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Optimal energy management of a group of air source heat pumps in a low-carbon industrial park considering its cold island effect

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ABSTRACT

This paper proposes an optimal energy management method for a group of air source heat pumps (ASHPs) in a low-carbon industrial park while considering the cold island effect of the ASHPs. The low-carbon industrial park is a real case in Binhai New District, Tianjin, China where 14 factories are based in. The heating loads of the 14 factories are satisfied by a group of ASHPs that are powered by distributed photovoltaic (PV) generations to reduce the carbon emissions of the whole industrial park. First, an optimal scheduling model for the operation of the group of the ASHPs considering the cold island effect is developed. The unit commitment of the ASHPs within the group is optimized while considering the operational constraints of each ASHP unit. Furthermore, the cold island effect of all the ASHPs is considered as a constraint to avoid the influence of the cold island effect as far as possible and thus keep the ASHPs in their efficient states. Then, the resistance-capacitance (RC) network is used to model the thermal dynamics of the factory buildings in the park. The thermal inertia and the schedules of the employee's working hours are also considered to explore the flexibility of the factory buildings. Finally, the operator of the industrial park can actively control the group of ASHP units to reduce the heating costs and meet the comfort requirements of the factory buildings. Numerical studies show that the proposed strategy can help to reduce the heating costs, improve the efficiency of the ASHP and reduce the carbon emissions as well for the low-carbon industrial park.

Keywords: Air source heat pumps; unit commitment; heating loads; carbon emission; low-carbon industrial park

NONMENCLATURE

Abbreviations	
ASHP	Air Source Heat Pump
PV	Photovoltaic
RC	Resistance-Capacitance
COP	Coefficient of performance
PLR	Part-load ratio

1. INTRODUCTION

Buildings still rely heavily on fossil fuels for heating purposes. This leads to significant greenhouse gas emissions. A shift to more reliable, energy-efficient, and green ways of heating buildings is pressing (World Energy Outlook Special Report the Future of Heat Pumps, 2022). As one of the main energy consumers, buildings have a great potential to save energy and reduce emissions (Jin et al., 2021). And air source heat pumps (ASHPs) have been widely used as heat output units in industrial projects and have achieved significant energy savings (Huang et al., 2023). Therefore, Under the development of integrated energy, it's important to improve the system's overall energy efficiency to save more energy in the electric power system. For a large group of buildings, e.g., residential buildings in a community or office/factory buildings in an industrial park, several heat pumps are used to form a group of ASHPs to satisfy its heating needs. However, in the practical application of ASHPs, the minimum spacing requirements between ASHPs may not be satisfied because of the limitations of the available space for ASHPs. A single ASHP can affect the air temperature around the evaporator of the ASHP thus affecting the heat absorption capacity of the other ASHPs. This is defined as the cold island effect (Sun et al., 2022), which has drawn great attention in studies for

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heat pumps and heating supplies. In the use of heat pumps, the cold island effect on the efficiency of the overall ASHP unit should be avoided as far as possible. It will increase the ASHPs' energy efficiency and thus achieve energy saving and carbon emission reduction.

In (Sun et al., 2022), physical field simulation software is used to simulate single air source heat pumps and heat pump units to expose the cold island effect over temperature fields. In (Lu et al., 2021), considering the thermodynamics of buildings, a detailed physical model of a building with adjustable indoor radiators is developed to describe the building's thermal inertia. In (Xie et al., n.d.), a two-level load optimal scheduling and control strategy for Air Source Heat Pumps considering the cold island effect using the model control method is proposed. In (Kim et al., 2016), a data-driven dynamic model of variable speed ASHP was developed, based on data from building thermal energy experiments. In (Marsik et al., 2023), an empirical model of ASHP efficiency as a function of two independent variables (i.e., environmental temperature and PLR) was developed.

However, the flexibility of source-side ASHPs has not been fully considered. Therefore, this paper proposes an optimal energy management method considering the flexibility from both the heating generation units (i.e., the ASHPs) and the heating consumers (i.e., the buildings).

Moreover, an optimal economic strategy is developed by adjusting the part-load ratio (PLR) of different ASHPs to avoid the worse effects of the cold island effect.

2. FRAMEWORK OF THE ENERGY MANAGEMENT IN A LOW-CARBON INDUSTRIAL PARK

The low-carbon industrial park consists of an energy center, a distributed network, and industrial heat users, as shown in Fig.1. The energy center provides electricity and heat for the consumers in the park. The energy center determines the power generation and ASHPs' PLR of the entire low-carbon industrial park based on the electrical price and the data about weather and buildings. The group of ASHPs is the heat source for the park.

In the traditional operating strategy of ASHPs, the individual ASHPs in the group are all at the same PLR and the impact of the cold island effect on the efficiency of the heat pump unit is not considered. It results in a waste of electrical energy. At the same time, in the planning of the low-carbon industrial park, the actual factors of space constraints make it impossible to meet the minimum spacing of individual ASHPs, which will result in a serious cold island effect. However, the ASHP is an inverter equipment. When the heat demand is at a low level, the ASHP that far away from other ASHPs would be switched on as a priority to avoid the cold island effect. When the heat demand is at a high level, increasing the PLR at the corners around the whole ASHP group would be considered to minimize the cold island effect in this paper. The base energy framework for the low-carbon industrial park from the source side to the heat consumers is shown in Fig.1.

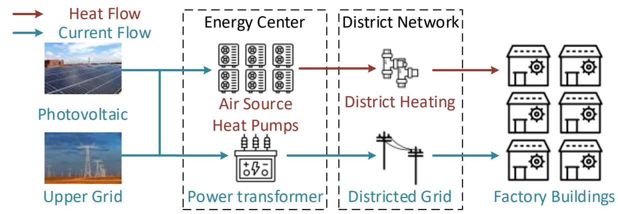


Fig.1 Schematic of the low-carbon industrial park

3. MATHEMATICS MODEL

3.1 Energy center model

There are a group of 25 ASHPs and a PV system on the roof of the energy center to meet the daily electricity and heating needs. The upper grid and local PV system meet the ASHPs' power consumption. The group of ASHPs transfers heat energy from the air to the industrial park heat pipe network by using electricity for the daily heating needs of the industrial park.

1) Objective

The objective of the energy center is the cost of purchasing electricity, as shown in (1):

$$\min \sum_{t=1}^{T} C_t^e \cdot P_t^{e,buy} \tag{1}$$

Where $P_t^{e,buy}$ is the electricity purchased from the upper power grid at time *t*; C_t^e is the electricity price at time *t*; *T* is the schedule of the operation which is 96; the time period is 15 min.

2) Constraints

a. Electrical power balance:

$$P_t^{e,buy} + P_t^{e,PV} = P_t^{e,ASHP} + P_t^{e,Building} \tag{2}$$

where $P_t^{e,PV}$ is the electricity generated by PV at time *t*; $P_t^{e,ASHP}$ is the electricity consumed by the group of ASHPs at time *t*; $P_t^{e,Building}$ is the electricity consumed by buildings of the Low-carbon industrial park at time *t*.

$$P_t^{e,ASHP} = \sum_{t=1}^{N_1} P_{n_1,t}^{e,ASHP} \tag{3}$$

where $P_{n_1,t}^{e,ASHP}$ is the ASHP of the number n_1 at time t; N_1 is the number of the ASHPs, which is 25 in the case of this paper.

$$P_t^{e,PV} = \eta \cdot Q_t^{rad} \quad (4)$$

where $P_t^{e,PV}$ is the electricity output of PV; Q_t^{rad} is the radiation intensity of the sun; η is the coefficient between them.

b. Heating power balance:

$$Q_t^{h,ASHP} = Q_t^{h,Building} = \sum_{n_1=1}^{N_1} Q_{n_1,t}^{h,ASHP} = \sum_{n_2=1}^{N_2} Q_{n_2,t}^{h,Building} \quad (5)$$

where $Q_t^{h,ASHP}$ is the heat produced by the group of ASHPs; $Q_t^{h,Building}$ is the heat needed by the buildings in the park; $Q_{n_1,t}^{h,ASHP}$ is the heat produced by the ASHP of the number n_1 at time t; $Q_{n_2,t}^{h,Building}$ is the heat needed by the building of the number n_2; N_1 is the number of ASHPs which is 25; N_2 is the number of buildings in the park which is 14.

c. Limits of energy purchases:

$$0 \le P_t^{e,buy} \le P_{max}^{e,buy} \quad (6)$$

where $P_{max}^{e,buy}$ is the maximum electricity consumption.

3.2 ASHP model

The ASHP are a device for electrical heat conversion, with an input of air and electrical energy and an output of heat energy. It is assumed that the ASHP used in the park can only be operated in the following constraint zones.

a. Power output constraints:

$$Q_{n_1,t}^{h,ASHP} = S_{n_1,t}^{ASHP} \cdot Q_{max}^{h,ASHP} \quad (7)$$

$$S_{n_1,t}^{ASHP} = 10\% \times m \;\; (m = 3, 4 \cdots 10) \quad (8)$$

where $S_{n_1,t}^{ASHP}$ is the switch status of the ASHP of the number n at time t; $Q_{max}^{h,ASHP}$ is the maximum heat power of an ASHP.

b. Electric-heat conversion constraint:

The COP is an important parameter for evaluating the efficiency of an ASHP and can be influenced by the outside temperature and the temperature of the discharge water. The relationship is shown in (9) and (10):

$$Q_{n_1,t}^{h,ASHP} = COP_{n_1,t}^{ASHP} \cdot P_{n_1,t}^{e,ASHP} \quad (9)$$

$$COP_{n_1,t}^{ASHP} = 4.71 + 0.058 \times T_{n_1,t}^{real} - 0.044 \times T_{output}^{ASHP} \quad (10)$$

where $COP_{n_1,t}^{ASHP}$ is the efficiency of the ASHP of the number n_1 at the time t; $T_{n_1,t}^{real}$ is the temperature at which the ASHP is located; T_{output}^{ASHP} is the output temperature of the ASHP's output pipe which is 55℃.

3.3 The cold island effect between ASHPs

When the distance between the ASHPs exceeds a certain number, it is assumed that they will not be affected by the cold island effect. The effect of an ASHP on the environmental temperature can be expressed by the Eq. (11):

$$\Delta T_{n_1}^{ASHP} = \begin{cases} 0.0048 \times l^2 - 0.4030 \quad (0 < l < l_{max}) \\ 0 \;\; (l \ge l_{max}) \end{cases} \quad (11)$$

where $\Delta T_{n_1}^{ASHP}$ is the difference in environmental temperature caused by the full load ASHP of the number n_1. l is the distance between two different ASHPs; l_{max} is the maximum distance of cold island effect and is 9.1629 m.

The environmental temperature at which a single heat pump is located, considering the cold island effect, is shown in (12):

$$T_{n_1,t}^{real} = T_{out,t} + \sum_{t=1}^{T} \Delta T_{n_1}^{ASHP} \cdot S_{n_1,t}^{ASHP} \quad (12)$$

where $T_{out,t}$ is the base environment temperature.

3.4 The thermal dynamics of the factory buildings

During the winter months, 14 factory buildings in the industrial park have heat demands and are heated by the thermal network heat end. The RC thermal network model of a factory building consists of thermal resistance (R) and thermal capacity (C). The R and C represent their ability to transmit and preserve heat individually. In the RC model, there are two types of nodes, wall nodes and room nodes. The two types of nodes are connected to each other by R and C based on thermal capacity. The structure of the RC thermal network model in typical factory buildings is shown in Fig.2.

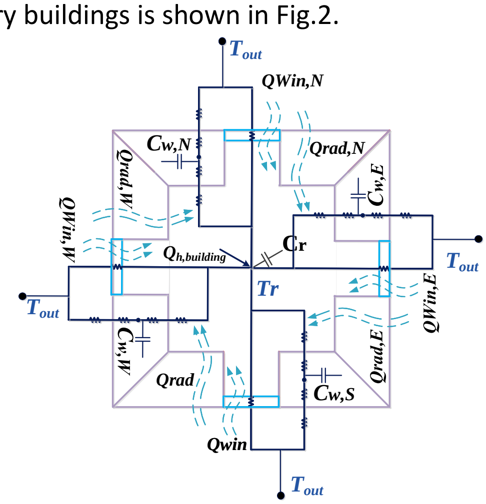


Fig.2 The RC thermal network model

In this model, the structure of the factory building is considered as walls and windows forming the surrounding and the wall forming the roof. This model also considered the difference in the radiation intensity of the sun on each face of the factory building.

Considering the slow dynamic process of heat dissipation and temperature change, the constraint conditions of the heating area are:

a. Thermal balance constraint of walls and the roof:

$$Cw_{n_2}^{R,d}\frac{dTw_{n_2}^{R,d}}{dt}=\frac{Tr_{n_2}-Tw_{n_2}^{R,d}}{Rw_{n_2}^{R,d}}+\frac{T^{out}-Tw_{n_2}^{R,d}}{Rw_{n_2}^{R,d}}+r^{R,d}\cdot\alpha\cdot Aw^{R,d}\cdot Q_{\text{rad}}^{R,d} \tag{13}$$

$$d\in D=\{East, South, West, North, Top\}$$

where the set D contains all directions of the factory; $Cw_{n_2}^{R,d}$ and $Rw_{n_2}^{R,d}$ are the thermal capacity and resistance of the roof and walls; $Tw_{n_2}^{R,d}$ is the temperature of the roof and walls; Tr_{n_2} is the temperature of the factory room; $r^{R,d}$ chooses 1 if the wall or roof receives sunlight on that direction, and 0 otherwise; α and $Aw^{R,d}$ are the rate of heat absorption and surface area of the four walls and the roof, respectively.

b. Thermal balance constraint of the zone

$$Cr_{n_2}\frac{dTr_{n_2}}{dt}=\sum_{d\in D}\frac{Tw_{n_2}^{R,d}-Tr_{n_2}}{Rw_{n_2}^{R,d}}+\sum_{d\in D}\frac{T_{out}-Tr_{n_2}}{Rwin_{n_2}^{R,d}}+\sum_{d\in D}\tau_{\text{win}}Awin_{n_2}^{R,d}Q_{\text{rad}}^{R,d}+Q_{n_2}^{h,Building} \tag{15}$$

$$D=\{East, South, West, North, Top\}$$

where Cr^{n_2} is the thermal capacity of the NO. n_2 factory building room; $Rwin_{n_2}^{R,d}$ and $Awin_{n_2}^{R,d}$ are the thermal resistance and the area of windows in different directions; the τ_{win} is the rate of light transmission through windows.

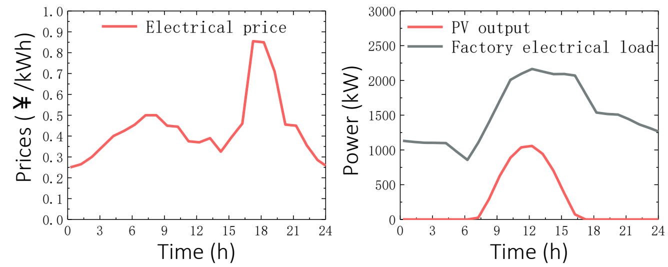
4. CASE STUDY

In this case study, the data of factory building is based on the real low-carbon industrial park which is located in Binhai New District, Tianjin, China and includes 14 buildings for staff production and offices. The park which is an intelligent unmanned equipment industrial park is shown in Fig.3.

Fig.3 The intelligent unmanned equipment industrial park

4.1 *The case setting*

Based on actual and projected operating data of the industrial park. The Electrical price, the PV output, and the factory electrical load is shown in Fig.4.



(a) Electrical price

(b) The power of PV output and factory electrical load

Fig.4 The base information of the industrial park

According to the solar altitude angle and solar azimuth and the data of the radiation intensity of the sun on the horizon, we can calculate the radiation intensity of light in each direction as shown in Fig.5.

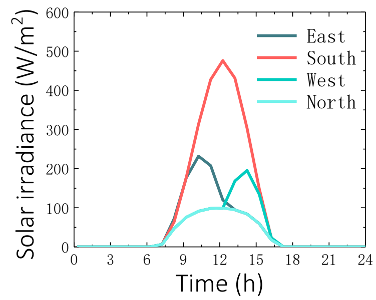


Fig.5 Solar irradiance in different directions

In this industrial park, there is a plan to implement low-carbon park transformation work by laying rooftop PV and replacing 25 ASHPs for heating. Fig.6 shows the planned installation of ASHPs in the park.

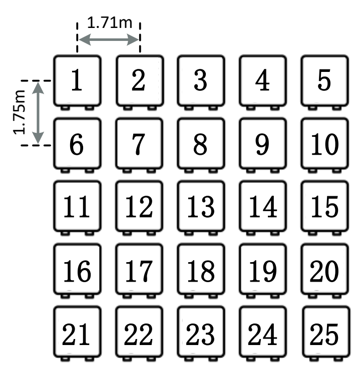


Fig.6 The planned installation of ASHPs

4.2 *The results*

In this paper, two different kinds of scenarios are set.

Scenario 1: Operational strategy for ASHPs considering the cold island effect.

Scenario 2: Operational strategy for ASHPs without considering the cold island effect.

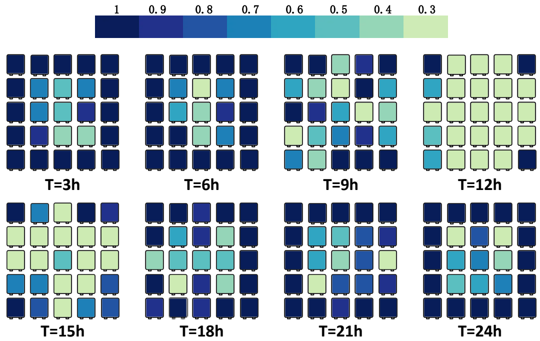


Fig.7 The state of ASHPs at different times in Scenario 1

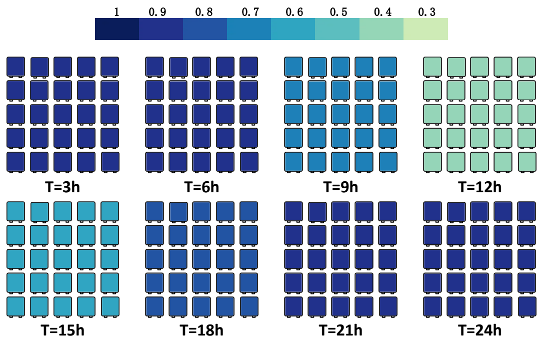
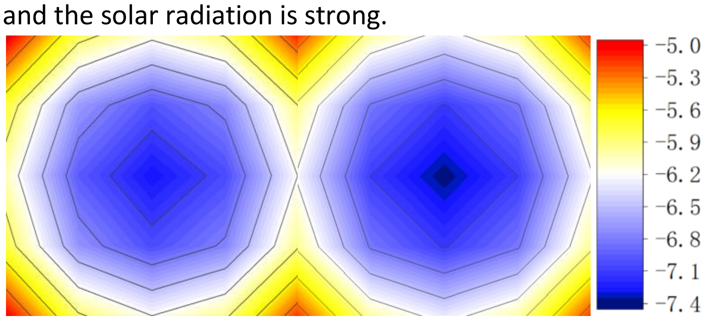


Fig.8 The state of ASHPs at different times in Scenario 2

a. Schedules of the ASHPs

In Figs.7 and 8, the different colors represent the different PLR of the ASHPs. As can be observed, in scenario 1, ASHPs located at the edge of the group are preferentially switched on, and the ASHPs located in the middle are operated with very low PLR to avoid the cold island effect.

It also can be seen from Figs.7 and 8, the ASHPs put out more power at night when the temperature is lower, and less power at noon when the temperature is higher and the solar radiation is strong.



The temperature in Scenario 1 The temperature in Scenario 2

Fig.9 The temperature of ASHPs at 18h in Scenario 1 and 2

In Fig.9, it can be seen that the temperature in Scenario 2 is lower than Scenario 1. It means that Scenario 2 has worse cold island effect.

b. The indoor temperatures of the factory buildings

The indoor temperatures of the 14 factory buildings are shown in Fig. 10. It can be seen from Fig.9 that the indoor temperatures are adjusted among their comfort zones (i.e., 18℃~22℃). However, the temperature maxima is nearly 18℃ because the factory envelope enclosure is made of materials such as steel sheets, resulting in poor thermal insulation.

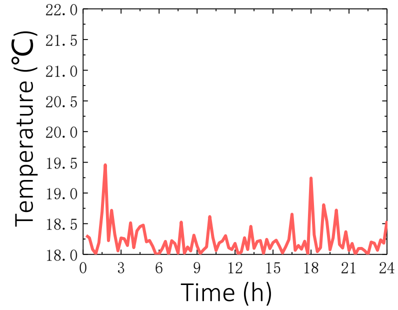


Fig.10 The temperature maxima in 14 factory buildings

c. The energy cost of the industrial park

As shown in Tab.1, Scenario 1 has a 3.29% reduction in energy consumption compared to Scenario 2. Scenario 1 has a 3.11% reduction in total cost compared to Scenario 2. This demonstrates that the proposes method contributes to energy consumption and energy cost reductions by considering the cold island effect of the ASHPs.

Tab.1 The total cost of the scenarios

Scenario	Energy consumption (kWh)	The total cost (￥)
1	97824.74	43825.08
2	101155.11	45231.64

5. CONCLUSIONS

This paper proposes an optimal energy management method of a group of ASHPs in a low-carbon industrial park while considering the cold island effect of the ASHPs. The impact of the cold island effect on the efficiency of ASHPs can be avoided as far as possible by the proposed method in low-carbon industrial parks. It further contributes to energy consumption and energy cost reductions.

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DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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