Business models analysis for micro compressed air energy storage considering the comprehensive cost in its life-cycle

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Abstract. Micro compressed air energy storage (M-CAES) has the characteristics of pollution-free, high comprehensive utilization of energy, and the ability of combined cooling, heating, and electrical power, which can better meet the energy application in many areas. Considering that the business models restrict the development of M-CAES, business models analysis for M-CAES considering the comprehensive cost in its life-cycle is studied. Firstly, this paper analyzes possible investment models of M-CAES projects with multiple market participants, and then the business models of the M-CAES system are designed. Secondly, a scheme of life-cycle cost/benefit assessment is proposed for M-CAES investment, including the construction cost and the operation cost of the M-CAES. Finally, the economic benefits of different business models are analyzed by the 1MW·h M-CAES. The results show that they can provide theoretical reference and engineering instruction for the research and engineering application of M-CAES.

1. Introduction
Under increasingly serious environmental issues and the energy crisis, vigorously developing renewable energy represented by wind power and solar power, and achieving a low-carbon and sustainable energy supply and energy consumption system is the effective way for China and the world to transition from green to low-carbon energy [1]. Among them, new energy systems will be one of the main forms of the future. It can be used to islands, large buildings, and factories. The new energy system can help consume local energy and improve energy efficiency [2]. However, Due to the volatility, intermittence and uncertainty of renewable energy generation in new energy, the load curve often cannot fit the energy availability curve, and the new energy system is difficult to operate stably. As a flexible resource, energy storage can effectively improve the safe and stable operation of new energy system [3].

At present, storage technologies include electrochemical batteries, supercapacitors, PH (pumped hydro), and CAES (compressed air energy storage). Because of the characteristics of CCHP, compressed air energy storage can improve the comprehensive utilization of energy; therefore, compressed air energy storage has been widely concerned in the new energy system, and scholars at
home and abroad have conducted a lot of research on it. Dynamic modeling of a hybrid CAES-wind turbine system for wind power fluctuation reduction is proposed in [4]. In [5] a thermodynamic model for a hybrid thermal CAES system is proposed. Energy storage operation modes in a cooling, heating and power system based on advanced adiabatic compressed air energy storage is proposed in [6]. We can see that the above article was research on the advantage of CAES, they did not consider technical and economics of the CAES.

To promote and apply the CAES in the grid, at the early commercialization of energy storage facilities, the bidding strategy in the day-ahead electricity market is crucial for the economic operation of AA–CAES plants [7]. In [8-9], robust optimization approach is employed to achieve the offering and bidding curves of compressed air energy storage which should be submitted to the pool market. In [10], based on the multi-scale forecast error characteristics of wind power, electricity demand and price-based demand response (PDR), and under the “looking before and behind” principle, a day-ahead and intra-day coordinated dispatch model for the CAES integrated system was proposed. In [11], the optimization scheduling model of the power system with AA-CAES plant considering the reverse market is established. In [12], the CAES could participate in electricity market operations such as electricity, auxiliary services, and real-time markets in the role of price setter and price acceptor. However, most of the researches use traditional large-scale CAES as the price recipient to study the market operation. This is not suitable for M-CAES combined cooling, heating, and electrical power. Also, there are few studies on the economy and business model of micro-compressed air energy storage (M-CAES) [13-14]. Some paper on M-CAES also achieved some successes. But, business models restrict make investor’s investment in M-CAES. At the same time, it is difficult to determine the actual operating benefits for the lack of economic evaluation methods of M-CAES. Secondly, economic analysis of the business models based on the initial investment appears to be unrealistic and relatively rough. Further, the above problems hinder the promotion and application of M-CAES.

Therefore, a quantitative analysis method of M-CAES considering the comprehensive cost in its life-cycle is proposed. Firstly, the business models of the M-CAES system are designed, and then a scheme of life-cycle cost/benefit assessment base on the M-CAES system is proposed. Finally, when the different factors change within the range, the 1MWh M-CAES system is used to analyze its economic benefit of different business models.

This paper is organized as follows: Description of M-CAES is presented in Section 2. Business models of M-CAES are discussed in Section 3. The economic analysis of M-CAES based on life-cycle cost is proposed in Section 4. The benefits evaluation model of M-CAES is built in Section 5. In Section 6, the effectiveness and feasibility performance of the proposed method is examined in the 1MWh M-CAES system. Section 7 is the conclusion.

2. Description of M-CAES

The M-CAES system mainly consists of a compression train, an expansion train and an air storage heat storage utilization subsystem, as shown in Figure 1. A CAES system reserves electrical energy in the form of air internal energy, and then recovers it through turbine expansion. The specific working process is: during the off-peak time, the compressor is driven by the power energy to compress the air from the atmosphere, and high-pressure air is stored by the gas tank; secondly, the heat removed from the compressed air is transferred directly to the heat users, the heat of the high-temperature air can be absorbed by the low-temperature heat storage medium; during the on-peak time, high-temperature working medium is used to heat the high-pressure air, and then the turbine generates electricity. The high-pressure air from the gas tank enters throttle valve to maintain constant pressure at the turbine inlet. The surplus compression heat can transfer directly users through the heat exchanger device, also the low-temperature can supply cooling to the users [15-16]. The M-CAES system has the function of combined cooling heating and power. Therefore, the M-CAES system can be widely used in new energy systems.
3. Business models of M-CAES

Market players involved in M-CAES investment and operation generally include the grid corporation, energy service investors, CAES equipment investors, social capital, and governments, etc. When the M-CAES is operating, the M-CAES provide electrical energy services to users. The operator is responsible for coordinating the resources of the source-net-storage and guarantee power safety and reliability. At the same time, the operator collects electricity fees from users by the electricity price. Each market subject can be assumed by different roles such as social capital, the grid corporation, energy service investors, governments, and social capital, thus forming a complex business investment model and operating model.

3.1. Investment models of M-CAES

(1) Single investment model

The grid corporation is solely responsible for all investment, construction, and operation modes of M-CAES. Grid corporation can use its professional advantages to make overall planning, optimize investment, and improve local power quality. The grid corporation owns the property rights of the M-CAES and collects electricity fees from users by the electricity price. Therefore, the main profit for the single investment model is the discharge power of the M-CAES. The biggest problem is the need to independently bear high investment costs.

(2) Cooperative investment model

The M-CAES project was built by cooperative with energy service investors, CAES equipment investors. The income of investors is divided according to the investment proportion agreement. If the government also participates in M-CAES project investment, PPP (public-private-partnership) model can be formed, which is also one of the cooperative investment models. The cooperative investment model alleviates the financial pressure of all investors. But, the coordination between all investors during the investment and construction period will affect the quality of the project construction.

(3) Financial crowdfunding model

The financial crowdfunding model is invested by grid corporations and social capital. Grid corporation can raise funds through public announcements, introduce social capital to invest in M-CAES projects, purchase energy storage equipment, and build and operate. They can use independent operation and equipment leasing to make profits. Grid corporations publicly raise funds for the M-CAES project. It is obtained fund from social capital. Then, the grid corporation is responsible for purchase equipment, construct and operate. The financial crowdfunding model can obtain profits by leasing.

3.2. Business models

By analyzing the investors and operating modes of different investment models, the business model of the M-CAES can be obtained, as shown in Table 1. we can obtain four business models of investment. We know that the construction of M-CAES can delay the construction of the power grid and obtain
government subsidies. At the same time, the operators collect electricity fees and cooling heating income from users. We consider that the grid cooperative operations may not collect delaying grid construction fees in this paper. The energy service investor can obtain saving service fees from the power grid. So, the type of income for different business models is as shown in Table 2.

| Investment models                      | Investors                        | Operating model                   |
|----------------------------------------|----------------------------------|-----------------------------------|
| Single investment model                 | State cooperative                | Grid cooperative operations       |
| Cooperative investment model 1         | Joint investment                 | Energy Service Investor           |
| Cooperative investment model 2         | Joint investment                 | Joint operation                   |
| Financial crowdfunding model            | Crowdfunding development         | Lease operation                   |

| Table 2. Types of income from different business models |
|--------------------------------------------------------|
| Investment models                                      | Type of income                   |
|--------------------------------------------------------|
| Single investment model                                 | Electricity fee income, cooling heating income, government subsidies |
| Cooperative investment model 1                         | Electricity fee income, cooling heating income, government subsidies, delaying grid construction cost, Energy-saving service fee |
| Cooperative investment model 2                         | Electricity fee income, cooling heating income, government subsidies, delaying grid construction cost |
| Financial crowdfunding model                           | Fixed rental income, government subsidies, delaying grid construction cost |

4. The economic analysis of M-CAES based on life-cycle cost

4.1. Life-cycle cost analysis

During the life cycle, the cost includes the costs of planning, manufacturing, design, purchase, installation, transformation, operation, maintenance, update, and recovery and disposal. The life-cycle cost of M-CAES is divided into two period: the construction period and the operation period. The construction period includes the cost of planning, design, manufacturing, purchase, installation, that is, the cost of construction period is equipment costs (compressor, air storage vessel, and turbine generator, etc.), installation costs, construction engineering costs, and basic reserve costs, etc. The operation period includes the cost of operation and maintenance, tax cost, etc. Therefore, the total cost of M-CAES is as follows:

\[ S = \alpha + \beta \]  (1)

where \( S \) is the total cost of M-CAES based on the life cycle; \( \alpha \) is the cost of M-CAES during the construction period; \( \beta \) is the cost of M-CAES during the operation period.

4.2. The revenue model of M-CAES

(1) Electricity fee income

\[ R_e = n \sum_{j=1}^{N} [A_d(\gamma) \cdot \varphi_d(\gamma) - A_c(\gamma) \cdot \varphi_c(\gamma)] \]  (2)

where \( R_e \) is the electricity fee income. \( n \) is the number of operating days per year for the M-CAES; \( A_d(\gamma), A_c(\gamma) \) are discharge electricity price and charging electricity price for the M-CAES, respectively; \( \varphi_d(\gamma), \varphi_c(\gamma) \) are discharge power and charging power at \( t \) time, respectively.

(2) Heating and cooling income

\[ R_h = n \sum_{j=1}^{N} [A_h \cdot \psi_h(\gamma)] \]  (3)

where \( R_h \) is the heating and cooling income of M-CAES; \( \psi_h(\gamma) \) is the heat and cooling supply of M-CAES at time \( t \); \( A_h \) is the cooling and heating price of M-CAES.
(3) Other income

$$R_3 = (A_{in} + A_{sw}) \cdot \varphi_d$$  \hspace{1cm} (4)$$

where $R_3$ is the other income of M-CAES, including government subsidies fee and delaying grid construction cost; $A_{in}, A_{sw}$ are the construction cost and government subsidies fee of unit power, respectively.

5. The benefits evaluation model of M-CAES

(1) The capital payback period for M-CAES systems

$$M_{Cap} = \frac{\alpha}{\alpha_{pr}}$$  \hspace{1cm} (5)$$

where $M_{Cap}$ is the capital recovery period (CRP) of M-CAES; $\alpha_{pr}$ is the total annual average profit of the M-CAES system.

(2) The net present value of M-CAES system

$$M_{NPV} = (\varepsilon_{in} - \varepsilon_{out}) \sum_{t=1}^{L} (1 + R_{in})^{-t} - \alpha$$  \hspace{1cm} (6)$$

where $M_{NPV}$ is the net present value (NPV) of the M-CAES system; $\varepsilon_{in}$ is cash inflow of M-CAES system; $\varepsilon_{out}$ is cash outflow of M-CAES system; $L$ is operating life of M-CAES system.

(3) Internal rate of return for M-CAES systems

$$ (\varepsilon_{in} - \varepsilon_{out}) \sum_{t=1}^{L} (1 + \Gamma_{IRR})^{-t} = \alpha$$  \hspace{1cm} (7)$$

where $\Gamma_{IRR}$ is the internal rate of return (IRR) for the M-CAES.

6. Simulation analysis

6.1. Parameter setting

In this paper use the 1MW·h M-CAES. The parameters of the 1MW·h M-CAES system are shown in Table 3. The installation cost is 8% of the equipment investment cost. The construction period is 2 years, and the operation period is 30 years.

| Technical Parameters                          | Value |
|-----------------------------------------------|-------|
| Compressor unit rated power /kW               | 415   |
| Turbine generation system rated power / kW    | 500   |
| air storage vessel volume / m³                | 200   |
| air storage vessel pressure range /MPa        | 3~10  |
| efficiency /%                                 | 60    |
| Charge time / h                               | 4     |
| Discharge time / h                            | 2     |

| Table 3. The key parameters of M-CAES system |

| Name                                   | Value (Ten thousand yuan) |
|----------------------------------------|---------------------------|
| Total investment cost                  | 974.93                    |
| Equipment costs and installation costs | 774.18                    |
| Construction cost                      | 84.54                     |
| Other construction costs               | 77.5                      |
| Basic reserve                          | 38.71                     |

| Table 4. The cost of M-CAES during the construction period |
Time-of-use electricity prices are set as follows: the on-peak period is 8:00~13:00, 19:00~22:00, the electricity price is 1.231 yuan/kW·h; the off-peak period is 00:00~7:00, 14:00~18:00 and 23:00~24:00, the electricity price is 0.292 yuan/kW·h [17]. The heating and cooling price of the M-CAES is 0.56 yuan/kW·h [18]. During the construction period, the cost of M-CAES is shown in Table 4. As shown in Table 4, the total investment cost of the M-CAES is 974.93 ten thousand yuan.

6.2. Economic benefits analysis
The life-cycle benefit of different business models for the 1MW·h M-CAES system is shown in Table 5. As shown in Table 5, the IRR and NPV of cooperative investment model 1 are the largest among the four business models, and the CRP is also the smallest. The IRR, NPV, and CRP of cooperative investment model 2 and the single investment model are second and third, respectively. The life-cycle benefit of the financial crowdfunding model is the smallest. The maximum economic benefit is obtained by investors choosing the cooperative investment model 1. It can attract more investors to the construction M-CAES system. If the financial crowdfunding model is used, it increases investment risk and reduces investment enthusiasm. However, the cost of residents can be appropriately reduced, and the use of the M-CAES system can be promoted.

Table 5. Life cycle cost benefits of different business models.

| Investment models              | IRR /% | CRP /year | NPV /(Ten thousand yuan) |
|--------------------------------|--------|-----------|--------------------------|
| Single investment model        | 9.3%   | 10        | 120.97                   |
| Cooperative investment model 1 | 11.7%  | 8.2       | 359.08                   |
| Cooperative investment model 2 | 9.5%   | 10.1      | 139.13                   |
| Financial crowdfunding model   | 8.1%   | 11.2      | 2.4115                   |

6.3. Sensitivity analysis
The construction costs of compressed, government subsidies, and sales (lease) electricity prices of M-CAES are selected as economic uncertainties factor. The economic benefits of the M-CAES are analyzed by using uncertainties factor. So, the sensibility tendency trend of different business models for M-CAES in the range of -40% to 40% is obtained as shown in Figure 2, Figure 3 and Figure 4, respectively.

Figure 2. The sensibility tendency of sales (lease) electricity prices and government subsidies change.

Figure 3. The sensibility tendency of construction costs and government subsidies change.
Figure 4. The sensibility tendency of construction costs and sales (lease) electricity prices change.

As shown in Figure 2, Figure 3 and Figure 4, cost changes during the construction period have the greatest impact on the revenue of the four business models. The impact of sales (lease) electricity price changes on the revenue of the four business models is second. When construction costs and government subsidies change within the range of −40% to 40%, the maximum economic benefit of cooperative investment model 1 can be obtained, and the minimal economic benefit of the financial crowdfunding model can be obtained. When the price of the sales (lease) electricity prices is lower than -25%, the income of the financial crowdfunding model is greater than the cooperative investment model 1 and the cooperative investment model 2, but the income of the financial crowdfunding model is negative. When the construction costs and the sales (lease) electricity prices change lower than 20%, the income of the financial crowdfunding model is slightly lower than the cooperative investment model 1, and the income of the single investment model and cooperative investment model 2 is lower than the financial crowdfunding model. It can be seen from the above that cooperative investment model 1 can effectively reduce resident's expenses and promote the use of the M-CAES system when reducing construction costs and sales (lease) electricity prices. It can increase investment enthusiasm.

7. Conclusions

Considering the benefit evaluation problem of business models for the M-CAES, it was appeared to be “unrealistic” and relatively "rough" by using the initial investment. Therefore, to solve the above problem, a business model evaluation method of M-CAES considering the comprehensive cost in its life-cycle is proposed. Firstly, the business models of the micro compressed air energy storage system are designed. Secondly, a scheme of life-cycle cost/benefit assessment is proposed for M-CAES investment, including phases of construction cost, operation cost. Finally, the economic benefits of four business models are analyzed by the 1MW·h M-CAES system. Also, the sensibility tendency trend of different business models for M-CAES is obtained. The results show that the construction costs and the sales (lease) electricity prices have the greatest impact on the revenue of different business models. When we may reduce the construction costs and the sales (lease) electricity prices, cooperative investment model 1 can effectively reduce resident's expenses and promote the use of the M-CAES system. The theoretical reference and engineering instruction for the research and engineering application of M-CAES also are provided.

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