Thermodynamic characteristics of a novel wind-solar-liquid air energy storage system

W Ji¹,², Y Zhou¹, Y Sun¹, W Zhang¹, C Z Pan¹ and J J Wang¹, ²

¹CAS Key Laboratory of Cryogenics, Technical Institute of Physics and Chemistry, Beijing 100190, China
²University of Chinese Academy of Sciences, Beijing 100049, China

E-mail: 13810112937@163.com

Abstract. Due to the nature of fluctuation and intermittency, the utilization of wind and solar power will bring a huge impact to the power grid management. Therefore a novel hybrid wind-solar-liquid air energy storage (WS-LAES) system was proposed. In this system, wind and solar power are stored in the form of liquid air by cryogenic liquefaction technology and thermal energy by solar thermal collector, respectively. Owing to the high density of liquid air, the system has a large storage capacity and no geographic constraints. The WS-LAES system can store unstable wind and solar power for a stable output of electric energy and hot water. Moreover, a thermodynamic analysis was carried out to investigate the best system performance. The result shows that the increases of compressor adiabatic efficiency, turbine inlet pressure and inlet temperature all have a beneficial effect.

1. Introduction

With the emergence of energy crisis and growing global warming problem, renewable energy has embraced an increasing presence in the electricity market. However, due to the nature of great uncertainty, randomness and intermittency of renewable energy, it will bring huge impacts such as power grid management, operation mode, reliability, power quality and operation costs to the power grid [1-3]. Thus a energy storage system is 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). Nevertheless, for grid-scale electric energy storage, only PHES and CAES can be considered as practical methods. Although both of them have mature application cases, they share a fatal shortcoming, which is geographic constraint. PHES needs a geopotential difference while CAES needs a large underground cavern. Unfortunately, ideal locations are hard to find, and the most attractive sites have already been used.

During recent years, different technologies have been studied to provide an efficient, geographically unconstrained and environmentally safe energy storage system. Among the innovative proposals for
energy storage, liquid air energy storage (LAES) seems to be the most promising. It relies on mature air liquefaction technology and equipment. Energy is stored in the form of liquid air which can considerably reduce the storage volume and no special geographic condition is required.

A number of LAES concepts exist at different levels of development with respective strengths and weaknesses. Ameel [4] conducted an analysis of the efficiency of storing liquefied air, starting from a basic thermodynamic cycle to a more complex combined cycle. It showed a conversion efficiency of 20 to 50%. Li [5] proposed a novel technology by integrating nuclear power generation with LAES. It could deliver around three times the rated electrical power of the nuclear power plant at peak hours. Morgan [6] presented an analysis and results from the design and testing of a novel pilot scale LAES prototype. The cycle efficiency was greatly improved through the storage and recycling of thermal energy. Guizzi [7] carried out a thermodynamic analysis of a LAES plant with the heat input in the energy recovery section provided by heat stored during the air liquefaction process. The results showed a global efficiency of 50% can be considered within reach. Sciacovelli [8] developed a validated model to address the dynamic performance of LAES. They found the temporary storage of cold thermal energy using packed beds with rocks as filler improves efficiency of LAES by 50%. Antonelli [9] presents a study about a hybrid solution including a large scale energy storage system coupled with power generation and fast responding energy storage systems. Li [10] provided a novel LAES system utilizing LNG cold energy to increase the air liquefaction ratio.

However, constrained by present compressor technology in China, the temperature of thermal energy stored during compression cannot be very high. Consequently, the electric power generated during energy release process in the previously mentioned LAES system will be difficult to enlarge and may not meet the requirements of grid-scale energy storage. Also, fossil fuels used in Ref. [9] are not preferable for renewable energy conversion. Therefore, a novel hybrid wind-solar-liquid air energy storage (WS-LAES) system is proposed to overcome the disadvantages of those available LAES concepts. During the energy storage process, wind and solar power are stored in the forms of liquid air and thermal energy, respectively. Then during the energy release process, liquid air is pumped and gasified to expand in an air turbine for power generation. Before entering the air turbine, the air is preheated by the stored thermal energy to increase generation capacity. In addition, the compression heat is employed to produce hot water. Hence, the cascade utilization of energy with different qualities was achieved in the WS-LAES system. Meanwhile, the good result is that unstable wind and solar power are both stored for a stable output of electric energy and hot water. 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-LAES system. The system is mainly composed of three units, i.e. wind power storage unit, solar heat storage unit and turbo-generation 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), two precoolers (HX1 and HX2), four refrigerant tanks (RT1-RT4), a throttle valve (TV), a liquid-vapor separator (SEP) and a liquid air tank (LAT). 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 air pump (LAP), two regenerators (HX3 and HX4), a preheater (HX5) and an air turbine (ATB).
During energy storage process, the compressor train is driven by electricity generated by wind power to produce high pressure air. Simultaneously, the air after each stage of compressor is cooled in intercoolers by cold water sequentially and the compression heat is transferred to hot water for domestic use. Then the high pressure air is precooled and throttled to produce liquid air stored in the LAT while the gaseous air backflows to help precool the air. The stored cryogenic refrigerants can also supplement the cold energy needed in HX1 and HX2. Meanwhile, low temperature thermal oil is heated by the solar thermal collector to get a high temperature and then stored in the HOT. As a result, intermittent wind and solar power are both stored in different forms.

During energy release process, liquid air is pumped from the LAT to a designed inlet pressure of air turbine. Before entering the air turbine, the liquid air is regenerated by the stored refrigerants to the environment temperature in HX3 and HX4. The air is preheated by high temperature thermal oil in HX5. Then it expands in the air turbine to generate shaft work. A generator coaxially connected to this air turbine is employed to produce electric energy.

3. Thermodynamic analysis model
To simplify the analysis of the proposed WS-LAES system, some reasonable assumptions are made as follows:
a. The air is treated as ideal gas.
b. The pressure drop of each heat exchanger and pipe is neglected.
c. All the operation processes reach steady state.

3.1. Energy analysis model
The energy analysis of the WS-LAES system is based on the first law of thermodynamics. It describes the process of energy transfer and conversion of each component.

The power consumption of compressor train is:

$$ W_{CP} = \sum_{i} W_{CPi} = \sum_{i} m_{A1} [h_{A2i} - h_{A(2i-1)}] , \ i = 1 - 4 $$

(1)

where \( m \) is the mass flow, \( h \) is the specific enthalpy, the subscripts \( A \) and \( i \) represent air and the sequence number for each stage of compressor, respectively.

For the throttle valve, the energy balance equation is:

$$ h_{A11} = h_{A12} $$

(2)

The output power of air turbine is:

$$ W_{ATB} = m_{A21} (h_{A21} - h_{A22}) $$

(3)

For the liquid air pump, the power consumption can be calculated as:

$$ W_{LAP} = m_{A17} (h_{A18} - h_{A17}) $$

(4)

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

$$ W_{net} = W_{ATB} - W_{LAP} $$

(5)

For all the heat exchangers (IC1-IC4 and HX1-HX5), the unified energy balance equation is:

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

(6)

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:

$$ Q_{STC} = m_{O2} (h_{O3} - h_{O2}) $$

(7)

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

3.2. Exergy analysis model
Although energy analysis can depict the energy flow in the WS-LAES system, it fails to quantify the qualities of different types of energy. Thus exergy analysis is also conducted here to tell the exergy destruction and irreversibility of each component. Generally, the enthalpy exergy of each state point can be written as:

$$ Ex_j = (h_j - h_0) - T_0 (s_j - s_0) $$

(8)

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:
\[ I = \sum Ex_{in} - \sum Ex_{out} \]  

(9)

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

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

(10)

However, in the WS-LAES system, there are different types of energy input and output, i.e. the electric power and thermal energy. In order to obtain more comprehensive evaluation criteria, two indexes are suggested 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:

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

(11)

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

\[ EPV = \frac{W_{net}}{V_{LAT}} \]  

(12)

4. Results and discussions
Based on the calculation methodology listed above, a thermodynamic simulation was carried out to validate the proposed WS-LAES system. All the components and streams in Figure 1 were analyzed, and some key alterable parameters were studied.

4.1. Thermodynamic simulation results
Some input parameters in this simulation are set to that of wind-solar-compressed air energy storage (WS-CAES) in Ref. [11] to make a comparison. The therminol 66 was chosen for solar thermal collector for its high boiling point. Considering the temperature zone of air liquefaction process, two refrigerants of R123 (dichlorotrifluoromethane) and propane were selected as the cold energy storage medium. Both of them have high heat capacity and would not solidify at respective working temperatures. Also, the temperature of hot water is 60 °C which is the recommended value for hot water supply in China.

Table 1 shows the performance comparison between the proposed WS-LAES and the WS-CAES in Ref. [11]. The ESE and \( \eta_{ex} \) of WS-LAES is less than that of WS-CAES because of a relatively low air liquefaction efficiency under the air pressure of 5.6 MPa. Also, the solar energy absorbed in WS-LAES is less than that in WS-CAES. However, the mass of hot water and EPV in WS-LAES are 2.2 times and 17.7 times of that in WS-CAES, respectively. This is because the density of liquid air is far larger than that of compressed air.
Table 1. Comparison between the proposed WS-LAES and the WS-CAES.

|                           | WS-LAES | WS-CAES [11] |
|---------------------------|---------|--------------|
| Power of compressor (kWh) | 8538    | 9178         |
| Power of air turbine (kWh)| 3900    | 7231         |
| Heat absorption of solar thermal collector (kWh) | 3827 | 10500 |
| Temperature of hot water (℃) | 60   | 60.5         |
| Mass of hot water (ton/day) | 205  | 94           |
| ESE (%)                   | 45.7    | 87.7         |
| $\eta_{ex}$ (%)           | 44.2    | 65.4         |
| EPV (kWh/m$^3$)           | 74.5    | 4.19         |

4.2. Parametric sensitivity analysis

Figure 2 shows that the ESE and $\eta_{ex}$ both increase with the increasing compressor adiabatic efficiency. Because the power consumption of compressor chain decreases as the adiabatic efficiency increases. Although a high adiabatic efficiency is beneficial, it bears a limit constrained by available technology. As no parameters change for the air turbine, the EPV remains a constant value of 74.5 kWh/m$^3$.

Figure 2. Effect of compressor adiabatic efficiency on ESE, $\eta_{ex}$ and EPV.

Figure 3 presents the effect of air turbine inlet pressure on ESE, $\eta_{ex}$ and EPV. As shown in Figure 3, all the three indexes embrace an increase with the increasing air turbine inlet pressure attributed to a larger power of air turbine under higher air turbine inlet pressure. Meanwhile, the increase of power consumption of liquid air pump is negligible. However, the growth rate gradually slows down while the equipment cost increases along with the increasing pressure. Thus the optimum air turbine inlet pressure is chosen by a tradeoff between the system performance and the economic cost.
Figure 3. Effect of air turbine inlet pressure on ESE, $\eta_{ex}$ and EPV.

Figure 4 shows that the ESE, $\eta_{ex}$ and EPV all increase with the air turbine inlet temperature as a result of greater heat absorption of solar thermal collector, which leads to a larger output power of air turbine. Therefore, a higher air turbine inlet temperature is preferable, but it is constrained by the properties of thermal oil. Nevertheless, as the input exergy of high temperature solar heat keeps increasing while the power of compressor remains constant, the growth rate of ESE is larger than that of $\eta_{ex}$.

Figure 4. Effect of air turbine inlet temperature on ESE, $\eta_{ex}$ and EPV.

5. Conclusions
For the purpose of solving difficulties in utilizing the unstable wind and solar power, a novel hybrid WS-LAES system was proposed and evaluated. The WS-LAES system can absorb wind power and solar heat during energy storage process, while yielding electric energy and hot water during energy release process. Moreover, the thermodynamic analysis and parametric sensitivity analysis were both
presented to investigate the best system performance. The results show that the ESE, $\eta_{ex}$, and EPV can reach 45.7%, 44.2% and 74.4 kWh/m$^3$ under the design conditions, respectively. Besides, 3900 kWh electric power and 205 tons/day of hot water with a temperature of 60 °C can be produced within a cycle. Considering the great advantage of high energy storage density, the WS-LAES system will be further studied in the future.

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