Industrial integrated energy system optimization with considering thermal power transferring process

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Abstract. In the regional integrated energy system, multiple resources on the demand side and supply side should be considered in integrated planning. In particular, how to realize measuring heat energy grade as well as considering thermal energy transferring medium characteristics in the integrated energy system optimization operation and resource allocation is a urgent research area to explore. In this paper, a typical industrial park integrated energy system considering thermal energy transferring process is established. In the beginning, multi-energy flows complementary characteristics of the industrial park have been introduced, which could improve energy usage efficiency by energy conversion, energy storage and energy substitution. Then the models of storage battery, micro-turbine and other resources have been established. In addition, the model of heat energy pipe network has been built considering thermal energy unidirectional transmission and various heat grade. Based on the previous models, the objective function of industrial park economic operation. Finally, the simulation results show that the proposed multi-energy flows model could satisfy the economical operation as well as energy supply balance while obeying energy conservation law and transferring process limit.

1. Introduction
With the rapid progress of global energy demand and supply, the substitution and complementation among multi-energy flows is an unavoidable tendency [1]. Especially, industrial energy consumption has a leading proportion in energy supply around worldwide. But various energy supply systems own diverse operation characteristics [2]. Besides, different energy supplies are often dispatched, distributed and planned independently. As a result, this phenomenon leads to the lack of coordination, which brings about poor self-healing ability, unimproved security and low energy efficiency in multiple integrated energy systems. In this way, how to integrate multi-energy systems resources such as electrical-thermal systems as well as improve dispatch flexibility is an urgent issue for studying and exploring.

In order to improve this phenomenon, the integrated energy system is one of the most distinct solutions due to its intensive complementarity and high efficiency. And the study in [3] has summarized preliminary energy operation characteristics and coupling mechanisms of integrated energy systems. In addition, a detailed model for considering the thermal energy storage capacity of pipelines in district heating network has been explored in Ref[4].Then, ref[5] use the multi-energy complementary strategy to improve the ability of renewable energy consumption and integrated
electricity-heat energy system. Moreover, an electrical-thermal energy flow model with steam as the heat medium and its risk assessment are proposed in ref[6].

In this paper, in order to achieve the optimal economical operation, we propose a typical industrial integrated multi-energy system by considering heat transfer process to achieve dispatch flexibility and stability. In the beginning, the framework of integrated energy management system consisting of cold, thermal, electric and other energy sources is put forward. And various energy managing methods are proposed put forward according to the characteristics of energy consumption of industrial users. Then constraints satisfying different types of production devices and energy requirements in the plant were established, and the mathematical model aiming at the economic optimization of the plant operation was determined. Eventually, the optimization results illustrate that the proposed optimization model can meet various energy requirements and thermal transfer constraints as well as respond to the electricity price effectively to reduce the energy cost.

2. Framework of industrial energy management

Industrial parks usually require the incorporation of diverse energy sources and power supply reliability, which means complex energy management methods. Therefore, in order to enable effective industrial demand response, it is essential to formulate a reasonable energy management system considering energy consumption and operation characteristics.

Figure 1 gives the total energy management system structure of industrial park, in which multiple energy sources, storages and loads are involved transversely as well as complementary operation of electric, thermal and cold energies are considered longitudinally. Distributed power sources, loads, energy storage devices and production equipment are integrated into a controllable energy management system. In addition, it makes it more convenient to improve the utilization rate as well as realize effective interaction.

Industrial parks have more sophisticated infrastructures and more flexible resources as well as long-term conversion and cooperation of various energy resources. Therefore, industrial parks have more diverse methods to participate in the demand response according to the different energy utilization modes. Energy transfer: According to the energy demand and electricity price signal of industrial production, on the premise of ensuring the reliability of electricity consumption and the continuity of production process, the high electricity consumption should be transferred from the peak electricity price period to other off-peak electricity price period. Energy substitution: A variety of energy supply methods coordinated with each other make it easier for users select cheaper energy resources to substitute more expensive resources. This action could avoid centralized power consumption and alleviate the power pressure of the power grid. Energy storage: If energy storage devices are equipped, certain energy can be stored in the low electricity price period by adjusting the production plan. In this way, it can maintain some production capacity in the peak period without power purchasing. Subsequently, the energy cost difference between peak electricity price period and low electricity price period could be reduced.
3. Multi-energy flow optimization operation model of industrial park

Due to the dynamic coupling of thermal energy transmission and electric power transmission process as well as energy conservation. Electricity and heat control variables have internal interactive links. As a matter of that, the model of integrated optimization scheduling has discontinuous, nonlinear and convex characteristics. Moreover, the optimization problem is transformed into a mixed integer nonlinear programming problem under the relevant linear and nonlinear constraints, which is reduced to the following optimization model in equation.

X and Y represent the decision variables of power supply equipment and heating equipment in the industrial park; F(X, Y) represents the objective economy function of the model; A(X) and B(X) are the inequality and equality constraints in the power supply process; C(X, Y) and D(X, Y) represent inequality constraints and equality constraints associated with the operation of the heating devices respectively.

\[
\min \ F(X, Y) \\
\text{s.t.} \quad A(X) \leq 0 \\
B(X) = 0 \\
C(X, Y) \leq 0 \\
D(X, Y) = 0
\]  

(1)

3.1. Objective function

The objective function of the industrial park is to minimize the total energy supply cost in order to improve the economy and energy consumption efficiency together. In addition, the total operation cost consists of operation cost of energy station, ladder battery charging-discharging cost and electricity purchasing cost in equation (2).

\[
\min W = \sum_{t=1}^{N} W_M + W_G + W_S
\]  

(2)

Where, \( W \) is the total cost of industrial park, \( W_M \) is the operation cost of energy station, \( W_S \) is the storage battery charging-discharging cost, \( W_G \) is the electricity purchasing cost.

(1) Energy station operation cost. In equation(3), the operation cost of energy station is mainly referred to the cost during the start-up action and operating period.

\[
W_M = \sum_{n=1}^{N_M} (C_{gas} P_{M,t} + C_{V} V_{M,t})
\]  

(3)

Where, \( N_M \) is the amount of energy station, \( C_{gas} \) is the unit gas cost, \( C_{V} \) is the unit start-up cost, and \( V_{M,t} \) is the start-up binary variable of energy station at time \( t \).

(2) Electricity purchasing cost. Where, \( \lambda_{G,t} \) is the external electricity price at time \( t \) and \( P_{G,t} \) is the electricity purchasing power at time \( t \).

\[
W_G = \lambda_{G,t} P_{G,t}
\]  

(4)

(3) Storage battery depreciation cost. As the electricity purchasing cost while charging process has been calculated in equation (4). The storage operation cost is mainly composed of depreciation cost while changing between discharging status and charging status in equation (5), which might decrease the total lifespan of ladder battery.

\[
W_S = \sum_{t=1}^{N_S} C_S (u_{S,t} \cdot (1-u_{S,t-1}) + u_{S,t-1} \cdot (1-u_{S,t}))
\]  

(5)

Where, \( C_S \) is the single charging-discharging cost, \( u_{S,t} \) is the charging variable of ladder battery at time \( t \), \( N_S \) is the amount of ladder battery.
3.2. Constraints

3.2.1. Ladder battery

1) Charging-discharging output limit. The output power of ladder battery should be limited into a fix operation, which has a maximum output and minimum output.

\[ P_{D}^{\text{max}} \cdot d_{S,t} \leq P_{S,t} \leq P_{C}^{\text{max}} \cdot u_{S,t} \]  

(6)

Where, \( u_{S,t} \) and \( d_{S,t} \) is the charging and discharging operation variable of ladder battery at time \( t \), \( P_{D}^{\text{max}} \) and \( P_{C}^{\text{max}} \) are the maximum discharging power and maximum charging power of ladder battery, is the output power of ladder battery.

2) Battery storage and release status exchange constraint. While battery is not able to charge and discharge at the same time, which means it could only charge or discharge at unit time \( t \) as shown in (7). Besides, operation variables should be limited according to the operation characteristic.

\[ u_{S,t} + d_{S,t} \leq 1 \]  

(7)

3) Gradeability constraint

\[ -\Delta R_{S}^{\text{min}} \leq P_{S,t} - P_{S,t-1} \leq \Delta R_{S}^{\text{max}} \]  

(8)

Where, \( R_{S}^{\text{min}} \) and \( R_{S}^{\text{max}} \) are the maximum climbing power and minimum climbing power of ladder battery, \( \Delta t \) is the operation slot.

4) Storage balance between initial time and end time. At the end of optimization period, the SOC capacity should be set as the initial state of battery SOC capacity in order to satisfy the power supply next day as shown in (9).

\[ S(0) = S(N) \]  

(9)

Where, \( S(0) \) is the initial state of SOC capacity of ladder battery, \( S(N) \) is the SOC state capacity of ladder battery at the end of optimization period.

5) Interactive power balance. Equation shows the interactive relation between SOC capacity at time \( t \) and SOC capacity at time \( t-1 \). In addition, the SOC capacity would increase while charging process, and the SOC capacity would decrease while discharging process

\[ S_{t} = \eta_{S} S_{t-1} + S_{t} \cdot \Delta t \]  

(10)

Where, \( \eta_{S} \) is the consumption efficiency of ladder battery, \( S_{t} \) is the SOC capacity of ladder battery at time \( t \).

6) SOC capacity constraint. Where, \( S_{\text{min}} \) and \( S_{\text{max}} \) are the maximum SOC capacity and minimum SOC capacity.

\[ S_{\text{min}} \leq S_{t} \leq S_{\text{max}} \]  

(11)

3.2.2. Energy station

1) Energy output power limit

\[ u_{M,t} \cdot P_{M}^{\text{min}} \leq P_{M,t} \leq u_{M,t} \cdot P_{M}^{\text{max}} \]  

(12)

Where, \( P_{M}^{\text{max}} \) and \( P_{M}^{\text{min}} \) are the maximum and minimum output power of energy station, \( u_{E,t} \) is the binary operation variable of energy station at time \( t \).

2) Energy climbing power limit

\[ -\Delta R_{M}^{\text{min}} \leq P_{M,t} - P_{M,t-1} \leq \Delta R_{M}^{\text{max}} \]  

(13)

Where, \( R_{M}^{\text{min}} \) and \( R_{M}^{\text{max}} \) are the maximum and minimum climbing power of energy station.

3) Start-stop constraint. As energy station is not allowed to start up or shut down at the same time, start-up variable, shut-down variable and operation variable should satisfy the continuity constraint during optimizing period as shown in equation (14).
Where, $g_{u,t}$ is the shut-down binary variable of energy station at time $t$.

4) Minimum operation constraint. Owing the rated characteristic of energy station, it could not start up quite frequently. Therefore, energy station should operate a minimum time once started up.

$$
\sum_{t=t+T_{\text{on}}^\text{min}}^{t+T_{\text{on}}^\text{min}-1} u_{M,t} \geq T_{\text{on}}^\text{min} \cdot g_{M,t}
$$

Where, $T_{\text{on}}^\text{min}$ is the allowed minimum operation time.

5) Minimum downtime constraint. Due to the energy station needs cooling time once shut down, it ought to stay shut-down status for a minimum time for enough cooling time in equation (16).

$$
\sum_{t=t+T_{\text{off}}^\text{min}}^{t+T_{\text{off}}^\text{min}-1} (1-u_{M,t}) \geq T_{\text{off}}^\text{min} \cdot d_{M,t}
$$

Where, $T_{\text{off}}^\text{min}$ is the minimum downtime of energy station.

3.2.3. Power flow constraint. Each node at electricity network ought to satisfy the relevant power balance constraint and voltage balance shown in equation (17).

$$
P_{\theta,ji}(t) = \sum_{j=1}^{N} P_{j,i}(t) \cdot (g_{ij} \cos \theta_{ij}(t) + b_{ij} \sin \theta_{ij}(t)) = 0,
$$

$$
Q_{\theta,ji}(t) = \sum_{j=1}^{N} Q_{j,i}(t) \cdot (g_{ij} \sin \theta_{ij}(t) - b_{ij} \cos \theta_{ij}(t)) = 0,
$$

$$
V_{\text{min}} \leq V_{i}(t) \leq V_{\text{max}}
$$

Where, $P_{\theta,ji}$, $Q_{\theta,ji}$, $V_{i}(t)$ are the active power, reactive power, and voltage respectively of node $k$ at time $t$, $\theta_{ij}(t)$ is phase angle difference between node $k$ and node $i$ at time $t$, $P_{G,ji}$, $P_{M,ji}$, $P_{S,ji}$, $P_{L,ji}$ are the active power of electricity purchasing, energy station output, ladder battery and load of node $k$ at time $t$, $Q_{M,ji}$, $Q_{S,ji}$, $Q_{L,ji}$ are the reactive power of electricity purchasing, energy station output and load, $V_{\text{max}}$ and $V_{\text{min}}$ are the maximum and minimum voltage of each node.

3.2.4. Heat pipe network operation constraint

![Figure 2. Water and heat flow in the multi-terminal thermal network.](image-url)
The thermal power flow of heat pipes should satisfy the hydraulic model and heat flow power. Figure 2 shows the accurate coupling interaction of water flow and thermal energy. Considering the operation method and adjusting difficulty, we apply the quality adjusting method in this paper by changing node temperature and keeping water flow in the heat pipe network.

1) Hydraulic model

\[ \sum m_i - \sum m_o = m_j \]  

Where, \( m_i \) is the going-in water flow for node \( j \), \( m_o \) is the going-out water flow from node \( j \), \( m_j \) is the injection water flow of node \( j \).

2) Heat transferring model of water supply pipe

The temperature loss should be taken in consideration while calculating the node temperature in the heat pipe network. Equation (19) shows the thermal power transferring between node \( i \) and node \( j \).

\[ T_{si} = (T_{yj} - T_a) e^{-\frac{\lambda_{ij}}{L_{ij}}} + T_a \]  

In which, \( T_{si} \) and \( T_{yj} \) are the water supply initial temperature and terminal temperature of pipe \( ij \) between node \( i \) and node \( j \), \( \lambda_{ij} \) is the unit heat transferring loss factor of the heat pipe, and \( L_{ij} \) is the length of pipe \( ij \), \( m_j \) is its water flow and \( C_p \) is the specific heat capacity of water.

3) Heat transferring model of water return pipe

Because the structure of water supply network and water return network nearly have no difference. As a matter of fact, the water temperature in the water return pipe and water supply pipe should keep in a dynamic balance. And mixed temperature of blend node during mixing process has been shown in equation (20).

\[ (\sum m_{out})T_{out} = \sum (m_{in}T_{in}) \]  

Where, \( T_{out} \) and \( T_{in} \) are the mixed temperature and injection temperature of mixed node in the water return network, \( m_{out} \) and \( m_{in} \) are its mixed water flow and injection water flow.

4) Thermal load power balance

By using the temperature difference of water supply pipe and water return pipe at the same node, it could meet the demand of thermal load shown in equation. Where, \( P_j \) is the thermal load of node \( j \), \( T_{yj} \) is its water return temperature.

\[ P_j = C_p m_j (T_{yj} - T_{rj}) \]  

5) Heat supply balance

The heat is mainly supplied by energy station and electric boiler at heat source node. Where, \( \alpha \) is the thermal supply efficiency of energy station, \( \beta \) is the thermal supply efficiency of electric boiler, and \( P_{br,t} \) is the output power of boiler at time \( t \).

\[ \alpha P_{G,t} + \beta P_{br,t} = C_p m_j (T_{yj} - T_{rj}) \]  

4. Optimization result of case study

We select basic weather and production data of typical industrial park in Shandong Provence to formulate the integrated energy system. In addition, a novel optimization method is used to achieve economical operation by considering above energy and production constraints. Then the optimization results of this case study has been shown in the following part:
4.1. Electricity supply
Figure 3 shows the electricity power supply in detail during the optimization period. As shown in figure 3, owing to the great demand of the integrated energy system, the majority of electricity demand is satisfied by outer grid. In particular, the quantity for electricity purchasing would be reduced while peak electricity price period in order to cut the electricity purchasing cost, and it would climb at its peak at 20:00. In addition, storage battery only changes its charge or discharge status for limited times during this period as a matter of its depreciation cost of state transition. While it discharges at electricity price period, and charges at electricity price period. As for energy station, it only operates from 9:00 to 19:00 to cut down electricity purchasing, which covers most of the electricity price peak period. But it would shut down at other periods owing to its limited energy efficiency.

4.2. Heat supply
Figure 4 illustrates the precise thermal power supply during the optimization period. It shows that the boiler could meet the thermal demand during non-peak price period. While peak price period, the energy station could satisfy most of thermal load because its high economy while combing heat and power at high price period.

4.3. Thermal transfer process
Figure 5 and figure 6 shows the detailed temperature of water supply pipe and water return pipe. As little flow and temperature loss has been taken into account in the water supply process, the change trend of node temperature for water supply pipe is similar with heat source node power variation tendency. Besides, these nodes temperature will decline to some different degrees with transfer distance increasing. By contrast, water return pipe node temperature is mainly influenced by the thermal load power because they provide thermal loads power with temperature difference. In particular, the water return temperature of heat source node is likely to be affected by the weighted average values of other heat source nodes. In addition, the water return pipe node temperature loss climbs with higher thermal sources power.
5. Conclusions
In this paper, thermal energy grade, energy transferring order and energy complementary characteristics have been taken into consideration. As a result of that, coupling loss and transferring features of heat pipe network and power system have been integrated to build industrial park multi-energy flows optimization operation model with thermal energy transferring process. And the case study shows that the proposed model could deal with thermal energy transferring process in the pipe network where thermal energy supply is coupling with heat energy grade effectively. Therefore, it is significant for handling with coordinated planning for heat energy network together with other energy systems.

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