

Analysis of Compressed Air Energy Storage System and Evaluation of Financial Feasibility—A Case Study [†]

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Abstract: We analyzed the performance and financial feasibility of a compressed air energy storage (CAES) system in a potential region in Miaoli County, Taiwan, with the aquifer in the underground structure. We conducted a performance analysis of the system using the commercial software Flownex 9.0. Initially, a model for the Huntorf case in Germany was built, and its performance was compared with others for validation. The calculation results showed a deviation of about 1% in terms of efficiency, confirming the analytical capabilities and accuracy of the model. After verifying the system performance, the scale of output power was adjusted to 2 MW for initial development and subsequent planning. Then, geological characteristics were analyzed using COMSOL to establish a multiphase flow analysis model. This model evaluated the flow rate and pressure required for the operation of the CAES system. Lastly, a financial analysis was conducted based on the obtained results. The cost for system components was estimated, and the levelized cost of the proposed CAES system was evaluated. A comparison with other energy storage technologies was conducted to assess the financial feasibility of the analyzed CAES system.

Keywords: compressed air energy storage; efficiency; financial feasibility



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1. Introduction

Taiwan's carbon reduction target by 2030 is 24%, and the renewable energy capacity is estimated to be 46.12 GW by the National Development Council. As an effort to improve the power system and implement energy storage, a 5500 MW energy storage system is planned for 2030, with a budget of approximately USD 6.4 billion. Therefore, complementary measures must be proposed for the planned projects for long-duration and cost-effective energy storage systems to enhance grid security and ensure stable electricity supply.

In 2022, the global capacity of energy storage systems reached 237.2 GW, comprising 188.1 GW of pumped hydro storage, 43.2 GW of electrochemical storage, and 3.3 GW of molten salt storage. Compressed air energy storage (CAES) and pumped hydroelectric storage (PHS) are mechanical storage techniques for long-duration energy needs, offering advantages such as lower cost and longer lifespan. As renewable energy installations, particularly wind and solar power, continue to expand, the demand for grid stability and regulation increases. The CAES technology is relatively mature and cost-competitive; its future applications are expected to significantly rise.

A CAES system employs off-peak electricity to compress air and store it in sealed underground reservoirs such as abandoned mines, subsided seabed storage tanks, salt caverns,

or decommissioned oil and gas wells. In peak electricity demand periods, the compressed air is released, heated, and expanded through turbines to generate electricity [1]. The newly developed advanced CAES (A-CAES) employs a thermal energy storage unit to reheat the high-pressure air in the decompression process, thereby avoiding direct combustion for heating. This improvement in the thermodynamic cycle increases overall conversion efficiency to 70%. Integrating CAES technology with the recent surge in renewable energy installations is beneficial in achieving carbon reduction goals.

The integration of the CAES system with renewable energy devices has been researched extensively. Chang et al. proposed a coupled design that combines wind and solar energy. Compressed heat, waste heat, and solar energy were used to replace traditional gas heating, thereby enhancing the overall efficiency of the system [2]. Minutillo et al. investigated the average storage air pressure and storage tank characteristics of the A-CAES system in conjunction with solar power systems and identified the optimal operational parameters for various pressure ranges [3]. Ghalelou et al. developed a computational program based on demand response mechanisms to account for the variability in renewable energy in the CAES system. The integration of CAES with demand response programs assists decision-makers in reducing operational costs, optimizing models, and validating parameters such as market prices, load, wind speed, temperature, and sunlight [4].

With the advancement of CAES and A-CAES technologies and the establishment of demonstration plants, the costs are gradually decreasing and are presently comparable to those of PHS. In 2022, the installation cost of a 100 MW A-CAES system was approximately USD 1700 per kW [5]. Evaluations of the levelized cost of storage (LCOS) also indicate that the costs of CAES and PHS are similar, reaching USD 0.10 per kWh [5]. Therefore, CAES demonstrates significant potential as an alternative option to PHS. It is also beneficial to the diversity and flexibility of energy configuration planning in Taiwan.

In the current development of international energy storage technologies, the CAES system is one of the primary options for high-rated power and long-duration storage, potentially serving as an alternative to PHS. In terms of large-scale energy storage systems, only the PHS system has been developed in Taiwan, while research on the CAES system has been limited. Since the cost of CAES has decreased to a level comparable to PHS, CAES has been a viable alternative option for long-duration and large-scale energy storage, particularly for storing electricity generated from renewable energy sources. Further development of the CAES system mitigates the impact of renewable energy fluctuations on the grid. Therefore, we conducted a feasibility study for the CAES system from the aspect of engineering and finance on a potential site in Taiwan. Focusing on the design, analysis, and financial feasibility assessment, the plausibility of implementing a CAES system in the Miaoli area was investigated.

2. Numerical Model

An analytical model was constructed to evaluate the designed CAES system. Flownex was used to verify the capability of the proposed model in the evaluation of the performance. The Huntorf plant in Germany was compared with the designed CAES system for validation. The results were compared with those of the relevant literature. The parameters employed in the model are shown in Table 1.

Table 1. Parameters employed in the system model [6].

Parameter	Value
Compressor operation time	8 h
Inlet air flux of compressor	108 kg/s
Stages of compressor	4

Table 1. *Cont.*

Parameter	Value
Number of intercoolers	3
Outlet air temperature of coolers	50 °C
Isentropic efficiency of centrifugal compressor	0.8
Compressor mechanical efficiency	0.99
Turbine operation time	2 h
Inlet air flux of combustion chamber	417 kg/s
Inlet air temperature of combustion chamber #1	50 °C
Inlet air pressure of combustion chamber #1	42 bar
Outlet temperature of combustion chamber #1	600 °C
Outlet temperature of combustion chamber #2	1050 °C
Outlet air pressure of combustion chamber #2	11 bar
Outlet pressure of LP gas turbine	1.13 bar
Isentropic efficiency of turbine	0.85
Turbine mechanical efficiency	0.99
LHV of natural gas	50,030 kJ/kg

The multi-phase model was built by the software COMSOL to analyze the characteristics of the air injection and extraction process in the underground gas storage reservoir for the CAES system. The employed geological parameters were determined based on data from potential sites in the Miaoli area. The analysis results were fed back into the previously developed Flownex model. The considered depth of the potential site was 1350 m. The hydrostatic pressure is 135 bar, and the safe injection pressure is 202 bar at the analyzed depth. The preliminary evaluation showed that the required volume is 8513 m³. The variation in pressure along the depth can be found in [7].

The financial feasibility was estimated based on installation and levelized costs of storage (LCOS). A comparison was made among the costs of the proposed system, those of previous studies, and the lithium-ion battery. Empirical formulas were used for the evaluation of the costs in the designed CAES system [8–12].

3. Results and Discussion

The results of the CAES system performance analysis model are shown in Figure 1. The variation in color indicates the increase and decrease in pressure during the operation of the CAES system. The calculated system efficiency was 41.8%, while Ref. [6] estimated it as 41.3%. The relative error in the comparison of system efficiency was 1.33%, validating the accuracy of the proposed CAES system model.

The behavior of gas injection and extraction in the storage reservoir was explored. Variation in the important parameters, including air saturation and pressure, was observed. In the gas injection process, sufficient gas must be supplied to the reservoir to displace the existing water and create a gas storage zone for subsequent power generation. For gas extraction, the designated gas extraction rate must not be decreased so that interior pressure maintains the threshold to extract the liquid water. The variation in air saturation within the gas reservoir at different locations by the developed COMSOL model is presented in Figure 2. At the location 18.1 m from the injection point, 30 days were needed to reach a saturation of 90%. However, at the location 25.5 m away, it took 120 days to reach over 90% saturation.

The air extraction process was simulated by using the proposed multi-phase model. The corresponding variation in air saturation and its flux are presented in Figure 3. The air flux was maintained above the threshold value within 50 h, and the air saturation was maintained above 0.4 [7] to avoid the liquid water extraction.

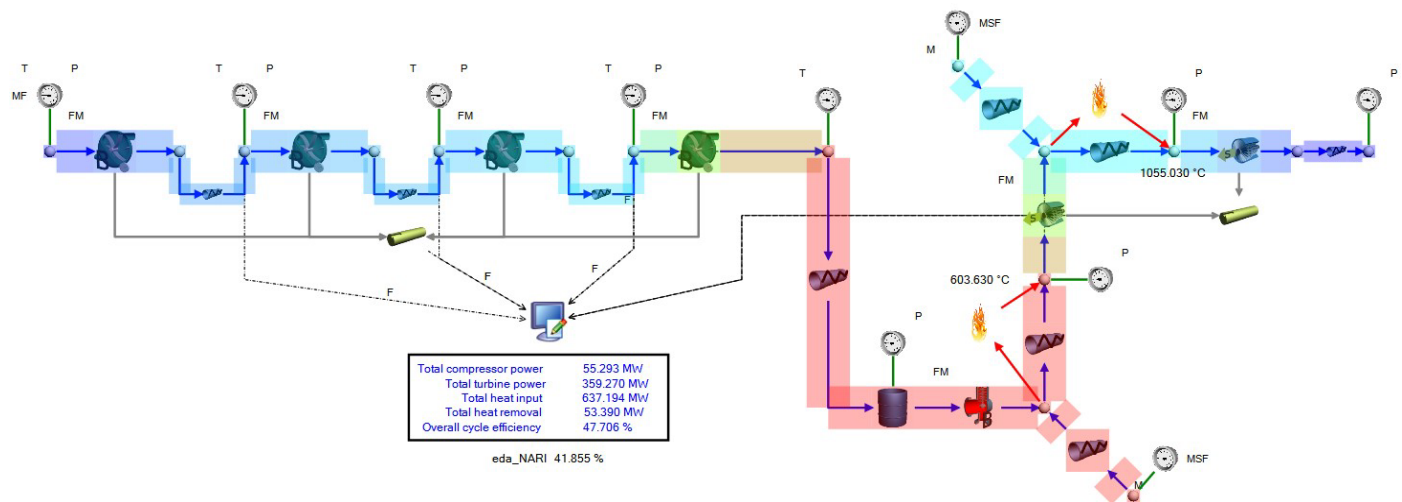


Figure 1. CAES model for the evaluation of system efficiency with color of pressure variation.

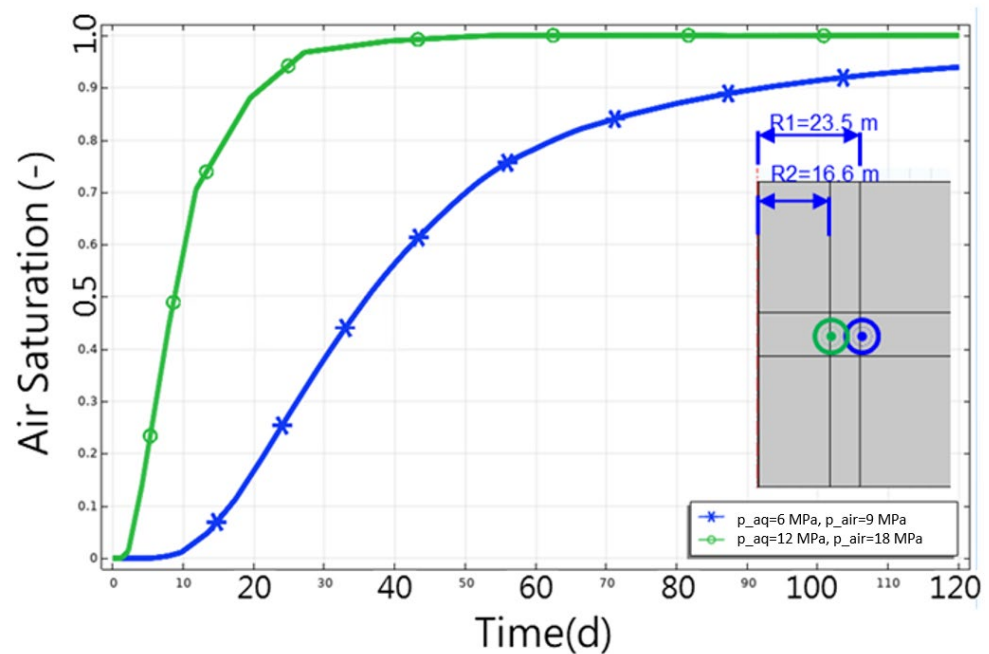


Figure 2. Variation in air saturation with time during the air injection process.

The financial evaluation was conducted by considering the following scenarios: CAES [11], lithium-ion battery [12], CAES-350 MW (for validation), designed 2 MW (CAES-cavern), 2 MW (CAES-Tank), and 25 kW, respectively. The calculated capital power cost (USD/kW) is compared in Figure 4. The comparison result of capital power cost shows that the data from the literature (CAES-ref) [11] is similar to the results calculated in this study (350 MW), with an average value between 513 and 731 USD/kW (Figure 5). However, it is more affordable than the lithium-ion battery (1918 USD/kW). This tendency is consistent with the findings of Ref. [11]. For the 2 MW capacity, the average capital power cost was 1525 to 1639 USD/kW due to the smaller scale. The design using tanks increased additional costs. For the 25 kW capacity, using the highest cost was found to be 2155 USD/kW.

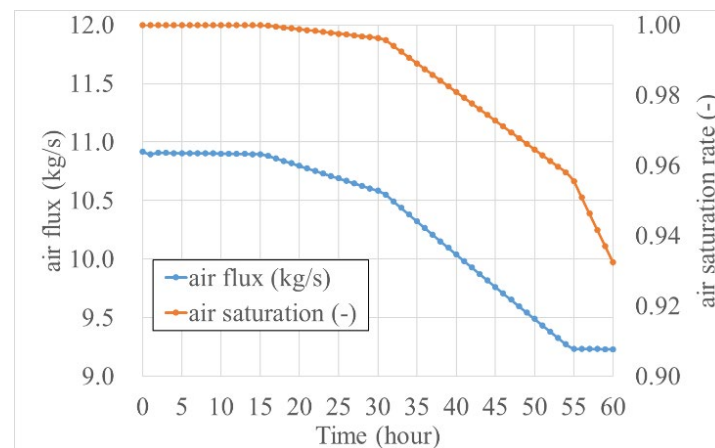


Figure 3. Variation in air saturation and flux during the extraction process.

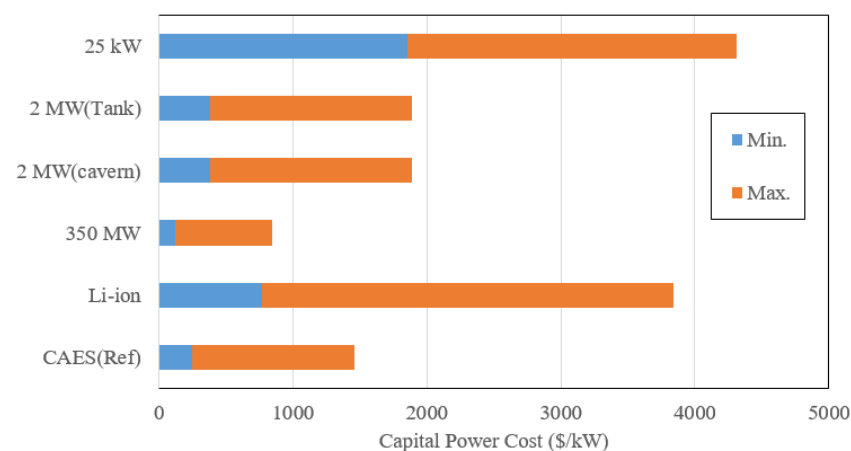


Figure 4. Comparison of capital power cost [11].

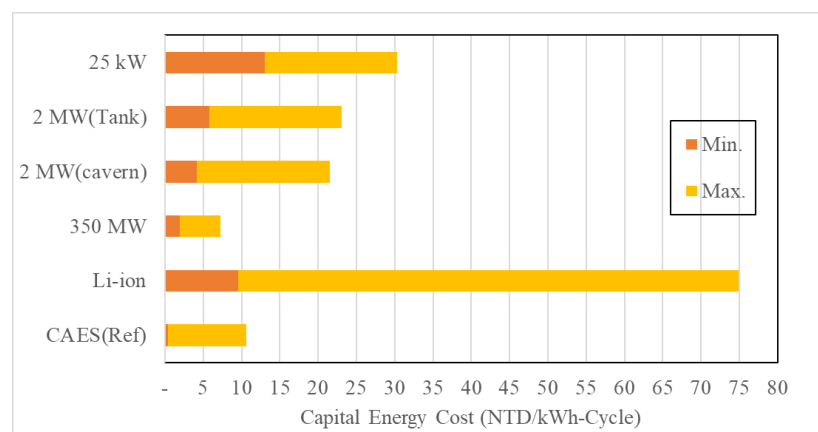


Figure 5. Comparison of capital energy cost.

Based on the operational parameters, the levelized cost (capital energy cost) after 40 years of operation was calculated (Figure 5). The CAES system reached a low value of 0.011 USD/kWh-cycle in its scenario using salt caverns. The highest possible value was 0.31 USD/kWh-cycle, and the average value was 0.16 USD/kWh-cycle, indicating that proper design and site selection are paramount in the development of the CAES system. The lithium-ion battery requires a higher cost, with an average value of 1.44 USD/kWh-cycle. For the 350 MW capacity, the average levelized cost was 0.11 USD/kWh-cycle, which was close to the values from previous results and significantly lower than that of the lithium-

ion battery. The 2 MW design in this study also required a high cost due to the effect of economies of scale (0.33 USD/kWh-cycle), and the energy cost of the tank-based design was slightly higher, averaging 0.35 USD/kWh-cycle. The smallest scale, 25 kW, required an average cost of 0.46 USD/kWh-cycle. These results indicate that the CAES system is more appropriate for large-scale designs (100 MW) to reduce costs. Smaller systems require higher costs in air storage components and compressors. If a demonstration project with the 2 MW level is conducted in Taiwan, the expected costs are higher than those of systems in other countries. However, the operation is more successful on an expanded scale, as the corresponding costs can be reduced close to the level in other systems.

4. Conclusions

We analyzed the feasibility of a CAES system in Taiwan from both engineering and financial perspectives. Specifically, the design, analysis, and financial assessment were conducted when implementing a CAES system at a potential site in the Miaoli region, Taiwan. The performance analysis model of the CAES system was developed and verified, and the system efficiency was evaluated accurately with a relative error of 1.33%. The injection and extraction processes were modeled with adjustments based on the designated air flow rate and corresponding pressure in the air reservoir for the stable operation of the designed system. The financial feasibility was assessed by calculating the power and levelized costs for selected cases. A larger-scale system is more cost-effective, while using a tank for air storage significantly increases the power and levelized costs. While the initial demonstration project for the CAES system is expected to have higher costs, the system scale needs to be increased over time.

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References

1. Desai, N. *The Economic Impact of CAES on Wind in TX, OK, and NM*; Texas State Energy Conservation Office: Austin, TX, USA, 2005.
2. Liu, C.; Xu, Y.J.; Hu, S.; Chen, H.S. Techno-economic analysis of compressed air energy storage power plant. *Energy Storage Sci. Technol.* **2015**, *4*, 158–168.
3. Minutillo, M.; Lavadera, A.L.; Jannelli, E. Assessment of design and operating parameters for a small compressed air energy storage system integrated with a stand-alone renewable power plant. *J. Energy Storage* **2015**, *4*, 135–144. [\[CrossRef\]](#)
4. Ghalelou, A.N.; Fakhri, A.P.; Nojavan, S.; Majidi, M.; Hatami, H. A stochastic self-scheduling program for compressed air energy storage (CAES) of renewable energy sources (RESs) based on a demand response mechanism. *Energy Convers. Manag.* **2016**, *120*, 388–396. [\[CrossRef\]](#)
5. Baxter, R. *2020 Energy Storage Pricing Survey*; Sandia National Laboratories: Albuquerque, NM, USA, 2021.
6. Liu, W.; Liu, L.; Zhou, L.; Huang, J.; Zhang, Y.; Xu, G.; Yang, Y. Analysis and optimization of a compressed air energy storage-combined cycle system. *Entropy* **2014**, *16*, 3103–3120. [\[CrossRef\]](#)
7. Hauer, A. *Advances in Energy Storage*; Wiley: Hoboken, NJ, USA, 2022. [\[CrossRef\]](#)

8. Jiang, R.; Yin, H.; Peng, K.; Xu, Y. Multi-objective optimization, design and performance analysis of an advanced trigenerative micro compressed air energy storage system. *Energy Convers. Manag.* **2019**, *186*, 323–333. [[CrossRef](#)]
9. Madlener, R.; Latz, J. Economics of centralized and decentralized compressed air energy storage for enhanced grid integration of wind power. *Appl. Energy* **2013**, *101*, 299–309. [[CrossRef](#)]
10. Zhang, X.; Zeng, R.; Deng, Q.; Gu, X.; Liu, H.; He, Y.; Mu, K.; Liu, X.; Tian, H.; Li, H. Energy, exergy and economic analysis of biomass and geothermal energy based CCHP system integrated with compressed air energy storage (CAES). *Energy Convers. Manag.* **2019**, *199*, 111953. [[CrossRef](#)]
11. Wang, J.; Lu, K.; Ma, L.; Wang, J.; Dooner, M.; Miao, S.; Li, J.; Wang, D. Overview of compressed air energy storage and technology development. *Energies* **2017**, *10*, 991. [[CrossRef](#)]
12. Lashgari, F.; Babaei, S.M.; Pedram, M.Z.; Arabkoohsar, A. Comprehensive analysis of a novel integration of a biomass-driven combined heat and power plant with a compressed air energy storage (CAES). *Energy Convers. Manag.* **2022**, *255*, 115333. [[CrossRef](#)]

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