N}\left(W_{Expa}^t p^t - W_{Comp}^t p^t\right) \quad (10)$$

The coal consumption reduction is recorded as indirect income, which is shown as Eq. (11) and (12).

$$K = k_0 + k_1 W_{Expa} + k_2 W_{Expa}^2 \quad (11)$$

$$CCR = K W_{Expa} t_d \quad (12)$$

where K is specific coal consumption; and k_0, k_1 and k_2 are coefficient, and their value are 335, -0.1081, and 0.0049 respectively [11].

3. CASE STUDY

A particular whole-day demand curve [12], as illustrated in Fig. 1, is taken into consideration as the load shifting case study in order to assess the CCES system's performance for load shifting. The variance of the load is 8725.4.

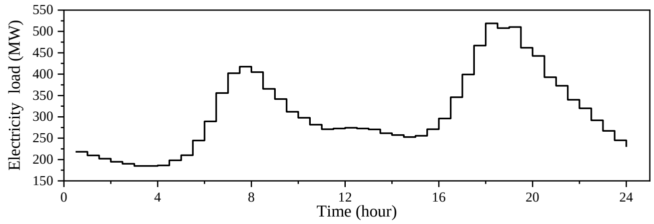

Fig. 1 The electricity load for the case study [12]

The electricity price can be considered the most effective element to encourage the participant to load shift [13]. The electricity price used in the paper is shown in Fig. 2.

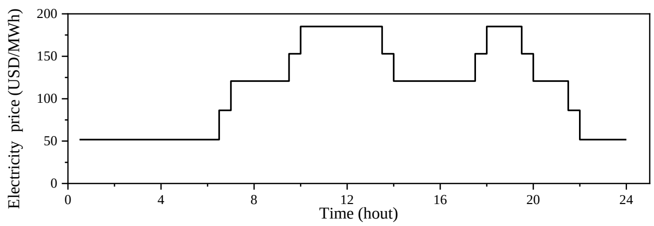

Fig. 2 The electricity price for case study [14]

The schematic of the CCES system used in the study is shown in Fig. 3, which consists of the low-pressure gas tank (LPT), compressor (Comp), expander (Expa), high-pressure gas tank (HPT), intercooler (IC), and heater (HT).

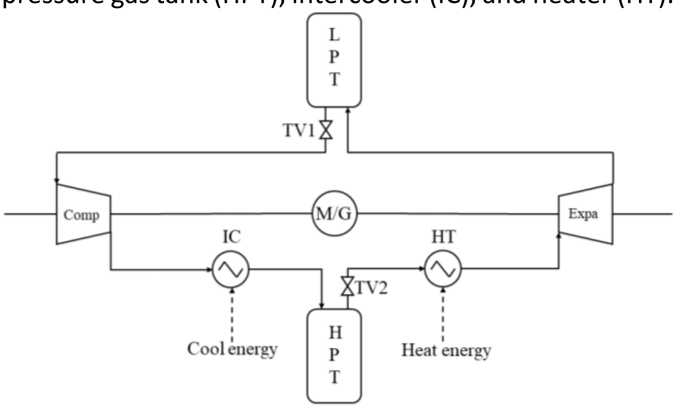

Fig. 3 The schematic of the CCES system

Table 1 provides a summary of the CCES system's comprehensive data. Based on our previous dynamic simulation [15], The range of charging capacity is from 57 MW to 110 MW. The range of discharging capacity is from 30 MW to 120 MW. The energy storage capacity of the CCES system is 147 MWh.

Table 1 the main parameters of the CCES system

Parameters	Value
Rated isentropic efficiency of compressor (%)	89
Rated isentropic efficiency of expander (%)	88
The volume of high-pressure gas tank (m^3)	7600
The volume of low-pressure gas tank (m^3)	36 000 00
The initial pressure of low-pressure gas tank (MPa)	1.0
The initial pressure of high-pressure gas tank (MPa)	2.3

4. RESULTS AND DISCUSSION

4.1 Result of single optimization result

Fig. 4 (a) shows the electric capacity of the CCES system (negative value represents the charging capacity, and positive value presents the discharging capacity), and Fig. 4 (b) shows the original and hybrid electricity demand.

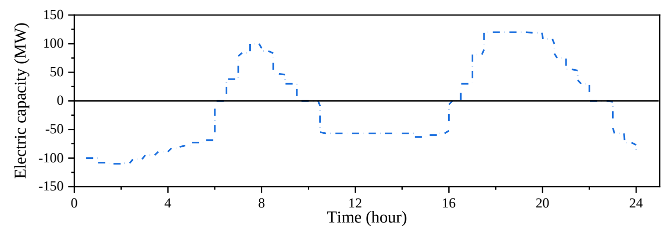

Fig. 4 (a) The electric capacity of the CCES system

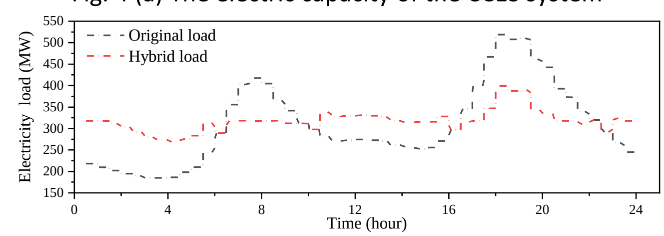

Fig. 4 (b) The original and hybrid electricity load

Fig. 4 The electric capacity of the CCES system and electricity load

In order to reduce the load curve's volatility, the CCES system performs two cycles of charging and discharging, as illustrated in Fig. 4(a). The CCES system charges at its lowest electric capacity during the valley period, which is 110 MW, and discharges at its highest capacity, 120 MW, during the peak period. The load's variance falls to 678.5 after it is shifted using the CCES system, which is lower by 92.2% than the variance of the original load. The CCES system, meanwhile, can generate an income of 49.6 kUSD.

4.2 Result of multi-objective optimization

Fig. 5 shows the Pareto optimality in multi-objective optimization.

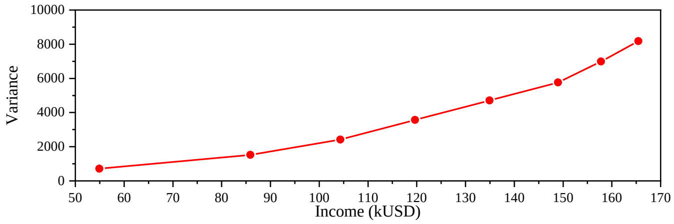

Fig. 5 The Pareto optimality in multi-objective optimization

According to Fig. 5, there is a negative correlation between the income of the CCES system and the load's flatness. The variation of the load grows as the CCES's income rises. It demonstrates load shifting's performance has gotten worse. The load has the worst flatness and its variance reaches 8176.1, which is only 6.3% less than the original variance, when the CCES system's income reaches its maximum value of 165.5 kUSD. The load is at its flattest when the CCES system's income falls to its minimum value of 54.9 kUSD, and its variance drops to 708.9, which is lower than the initial variance by 91.9%.

5. CONCLUSIONS

For the first time, this paper investigated the techno-economy performance of a compressed CO_2 energy storage system for load shifting. Two optimization modes were proposed to determine the operation of the CCES system, including single-objective and multi-objective optimizations. The reduction of load variance is the sole objective of single-objective optimization. In the case of multi-objective optimization, the objective is to maximize CCES system income while minimizing load variation. The optimization problem was solved by Mixed Inter Non-Linear Programming (MINLP). The parameters, namely variance, was used to evaluate the volatility of the load. Main findings include the follows.

In the single-objective optimization, the CCES system charges at valley period and discharges at peak periods. The variance of the load is 678.5, which is lower 92.2% than original load’s variance of 8725.4. The CCES system can make income of 678.5 kCNY.

The flatness of the load and the CCES system's income have a negative association in multi-objective optimization. The flatness of the load becomes worse and its variance is 8176.1 when the income of the CCES system reaches its maximum value of 165.5 kUSD. The flatness of the load becomes optimal and its variance is 708.9 when the CCES system's income falls below its minimal value of 54.9 kUSD.

DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

REFERENCE

[1] Kebede AA, Kalogiannis T, Van Mierlo J, Berecibar M. A comprehensive review of stationary energy storage devices for large scale renewable energy sources grid integration. Renewable and Sustainable Energy Reviews. 2022; 159:112213.

[2] Budt M, Wolf D, Span R, Yan J. A review on compressed air energy storage: Basic principles, past milestones and recent developments. Applied Energy. 170:250-68.

[3] Luo X, Wang J, Dooner M, Clarke J. Overview of current development in electrical energy storage technologies and the application potential in power system operation. Applied energy. 2015; 137:511-36.

[4] Liu S, Wu S, Hu Y, Li H. Comparative analysis of air and CO_2 as working fluids for compressed and liquefied gas energy storage technologies. Energy Conversion & Management. 2019; 181(FEB.):608-20.

[5] Jia L, Chen H, Xu Y, Liang W, Tan C. A solar energy storage and power generation system based on supercritical carbon dioxide. Renewable Energy. 2014; 64(apr.):43-51.

[6] Vazquez S, Lukic SM, Galvan E, Franquelo LG, Carrasco JM. Energy storage systems for transport and grid applications. IEEE Transactions on industrial electronics. 2010; 57(12):3881-95.

[7] Battery energy storage system load shifting control based on real time load forecast and dynamic programming. Proceedings of 2012 IEEE International Conference on Automation Science and Engineering (CASE), 2012. IEEE.

[8] Han X, Ji T, Zhao Z, Zhang H. Economic evaluation of batteries planning in energy storage power stations for load shifting. Renewable Energy. 2015; 78:643-7.

[9] Parra D, Norman SA, Walker GS, Gillott M. Optimum community energy storage system for demand load shifting. Applied Energy. 2016; 174:130-43.

[10] Sciacovelli A, Vecchi A, Ding Y. Liquid air energy storage (LAES) with packed bed cold thermal storage–From component to system level performance through dynamic modelling. Applied Energy. 2017; 190:84-98.

[11] Zhang H, Zhao J. Joint peak shaving energy consumption optimization model and simulation analysis of pumped storage power unit and coal-fired power

units. Chemical Engineering Transactions. 2016; 51:1279-84.
[12] Wang Y, Fu Y, Lin H, Sun Q, Scartezzini J-L, Wennersten R. Uncertainty modeling of household appliance loads for smart energy management. Energy Reports. 2022; 8:232-7.
[13] Wang Y, Lin H, Liu Y, Sun Q, Wennersten R. Management of household electricity consumption under price-based demand response scheme. Journal of Cleaner Production. 2018; 204:926-38.
[14] Fu Y, Lin H, Ma C, Sun B, Li H, Sun Q, Wennersten R. Effects of uncertainties on the capacity and operation of an integrated energy system. Sustainable Energy Technologies and Assessments. 2021; 48:101625.
[15] Huang Q, Feng B, Liu S, Ma C, Li H, Sun Q. Dynamic operating characteristics of a compressed CO2 energy storage system. Applied Energy. 2023; 341:120985.