Application of Compressed Air Energy Storage in Urban Buildings Energy Supply

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Abstract: Urban buildings consume a lot of energy every year. Through analyzing the characteristics of urban buildings energy supply and compressed air energy storage (CAES) and considering the electric energy, thermal and cold energy output from CAES, this paper constructs the overall framework of CAES providing urban buildings with combined cooling, heating and power (CCHP), which can meet the energy demand of urban buildings, improve the system efficiency of CAES, make profit from the peak and valley electric charges difference of power grid, and it also has a broad range of popularization and application.

1. INTRODUCTION
Compressed air energy storage (CAES), having the advantages of large capacity, low pollution, distributed deployment and so on, is considered one of the most promising large-scale physical energy storage technologies [1,2,3].

Urban buildings energy consumption, which refers to the energy used by heating, ventilation, air conditioning, refrigeration and household electric appliances in urban buildings. To meet people’s demand for seeking a better life, it is necessary to ensure the safe and economical use of energy, reduce air and environmental pollution, and enhance people’s life comfort. China is a large construction country and consumes a lot of energy during the peak period of construction, mainly electric energy. Zhang et al. [4] established a CCHP model of advanced adiabatic compressed air energy storage (AA-CAES) system on the basis of changing the heat distribution in the thermal storage tank. The result showed that changing the output ratio of cooling, heating and power in the CCHP model by adjusting the heat distribution in the thermal storage tank, makes adaptability to load changes better. Yao et al. [5] presented a new CCHP system based on small CAES, and studied the dependence of system thermodynamic performance on
design variables through sensitivity analysis. Lv et al. [6] proposed a CAES-CCHP system based on electric energy peak load shifting, which confirmed the feasibility of this new system and its economical benefit compared with traditional CAES.

There are many present researches on the combination of CAES with power grid and new energy, such as wind energy, while fewer on CAES with multiple energy supply in urban buildings. This paper presents a CAES-CCHP system which can meet the multiple energy needs of urban buildings at the same time, and has a wide range of application prospects due to its higher conversion efficiency and profit margin.

2. URBAN BUILDINGS ENERGY SUPPLY ANALYSIS

Urban buildings are not only the place where humans live, but also the place where a lot of energy and resources are consumed. At present, the energy supply mode of urban buildings is generally: power grid + boiler + air conditioning (compression refrigeration unit), which are shown in Fig. 1.

![Figure 1. Schematic diagram of energy supply for Typical urban buildings](image)

The 10kV bus in the power grid is converted to 380V/220V through step-down transformer, and input into urban buildings for users throughout the year.

The fuel is burned in the boiler to release heat to heating the water and output hot water/steam. The boiler usually provides domestic hot water for users and heating in winter.

In summer, turning on compression refrigeration unit and increasing the pressure of refrigerant by a compressor is to achieve the refrigeration cycle, which provides the cold air for air conditioning system.

![Figure 2. Energy consumption for typical urban buildings during a year](image)

Fig. 2 shows the energy consumption diagram of typical urban buildings during a year. It can be seen from Fig. 2 that the demand for electric energy in the building is relatively average in the whole year, and the change is relatively gentle. Then, heat is needed throughout the year, and it accounts for a large proportion in winter, cold energy is mainly needed in summer.
3. CAES ENERGY SUPPLY ANALYSIS

3.1 Working process

Fig. 3 illustrates the working process of CAES. Among them, 1 means motor, 2 means compressor, 3 means storage tank, 4 means turbine, 5 means generator.

![Figure 3. Schematic diagram of working process of CAES](image)

Working process:

To realize the storage of electric energy in the energy storage stage, the remaining power or new energy power in the power grid drives the multistage compressor unit to compress air to a state of high temperature and pressure, and at the same time, the medium in the cold storage tank collects compression heat through heat exchanger and store it in the thermal storage tank. Then, the air gets into the storage tank at a high-pressure state.

In the energy release stage, the high-pressure air is released from the gas storage tank, reheated by the medium in the heat exchanger, and finally expanded in the turbine to drive the generator to generate electricity. CAES can output heat and cold energy respectively in the compression and expansion stage.

3.2 Mathematical model

According to conservation of mass and energy, ideal gas state equation and the fundamental laws of thermodynamics, the mathematical model of each component of CAES is established. The compressor adopts adiabatic compression mode and compresses the intake air with the set compression ratio to obtain high-pressure air. The turbine adopts adiabatic expansion mode, and works with the expansion of high-pressure air at rated expansion ratio.

From the mass conservation equation:

$$\frac{dm}{dt} = m_{out} - m_{in}$$  \hspace{1cm} (1)

Where $m$ is the air mass, $m_{out}$ and $m_{in}$ respectively represent the air mass with outlet and inlet.

From the energy conservation equation:

$$\frac{d(pu)}{dt} = m_{out}h_{out} - m_{in}h_{in} - Q + W_s$$  \hspace{1cm} (2)

Where $V$ is the air volume (m$^3$), $\rho$ is the air density(kg/m$^3$), $h_{out}$ is the enthalpy of the outlet air (J/kg), $h_{in}$ is the enthalpy of the inlet air (J/kg), $Q$ is the heat loss (J), $W_s$ the work done by the outside world in the air (J).

The exhaust temperature and consumed power of the compressor can be respectively expressed as Equations (3) and (4):

$$T_e = T_i \cdot \varepsilon_c^{k-1}$$  \hspace{1cm} (3)

Where $T_e$ is the exhaust temperature of the compressor (K), $T_i$ is the inlet temperature of the compressor (K), $\varepsilon_c$ is the compression ratio, $k$ is the adiabatic exponent.
\[ P_c = P \cdot V \cdot \frac{k}{k-1} \left(\frac{k-1}{\varepsilon_t^k - 1}\right) \]  

(4)

Where \( P_c \) is the consumed power of the compressor (kW), \( P \) is the air pressure (Pa).

The exhaust temperature and consumed power of the turbine can be respectively expressed as Equations (5) and (6):

\[ T_t = T_i \cdot \varepsilon_t^k \]  

(5)

\[ P_t = P \cdot V \cdot \frac{k}{k-1} \left(\frac{k-1}{\varepsilon_t^k - 1}\right) \]  

(6)

Where \( T_t \) is the exhaust temperature of the turbine (K), \( \varepsilon_t \) is the expansion ratio, \( P_t \) is the consumed power of the turbine (kW).

3.3 Efficiency analysis

CAES just stores and releases electric energy, and its electric efficiency (electric energy output divided by electrical energy input) is described by:

\[ \eta_e = \frac{E_{\text{out}}}{E_{\text{in}}} \]  

(7)

Where \( \eta_e \) is the electric efficiency, \( E_{\text{out}} \) is electrical energy output in a complete cycle of energy storage and release, \( E_{\text{in}} \) the electrical energy input in a complete cycle of energy storage and release. And according to the current technical practice, the electric efficiency of 10MW CAES system can reach 60%.

CAES system can provide three kinds of energy, including electric energy, thermal and cold energy. Based on the first law of thermodynamics and conservation of energy quantity, which reveals the law of quantity transfer and conversion of energy in the CAES system, this paper characterizes the total energy utilization of the CAES system.

System total energy efficiency is defined as the sum of electric energy, thermal and cold energy output divided by electrical energy input in a complete cycle of energy storage and release, which can be expressed as:

\[ \eta_{en} = \frac{E_{\text{out}} + Q_{h,\text{out}} + Q_{c,\text{out}}}{E_{\text{in}}} \]  

(8)

Where \( \eta_{en} \) the system total energy efficiency, \( Q_{h,\text{out}} \) is the thermal energy output, \( Q_{c,\text{out}} \) is the cold energy output. Under the identical conditions, the system total energy efficiency is increased by more than 20% compared with the electric efficiency.

4. APPLICATION SCENARIOS

4.1 Overall framework

The main energy consumption in urban buildings is electric energy, thermal and cold energy.

Electric energy is provided by power grid. Thermal energy is provided by heating companies or separate boilers. And cold energy is generally provided by air conditioning, which is powered by electricity or fuel gas.

Among of these energy, electric energy is the widest used, mainly in the public part and indoor part. The public part includes public lighting, elevators, and central air conditioning, and the indoor part is household electric appliance or office equipment, such as water heaters, air conditioning, refrigerators, computers, and indoor lighting.
The application of heat is mainly for air conditioning heating, domestic hot water, heating. And air conditioning cooling is the main application of cold energy.

According to the characters of CAES, we have constructed the overall framework of CAES providing urban buildings with electric energy, thermal and cold energy at the same time, which are shown in Fig. 4.

![Figure 4. Overall framework diagram of CAES-CCHP in urban buildings](image)

CAES system can simultaneously provide electric energy, thermal and cold energy to users with different needs in urban buildings.

### 4.2 Electric Energy

The daily electric energy load of typical urban buildings is shown in Fig. 5. There are two peaks every day, one is the morning peak which usually appears from 7:00 to 11:00, another is the evening peak generally appearing from 17:00 to 21:00. And the night from 1:00 to 6:00 is valley.

![Figure 5. Daily electricity consumption of typical urban buildings](image)

According to the peak-valley characteristics of electricity, in the world many countries have implemented the policy that electricity prices are different at different times. Table 1 shows the peak-valley difference electricity prices of major provinces and cities in China. In view of the electricity prices difference between peak and valley, the power department can use price signals to guide users’ electricity usage, which is useful to achieve the power peak load shifting in the power demand side.

| Areas   | Peak price | Valley price | Parity price | Difference |
|---------|------------|--------------|--------------|------------|
| Beijing | 1.466      | 0.3113       | 0.8110       | 1.1547     |
| Shanghai| 1.022      | 0.22         | 0.634        | 0.802      |
| Tianjin | 1.0945     | 0.4432       | 0.7277       | 0.6513     |
| Henan   | 1.0129     | 0.3445       | 0.6568       | 0.6684     |

Table 1. Peak-valley difference electricity price table of major provinces and cities in China
### Table

| Areas  | Peak price | Valley price | Parity price | Difference |
|--------|------------|--------------|--------------|------------|
| Jiangsu| 1.1757     | 0.3351       | 0.7054       | 0.8406     |
| Zhejiang| 1.2619   | 0.4339       | 0.9569       | 0.828      |
| Shandong| 1.0947    | 0.3425       | 0.6559       | 0.7522     |

Through storing energy at the valley with low electric price, and releasing energy at the peak with high electric price, CAES system can make profit from the peak and valley electric price difference of power grid.

#### 4.3 Thermal energy

CAES releases a large amount of heat during the compression process. And if the heat is not recycled in multi-stage compression, the final temperature of air will reach 400~600℃.

The heat is directly supplied to domestic hot water, air conditioning and heating in the urban buildings after heating the water through the heat exchanger. Referring to the current exhaust temperature of air conditioning heating, the steam / hot water in a temperature range of 20 ~ 50℃ can directly flow into the building environment for heating, while the air above 70℃ can be used to produce domestic hot water through the heat exchanger.

#### 4.4 Cold energy

CAES stores a lot of heat during the expansion process. The cold energy recovered by the heat exchanger in multi-stage expansion can keep the exhaust temperature of turbine more than 0℃, which can prevent the moisture in the air from freezing to damage the high-speed rotating turbine impeller.

There are two ways to apply cold energy to the building environment. One is the exhaust gas of the turbine directly act with air conditioning and refrigeration system. The other is to apply the cooling medium of the cold storage tank to the air conditioning and refrigeration system through the heat exchanger.

### 5. CONCLUSION

The energy storage and power generation phases of CAES are separately carried out. Therefore, CAES can participate in the primary frequency regulation of power grid on the power generation side and power side.

1) CAES can output electric energy, thermal and cold energy, which can meet the energy demand of urban buildings. At the same time, it can improve the overall system efficiency of CAES.

2) CAES stores energy during the valley of the power grid, while releases electricity during the peak. For this, it can get profits from the peak and valley charge difference. Meanwhile, it is also a way to gain earnings by providing thermal and cold energy.

3) The next step is to strengthen the coupling utilization with new energy such as wind energy and photovoltaic, wind turbines and photovoltaic power generation panels are arranged in urban buildings. The excess power of wind turbines drive the compressor to compress and store the compressed air by the valley of the power grid. Meanwhile, the solar thermal energy is stored in heat storage device, which effectively improve the efficiency of new energy utilization system.

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