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The Optimisation of Port Integrated Energy System (PIES) based on Moth Flame Optimization

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Abstract

This paper focuses on the optimisation of the energy allocation in port areas considering integrated demand response (IDR). An Energy Hub model (EH) is built first in order to model the energy configuration in port areas integrating all the energy forms, and on top of that, demand response is applied so as to dynamically fulfil the turbulent load. In the end, an innovative algorithm Moth Flame Optimization (MFO) is used to improve the calculation efficiency and accuracy.

Keywords

Port Integrated Energy System; Integrated Demand Response; Moth Flame Optimization; Energy Hub.

1. Introduction

In 2021, China issued the plan of to achieve carbon peaking and carbon neutrality goals under the new development philosophy, laying out key specific targets and measures for upcoming decades.

By 2030, China's carbon dioxide emissions will peak, stabilize and then decline, and by 2060, China will be carbon neutral and have fully established a green, low-carbon and circular economy, reiterating the country's previous pledge.[1].

Toward this goal, as well as under the general background of reducing carbon emission, environment protection and energy saving have become one of the most important challenges not only China but also the international community have been faced with. [2].

Today, our society's demand for energy is divided into many types, among which electricity demand, heating demand and cooling demand account for a relatively high proportion. So, how to use energy efficiently and economically has drawn great attention in the energy field. As a result, Integrated Energy System has emerged.

According to different energy demands, the integrated energy system can control the mutual conversion of different energy sources through the coupling device, and change the energy output state through the energy storage device, so as to realize the unified scheduling and optimal operation of multiple energy sources.

The past few years have witnessed the great development of IES which has been applied to various places or scenarios in order to optimally operate the energy system under the global circumstance of reducing carbon emission. On the other hand, in ports around the world, pressure is rising to ‘go green’ – whether that is transitioning to Net Zero Carbon and reducing emissions or in meeting the demands of the public and industry bodies alike in operating more efficiently and with greater sustainability.

In response to this trend, Port Integrated Energy System (PIES) has been invented in order to apply the success achieved by IES to the maritime industry.

To understand the complicated energy system in ports, an Energy Hub (EH) is proposed in this article. EH serves as a central unit which converts one energy form into another one, which is exactly the key function of a PIES.

As we know, there are multiple energy sources in a port, such as a Combined Cooling Heating Power unit (CCHP), Gas Boiler, AC unit, etc while different types of loads. So, it is important to address the changeable and turbulent load trait in different seasons or different time in a day. Demand Response (DR) is an approach proposed a few years ago which meets this requirement. However, given the complexity of ports, Integrated Demand Response based on EH was invented which takes all the factors such as energy price, system cost, pollution, etc into consideration.[3,4].

In the end, an innovative algorithm Moth Flame Optimization (MFO) is used to calculate the minimum total cost of the PIES.

2. Port Integrated Energy System

2.1 Device Modelling

There are many different types of energy in a modern port such as the power grid, wind power, gas turbine, air conditioner, etc. Whereas there are also various loads such as cranes, shore electricity, residential electricity, industrial electricity, heating, car chargers, etc, which can be concluded by Fig.1.

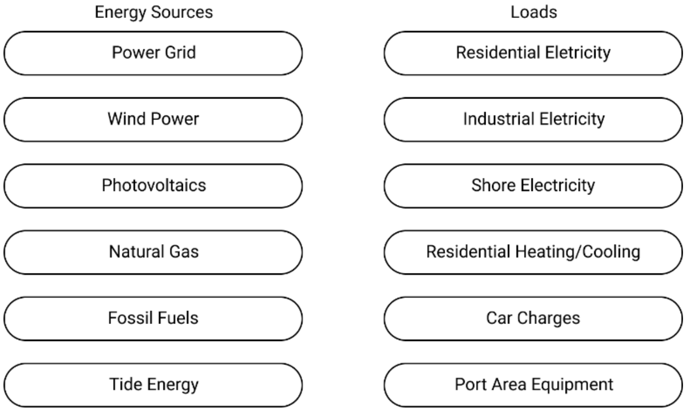


Figure 1. Typical energy sources and loads in a port area

2.1.1 CCHP

Combined Cooling Heating Power system (CCHP) is a very important energy source in port areas. It converts natural gas into electricity, heat and cooling, which makes the most of the natural gas by cascade utilization. It mainly consists of a gas turbine, a lithium bromide refrigerator and a heat exchanger. The gas turbine converts natural gas into mechanical energy which generates electricity while the heat exchanger absorbs the heat produced in this process. On the other hand, the refrigerator can also make use of the heat to produce cooling energy. The process can be expressed as following: [5].

a) Gas Turbine

$$P_{CCHP}^{e} = \beta \cdot \eta_{GT} \cdot H^{g} \cdot G_{pur} \tag{1}$$

b) Refrigerator

$$P_{CCHP}^{c} = \eta_{Re} \cdot (1-\delta) \cdot \beta \cdot (1-\eta_{GT}) \cdot \eta_{HE} \cdot H^{g} \cdot G_{pur} \tag{2}$$

c) Heat Exchanger

$$P_{CCHP}^{h} = \delta \cdot \beta \cdot (1 - \eta_{GT}) \cdot \eta_{HE} \cdot H^{g} \cdot G_{pur} \tag{3}$$

where H^{g} is the heating value of natural gas. $P_{CCHP}^{e}, P_{CCHP}^{c}\ and\ P_{CCHP}^{h}$ is the electricity, cooling and heating generated by CCHP. G_{pur} is the natural gas purchased from the natural gas pipeline. η_{GT} and η_{HE} is the efficiency of the gas turbine and the heat exchanger while η_{Re} is the coefficient of performance of the refrigerator. δ and β are the dispatch factor of natural gas and the remaining heat left by the gas turbine.

2.1.2 Gas Boiler

While CCHP can generate heat, its capacity is subject to the remaining steam left by gas turbine. So sometimes it cannot fulfil the need of heating loads. It is necessary to have gas boilers to provide stable and abundant thermal energy. The mechanism of a gas boiler is quite simple, which can be expressed as following:

$$P_{GB}^{h} = \eta_{GB} \cdot (1 - \beta) \cdot H^{g} \cdot G_{pur} \tag{4}$$

where P_{GB}^{h} is the heat generated by the gas boiler while η_{GB} is the efficiency of the gas boiler.

2.1.3 Air Conditioner

Just like the case for heat energy, there should be a way to provide stable cooling energy, which will be air conditioners. Its mechanism can be expressed as following:

$$P_{AC}^{c} = \alpha \cdot P_{pur}^{e} \cdot \eta_{AC} \tag{5}$$

where P_{AC}^{c} is the cooling energy generated by the air conditioner. P_{pur}^{e} is the electricity purchased from the power grid. η_{AC} is the efficiency of the air conditioner. α is the dispatch factor of purchased electricity.

2.2 EH Modelling

Because of the multiple energy sources in a typical port area, as is shown in the last paragraph, it is very important to make the most of all these sources based on the characteristic of both load and energy source.

To better understand how different energy sources are used at the same time to provide energy for different loads, the concept of Energy Hub was proposed. The structure of an EH in a port area can be shown as Fig.2.[6].

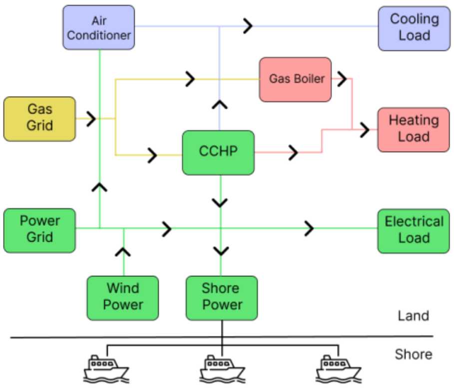


Figure 2. The structure of an Energy Hub in a port area

Based on the device modelling and EH modelling, we can summarise the energy matrix of energy source and load as following:

$$\begin{bmatrix} L_e \\ L_h \\ L_c \end{bmatrix} = \begin{bmatrix} (1-\alpha) & 1 & \beta \cdot \eta_{GT} \cdot H^g \\ 0 & 0 & \delta \cdot \beta \cdot (1-\eta_{GT}) \cdot \eta_{HE} \cdot H^g + \eta_{GB} \cdot (1-\beta) \cdot H^g \\ \alpha \cdot \eta_{AC} & 0 & \delta \cdot \beta \cdot (1-\eta_{GT}) \cdot \eta_{HE} \cdot H^g \end{bmatrix} \cdot \begin{bmatrix} P_{pur}^e \\ P_{WP}^e \\ G_{pur} \end{bmatrix} \tag{6}$$

where P_{WP}^e is the electrical power of wind power, P_{pur}^e is the purchased electricity, and G_{pur} is the natural gas purchased from the gas grid.

2.3 IDR Modelling

Integrated Demand Response (IDR), is a concept to motivate the end user to change its energy usage, for example: reducing the energy usage at peak hours, so as to benefit the energy supplier, which often results in reward for the end user such as discounted energy price at non-peak hours. To realise this concept, we need to analyse the different loads in a port area.[7,8].

Based on the characteristic of loads, we can classify the loads in a port area into 3 different types: Fixed load, Transferrable Load, and Shiftable Load. If we can optimise the operation mode of these different loads, we can further optimise the operation of PIES. [9].

2.3.1 Fixed Load

This type of load is the most common load in a port area, it’s capacity and operation time are strictly fixed, so it is not possible to modify this type of load. Such as port mechanical equipment, which is subject to the operation hours of the port itself, lights, etc. So there is no need to change optimise this type of load.

2.3.2 Transferrable Load

This type of load can be transferred to another period during the day. However, once this type of load has started to function, it cannot be paused again for further transfer. Such as shore power, residential cooling/heating. This type of IDR can be summarised as:

$$L\_trans_{i,t+\Delta t}^{+} = L\_trans_{i,t}^{-} \tag{7}$$

where $L\_trans_{i,t}^{-}$ is the amount of decreased load and $L\_trans_{i,t+\Delta t}^{+}$ is the amount of increased load. Δt means the duration of this load.

2.3.3 Shiftable Load

This type of load is the most flexible load in a port area, it can be transferred to any other period multiple times, as long as the total energy demand is met. Such as electric car charger, industrial heating/cooling. This type of IDR can be summarised as:

$$\sum_{t=1}^{T} L\_shift_{i,t}^{+} = \sum_{t=1}^{T} L\_shift_{i,t}^{-} \tag{8}$$

where $L\_shift_{i,t}^{+}$ and $L\_shift_{i,t}^{-}$ is the increased and decreased amount of shiftable load.

the total IDR model of PIES can be summarised as:

$$L_{IDR}^{i} = L\_shift_{i,t}^{+} + L\_trans_{i,t+\Delta t}^{+} - L\_trans_{i,t}^{-} - L\_shift_{i,t}^{-} \tag{9}$$

where L_{IDR}^{i} is the amount of load that has been applied to IDR of energy type i.

$$i \in \{E(Electricity), C(Cooling), H(Heating\}$$

3. System Operation Optimisation

3.1 Objective Function

To optimise the PIES, we want to minimise the total operation cost. So, in order to get the best economic and environmental strategy to operate the PIES, this paper takes energy price, operational cost, maintenance cost and environment cost into consideration. The objective function can be expressed as following:

$$C_{PIES} = C_{pur} + C_E + C_{oper} + C_{IDR} \tag{10}$$

$$C_{pur} = \sum_{t=1}^{T}(\lambda_E \cdot P_{pur}^{e} + \lambda_G \cdot G_{pur}) \tag{11}$$

$$C_E = \lambda_{CE} \cdot \sum_{t=1}^{T}(E_G \cdot G_{pur}) \tag{12}$$

$$C_{oper} = \sum_{t=1}^{T}(\varepsilon_j \cdot P_j), j \in \{GT, HE, Re, GB, AC, WP\} \tag{13}$$

$$C_{IDR} = \lambda_{IDR} \cdot \sum_{t=1}^{T}(L\_trans_{i,t+\Delta t}^{+} + L\_shift_{i,t}^{+} + L\_trans_{i,t}^{-} + L\_shift_{i,t}^{-}) \tag{14}$$

where C_{PIES} is the total cost of PIES, $C_{pur}, C_E, C_{oper}, C_{IDR}$ is the cost of purchased energy, cost of energy pollution, operation cost of all the devices in PIES and the cost of IDR. λ_E is energy price, E_G is the air pollution coefficient, λ_{CE} is the price of CO_2 emission, ε_j is the operation cost of energy source P_j, λ_{IDR} is the cost of IDR.

3.2 Constraints

3.2.1 Energy Balance Constraint

The generated energy must equal to the load demand.

Electricity:

$$P_{pur}^{e} + P_{WP}^{e} + P_{CCHP}^{e} = L_e + P_{AC}^{e} \tag{15}$$

Cooling:

$$P_{CCHP}^{c} + P_{AC}^{c} = L_c \tag{16}$$

Heating:

$$P_{CCHP}^{h} + P_{GB}^{h} = L_h \tag{17}$$

3.2.2 Device Operation Constraint

The power of each device must be greater its minimum power and smaller than its maximum power:

$$P_{j,min}^{i} \le P_{j}^{i} \le P_{j,max}^{i} \tag{18}$$

$$i \in \{E(Electricity), C(Cooling), H(Heating\}$$

$$j \in \{GT, HE, Re, GB, AC\}$$

3.2.3 IDR Constraint

IDR must meet energy balance as well, as well as operation constraint.

$$0 \le L_{IDR}^{i} \le \lambda_{IDR}^{i} \cdot L_{i} \tag{19}$$

$$\sum_{t}^{T} L_{IDR}^{i} = 0 \tag{20}$$

λ_{IDR}^{i} is the percentage of load applied to IDR of load L_i and equation (20) means the total decreased load must equal to the increased load within a operation term.

3.3 Moth Flame Optimisation

Moth Flame Optimisation is an intelligent algorithm proposed in 2015. It essentially simulates the behaviour of moth searching for the flame in a certain space. It has multiple advantages such as simple model, fewer parameters, low probability of local optima stagnation, etc. [10].

In MFO algorithm, it is assumed that the candidate solutions are moths and the problem's variables are the position of moths in the space. The set of moths is represented in a matrix as following:

$$\text{M}=\begin{bmatrix} m_{1,1} & m_{1,2} & \cdots & m_{1,d} \\ m_{2,1} & m_{2,2} & & m_{2,d} \\ \vdots & & \ddots & \vdots \\ m_{n,1} & m_{n,2} & \cdots & m_{n,d} \end{bmatrix} \tag{21}$$

where n is the number of moths and d is the number of variables (dimension).

For all the moths, the array for storing the corresponding fitness values can be expressed as following:

$$\text{OM}=\begin{bmatrix} OM_1 \\ OM_2 \\ \vdots \\ OM_n \end{bmatrix} \tag{22}$$

where OM_n is the best fitness value of each moth.

Another key components in MFO is the matrix of flames. A matrix similar to the moth matrix is considered as following:

$$\text{F}=\begin{bmatrix} f_{1,1} & f_{1,2} & \cdots & f_{1,d} \\ f_{2,1} & f_{2,2} & & f_{2,d} \\ \vdots & & \ddots & \vdots \\ f_{n,1} & f_{n,2} & \cdots & f_{n,d} \end{bmatrix} \tag{23}$$

where n is the number of flames, equivalent to the number of moths, and d is the number of variables (dimension).

Similarly, we have the array for storing the corresponding flame fitness values as following:

$$\text{OF}=\begin{bmatrix} OF_1 \\ OF_2 \\ \vdots \\ OF_n \end{bmatrix} \tag{24}$$

The mechanism of updating each moth's relative position of flames is:

$$M_i = S(M_i \cdot F_j) \tag{25}$$

$$S\big(M_i \cdot F_j\big) = D_{i,j} \cdot e^{bt} \cdot \cos(2\pi t) \cdot + \ F_j \tag{26}$$

$$D_{i,j}=|M_i - F_j| \tag{27}$$

where M_i and F_j are moth i and flame j while S is the spiral function, $D_{i,j}$ is the distance between Moth i and flame j, b is spiral constant and t is a random number between (r,1) while r decreases from -1 to -2 in linearisation as the iteration continues.

Because in every iteration, the position of each moth will be updated based on all the flames in the search space, which compromises the local optimisation ability of the algorithm. To resolve this issue, an adaptive way to change the flame number can be expresses as following:

$$F_n = round(N - l * \frac{N-1}{T}) \tag{28}$$

where round() means rounding function, N is the original number of flames, l is current iteration times and T is the total iteration times.

In conclusions, MFO can be summarised as following steps:

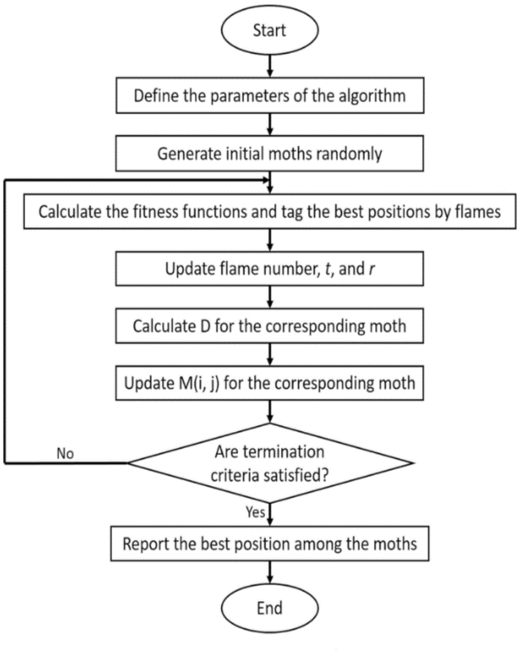


Figure 3. Steps of MFO

4. Case Study

Based on the research above, this paper chooses a port in Eastern China to verify the proposed optimisation strategy. The operation term is a typical day in the middle of year when the cooling load and heating load are approximately and relatively balanced. The day is divided into 24 periods which will be 1 hour for each period.

Two scenarios will be simulated and compared:

Scenario 1: Simply meeting the daily demand of this port and optimising the cost, without considering IDR.

Scenario 2: On top of meeting the daily demand of this port and optimising the cost, IDR is also applied.

For the convenience of calculation, the load of shore power is added into electricity load.

4.1 Key Parameters

Table 1. Key parameters

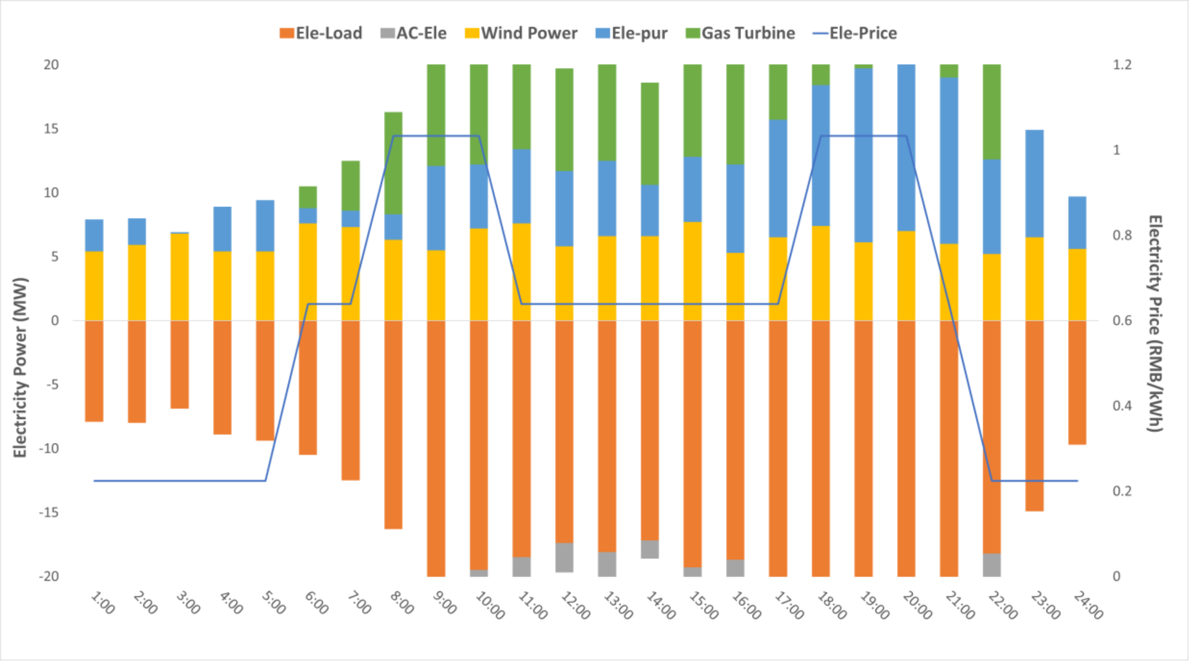
H^g	λ_{CE}	E_G	ε_{CCHP}	ε_{GB}
9.7kWh/Nm^3	49 MB/1000KG	2.92kg /m^3	32RMB/MWh	26RMB/MWh
ε_{AC}	ε_{WP}	λ_{IDR}	λ_{IDR}^i	λ_G
21RMB/MWh	5RMB/MWh	150RMB/MWh	0.2	4.2RMB/m^3

Table 2. Electricity price

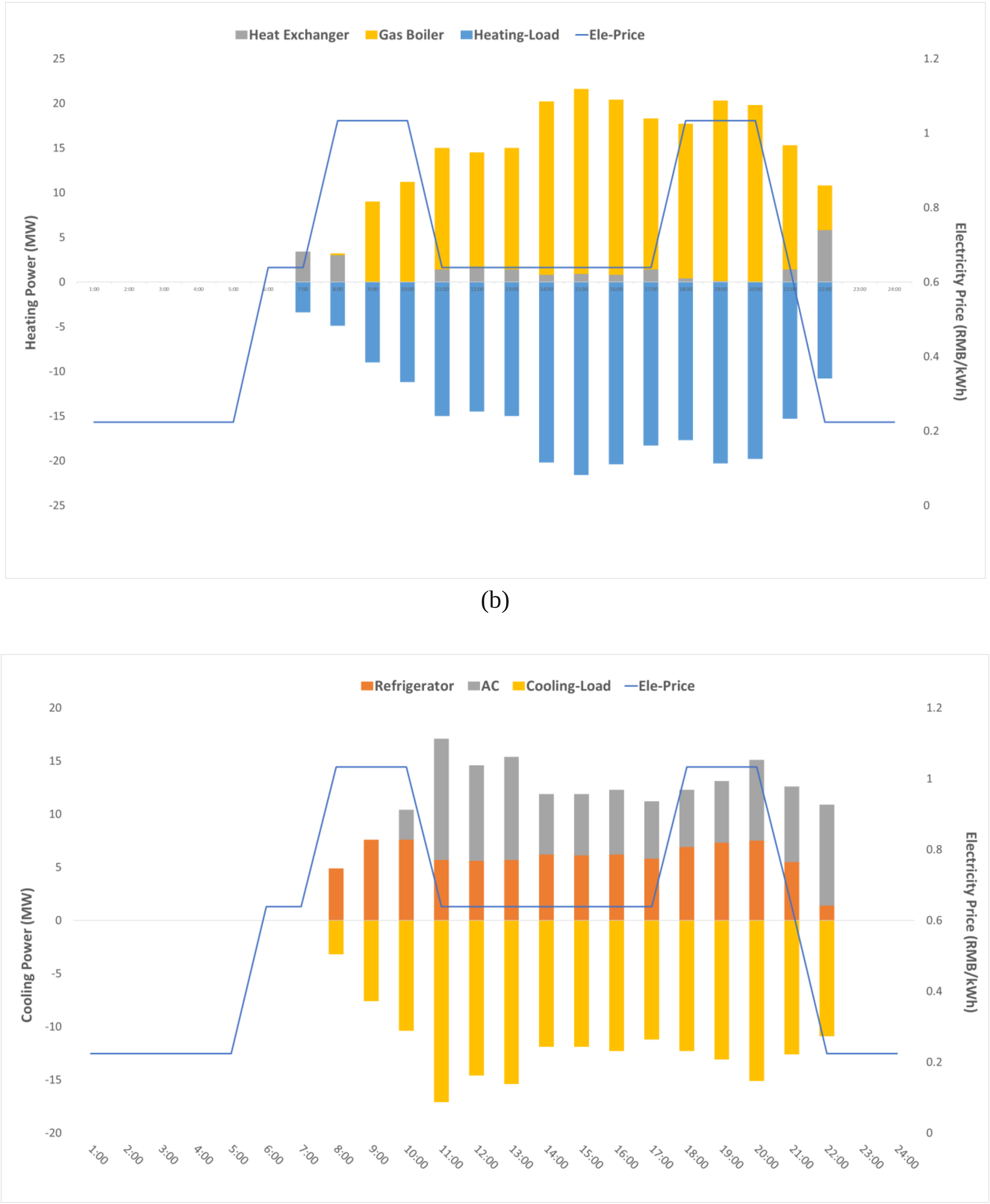
8:00-11:00 & 18:00-21:00	1.033
6:00-8:00 & 11:00-18:00 & 21:00-22:00	0.639
22:00-6:00	0.224

4.2 Results

4.2.1 Scenario 1:



(a)

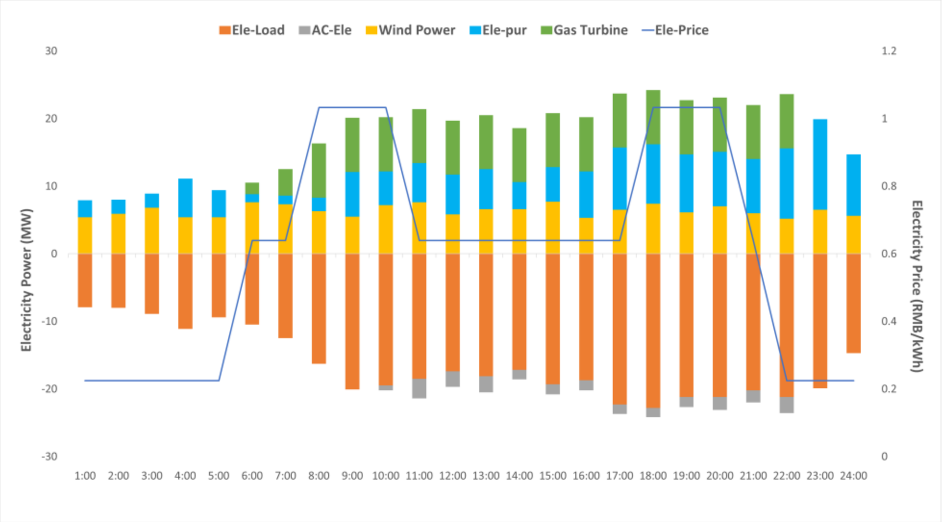


(b)

(c)

Figure 4. The energy balance of electricity, cooling and heating under scenario 1

4.2.2 Scenario 2:



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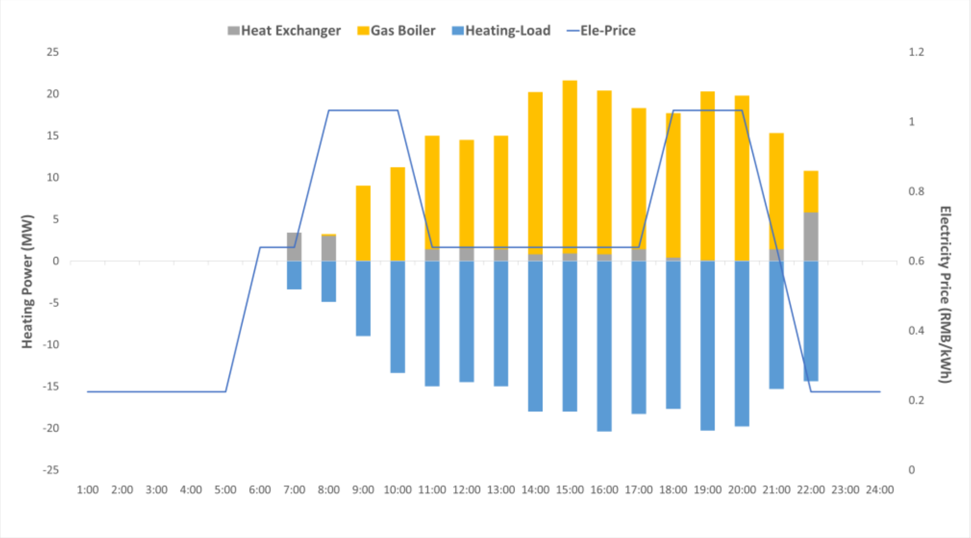

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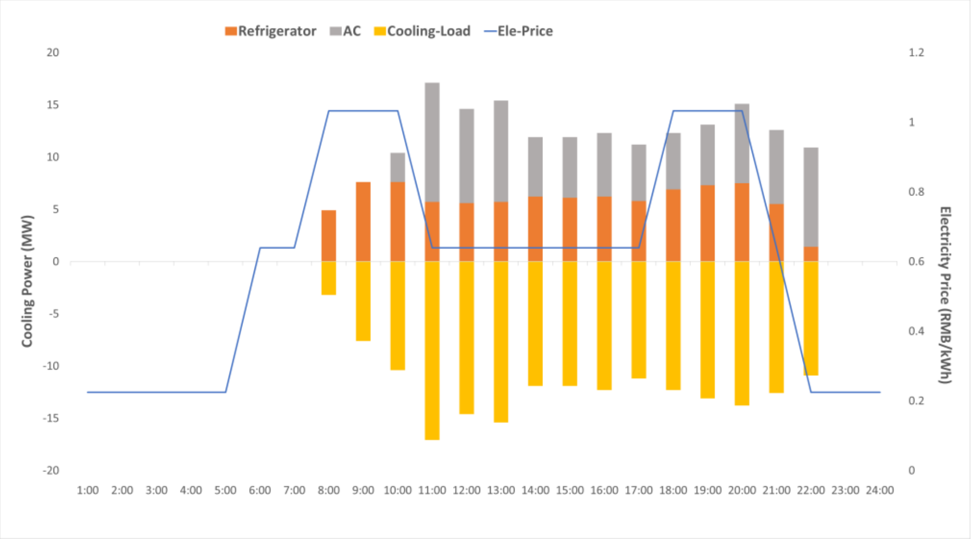

(c)

Figure 5. The energy balance of electricity, cooling and heating under scenario 2

In scenario 1, due to the low electricity price in the beginning, most of the electricity supply is met by directly purchased electricity and wind power. When daylight comes, the cooling and heating demand starts to increase. The system first uses CCHP to meet the cooling and heating demand, but both of them get maxed out quickly. Due to the high electricity price during the peaking hours, most of the remaining steam from gas turbine is allocated to refrigerator to reduce the usage of AC so as to reduce purchased electricity. When the electricity price falls down again, AC is rapidly put into use as well, but the heating demand also increase so gas boiler is still heavily used. When the night comes, electricity price falls to the trough again so most electricity demand is met by directly purchased electricity.

In scenario 2, the application of IDR greatly reduced the peak of electricity demand especially during peak hours, thus reducing the total electricity cost effectively and balance heat exchanger and refrigerator as well.

Table 3. Total system cost of PIES (RMB)

	Scenario 1	Scenario 2
Purchased Energy	394786	359376
Environmental Cost	13568.4	15128.7
Operational Cost	11488.8	13439.6
IDR Cost	0	6325.5
Total Cost	419843.2	394269.8

According to Table 3, the introduction of IDR has reduced the total cost of PIES by 6.01%.

5. Conclusion

This paper has proposed an innovative algorithm on top of IDR to optimise the operation of a typical PIES. When IDR is applied, the system cost can be effectively reduced.

However, many cases in this research has been idealised beforehand to simplify the research, such as the uncertainty of wind power, the energy loss on the power cable, etc. There is more work to be done in the future.

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