A review of energy storage and its utilization in Integrated Energy Systems

Wenjia Ji¹, Han Zhang², Fei Ding³, Jiale Wang⁴, Rui Zhang⁵, Su Guo⁶*

¹College of Energy and Electrical Engineering, Hohai University, Nanjing, Jiangsu, 211100, China
²College of Energy and Electrical Engineering, Hohai University, Nanjing, Jiangsu, 211100, China
³College of Energy and Electrical Engineering, Hohai University, Nanjing, Jiangsu, 211100, China
⁴College of Energy and Electrical Engineering, Hohai University, Nanjing, Jiangsu, 211100, China
⁵College of Energy and Electrical Engineering, Hohai University, Nanjing, Jiangsu, 211100, China
⁶College of Energy and Electrical Engineering, Hohai University, Nanjing, Jiangsu, 211100, China
*Corresponding author’s e-mail: guosu81@126.com

Abstract. Energy storage system is the central facility in the Integrated Energy System. It plays a significant role in the stable operation of the system and the distribution of the renewable energy sources. This thesis is based on the overall consideration of diverse systems and make a review of the different working conditions, classification, constraint conditions, operational modes and so on in the energy storage system.

1. Introduction
Energy Storing System(ESS), the core of Integrated Energy System(IES), is the key device to realize the high-efficiency operation of IES. Energy storage is a procedure to make energy stored by means of mediums or devices, and release the energy when used. To the demand side, it can be used in the management of demand and the energy emergency. Because energy supply is often planned, designed and operated independently, energy storage technology is a necessary supporting technology to coordinate all kinds of energy conversion and adapt to load demand in IESs.

In [1-2,9], it explains and classifies the energy storage technology, and explains the function of ESS in IESs. In [3-5], the working models, constraints and working modes of gas, heat and electricity energy storage are analysed, and the profit strategy of energy storage scheduling in Integrated Energy System is put forward. In [6-8,10-12], it briefly introduces some typical utilization of IES and functions and advantages of the IES. In [13-16], the synergies among gas, electricity and heating storage are discussed, including their affect to each other and their economy, with specific applications and characteristics.
In this paper, we conclude the significance, working constraints and working modes of energy storage in Integrated Energy Systems, and also summarize the influence factors of the configuration between heat and power. At last, we analyse the synergies among gas, power and heat storage, which can influence the working and economy efficiency of Integrated Energy Systems.

2. Significant of energy storage in Integrated Energy Systems
The obvious randomness, indirectness and uncertainty of renewable energy sources will inevitably lead to inadequate and untimely use of renewable energy. At this time, the energy storage system in the role of integrated energy will appear. It includes:
- Maintaining the stability of the system operation.
- Reasonable regulation of energy distribution.
- Realizing the cascade utilization of energy.
- Choosing a reasonable mode of operation.
- Increasing profitability.
- Connecting objects of energy production and utilization.

3. Models of energy storage
Generally speaking, electricity, heat, gas three kinds of energy use is more universal in IESs, and then the three kinds of energy storage methods are discussed.

1. Electrical power storage:
The storage capacity is related to the charging and discharging power and efficiency, and satisfies the following relations:

$$E(t) = E(0) + \int_0^t \left[ \eta_{e,store} P_{e,store}(t) - \frac{P_{e,release}(t)}{\eta_{e,release}} \right] dt$$  \hspace{1cm} (1)

In equation (1), $P_{e,store}(t)$, $P_{e,release}(t)$, $\eta_{e,store}$, $\eta_{e,release}$ are the charging and discharging power and efficiency at time $t$ respectively.

2. Thermal energy storage:
The storage characteristics of thermal energy storage show the relationship between storage capacity, input power and thermal efficiency. The mathematical model can be expressed as:

$$H(t) = H(0) + \int_0^t \left[ \eta_{h,store} P_{h,store}(t) - \frac{P_{h,release}(t)}{\eta_{h,release}} \right] dt - \eta_T H(0)$$ \hspace{1cm} (2)

In equation (2), $\eta_T$ is the loss rate of heat storage device after unit time.

3. Gas energy storage:
The gas storage capacity is related to the charging and discharging power of the time period and the gas storage capacity of the previous time period. It can be described by the following equations:

$$Q(t) = Q(t-1) + \left[ \frac{\eta_{g,store} P_{g,store}(t)}{H} - \frac{P_{g,release}(t)}{\eta_{g,store} H} \right] \Delta t$$ \hspace{1cm} (3)

In the equation (3), $H$ is the low calorific value of natural gas, and the low calorific value of natural gas is 50.07 MJ/kg, and that of hydrogen is 119.64 MJ/kg.

4. Constraint conditions
In order to make the whole energy storage system run safely and efficiently, it is necessary to discuss the constraint conditions of the energy storage device in the process of the system operation.

4.1 Energy storing constraints
Energy storing constraints are the constraint conditions of energy storage device during its operation, which mainly includes capacity constraint, power constraint and complementary constraint.

1. Capacity constraints:
The capacity constraint is that when the energy storage device is working, the storage capacity should be within the allowable operating range of the device. It can be described as:

\[
\begin{align*}
E_{\min} &\leq E(t) \leq E_{\max} \\
H_{\min} &\leq H(t) \leq H_{\max} \\
Q_{\min} &\leq Q(t) \leq Q_{\max}
\end{align*}
\] (4)

2. Power constraint:

The power constraint means that the charging and discharging power of the energy storage device should be in the allowable range of the device when the energy storage device works.

\[
\begin{align*}
\text{u}_0(t) P_{\min} & \leq P_{\text{store}}(t) \leq \text{u}_0(t) P_{\max} \\
\text{u}_r(t) P_{\min} & \leq P_{\text{release}}(t) \leq \text{u}_r(t) P_{\max}
\end{align*}
\] (5)

In equation (5), \(P_{\max}, P_{\min}, P_{r_{\max}}, P_{r_{\min}}\) respectively represent the maximum and minimum value of the energy storage device storing and releasing energy; \(\text{u}_0(t), \text{u}_r(t)\) represent the storage state of the energy storage equipment at time \(t\), and satisfies (1 means it is in working state, 0 means not): \(\text{u}_0(t) = \{0,1\}, \text{u}_r(t) = \{0,1\}\).

3. Complementary constraint:

Complementary constraint is a constraint on the working state of energy storage system, which limits the unity of its energy storage state:

\[0 \leq \text{u}_0(t) + \text{u}_r(t) \leq 1\text{ or } \text{u}_0 \cdot \text{u}_r = 0\] (6)

4.2 System constraints

System constraints ensure the meshing of the components of the IESs, which achieve better security, economy and applicability in systems used in production and life.

1. Load balance:

The system should meet energy loads simultaneously. The mathematical expression is:

Power balance: \(E_0(t) + E(t) - E(t-1) + E_{in}(t) - E_{out}(t) = E_{load}(t)\) (7)

Heat balance: \(H(t) - H(t-1) + H_{in}(t) - H_{out}(t) = H_{load}(t)\) (8)

Gas balance: \(Q_0(t) + Q(t) - Q(t-1) + Q_{in}(t) - Q_{out}(t) = Q_{load}(t)\) (9)

In equation (7)-(9), in some specific systems, energy is not only used to store or respond to energy load, but also used to other ways. At this point, to the left side of the equation, it increases the amount of energy generated and in the right side of the equation, it increases the amount of gas consumption.

2. Networks:

The IES will interact with power grid, heat grid and gas grid from time to time during its operation:

\[
\begin{align*}
P_{\text{in}_{\text{min}}} &\leq P_{\text{in}}(t) \leq P_{\text{in}_{\text{max}}} \\
P_{\text{out}_{\text{min}}} &\leq P_{\text{out}}(t) \leq P_{\text{out}_{\text{max}}}
\end{align*}
\] (10)

3. Maximum capacity in hybrid energy storage system:

The maximum capacity of hybrid energy storage system is limited in its working process. The mathematical expression is:

\[C_{am}(1 - DOD) U_a \leq P_{\text{BAT}} \leq P_{\text{BAT}_{\text{max}}}
\] (11)

In equation (11), \(P_{\text{BAT}}\) is the power supply of the hybrid energy storage device.

5. The key factors in configuration of heat and power

The configuration of energy storage is a key problem in the electro-thermal energy storage, which affects the meshing between the optimization of energy storage configuration and operation.

- Structure of building load:
Considering the time to transfer heat and cold loads, electricity storage capacity is more in a continuous-load building and heat storage capacity is more in intermittent-load building.

- Grid connection restriction condition:
  Under the condition of selling electricity to the power grid, power storage has a larger capacity in the system. If contrary, heat storage has a larger capacity.
- Unit cost of energy storage:
  The lower the price of electric energy storage, the smaller the thermal energy storage capacity, but there is a minimum value; If contrarily, the outcome will change contrarily.

6. Operation modes in energy storage system

In order to maximize the operating benefit of IES, different operation modes are usually needed because of different load demand and different electricity price in different periods.

![Figure 1 Output of gas(a), heat(b) and power(c).](image-url)

6.1 Classification of operating modes

In [2,5,9,13-16], the operation mode of ESS can be divided into:

- Single equipment: single gas storage, single electric storage and single thermal storage;
- Double equipment: gas-elecricity storage, gas-heat storage and electricity-heat storage;
- Multi-energy storage equipment: gas-heat-electricity combined storage.

6.2 Analysis of operating conditions

During the operation of the IES, the energy efficiency can be maximized by using different energy storage devices according to its operation characteristics.

1. Single device:
   - In single electricity mode, the output in figure 1(c) is balanced. The electricity is affected by time fluctuation and it is stored in the time when electric load is small and the energy content is rich.
   - In single heat mode, the output in figure 1(b) is most. This mode is suitable when used in a park which heat load is most working like single electricity. When power price peak, the stored heat can be used to convert into electricity to reduce the cost of electricity.
   - In single gas mode, the output in figure 1(a) is middle. As a kind of energy which also used less than electricity, it works like single heat mode.

   The advantages of single energy storage mode are simple structure, clear operation mode, convenient maintenance and so on. However, its low level of energy consumption and single form of energy supply limit its more application space.

2. Double device:
   - In gas-electricity storage mode, compared with single device modes, the output of power is close to same, and the output of gas is reduced. But by adjusting the amount of gas released, we can concentrate the time of power storage on the lower price of electricity grid, and the time of power release on the higher price of electricity grid. It optimizes the interaction between power and gas.
   - In electricity-heat storage mode, compared with single device modes, the output of power is close to same, and the output of heat is reduced. With power staying the same, the heat in a period is
relatively reduced. At the same time, the stored electricity can be converted into heat, promoting the efficient use of energy, resulting in a relative reduction of stored heat energy. Therefore, the storage equipment can be used as a thermal storage equipment, adjust the output of each moment; heat storage equipment has also affected the storage capacity during valley time and peak [5].

In gas-heat storage mode, compared with other storage modes, the output of gas is highest, and the output of gas is lowest. Because of the absence of electricity, the excess energy needs to be converted into gas to store with reducing the output of heat storage. Therefore, the gas storage can bring adjustment and supplement to heat storage, enhancing the ratio of energy utilization.

Under the double-equipment energy storage mode, the energy absorption degree is improved, and the two energy storage types can complement each other according to their own characteristics.

3. Multi-device:
In gas-heat-electricity storage mode, compared with other modes, the output of heat is at a lower level, the output of power is slightly lower, and the output of gas is higher. On the one hand, gas-heat storage regulates the power storage, and the power storage output is mainly affected by the grid price and the electricity load of consumers, so that the release of energy storage can mainly cope with the time when grid price is high and the demand of consumers is high; On the other hand, because of the increase of gas-electricity storage, the heat storage mainly faces the peak heat load.

In multi-device mode, the energy absorption degree reaches a very high level. The three energy storage devices interact with each other, not only meeting the environmental protection requirements of the modern energy utilization system, but also improving the pertinence of energy application, meet load requirements efficiently.

6.3 Operating conditions of energy storing modes differing in seasons
The type of demand varies with the seasons, which requires the storage mode to change accordingly in different seasons. According to [9], in the spring and autumn, the electric load is dominant and the heat/cold demand is low; in the summer, the cooling load is the largest, the heat load demand is the lowest and the electric load is low; in the winter, the heat load is the largest, the electric load is in the middle, and cold load demand is very low.

The main energy storage devices vary with the seasons as shown in table 1 (√ means the device is used as common. √√ means the device is used more frequently).

Table 1 Operation of different energy storage modes in different seasons.

| Device                  | Condition    | Electricity | Heat | Cold |
|-------------------------|--------------|-------------|------|------|
| Single electricity      | Spring/Autumn| √√          |      |      |
| storage                 | Summer/Winter| √           |      |      |
| Single heat storage     | Spring/Autumn| √           |      |      |
|                         | Summer       | √√          |      |      |
|                         | Winter       | √√          |      |      |
| CHP                     | Spring/Autumn| √√          |      |      |

7. Conclusion
The Integrated Energy System is an important direction of the development of renewable energy technology at present, and the Energy Storage System is the key of this technology, which have core meaning in improving the operation benefit and economic benefit of systems.

The charging and discharging states of the energy storage system are both subject to the upper and lower limits of the capacity of the energy storage equipment, which can be divided into three types: electricity storage, heat storage and gas storage, in order to ensure the safe and efficient operation of the energy storage device. It is restricted by the energy storage device itself and the specific system operating environment to ensure safe and efficient operation.

In order to improve the energy absorption capacity of energy storage system and obtain more economic benefits, the ratio of three kinds of energy storage equipment is the key. The configuration of electric thermal energy storage is restricted by three aspects: building structure, grid connection
restriction and energy storage unit cost. Different energy storage ratios result in various energy storage modes, among which the energy has the ability of mutual adjustment, which has an effect on the efficiency and economy of the whole system. On the whole, the hybrid energy storage of three kinds of energy storage equipment has the best energy absorption capacity and economic benefit under the universal situation.

References
[1] Monesha, S., Kumar, S.G., Rivera, M. (2018) Methodologies of energy management and control in microgrid. IEEE Latin America Transactions, 16:2345-2353.
[2] Dragicevic, T., Lu, X.N., Vasquez, J.C., et al (2016) DC microgrids-part I: A review of control strategies and stabilization techniques. IEEE Transactions on Power Electronics, 31:4876-4891.
[3] Barati, F., Seifi, H., Sepasian, M.S. (2015) Multi-period integrated framework of generation, transmission, and natural gas grid expansion planning for large-scale systems. IEEE Transactions on Power Systems, 30:2527-2537.
[4] Shi, Q.S., Ding, J.Y., Liu, K., Yan, W. (2019) Economic optimization operation of micro-grid Integrated Energy System with electricity, gas and heat storage. Electric Power Automation Equipment, 39:269-293.
[5] Men, X.Y., Cao, J., Wang, Z. S., Du, W.J. (2018) The constructing of multi-energy complementary system of energy internet microgrid and energy storage model analysis. Proceedings of the CSEE, 38:5727-5737.
[6] Tan, Z.F., Tan, Q.K., Zhao, R. (2017) Review of key technologies for multi energy complementary system. Distributed Energy, 2:1-10.
[7] Gong, F.X., Li, D.Z., Tian, S.M., et al (2019) Review and prospect of key technologies of integrated energy system. Renewable Energy Resources, 37:1229-1235.
[8] Sun, M., Su, Qi, Z.Y., Gui, X. (2019) Heating System of Residential Area Based on the Use of Wind Power, Gas and Storage. Building Energy Efficiency, 47:44-49+134.
[9] Gu, Z.Y., Su, X.L., Qin, H., et al (2019) Research on Energy Storage Planning of the Integrated Energy System. Electrical Automation, 41:31-34.
[10] Branco, H., Castro, R., Setas Lopes, A. (2018) Battery energy storage systems as a way to integrate renewable energy in small isolated power systems. Energy for Sustainable Development, 43:90-99.
[11] Li, H.H., Tan, Z.F., Chen, H.T., Guo, H.W. (2018) Integrated heat and power dispatch model for wind-CHP system with solid heat storage device based on robust stochastic theory. Wuhan University Journal of Natural Science, 23:31-42.
[12] Wu, J.Z., Yan, J.Y., Jia, H.J. (2016) Integrated energy systems. Applied Energy, 167:155-157.
[13] Pan, Z.G., Guo, Q.L., Sun, H.B. (2016) Interactions of district electricity and heating systems considering time-scale characteristics based on quasi-steady multi-energy flow. Applied Energy, 167:230-243.
[14] Nielsen, M.G., Morales, J.M., Zugno, M., et al (2016) Economic valuation of heat pumps and electric boilers in Danish energy system. Applied Energy, 167:189-200.
[15] Bai, L.Q., Li, F.X., Cui, H.T., et al (2016) Interval optimization based operating strategy for gas-electricity integrated energy systems considering demand response and wind uncertainty. Applied Energy, 167:270-279.
[16] Liu, X.Z., Mancarella, P. (2016) Modelling, assessment and Sankey diagrams of integrated electricity-heat-gas networks in multi-vector district energy systems. Applied Energy, 167:336-352.