Day-ahead Scheduling of Integrated Energy System Coupled with Liquid Air Energy Storage System

Ruifang Zeng
School of Automatiion
Central South University
Changsha, China
cactus20@csu.edu.cn

Chunsheng Wang
School of Automatiion
Central South University
Changsha, China
wangcsu@csu.edu.cn

Yuan Cao
School of Automatiion
Central South University
Changsha, China
caoyuan3116@csu.edu.cn

Yukun Hu
Department of Civil, Environment & Geomatic Engineering
University College London
London, UK
yukun.hu@ucl.ac.uk

***Abstract*—This paper implements scheduling optimization on an integrated energy system to utilize waste heat recovered from steel mills. The system includes liquid air energy storage system (LAES), thermal energy storage system (TES), photovoltaic (PV) power generation and thermal and electrical loads. Liquid air energy storage is used to act as electrical energy storage, and waste heat is utilized in the form of superheating the air entering the turbine to increase the round-trip efficiency of the liquid air energy storage system. Through the constructed Mixed-Integer Linear Programming (MILP) model to forecast the day-ahead scheduling scheme of the system components, scheduling results of 4 cases with different power demand are solved to discuss the impact on system cost with and without liquid air energy storage. The results show the utilization of LAES has a positive effect on reducing system costs However, the limitation of LAES' maximum output power and the constraint of thermal balance make the effect of LAES on reducing the total cost of the system limited.**

Keywords—Integrated energy system, Liquid air energy storage system, Waste heat utilization, Day-ahead scheduling

I. INTRODUCTION

Since the 21st century, the non-renewable fossil energy and the deterioration of the ecological environment have made the development of green energy and the improvement of energy utilization efficiency one of the priorities. Then the concept of an integrated energy system was born [1]–[3]. The steel mill park is a worthwhile research target to be explored due to great electricity demand and recyclable waste heat resources [4]. The scheduling and use of integrated energy is beneficial to the economic operation of the steel mill park and environmental protection.

The energy storage system is an essential component of an integrated energy system, liquid air energy storage(LAES) is an emerging energy storage method, and its advantages of ease of storage, environmental friendliness, and enhanced commercial viability [5]. Most of the current research on LAES is directed to the thermodynamic and exergy analysis of the system to improve round-trip efficiency [6]–[12]. References [6]-[9] combine liquid air energy storage and solar energy to improve efficiency. In Refs. [10] and [11], combined cooling, heating and power (CCHP) is combined with liquid air energy storage to improve round-trip efficiency and economic performance. In Ref. [12], a new liquid air energy storage system driven by wind and natural gas combined with a two-stage supercritical CO_2 cycle is proposed and investigated, considering the use of different sensible thermal energy storage to improve system performance. System performance is the main drawback of the current system [13]. The combination of LAES and steel mill waste heat can improve LAES round-trip efficiency for LAES and improve energy utilization efficiency for steel mill, reduce operating costs and mitigate the environmental impact caused by waste heat emissions. Among the existing studies on incorporating liquid air energy storage, waste heat utilization is not well considered.

In order to solve the issue mentioned above, the objective of this paper is to investigate the impact of using LAES on system costs by analyzing the results of component scheduling for the integrated energy system with 4 different power demand cases.

II. INTEGRATED ENERGY SYSTEM COUPLED WITH LIQUID AIR ENERGY STORAGE

Fig. 1 shows the structure of the integrated energy system, which targets a steel mill park and involves the combination of renewable energy sources and waste heat utilization. The park purchases electricity from the grid, photovoltaic panels are set up in the park to generate electricity, LAES operates as a power storage system, and TES is used for waste heat storage and utilization. The role of the system is to schedule various energy sources in the steel mill park to utilize energy efficiently and enable stable and economic operation of the system.

A. LAES

The operation of the liquid air storage system is illustrated in Fig. 2. During off-peak hours, the air is liquefied under pressure and stored in a storage tank, where electrical energy is converted to the internal energy of the liquid air. During peak tariff hours, the liquid air in the storage tank is pumped out under pressure, vaporized, superheated by an external waste heat source, and expanded to do work in the turbine to produce electrical energy. According to data from the pilot plant, the expansion interstage reheat temperature has a significant impact on the output power; an increase of 1℃ results in an increase of about 0.45% in power generation[14].

This work is supported by National Natural Science Foundation (NNSF) of China under Grant 62103443 and 61973322, and by Hunan Natural Science Foundation under Grant 2022JJ40630.

Most of the unused waste heat sources in steel mills are of low to medium taste and can be effectively combined with liquid air storage to increase power generation. In (1) and (2), P_{ch} and P_{dis} represent the charging and discharging power of LAES, M_{ch} and M_{dis} represent the charging and discharging air mass of LAES, SC and SP represent the special consumption in charging process and the special power generation in discharging process. In (3),Exp represents the waste heat used to superheat the air during expansion, and η_{hu} represents the coefficient between the waste heat required for expansion and the discharging power. The relationship between the charging/discharging power and the charging/discharging air mass is shown in (1) and (2) [15]. The numerical relationship between the waste heat used for expansion and the discharge power is shown in (3).

$$P_{ch} = SC * M_{ch} \tag{1}$$

$$P_{dis} = SP * M_{dis} \tag{2}$$

$$Exp = \eta_{hu} P_{dis} \tag{3}$$

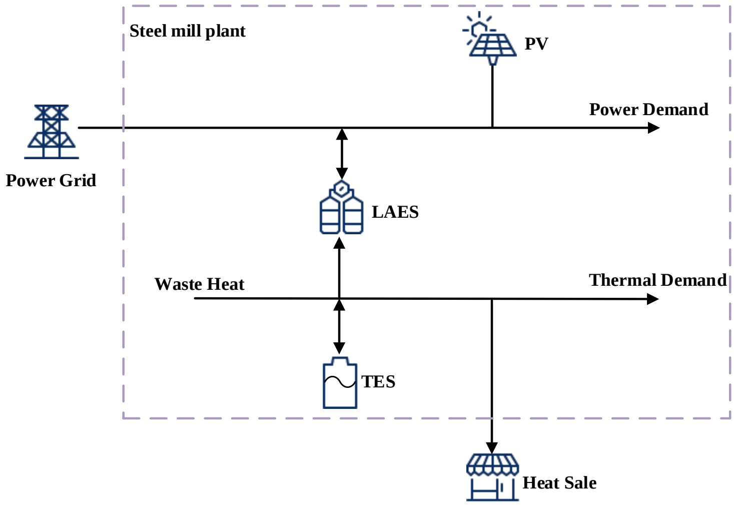

Fig. 1. The sheme of integrated energy system

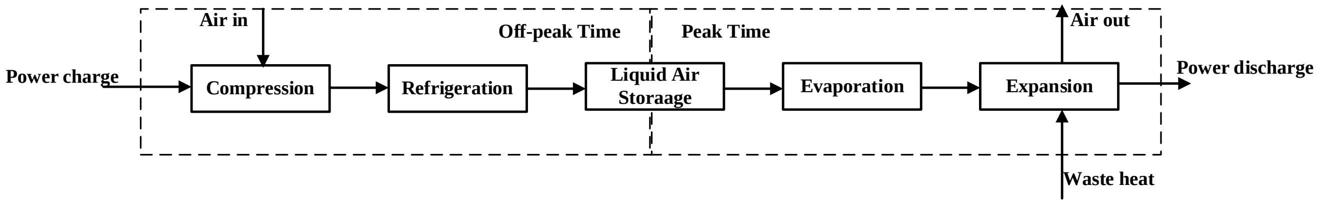

Fig. 2. The sheme of LAES operation

B. Other Components

The role of TES is to store waste heat after the waste heat meets the heat demand of the park, and to release the stored waste heat when the waste heat is insufficient to meet the heat balance, so as to reduce the waste heat resource waste and realize the rational use of waste heat. At the same time, waste heat can be recovered and purified and sold to the thermal market to enhance the economic efficiency of the steel mill park. In the integrated energy system structure of this paper, waste heat recovery is mainly used for LAES. The TES aims to provide waste heat to the liquid air energy storage system more conveniently, and the purpose of selling heat to the outside is to increase the income. If the LAES is not used, after meeting the heat demand and selling it to the outside, there will be a large amount of waste heat surplus, which is difficult to make full use of. Compared to other renewable energy sources that have geographical location constraints, PV power generation is not constrained by geographical location, the size of PV panels can be adjusted according to the object they are combined with, and there are currently some factory plants that have introduced PV power generation to resist the effects of power restriction policies. The equations of other components come from Ref.[16] .

C. Balancing Constraints

At each moment of system operation, the sum of the power purchased by the park from the grid P_{grid} , the PV generation P_{PV} , and the liquid air storage discharge power P_{dis} is equal to the sum of the park power load D_P and the liquid air storage charging power P_{ch}, while at the same time, the sum of the waste heat recovered by the park Wh and the final heat released by the TES Dis_{final} is equal to the sum of the park heat load D_{th} , the TES charging heat Ch, and the heat sold out to the park $Sale$. This is the meaning of power balance and heat balance as shown in (4)-(5).

$$P_{grid}(t) + P_{PV}(t) + P_{dis}(t) = P_{ch}(t) + D_P(t) \tag{4}$$

$$D_{th}(t) + Exp(t) + Ch(t) + Sale(t) = Dis_{final}(t) + Wh(t) \tag{5}$$

D. Objective function

The objective function of the proposed system model is the total operating cost TC as shown in (6), including the cost of power purchase C_{grid}, maintenance cost of LAES, PV, TES C_{main}, profit of heat sales P_S, and loss cost of LAES, TES, PV

C_{loss} . ξ_{OC} represents the operation cost coefficient, ξ_{loss} represents the loss cost coefficient and Pr represents the price.

$$TC = min\sum\{C_{grid} + C_{main} + C_{loss} - P_S\} = min\sum\{P_{grid}(t)Pr_e(t) + \xi_{OC}^{LAES}[P_{ch}(t) + P_{dis}(t)] + \xi_{OC}^{TES}[Ch(t) + Dis(t)] + \xi_{OC}^{PV}P_{PV}(t) + \xi_{loss}^{LAES}[P_{ch}(t) + P_{dis}(t)] + \xi_{loss}^{TES}[Ch(t) + Dis(t)] + \xi_{loss}^{PV}P_{PV}(t) - Sale(t)[Pr_h(t) - Pr_{puri}]\} \quad (6)$$

E. Input Data

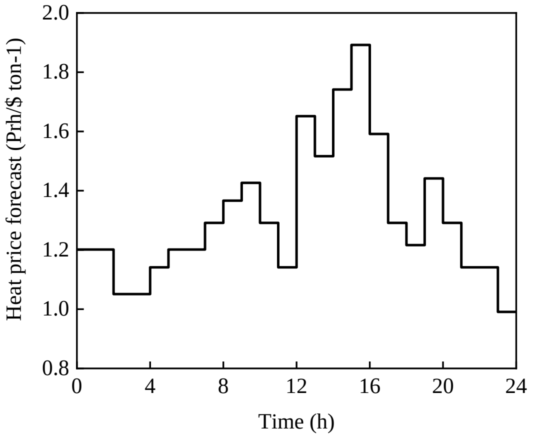

Fig. 3. Heat price

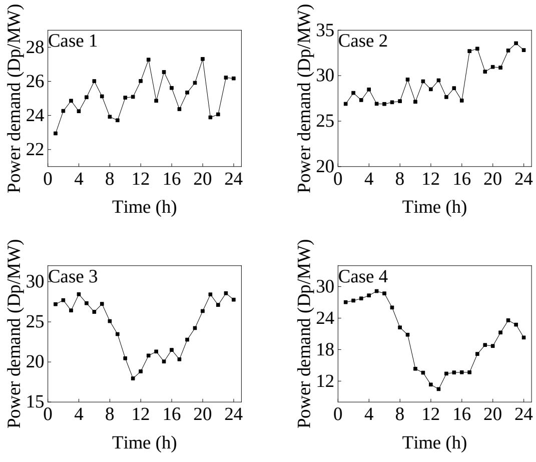

Fig. 4. Power demand in 4 cases

Taking a steel mill park as the object, the input data of the system includes the power load of the steel mill and the predicted PV power, the thermal load as well as the waste heat mass. Fig. 4 shows the four power load changes that occur in the steel mill. In case 1, the steel mill is operating normally, the power load changes caused by equipment switching are small, and the power load fluctuates within a small range. In case 2, when the small-load equipment is switched, the power load does not change much. After the large-load equipment is started, the power load gradually increases. In case 3, the steel mill has set up a maintenance plan. After the large-load equipment was shut down, there as a continuous power load reduction, and the maintenance was completed. After the heavy-load equipment was restarted again, the power load increased, gradually returning to the initial power load range. Compared with Case 3, Case 4 was that some equipment was restarted after the maintenance, and the power load increased, but it could not be restored to the initial power load range. The corresponding cases of waste heat mass are shown in Fig. 5.The forecast PV generation and thermal demand are shown in Fig. 6. Changes in the power load of a steel mill cause the mass of waste heat recovered from the mill to change as well, with the trend of waste heat mass fluctuations being broadly similar to the power load, with a greater range and magnitude. Time-of-use electricity price is shown in table I and the heat price is shown in Fig. 3. Table I shows the time-of-use electricity price of the grid. Other data are taken from the Refs.[15]–[18]. In table II, the special consumption in charging process SC is 168 KW/ton and the special power generation in discharging process SP is 137.3 KW/ton. Waste heat utilization coefficient η_{hu} is 1.654 ton/KW. The loss cost coefficient of LAES ξ_{loss}^{LAES} and TES ξ_{loss}^{TES} are 1.515 $/MW and 0.0003787 $/ton respectively. The price for the purification of waste heat sale Pr_{puri} is 0.3787 $/ton. The proposed Mixed-Integer Linear Programming (MILP) model is solved by general algebraic modeling system(GAMS) to obtain the scheduling results [19].

TABLE I. TIME-OF-USE ELECTRICITY PRICE

	Valley	Flat	Peak
Period	1-8	9-11,14-16,22-24	12-13,17-21
Price($\boldsymbol{Pr_e}$/$/MW)	45.045	75.075	120.120

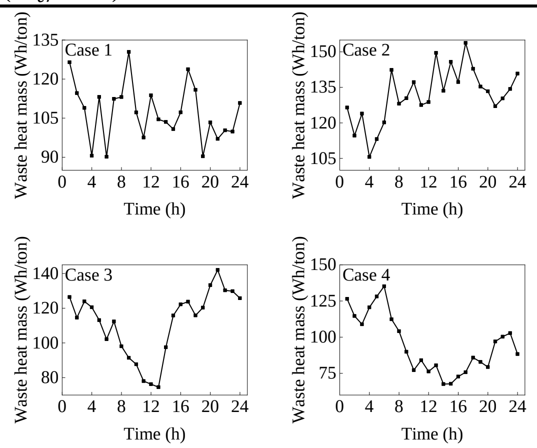

Fig. 5. Waste heat mass in 4 cases

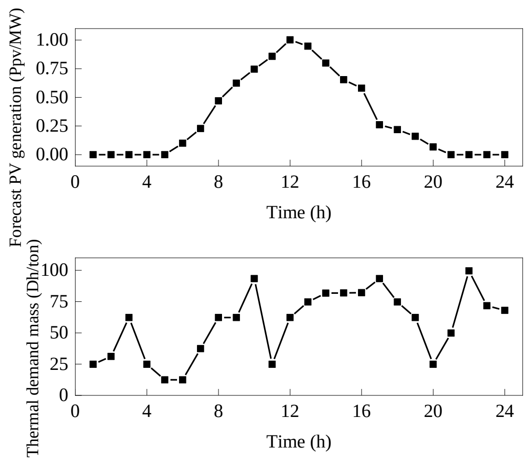

Fig. 6. Forecast PV generation and thermal demand

TABLE II. OTHER PARAMETERS

parameter	value	parameter	value
SC	168 KW/ton	ξ_{loss}^{LAES}	1.515$/MW
SP	137.3 KW/ton	ξ_{loss}^{TES}	0.0003787$/ton
η_{hu}	1.654 ton/KW	Pr_{puri}	0.3787$/ton

III. ANALYSIS OF SIMULATION RESULTS

The following Fig. 7-9 are obtained from the model solution results. The LAES charging and discharging states under different power demand changes are shown in Fig. 7. It is obvious that in all four cases, LAES has the action of charging with the maximum power when the electricity price is low, and discharging with the maximum power when the electricity price is peak. Comparing Case 1 and Case 2, the increase in power demand increases the total charging power of LAES during the parity period, and the discharge power increases significantly during the high electricity price period to reach the maximum output power. The LAES charging and discharging level of Case 3 is between Case 2 and Case 4. It can be seen from the figure that the total charging power of Case 3 during the parity period and the total discharging power of Case 3 during the period of high electricity price are between Case 2 and Case 4. Case 4 is because the power demand does not reach the initial demand range, and the total discharge power of LAES is smaller than that of case 1 in which the power demand is dynamically balanced.

Fig. 8 shows the charging and discharging state of TES under different waste heat mass changes. In four cases, the charging time of LAES coincides with the charging time of TES to a great extent. Obviously, there is no expansion heat demand in the charging period of LAES. After meeting the heat demand of the steel mill and selling it for profit, the remaining waste heat is charged into TES. Case 2 Compared with case 1, the time of TES releasing heat appeared interval, because LAES was charged in parity period, and TES was also charged at the same time. Because the waste heat mass is sufficient, the fluctuation of TES' heat release quality in peak electricity price period tends to be gentle compared with case 1. Compared with case 1, in case 3 it is obvious that although the waste heat mass finally rises to the initial waste heat mass range, the heat release of TES is still affected, which is manifested by the reduction of heat release time and total heat release quality. However, in case 4, there is also heat release in the period of flat peak electricity price. This is because under the same heat demand, the less the waste heat mass is, the stronger the heat release time constraint of TES is, and the weaker the influence of LAES is. The charging and discharging state of TES corresponds to that of LAES. When LAES is not in discharging state, TES is in charging state. When LAES is in discharging state, TES is in exothermic state, which is caused by the limitation of waste heat mass.

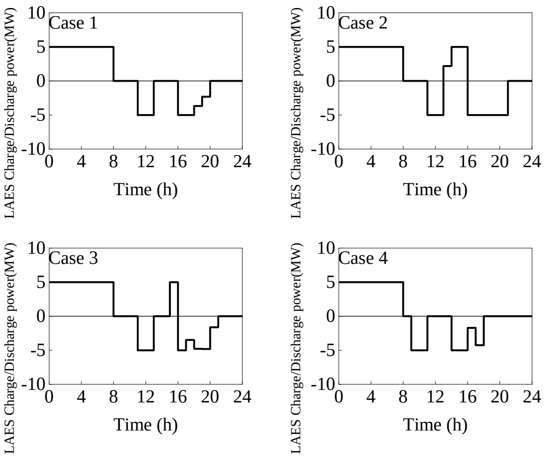

Fig. 7. The operation state of LAES

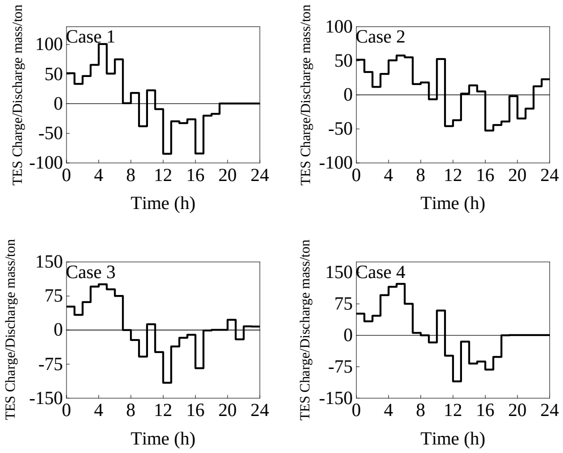

Fig. 8. The operation state of TES

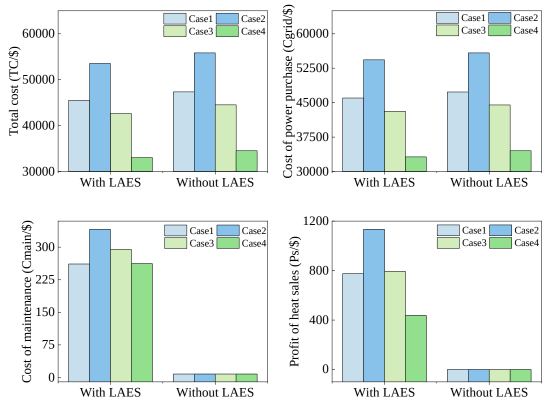

Fig. 9. Comparison of costs with and without LAES

The results of the comparison of each cost in 4 cases obtained from the solution are shown in Fig. 9; for each case the cost of purchasing electricity from the grid C_{grid} with LAES and without LAES is clearly compared with the total cost, the cost of purchasing electricity with LAES is smaller than without LAES because of the peak use of electricity in the valley, and the total cost TC of using LAES is smaller than without LAES because of the reduction of the cost of purchasing electricity and the gain of selling heat to the outside. In terms of maintenance cost C_{main} , the use of LAES increases the cost of maintenance and, but the increase in maintenance is not much compared to the cost reduction by using LAES. The loss cost C_{loss} compared with the total cost is really small so it is not discussed. From the values of maintenance costs and heat sales gain P_S can be found, the profit of heat sales can cover the increased maintenance costs because of the use of LAES, TES, in the future if the scale of LAES and TES increases, maintenance costs are bound to increase, the increase in the scale of TES will make the time and quantity of heat sales more flexible, and the heat sales gain to cover the maintenance costs has a certain possibility of continuation. This has a positive effect on steel mills to increase the utilization rate of waste heat.

Electricity purchase cost accounts for the vast majority of the total cost, and the power demand of the four cases determines the total cost of the case. Obviously, the case 2 with the largest power demand also has the largest total cost. LAES carries out peak power utilization to reduce the electricity purchase cost and thus reduce the total cost, while the two limitations of using LAES are the maximum output power of LAES and the thermal balance constraint. The former is not only the technical limitation of LAES itself, but also the general advantage of LAES output compared with the hourly power demand value. The latter is that the waste heat mass is affected by the change of power demand, which leads to the shortage of waste heat mass used for LAES energy release in the heat balance constraint, which makes LAES output limited. At the same time, case 4, which has the lowest profit from selling heat, is also the case with the lowest waste heat mass. When the waste heat mass decreases, the output power of LAES and the external selling heat are affected. These two factors make the cost reduction of case 4 much smaller than that of case 2.

Due to the limitation of heat balance and the maximum discharge power of LAES, the reduction of power purchase cost brought by the peak use of valley power is relatively limited compared with the total cost, and the scale of LAES will increase with the improvement of LAES technology in the future, then the cost reduction and the utilization rate of waste heat resources brought by using LAES will be further increased, and the dispatching effect of the proposed integrated energy system will be further enhanced; this will also have a positive impact on the economic operation of steel mills and environmental protection. This will also have more positive impact on the economic operation and environmental protection of the steel mill park.

IV. Summary

This paper optimizes scheduling with 4 different power demand cases based on an integrated energy system combining LAES, TES, and photovoltaic power generation to use waste heat from a steel mill park. The solved scheduling results show that the use of LAES helps to reduce the operating cost of the system, but the cost reduction is limited due to the size of LAES and the quality of waste heat, and the development of LAES technology and waste heat recovery technology will help to improve the effectiveness of the system. The development of LAES technology and waste heat recovery technology will help to improve the utility of the system.

References

[1] V. G. Gude and V. Fthenakis, "Energy efficiency and renewable energy utilization in desalination systems," *Prog. Energy*, vol. 2, no. 2, p. 022003, Jul. 2020, doi: 10.1088/2516-1083/ab7bf6.

[2] "Energy efficiency and renewable energy utilization in desalination systems - IOPscience." https://iopscience.iop.org/article/10.1088/2516-1083/ab7bf6/meta (accessed Jun. 06, 2022).

[3] M. Mahi, I. Ismail, S. W. Phoong, and C. R. Isa, "Mapping trends and knowledge structure of energy efficiency research: what we know and where we are going," *Environ Sci Pollut Res*, vol. 28, no. 27, pp. 35327–35345, Jul. 2021, doi: 10.1007/s11356-021-14367-7.

[4] P. Li, Z. Wang, H. Liu, J. Wang, T. Guo, and Y. Yin, "Bi-level optimal configuration strategy of community integrated energy system with coordinated planning and operation," *Energy*, vol. 236, p. 121539, Dec. 2021, doi: 10.1016/j.energy.2021.121539.

[5] M. Qi, J. Park, I. Lee, and I. Moon, "Liquid air as an emerging energy vector towards carbon neutrality: A multi-scale systems perspective," *Renewable and Sustainable Energy Reviews*, vol. 159, p. 112201, May 2022, doi: 10.1016/j.rser.2022.112201.

[6] M. H. Nabat, M. Zeynalian, A. R. Razmi, A. Arabkoohsar, and M. Soltani, "Energy, exergy, and economic analyses of an innovative energy storage system; liquid air energy storage (LAES) combined with high-temperature thermal energy storage (HTES)," *Energy Conversion and Management*, vol. 226, p. 113486, Dec. 2020, doi: 10.1016/j.enconman.2020.113486.

[7] M. H. Nabat, M. Soltani, A. R. Razmi, J. Nathwani, and M. B. Dusseault, "Investigation of a green energy storage system based on liquid air energy storage (LAES) and high-temperature concentrated solar power (CSP): Energy, exergy, economic, and environmental (4E) assessments, along with a case study for San Diego, US," *Sustainable Cities and Society*, vol. 75, p. 103305, Dec. 2021, doi: 10.1016/j.scs.2021.103305.

[8] M. Yang, L. Duan, Y. Tong, and Y. Jiang, "Study on design optimization of new liquified air energy storage (LAES) system coupled with solar energy," *Journal of Energy Storage*, vol. 51, p. 104365, Jul. 2022, doi: 10.1016/j.est.2022.104365.

[9] X. Ding, L. Duan, Y. Zhou, C. Gao, and Y. Bao, "Energy, exergy, and economic analyses of a new liquid air energy storage system coupled with solar heat and organic Rankine cycle," *Energy Conversion and Management*, vol. 266, p. 115828, Aug. 2022, doi: 10.1016/j.enconman.2022.115828.

[10] C. Wang, N. Akkurt, X. Zhang, Y. Luo, and X. She, "Techno-economic analyses of multi-functional liquid air energy storage for power generation, oxygen production and heating," *Applied Energy*, vol. 275, p. 115392, Oct. 2020, doi: 10.1016/j.apenergy.2020.115392.

[11] X.-D. Xue *et al.*, "Performance evaluation and exergy analysis of a novel combined cooling, heating and power (CCHP) system based on liquid air energy storage," *Energy*, vol. 222, p. 119975, May 2021, doi: 10.1016/j.energy.2021.119975.

[12] S. Sadeghi, N. Javani, S. Ghandehariun, and P. Ahmadi, "Design and optimization of a novel wind-powered liquefied air energy storage system integrated with a supercritical carbon dioxide cycle," *Energy Storage*, vol. 3, no. 6, p. e274, 2021, doi: 10.1002/est2.274.

[13] E. Borri, A. Tafone, G. Zsembinszki, G. Comodi, A. Romagnoli, and L. F. Cabeza, "Recent Trends on Liquid Air Energy Storage: A Bibliometric Analysis," *Applied Sciences*, vol. 10, no. 8, p. 2773, Apr. 2020, doi: 10.3390/app10082773.

[14] A. Sciacovelli *et al.*, "Performance Analysis and Detailed Experimental Results of the First Liquid Air Energy Storage Plant in the World," *Journal of Energy Resources Technology*, vol. 140, no. 2, p. 020908, Feb. 2018, doi: 10.1115/1.4038378.

[15] A. Tafone, A. Romagnoli, E. Borri, and G. Comodi, "New parametric performance maps for a novel sizing and selection methodology of a Liquid Air Energy Storage system," *Applied Energy*, vol. 250, pp. 1641–1656, Sep. 2019, doi: 10.1016/j.apenergy.2019.04.171.

[16] C. Yan, C. Wang, Y. Hu, M. Yang, and H. Xie, "Optimal operation strategies of multi-energy systems integrated with liquid air energy storage using information gap decision theory," *International Journal of Electrical Power & Energy Systems*, vol. 132, p. 107078, Nov. 2021, doi: 10.1016/j.ijepes.2021.107078.

[17] C. Xie, Y. Hong, Y. Ding, Y. Li, and J. Radcliffe, "An economic feasibility assessment of decoupled energy storage in the UK: With liquid air energy storage as a case study," *Applied Energy*, vol. 225, pp. 244–257, Sep. 2018, doi: 10.1016/j.apenergy.2018.04.074.

[18] A. R. Jordehi, M. S. Javadi, M. Shafie-khah, and J. P. S. Catalão, "Information gap decision theory (IGDT)-based robust scheduling of combined cooling, heat and power energy hubs," *Energy*, vol. 231, p. 120918, Sep. 2021, doi: 10.1016/j.energy.2021.120918.

[19] "GAMS User's Guide." https://www.gams.com/latest/docs/UG_MAIN.html (accessed Jun. 14, 2022).