Theoretical investigation of a closed liquid CO₂ energy storage system

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Abstract. In order to overcome the disadvantages of uncertainty, randomness and intermittency brought by wind and solar energy, different energy storage systems were put forwarded. Liquid air energy storage is an important technology in solving the grid connection problem of large-scale renewable energy. However, the production of liquid air needs a cryogenic liquefaction technology below a temperature of -150°C, which has a high facility cost and cold loss. Therefore a closed hybrid wind-solar-liquid CO₂ energy storage (WS-LCES) system was proposed. In the WS-LCES system, wind power was used to liquefy CO₂ and the CO₂ was stored in liquid phase with different pressures (90 bar and 8 bar) and temperatures (35°C and -45°C) at both energy storage and release stages. Also, the solar power was stored to increase the energy storage efficiency. For the high density of liquid CO₂, the system has a large storage capacity and no geographic constraints. A thermodynamic and parametric analysis was conducted to investigate the optimum system performance.

1. Introduction

With the increasing penetration of renewable energy in the electricity market, the problems of energy crisis and global warming have been mitigated. However, due to the characteristics of randomness and intermittency of renewable energy, huge impacts to the power grid such as the operation mode, reliability, power quality and operation costs will be brought [1-2]. Thus the energy storage system has been developed to improve the application of renewable energy. Currently, available energy storage system can be classified into (1) Superconducting magnetic energy storage (SMES); (2) Pumped hydro energy storage (PHES); (3) Compressed air energy storage (CAES); (4) Flywheel energy storage (FES); (5) Battery energy storage (BES) [3]. Nevertheless, for grid-scale electric energy storage, only PHES and CAES can be considered as practical methods. But both of them have a fatal shortcoming, which is geographic constraint. PHES needs a geopotential difference while CAES needs a large underground cavern. Unfortunately, ideal locations are very scarce.

In the past few years, different energy storage technologies which are efficient and geographically unconstrained have been investigated. Among those innovative proposals, liquid air energy storage
(LAES) seems to be the most promising. Energy is stored in the form of liquid air which can considerably reduce the storage volume and overcome the geographical constraints. A lot of LAES concepts exist at different levels of development [4-8]. Nevertheless, the production of liquid air needs a cryogenic liquefaction technology below a temperature of -150°C, which has a high facility cost and cold loss, leading to a low cycle efficiency. Thus Wang [9-10] provided a novel energy storage system based on liquid CO₂. The mathematical model was developed and the parametric analysis was conducted to examine the effect of some key thermodynamic parameters on the system performance. Compared with LAES, the liquid CO₂ energy storage (LCES) has a higher cycle efficiency of 56.64%.

However, constrained by current compressor technology, a high temperature of compression heat cannot be reached. Consequently, the electric power generated during energy release process in the LCES system mentioned above will be difficult to enlarge and may not meet the requirements of grid-scale energy storage. Also, fossil fuels are unwelcome for renewable energy conversion.

Therefore, a novel hybrid wind-solar-liquid CO₂ energy storage (WS-LCES) system is proposed to overcome the disadvantage of the available LCES concepts. During the energy storage process, wind and solar power were stored in the forms of liquid CO₂ and thermal energy, respectively. Then during the energy release process, a stable output of both electric energy and hot water are provided. In addition, the low pressure CO₂ was condensed again by a self-throttling process. Hence, the cascade utilization of energy with different qualities was achieved in the closed WS-LAES system. Furthermore, the thermodynamic analysis and parametric sensitivity analysis were carried out for this system.

2. System description

Figure 1 shows the schematic diagram of the proposed WS-LCES system. The system is mainly composed of four units, including the wind power storage unit, solar heat storage unit, turbo-generation unit and CO₂ liquefaction unit. The wind power storage unit contains a compressor train (CP1-CP4), four intercoolers (IC1-IC4), a cold water tank (CWT), a hot water tank (HWT) and a liquid CO₂ tank (LCT1). The solar heat storage unit consists of a solar thermal collector (STC), a cold oil tank (COT) and a hot oil tank (HOT). The turbo-generation unit includes a liquid CO₂ pump (LCP), a preheater (HX1), a CO₂ turbine (CTB) and an aftercooler (HX2). The liquefaction unit includes a regenerator (RG), a liquid CO₂ tank (LCT2) and a throttle valve (TV).

During energy storage process, the low pressure liquid CO₂ from LCT2 was firstly throttled by TV to provide cold energy in RG and evaporates. Then the compressor train is driven by electricity generated by wind power to produce high pressure CO₂. Simultaneously, the CO₂ after each stage of compressor is cooled in intercoolers by cold water sequentially and the compression heat is transferred to hot water. Then the high pressure CO₂ is liquefied and stored in LCT1. Meanwhile, low temperature thermal oil is heated by STC to reach a high temperature and then stored in HOT. As a result, intermittent wind and solar power are both stored in different forms.

During energy release process, liquid CO₂ is pumped from LCT1 to a designed inlet pressure of CTB. Before entering CTB, the liquid CO₂ is preheated by high temperature thermal oil in HX1. Then it expands in CTB to generate shaft work. A generator coaxially connected to CTB is employed to produce electric energy. Also, the waste heat from expanded CO₂ was utilized to produce hot water. After this, the low pressure CO₂ was condensed in RG and stored in LCT2.
3. Thermodynamic analysis model

To simplify the analysis of the proposed WS-LCES system, some reasonable assumptions were made as follows:

a. The CO$_2$ was treated as ideal gas.
b. The pressure drop of each heat exchanger and pipe was neglected.
c. All the operation processes reached steady state.

3.1. Energy analysis model

The power consumption of compressor train is:

$$W_{CP} = \sum_i W_{CPi} = \sum_i m_{C1}[h_{C2i} - h_{C(2i-1)}], \quad i = 1 - 4$$

(1)

where $m$ is the mass flow, $h$ is the specific enthalpy, the subscripts $C$ and $i$ represent CO$_2$ and the sequence number for each stage of compressor, respectively.

The output power of CO$_2$ turbine is:

$$W_{CTB} = m_{C12}(h_{C12} - h_{C13})$$

(2)

For the liquid CO$_2$ pump, the power consumption can be calculated as:

$$W_{LCP} = m_{C10}(h_{C11} - h_{C10})$$

(3)

Therefore, the net power output during energy release process can be expressed as:

$$W_{net} = W_{CTB} - W_{LCP}$$

(4)

For all the heat exchangers (IC1-IC4, HX1-HX2 and RG), the unified energy balance equation is:

$$m_H (h_{H,in} - h_{H,out}) = m_C (h_{C,out} - h_{C,in})$$

(5)
where the subscript \( H, C, \) in and out represent hot fluid, cold fluid, inlet and outlet, respectively.

For the solar thermal collector, the effectively absorbed solar heat is:

\[
Q_{STC} = m_o (h_{02} - h_{01})
\]

where the subscript \( O \) represents thermal oil.

For the throttle valve, the energy balance equation is:

\[
h_{c16} = h_{c17}
\]

### 3.2. Exergy analysis model

As energy analysis was incapable of quantifying the qualities of different types of energy, exergy analysis was conducted to reveal the exergy destruction and irreversibility of each component. Generally, the enthalpy exergy of each state point can be written as:

\[
Ex_j = (h_j - h_0) - T_0(s_j - s_0)
\]

where \( s \) is the specific entropy, the subscripts \( j \) and \( 0 \) represent stream number and ambient condition, respectively.

For each component, the unified exergy destruction equation can be given as:

\[
l = \sum Ex_{in} - \sum Ex_{out}
\]

### 3.3. Performance assessment indexes

Generally, electric energy storage efficiency (ESE) can be used to measure the performance of a LCES system. It is expressed as a ratio of the net power output during energy release process to the net power input during energy storage process, which is:

\[
ESE = \frac{W_{net}}{W_{CP}}
\]

However, in the WS-LCES system, there are different types of energy input and output, which are the electric power and thermal energy. To obtain more comprehensive evaluation criteria, two indexes are adopted below.

The exergy efficiency is the ratio of the total exergy output during energy release process to the total exergy input during energy storage process, which is:

\[
\eta_{ex} = \frac{Ex_{output}}{Ex_{input}}
\]

To assess the energy storage density, an index of energy generated per unit volume of the liquid CO\(_2\) tank (EPV) is employed here, which is:

\[
EPV = \frac{W_{net}}{V_{LCT1} + V_{LCT2}}
\]

### 4. Results and discussions

The thermodynamic simulation was carried out to validate the proposed WS-LCES system. All the components and streams in Figure 1 were analyzed, and some key alterable parameters were studied.
4.1. Thermodynamic simulation results
Table 1 shows the simulation results of the proposed WS-LCES system. All the parameters in this simulation were set based on current industrial level. For example, the isentropic efficiency of the turbine and pump were set as 85% and 80%, respectively. According to reference [3], therminol 66 was chosen for solar thermal collector for its high boiling point. Also, the temperature of hot water is 60°C which is the recommended value for hot water supply in China. Besides, the environmental temperature is 25°C and the inlet and outlet oil temperatures of STC are 50°C and 310°C, respectively. The outlet pressure of CO₂ after expansion is 8 bar. The $\eta_{ex}$ of WS-LCES is 58.64%, which is higher than that (56.64%) in reference [9].

Table 1. Simulation results of the proposed WS-LCES system.

| Term                        | Unit     | Value  |
|-----------------------------|----------|--------|
| Power of CP1-CP4            | kW       | 9370   |
| Power of LCP               | kW       | 695    |
| Power of CTB               | kW       | 10490  |
| Net output power           | kW       | 9790   |
| Heat absorption of STC      | kW       | 22300  |
| Mass flow of CO₂           | kg/h     | 196300 |
| Mass flow of hot water (60°C) | t/h   | 521    |
| ESE                        | %        | 104.5  |
| $\eta_{ex}$                | %        | 58.64  |
| EPV                        | kWh/m³   | 19.31  |

4.2. Parametric sensitivity analysis
Figure 2 shows that the ESE and $\eta_{ex}$ both increase with the increasing compressor adiabatic efficiency, for a lower power consumption of compressor was needed under a higher adiabatic efficiency. But the adiabatic efficiency is constrained by available technology. As no parameters change for the CO₂ turbine, the EPV remains a constant value.

Figure 2. Effect of compressor adiabatic efficiency on ESE, $\eta_{ex}$ and EPV.
Figure 3 presents the effect of CO₂ turbine inlet pressure on ESE, \( \eta_{ex} \) and EPV. As the power of CO₂ turbine and liquid CO₂ pump both increase with the increasing turbine inlet pressure, the net output power only has a small increase. Besides, as no parameters change for the compressor, the power consumption of compressor remains a constant value. Therefore all the three indexes have little change. However, the equipment cost increases significantly with the increasing pressure. Thus the optimum CO₂ turbine inlet pressure should not be too high.

![Figure 3. Effect of CO₂ turbine inlet pressure on ESE, \( \eta_{ex} \) and EPV.](image)

Figure 4 shows that both the ESE and EPV increase with the CO₂ turbine inlet temperature as a result of a higher enthalpy drop, which leads to a larger output power of CO₂ turbine. But a greater heat absorption of solar thermal collector is needed, so the \( \eta_{ex} \) decrease with the increase of the CO₂ turbine inlet temperature. Therefore the optimum CO₂ turbine inlet temperature is chosen by the tradeoff between the ESE and \( \eta_{ex} \).

![Figure 4. Effect of CO₂ turbine inlet temperature on ESE, \( \eta_{ex} \) and EPV.](image)

5. Conclusions
In order to solve the problem in utilizing the unstable wind and solar energy, a novel hybrid WS-LCES
system was proposed and analyzed. The WS-LCES system can absorb wind power and solar heat during energy storage process, while yielding electric energy and hot water during energy release process. Also, the CO₂ was liquefied in both the energy storage and release stage, overcoming the difficulties of CO₂ storage. Moreover, the thermodynamic analysis and parametric sensitivity analysis were both conducted to investigate the optimum system performance. The results show that the ESE, \( \eta_{ex} \) and EPV can reach 104.5%, 58.64% and 19.31 kWh/m³ under the design conditions, respectively. Besides, 10490 kW electric power and 521 t/h hot water (60 °C) can be obtained within one energy storage cycle.

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