Study on the influence of heat pump and heat storage device on the accommodation of wind power curtailment in the integrated energy system

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Abstract. In order to solve the wind curtailment problem in an integrated energy system (IES), this paper starts from the structure of the IES and analyzes the related contents of heat pump, heat storage device and cogeneration units in the IES. At the beginning of this article, the principle, performance coefficient model and energy efficiency curve of the heat pump are first studied. Correspondingly, the principle of heat storage device and the model of heat storage and release strategy are studied. Then the principle and operating characteristic model of cogeneration units are studied. Based on the principle of each part, combined with the operating constraint conditions of the IES, the IES including heat pump, cogeneration units and heat storage device is constructed. An example is used to simulate the operation in the Energy Plan software, different scenarios were established in the simulation process for analysis to study the influence of heat pumps on the accommodation of curtailed wind power in the IES. The simulation results show that the heat pump can promote the accommodation of wind power, reduce the curtailment rate and the cost of power generation to a certain extent in the IES. From the results of simulation analysis, it can also be concluded that the IES including both heat pump and heat storage device has better wind power accommodation capacity.

1. Introduction
The comprehensive utilization of clean and renewable energy is increasingly valued by people from all walks of life in today's society. Wind energy resources are also generally considered by scientists as one of the most promising new energy sources, which will play a huge role in addressing the global energy and ecological environment issues we are facing today. However, due to synchronization planning and development of wind power projects and power network infrastructure, there is still a serious phenomenon of wind curtailment in China. This phenomenon is particularly evident in Three-north areas of China, where utilization rate of the wind power is low due to limited transmission capacity between some connected areas. Another reason behind is due to non-flexible operation of the combined heat and power (CHP) plants which mostly work in a heat-driven mode in winter.

In order to solve the problem of wind curtailment, an integrated energy system (IES) approach has been lately adopted by scholars from worldwide. As in [1]-[9], the IES approach is used to tackle the
challenges of renewable integration by optimally coordinating the flexibility of components, networks
and systems related to multi-user carriers within the IES. [1] presented a planning method for heat and
power. [2] studied an optimal dispatching model of wind power plants and CHP with heat storage. A
detailed techno-economic analysis for combined operation of wind power and electric heating was
done in [3]. [4], [5] proposed advanced optimization methods for dispatching the flexibility of Caps. [6]
and [7] emphasized on mode-based optimal use of the flexibility of heat storage units. Coordination of
the flexibility of multiple RESs were investigated by [8], wherein geographically distributed heat and
power systems were taken into account.

In this paper, an IES including heat pump, heat storage devices and cogeneration units is framed
and represents a live example. A particular focus is given to examine the impacts of the addition of heat
pumps and heat storage devices at varying capacity on the economics of the IES, when they are used
to meet the heat demand and to support wind power integration at the same time. The related
mathematical models and case study are presented in Section 2 and Section 3 respectively. Section 4
concludes the work.

2. Optimization model of the IES

2.1 Objective function
The objective includes two parts that can be either combined or treated separately.

Minimize annual power generation costs

\[
C = N_m J_m
\]  

(1)

\(C\) is annual total power generation cost of IES, \(N_m\) is annual coal consumption of IES, \(J_m\) is
standard price per ton of coal.

Minimize the wind curtailment rate

\[
Q_w = \frac{P_w - P_{st}}{P_w}
\]  

(2)

\(Q_w\) is wind curtailment rate of IES, \(P_{st}\) is the actual output of wind power in a certain
period, \(P_w\) is the forecast output of wind power in a certain period.

2.2 Constraints
Constraints of power supply balance:

\[
\sum_{j=1} P_{e,c,j} + \sum_{j=1} P_{w,j} - \sum_{j=1} P_{h,c,j} - P_{l,e} = 0
\]  

(3)

\(P_{e,c,j}\) is the electrical power of CHP; \(P_{w,j}\) is the power of wind turbines, \(P_{h,c,j}\) is the power consumed
by heat pump, \(P_{l,e}\) is the power of electric load.

Constraints of heating balance:

\[
\sum_{j=1} Q_{h,h,j} + \sum_{j=1} Q_{c,h,j} + \sum_{j=1} Q_{s,j} = Q_{l,h}
\]  

(4)

\(Q_{h,h,j}\) is the heating production of heat pump, \(Q_{c,h,j}\) is total heating production of CHP, \(Q_{s,j}\) is
heating production of heat storage device, \(Q_{l,h}\) is demand of heat load.

Energy conversion and capacity constraints of Heat pump
\[ P_{h,e,j} = COP \cdot P_{h,e,j} \]
\[ 0 < P_{h,e,j} < P_{h,e,\text{max}} \] (5)

\( P_{h,e,\text{max}} \) is the maximum power of compression water source heat pump; \( COP \) = Performance coefficient of compression water source heat pump.

Dynamic balance and capacity constraints of heat storage:

\[
\begin{align*}
Q'_{h,j} - Q'_{h,j-1} &= Q'_{sc,j}, Q_{sc,j} \leq Q_{sc,j}^\text{max} \\
Q'_{h,j} - Q'_{h,j-1} &= Q'_{sf,j}, Q_{sf,j} \leq Q_{sf,j}^\text{max} \\
Q'_{h,j} &\leq Q_{h,j}^\text{max} \\
\sum_{t=1}^{T} P'_{s,j} &= 0 
\end{align*}
\] (6)

\( Q'_{h,j} \) is Heat storage capacity of heat storage tank \( j \) at time \( t \), \( Q_{sc,j}^\text{max}, Q_{sf,j}^\text{max} \) is maximum heat storage power and maximum heat release power of heat storage tank \( Q'_{s,j} \) is the power of heat storage or heat release of the heat storage tank \( j \) at time \( t \), the periodic capacity of the heat storage tank is fixed.

Operation balance and limits of CHP:

\[
\begin{align*}
0 &\leq Q_{c,h,j} \leq Q_{c,h,j}^\text{max} \\
P_{c,e,j}^\text{min} &\leq P_{c,e,j} \leq P_{c,e,j}^\text{max} \\
P_{c,e,j} + \lambda_i \cdot Q_{c,h,j} &= P_{c,f,j} \cdot \eta_{c,f,j}
\end{align*}
\] (7)

\( Q_{c,h,j}^\text{max} \) is the upper limit of heating power of CHP, \( P_{c,e,j}^\text{min} \) is the lower limit of heating power of CHP, \( P_{c,e,j}^\text{max} \) is the upper limit of generating power of CHP, \( P_{c,f,j} \) is fuel consumption of CHP, \( \eta_{c,f,j} \) is the fuel efficiency of CHP, \( \lambda_i \) is heat to power ratio of CHP.

Combining the above constraints, this section presents an optimization model used for evaluating the impacts of heat pump and heat storage on wind power integration, the energy flow of the IES can be found in Figure 1.

![Energy structure and flow in IES](image)

Figure 1 Energy structure and flow in IES
3. Simulation-based case study

3.1 Case Description

The case simulated in this paper is based on representative energy load curves and wind power profiles in North China. The operating parameters of the system are as follows, the wind turbine 1000MW; CHP power capacity is 600MW, heat capacity is 750; Hp electric capacity is 100, Hp COP is 3, heat storage is 900MW h.

The power demand, heat demand and the wind forecast for the area on January 2 is shown in Figure 2, Figure 3 and Figure 4 respectively.

Figure 2 Power demand on January 2

Figure 3 Heating demand on January 2

Figure 4 Predicted wind power on January

3.2 Simulation results and analysis

In order to study the impact of heat pumps and heat storage devices on the accommodation of wind power and energy costs in the IES, the following five scenarios are established for analysis:

Scenario 1: The CHP unit is the only heat source.
Scenario 2: A 100MW heat pump is the only heat source;
Scenario 3: A 900MWh heat storage tank is the only heat source;
Scenario 4: 100MW heat pump and 900MWh heat storage tank are heat sources;
Scenario 5: 150MW heat pump and 900MWh heat storage tank are heat sources

3.2.1 The effectiveness of IES for facilitating wind power integration

In Figure 5, the contribution of IES on wind power integration for different scenarios. It can be found that adding heat pump or heat storage can reduce the abandoned amount of wind power. The benefits are increased when both technologies are included. Further, increasing the capacity of heat pump will also support wind power integration.
3.2.2 Power generation cost
The annual cost of power generation is shown in Figure 10 for various scenarios. Scenarios including heat pump, i.e. scenario 1, 2 and 4, result in low power generation cost. However, the difference is not big, implying an optimal investment plan with right selection of the capacity of heat pump and storage need to be made.

4. Conclusion
The paper presented a study on the influence of heat pump and heat storage device on the accommodation of wind power in the integrated energy system. In general, an IES system with heat pump or heat storage device installed alone will have a lower wind curtailment rate than a system without both, and the cost of power generation is lower, wind power accommodation is more. When both heat pump and heat storage are deployed, appropriate increasing the heat of heat pump can further improve the wind power accommodation capacity at the expense of increasing cost. A dedicated planning study regarding optimal sizing of heat pump and storage in IESs will be considered as future work.

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