Adjustable capability of the distributed energy system: definition, framework, and evaluation model

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ABSTRACT

The adjustable capability of distributed energy systems responding to the incentives of the upper energy supply system has been significantly improved by energy storage and renewable energy technologies. Most existing research focuses on evaluating the flexibility of distributed energy system itself or the demand response potential of end-users, but there is no specific model which takes the distributed energy system as an integrated load and evaluates its adjustable capability from the perspective of the upper energy supply system.

To fill the research gap, this paper defines the adjustable capability of distributed energy systems, describes its characteristics, and proposes a unified evaluation model. Then, from the perspective of energy demand and supply sides, it quantifies the impact of each influential factor in different energy links on the adjustable capability and studies the interactive mechanism between devices within the system. Thereafter, the adjustable capability of distributed energy systems under typical scenarios at a single moment is evaluated, and the impact of economic constraints on the adjustable capability is also extensively analyzed. Accordingly, this paper proposes a sequential recurrence method to evaluate the adjustable capability of distributed energy systems against three different initial states: unknown initial state, fixed initial state, uncertain initial state. Finally, the adjustable capability concept is demonstrated on a practical industrial park to verify the effectiveness and practicability.

This study deepens the connection between distributed energy systems and upper energy supply system in the Energy Internet at the energy information level. which enables distributed energy system to quantize its energy demand range for the upper energy supply system and realize its own reliable operation and rolling optimization. In addition, this evaluation method allows upper energy supply system to plan, overhaul and dispatch more economically and reliably on the basis of understanding the energy demand of distributed energy system. Moreover, upper energy supply system can formulate the demand response strategy with the maximum revenue by balancing the size of adjustable capability interval of distributed energy system and the investment cost of demand response.

KEYWORDS

Distributed energy system; Adjustable capability; Dynamic evaluation; Multi-energy complementarity

Nomenclature

$C_{i\text{-}j}$	Cold in the conversion from Energy i to j, kW·h

CO	Operating costs, ¥
CO_{st}	Operating cost with economic constraints, ¥
CO_{best}	Cost of optimal economic operation, ¥
CO_{r}	Remaining operating cost, ¥
$\mathrm{D}_i(t)$	Discharging energy of energy *i* at time interval *t*, kW·h
$E_{i\text{-}j}$	Electricity in the Conversion from Energy *i* to *j*, kW·h
E_{in}	Electricity demand of the system, kW·h
G_{in}	Natural gas demand of the system, m^3
$G_{\mathrm{in,max}}(t)$ / $G_{\mathrm{in,min}}(t)$	Maximum/minimum natural gas demand of the system at time interval *t*, m^3
$H_{i\text{-}j}$	Heat in the conversion from Energy *i* to *j*, kW·h
$L_{i.\mathrm{min}}(t)$ / $L_{i.\mathrm{max}}(t)$	Maximum/minimum load at time interval *t*, kW·h
$M_{i,max}$ / $M_{i,min}$	The energy demand intervals when load is maximum/minimum
P_{CHP}	Output power of CHP system, kW
$P_{\mathrm{C}}^{m}(t)$	Energy stored by energy storage devices at time interval *t*, kW
$P_{i,\mathrm{Umax}}^{\mathrm{V}}(t)$	Output power of factor V when factor U works under its maximum condition
$P_{\mathrm{D}}^{\mathrm{ES}}$	ES discharging power, kW
$P_{i,\ \mathrm{max}}{}^{\mathrm{c}}$ / $P_{i,\ \mathrm{max}}{}^{\mathrm{d}}$	Maximum charge/discharge power of energy *i*, kW
$P_i{}^{\mathrm{UV}}$	Power of the energy *i* flowing through the influencing factor U and V, kW
$P_{i,\mathrm{max}}{}^{\mathrm{U}}(t)$ / $P_{i,\mathrm{max}}{}^{\mathrm{V}}(t)$	Maximum output power of factor U and V, kW
$P_{i,\mathrm{max}}^{\mathrm{V}}(t)$ / $P_{i,\mathrm{min}}^{\mathrm{V}}(t)$	Maximum/minimum power of factor V before considering the interaction at time interval *t*, kW
$\bar{P}_{i,\mathrm{max}}^{\mathrm{V}}(t)$ / $\bar{P}_{i,\mathrm{min}}^{\mathrm{V}}(t)$	Maximum/minimum power of factor V after considering the interaction at time interval *t*, kW
$P_w(t)$	Output power of device *w* at time interval *t*, kW
$P_{w,\mathrm{max}}$ / $P_{w,\mathrm{min}}$	Maximum/minimum output power of device *w*
$Q_{i,\mathrm{max}}(t)$ / $Q_{i,\mathrm{min}}(t)$	Maximum/minimum demand of energy *i* at time interval *t* , kW·h
$Q_{i,\mathrm{max}}{}^{\mathrm{c}}(t)$ / $Q_{i,\mathrm{max}}{}^{\mathrm{d}}(t)$	Maximum amount of energy that a storage device can charge/discharge at time interval *t*, kW·h
$Q_i{}^{\beta}(t)$	Supply of energy *i* at time interval *t* , kW·h
$Q_i{}^{\gamma}(t)$	Demand of energy *i* at time interval *t* , kW·h
Q_{h}	Heat load to be satisfied by CCHP system, kW
$R(t)$	Output power of renewable energy at time interval *t*, kW·h
$\mathrm{S}_{i,\mathrm{max}}$ / $\mathrm{S}_{i,\mathrm{min}}$	Maximum/minimum energy storage capacity of energy *i*. kW·h
$\mathrm{S}_i(t)$	Charging energy of energy *i* at time interval *t*, kW·h
U/V	Influencing factor

a	Working point when the system determines power generation by heat
b	Working point when the system determines power generation by electricity
c	Cold
e	Electricity
g	Gas
h	Heat
m	Time of fixed strategy operation
n	Number of operation strategy
w	Load point
x	Value of abscissa
y	Value of ordinates
α_i^c/α_i^d	Charging and discharging states of energy storage devices
$\rho_i(t)$	Unit price of energy i at time t, ¥/ kW·h or ¥/ m^3
λ_i	Energy contribution ratio
μ_k	Repair rate of k^{th} device component, r/a
υ_{CHP}	ramp rate of CHP system
η_{CHP}	Efficiency of CHP system

1 Introduction

The definition of a distributed energy system (DES) is given in [1] as "*a system where energy is made available close to energy consumers, typically relying on a number of small scale technologies*". DES involves the links of energy production, transmission, conversion, storage and consumption, and realizes complementary couplings between energy resources, such as electricity, gas, heating, and cooling [2]. Additionally, DES interacts with the upper energy supply system (UESS) by purchasing energy such as electricity and natural gas. Due to the complementary coupling of multi-energy resources in DES, the energy demand of DES for the UESS is no longer a fixed value of a single energy resource, but a demand interval of multi-energy resources. DES is an integrated load with adjustable potential for UESS, and thus UESS can guide DES to participate in demand response (DR) by adjusting incentives.

Adjustable capability of DES(ACDES) is defined as the potential of DES to participate in DR while meeting its own needs, expressed as the fluctuation interval of energy demand for UESS. The evaluation of ACDES can be understood as taking DES as a new type of integrated load with demand response potential and studying its overall energy demand from the perspective of UESS. With the increasing complexity of DES, there are more factors affecting its adjustable capability, which are divided into three categories and the related research is introduced as follows.

(1) Energy coupling equipment in DES

ACDES has been greatly improved due to the complementary couplings between various elements, including gas turbine, heat pump [3], energy storage devices [4-5], and CCHP system [6-7], etc. In addition, as an important energy resource in DES, renewable energy [8] significantly changes the energy demand of UESS due to its uncertainty [9]. Previous research on the flexibility evaluation considered the high penetration of renewable energy with great unpredictability and variability characteristics [10]. Ref.[11] presented a method for calculating the adjustable capability of renewable energy based on probabilistic production simulations.

(2) Demand response (DR) in DES

DR has been recognized as a valuable tool to provide adjustable capability for DES. Both flexible load reduction of end-users and complementary coupling in energy systems make DES adjustable. In general, existing research on DR mainly aims at single end-user or building energy system（BES）with integrated users.

1) Resident users are adjustable as they can change load by determining when and how to use electric appliances properly. Ref. [12] analyzed the demand response potential of devices at the end-user level. As a special end-user, electric vehicles can spatiotemporally shift energy. Ref. [13] studied the controllable load margin boundaries of backup batteries in battery swapping stations and proposed a recursive modelling method for load margin zone.

2) Heating, ventilation and air-conditioning (HVAC) system, virtual energy storage technologies, and temperature control technologies contribute to the adjustable capability of BES. Previous research on DR of HVAC systems can be divided into two categories. On the one hand, the flexibility of BES is assessed by various indicators. Ref. [14] evaluated the flexibility of BES from three aspects: time, power and energy. Ref. [15] introduced three indicators of active demand response to quantify energy flexibility: available capability, energy storage efficiency and energy transfer capacity. A systematic approach was proposed to quantify electricity flexibility in BES, including electricity flexibilities of thermal mass, HVAC and appliances in [16]. On the other hand, by comparing building flexibility, the flexible control of BES was realized. According to the quantity and duration of DR, a demand response potential model was established to guide air conditioning systems to participate in grid operation in [17]. A decision-support model was proposed in [18], which can be used to control the demand-side flexibility of buildings. Ref. [19] compared the effectiveness and efficiency of four flexibility improvement methods. Ref. [20] quantified the impact of different devices on flexibility and summarized the methods to improve energy flexibility in buildings.

(3) Economic index of DES

Economic indexes are important for guiding the dispatch and dynamic recurrence of DES, Most existing research used operating costs as an index to measure the economics of different operation strategies. Ref. [21-23] reviewed the relevant operation optimization algorithms of DES. Existing studies mostly use single-objective optimization to develop the optimal economic operation strategy of DES [24-26]. Some use multi-objective optimization [27-29] to operate DES, considering economic indicators (such as operating cost), environmental indicators (such as CO2 emissions), and energy efficiency. Meanwhile, the constraint of operating costs will constrain the energy demand of DES for UESS, which will narrow the size of adjustable capability interval (ACI) .

At present, there are some similar researches on the adjustable capability of energy systems, which are focused on the energy flexibility, energy demand flexibility, demand response potential and flexible load potential, etc. Flexibility was first proposed in power systems, defined as the ability of a system to deploy its resources to respond to changes in demand not served by variable generation [30]. Ref. [31] summarized relevant indicators and calculation methods for quantifying flexibility of power systems and established a unified flexibility evaluation framework. Subsequently, flexibility was extended to energy systems, Ref. [32] proposed a flexibility region method to formulate the flexibility of district heating systems in terms of power capacity and energy capacity. During extending flexibility research from power systems to energy systems, a new index - demand response potential has been proposed to assess the potential of flexible energy demand. Ref. [33] standardized demand response potentials into four main categories: technicality, economy, theory and realizability, and proposed a new user-friendly framework to gradually determine different types of demand response potential. Ref. [34] quantified the potential of individual flexible load users for participation in DR. A methodology for rating the energy flexibility performance of buildings is introduced and the potential to adjust energy demand according to external requests is quantified in [35].

The biggest difference between our study and existing research lies in the evaluation angle. The existing research mainly focused on DES. They quantified the influencing factors of energy flexibility; proposed the evaluation indicators, such as energy flexibility and demand response potential; and assessed the ability of systems to cope with certain changes from its own perspective. However, it is urgent for UESS to understand the overall ACDES to formulate effective incentive measures to promote DES to participate in DR. Therefore, this paper focused on, from the perspective of UESS, the adjustable capability to evaluate the ability of DES that can be regulated by UESS, by making use of the internal factors in DES.

Besides, existing research still has the following deficiencies. Firstly, different influencing factors of ACDES are not in a simple superposition relationship, but interact with each other, while the mechanism of the interaction has not been clearly revealed. Secondly, response time is often adopted in most research to characterize the dynamic characteristics, but the rolling recurrence of ACI has not been assessed yet. In addition, regarding economic indicators, previous research mostly optimizes the operating cost and develops operational strategies by using optimization algorithms. However, they can only output a specific operational strategy, which cannot reveal the change of ACDES under various economic constraints. While in practice, operating cost is often not strictly limited to the minimum value, but expected to be controlled within a certain interval.

To address the above problems, this paper proposed an interval evaluation model of energy demand adjustable capability of DES. The novelties and contributions of this paper are as follows:

1) We defined the ACDES, described its characteristics, and proposed a unified model to evaluate it from the perspective of UESS.

2) We quantified the energy demand interval of each influencing factor. Additionally, we also revealed the interaction mechanism of influencing factors by dividing their coupling relationship into two categories according to the connection of device ports.

3) We divided the original operating states of DES into three categories: unknown, fixed and interval values, and proposed a sequential recurrence method to evaluate the adjustable capability interval (ACI) of DES in the three cases.

4) We studied the impact of economic constraints on ACDES, and proposed an analytical method to realize the sequential recurrence of ACI with economic constraints.

The rest of this paper is organized as follows. Section 2 defines the ACDES and emphasizes its significance and application value. Section 3 quantifies the dynamic energy demand of the influencing factors and studies the intrinsic interactive mechanism among them. Section 4 proposes two methods for interval evaluation. Section 5 proposes the recursive method. Section 6 presents the discussion and the application value of evaluation results. Section 7 concludes this paper.

2 The adjustable capability of DES(ACDES)

2.1 Definition and characteristics of ACDES

Due to the complex coupling of multi-energy flows in DES, its energy demand for UESS is different from that of an ordinary load. Therefore, it is important to evaluate the ACDES from the perspective of UESS, which is the focus of this paper.

The energy flow of a typical multi-energy system is shown in Fig. 1. As a complex comprehensive load, DES interacts with UESS by purchasing energy, such as electricity and natural gas. Meanwhile, DES needs to satisfy the terminal load through energy production, transportation, and conversion devices.

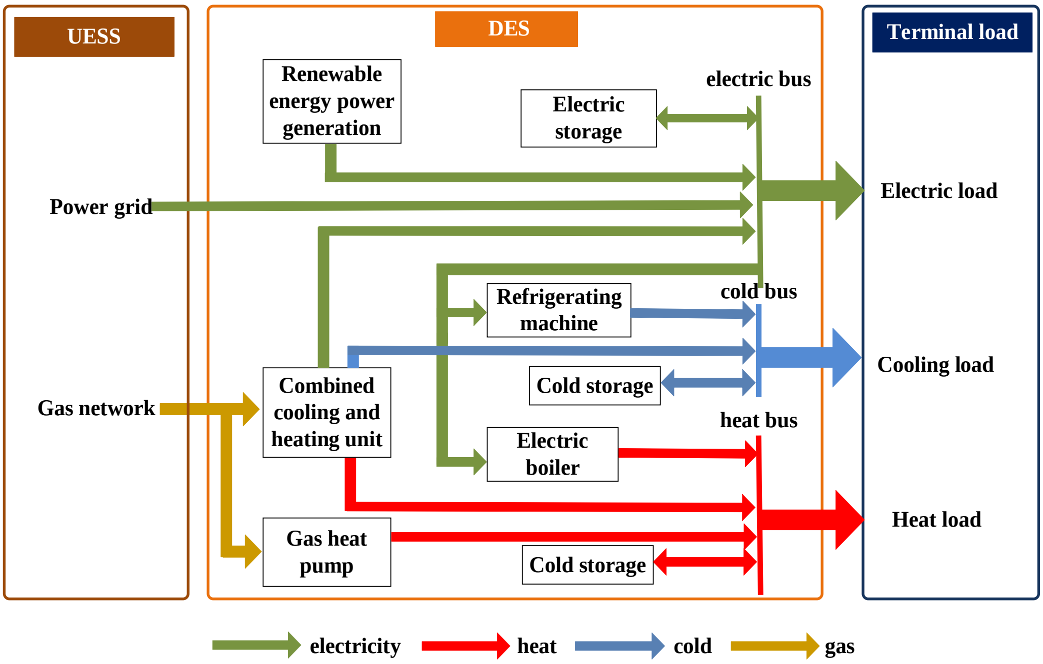

Fig. 1 Structure of the multi-energy system

The adjustable capability of DES(ACDES) is defined as its potential to participate in DR while meeting its own needs, expressed as the fluctuation interval of energy demand for UESS. Due to the complex multi-energy coupling within DES, the energy demand for UESS is not a fixed value, but an interval value. Therefore, ACDES can be expressed by an interval, which is called the adjustable capability interval (ACI).

The characteristics of this interval are as follows:

1) Uniqueness. Many factors affect ACDES. With one or more influencing factors, the ACI is unique. When there are no influencing factors or the operation strategy is fixed, the energy demand of DES for UESS is fixed and there is no ACI.

2) Connectivity. The ACI is the aggregation of energy demand for the UESS under all operational strategies. Therefore, for any point in the interval, there is an operational strategy to achieve the balance of energy demand and supply, and each point in the interval can be achieved.

3) Dynamics. As the dynamic constraints of DES change over time, the ACI also illustrates sequential dynamic characteristics.

2.2 Significance and application of ACDES

The research on adjustable capability is not only valuable to DES itself as showing in the current research, but also of great significance to UESS. UESS can understand the energy demand interval of DES by evaluating the ACDES more intuitively and specifically.

1) The upper boundary of ACI refers to the maximum energy demand of DES. Based on this, UESS can determine energy supply capacity at the access point of DES, e.g., power supply capacity and gas supply capacity, to guide the reliable planning of UESS.

2) The lower boundary of ACI refers to the minimum energy demand of DES, and thus, UESS can choose the time period with less energy demand to design a maintenance plan with less expectation for the lack of energy supply.

3) UESS guides users to participate in demand response programs by adjusting energy prices or giving subsidies. As a new type of end-users, DES has strong potential to participate in DR due to the internal complementary energy coupling. However, the demand response potential of DES is constrained, and the positive correlation between incentive measures and user participation in DR is not linear. The impact of incentive measures on DR will reach saturation. Therefore, by evaluating ACDES under different energy prices or subsidy policies, UESS can formulate energy prices or subsidies with the highest profit to mobilize the best use of DR in DES by selecting the scheme with the largest ACI.

Obviously, as mentioned in references, it is also important to evaluate the adjustable capability for DES itself.

1) Evaluating the ACDES under different planning and configuration schemes is conducive to the reasonable planning of DES and also lays the foundation for participating in DR.

2) Evaluating the ACDES under different operation strategies can help DES select the operation strategy with largest ACI under the operation cost constraint. The largest ACI allows DES to deal with the failure or maintenance of UESS furthest, because of the largest potential that DES can participate in DR to reduce the load in this situation. In addition, the dynamic recursive evaluation of ACDES can also be used in the rolling optimization operation of DES to realize its intraday optimal scheduling.

To conclude, the evaluation method of ACDES proposed in this paper can be applied to the planning and maintenance of UESS as well as to the formulation of energy prices or incentive subsidies for DR. In addition, it can be used as a constraint in the optimized operation dispatching of DES, or as an optimization objective in multi-objective optimization to achieve the balance between maximizing adjustable capability and minimizing the investment.

3 Modelling of influencing factors and their coupling relationship

Many factors affect the ACDES, including energy production devices, renewable energy,

energy storage resources, and elastic load from DR. Besides, some energy conversion devices, such as gas-fired boilers, electric heating device, absorption refrigerators and electric refrigerators, cannot provide the adjustable potential for DES when working in isolation, but they are adjustable when working in combination.

3.1 Modeling of influencing factors of ACDES

As a type of energy hub, the modelling of various equipment and overall coupling matrix of DES is very mature [36]. Accordingly, the energy demand interval and sequential recurrence constraints of each influencing factor are modelled as follows.

3.1.1 CHP system

A CHP system converts natural gas into electricity and heat through gas turbines and heat recovery devices. CHP systems have two operation modes: heat-fixed power mode and electricity-fixed heat mode. As electricity and heat produced under these two operating modes are different, DES can adjust the demand for UESS by switching between the two operating modes.

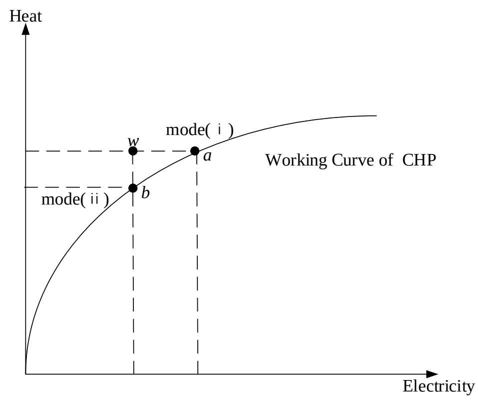

Fig. 2 Schematic diagram of operating modes of the CHP system

As shown in Fig. 2, the load point corresponding to the pure electricity load and thermal load is point w. If the CHP system operates according to mode (i), which means it determines power generation by heat (point *a*). The natural gas demand is $G_{\mathrm{in},a}$, and the residual electricity stored in energy storage equipment (ESE) after generating by CHP system is $x_a - x_w$. If the CHP system operates according to mode (ii), which means it determines power generation by electricity (point *b*). The natural gas demand is $G_{\mathrm{in},b}$, and the heat to be satisfied by other heating device is $y_w - y_b$.

In addition, the ramp rate constraint of CHP system should be considered in the sequential recurrence：

$$\left|P_{\mathrm{CHP}}(t) - P_{\mathrm{CHP}}(t-1)\right| \le \upsilon_{\mathrm{CHP}} \tag{1}$$

The ramp rate constraint indicates that the absolute difference of CHP system (P_{CHP}) output power at adjacent time periods should not be higher than the upper limit υ_{CHP}. The upper and lower boundaries of energy demand interval at time t ($G_{\mathrm{in,max}}(t)$, $G_{\mathrm{in,min}}(t)$) are ：

$$\mathrm{G}_{\mathrm{in,max}}(t) = \min\left(G_{\mathrm{in},a}(t), \left(P_{\mathrm{CHP}}(t-1) + \upsilon_{\mathrm{CHP}}\right) \big/ \eta_{\mathrm{CHP}} \right) \tag{2}$$

$$\mathrm{G}_{\mathrm{in,min}}(t) = \max\left(G_{\mathrm{in},b}(t), \left(P_{\mathrm{CHP}}(t-1) - \upsilon_{\mathrm{CHP}}\right) \big/ \eta_{\mathrm{CHP}} \right) \tag{3}$$

3.1.2 Renewable energy

DES can adjust energy demand for UESS by changing the absorption of renewable energy. The output range of renewable energy is [0, $R(t)$], and the energy demand without renewable energy is [$Q_{i,\min}(t)$, $Q_{i,\max}(t)$]. After considering renewable energy, the net energy demand of DES is as follows.

$$Q_{\mathrm{RE}} = [Q_{i,\min}(t) - R(t),\ Q_{i,\max}(t)] \tag{4}$$

3.1.3 Energy storage equipment(ESE)

ESE can temporally transfer energy demand by increasing energy demand when they are charged, vice versa. Therefore, DES can respond to the incentives of UESS by changing storage operation strategies. After considering the capacity constraint of ESE, it is necessary to divide them into three categories according to their real-time capacity at time *t* when analyzing the constraints and dynamic characteristics.

State I: The existing energy of ESE enables them to be charged and discharged according to the rated power at the next moment. Thus, they are not constrained by storage capacity, and the maximum amount of energy that they can charge or discharge at time *t* ($Q_{i,\max}{}^{\mathrm{c}}(t)$、$Q_{i,\max}{}^{\mathrm{d}}(t)$) are the maximum charge or discharge power ($P_{i,\max}{}^{\mathrm{c}}$, $P_{i,\max}{}^{\mathrm{d}}$) respectively.

State II: The existing energy of ESE at time *t*-1 is close to the upper limit of capacity ($S_{i,\max}$). Therefore, they cannot be charged at the rated power at time *t*, but only charged with remaining capacity. $P_{i,\max}{}^{\mathrm{c}}$ is shown in Formula (5), and $P_{i,\max}{}^{\mathrm{d}}$ is the same as that in State I.

$$Q_{i,\max}{}^{\mathrm{c}}(t) = S_{i,\max} - S_i(t-1) \tag{5}$$

State III: The existing energy of ESE at time *t-1* is close to the lower limit of capacity ($S_{i,\min}$). They cannot discharge at the rated power at time *t*, but release the remaining energy. $P_{i,\max}{}^{\mathrm{c}}$ is shown in Formula (6) and $P_{i,\max}{}^{\mathrm{d}}$ is the same as that in State I.

$$Q_{i,\max}{}^{\mathrm{d}}(t) = S_i(t-1) \tag{6}$$

The demand interval of energy *i* is [$Q_{i,\min}(t)$,$Q_{i,\max}(t)$] without ESE, and the energy demand interval Q_{ESE} is shown in Formula(7) after considering ESE.

$$Q_{\mathrm{ESE}} = [Q_{i,\min}(t) - Q_{i,\max}{}^{\mathrm{d}}(t),\ Q_{i,\max}(t) + Q_{i,\max}{}^{\mathrm{c}}(t)] \tag{7}$$

3.1.4 Elastic load

The terminal load of DES is elastic and can be reduced flexibly, and thus the load is no longer constant but varies within a certain range ***L***.

$$L = [L_{i,\min}(t),\ L_{i,\max}(t)] \tag{8}$$

When the load of DES is the lower boundary of load interval ($L_{i.\min}(t)$), the energy demand interval for UESS is aggregation $\mathrm{M}_{i,\min}$, vice versa. The demand interval of energy *i* is the union of two aggregations:

$$\mathrm{Q}_{i,\mathrm{in}} = \mathrm{M}_{i,\min} \cup \mathrm{M}_{i,\max} \tag{9}$$

3.2 Coupling relationship inside DES

The diversity of devices complicates the complementarity and couplings between energy resources, making the ACI more complex. According to their input and output configurations, the relationship between these devices can be divided into two categories: continuing relationship and juxtaposing relationship. These relationships and their examples are given in Fig. 3.

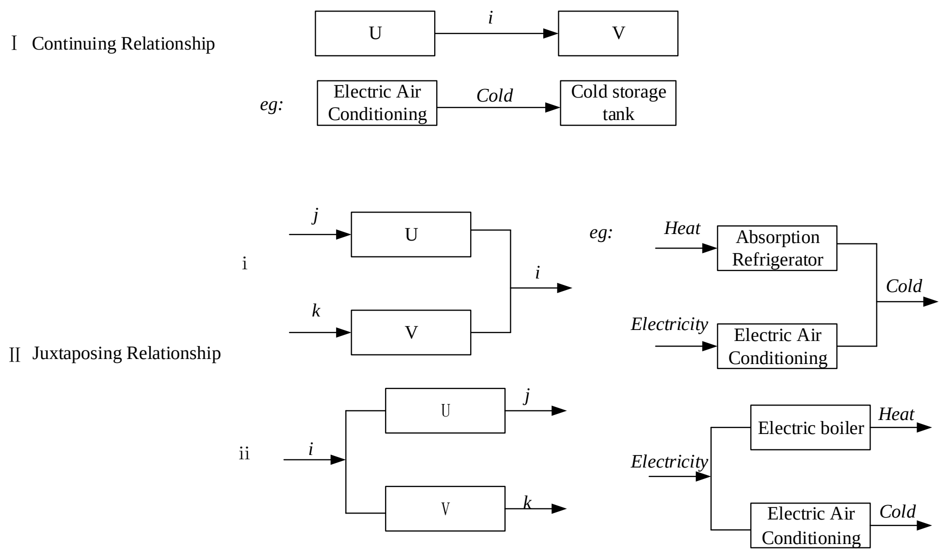

Fig. 3 Interconnection between input and output ports of devices

3.2.1 Continuing relationship

The continuing relationship means that the output and input ports of the two devices are connected. Energy *i* is transferred from the output port of device U to the input port of device V. Considering the transmission constraint between two devices, i.e. the power and capacity limitations, the maximum power of energy *i* from device U to V (P_i^{UV}) is the smaller value of the maximum output power of device U ($P_{i,\max}^{U}(t)$) and the maximum input power of device V($P_{i,\max}^{V}(t)$), as shown in formula (10).

$$P_i^{UV}(t) = \min\left(P_{i,\max}^{U}(t), P_{i,\max}^{V}(t)\right) \quad (10)$$

3.2.2 Juxtaposing relationship

The juxtaposing relationship means that the input or output energy of the two devices are the same. It can be divided into two categories in Fig. 3, state (i), where the output energy of the two devices are the same, and state (ii), where the input energy of the two devices are the same. Since these two devices are complementary and substitutional, energy balance should be considered in both states. When device U operates at the maximum power mode, device V operates at minimum power mode, vice versa.

$$\bar{P}_{i,\max}^{V}(t) = \min\left(P_{i,\max}^{V}(t), P_{i,\mathrm{Umin}}^{V}(t)\right) \quad (10)$$

$$\bar{P}_{i,\min}^{V}(t) = \max\left(P_{i,\min}^{V}(t), P_{i,\mathrm{Umax}}^{V}(t)\right) \quad (11)$$

Formula (10) indicates that the maximum power of device V ($\bar{P}_{i,\max}^{\mathrm{V}}(t)$) with the interaction of two devices is the smaller value of the maximum power of device V without the interaction($P_{i,\max}^{\mathrm{V}}(t)$) and the output power of device V when device U works under its minimum condition ($P_{i,\mathrm{Umin}}^{\mathrm{V}}(t)$). By contrast, Formula (11) illustrates that the minimum power of device V with the interaction ($\bar{P}_{i,\min}^{\mathrm{V}}(t)$) is the larger value of the minimum power of device V without the interaction($P_{i,\min}^{\mathrm{V}}(t)$) and the output power of device V when device U works under its maximum condition($P_{i,\mathrm{Umax}}^{\mathrm{V}}(t)$).

Therefore, it can be seen that in juxtaposing relationship, the maximum output power of the influencing device V at time *t* should not only consider its own output, but also the output of device V when device U works under its lowest output power, vice versa.

4 Evaluation of ACDES

4.1 Evaluation method for ACDES

According to the complexity of DES, there are two methods to evaluate the ACDES, as follows:

1) Analytical method: It sequentially analyzes energy demand range of each influencing factor, and then integrates and superimposes them. This method can effectively analyze the internal mechanism of each influencing factor and the impact on ACDES, but it is only applicable to DES with simple couplings.

2) Optimization method: It is necessary to evaluate the ACDES through optimization algorithms when the coupling inside DES is complex. Due to the internal connectivity, ACI can be described by upper and lower boundaries. The optimization objectives are the maximum/minimum energy demand for UESS, and the constraints include the internal energy balance, component power, ramp rate, capacity of each device, etc.

There may be more than one types of energy demand for UESS in DES. If there is only one type, the optimization problem has one single objective and can be solved by heuristic algorithms or intelligent algorithms. If there are more than one types, the optimization problem has multiple objectives. Usually, the two optimization objectives are the maximum or minimum electricity and natural gas demand for UESS. In Fig. 4, the black points are all possible solutions, and the green point is the ideal solution. However, the two optimization objectives are mutually restricted and the optimum cannot be reached at the same time. The red points are the Pareto optimal solutions and the black curve is the Pareto front. The upper and lower boundaries of ACI are the Pareto front corresponding to the maximum and minimum energy demand.

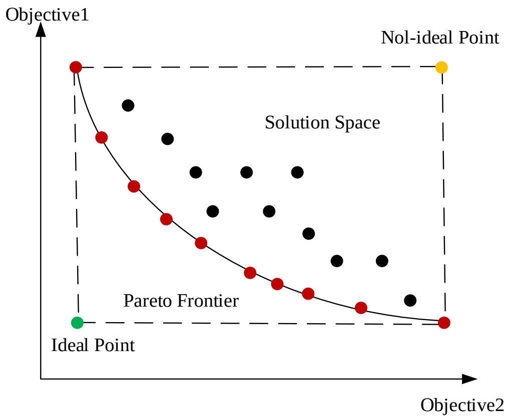

Fig 4 The schematic diagram of the solution of the multi-objective optimization algorithm

4.2 ACI in two typical configuration cases

4.2.1 Case I : Multi-energy complementary supply mode without ESE

In Case I, DES is configured with CCHP system, gas heating device, electric refrigeration device and electric heating devices. The supply and demand balance constraints are as follows：

$$E_{\text{in}}(t)+E_{\text{g-e}}(t)=L_{\text{e}}(t)+E_{\text{e-h}}(t)+E_{\text{e-c}}(t) \tag{12}$$

$$H_{\text{g-h}}(t)+H_{\text{e-h}}(t)=L_{\text{h}}(t)+H_{\text{h-c}}(t) \tag{13}$$

$$C_{\text{e-h}}(t)+C_{\text{h-c}}(t)=L_{\text{c}}(t) \tag{14}$$

According to Formula (12), the right side of the equation is fixed, and thus the maximum/minimum of E_{in} corresponds to the minimum/maximum of $E_{\text{g-e}}$. It means that the upper/lower boundaries of electricity demand correspond to the lower/upper boundaries of natural gas demand. The multi-objective problem can be converted into a single-objective problem of maximising/minimising electricity demand. The optimization objective is either of the following two:

$$\max \quad Q_{\text{E}}(t) \tag{15}$$

$$\min \quad Q_{\text{E}}(t) \tag{16}$$

Since the sequential characteristics are not considered in this section, the constraints only include energy balance (Formula12-14) and the static limits of each device in Formula 17.

$$\begin{aligned} s.t.\quad & P_{w,\min} < P_w(\text{t}) < P_{w,\max} \\ & S_{i,\min} < S_i(t) < S_{i,\max} \\ & \alpha_i^{\text{c}}(t)+\alpha_i^{\text{d}}(t)=1,\quad \alpha_i^{\text{c}}(t),\ \alpha_i^{\text{d}}(t)\in\{0,1\} \end{aligned} \tag{17}$$

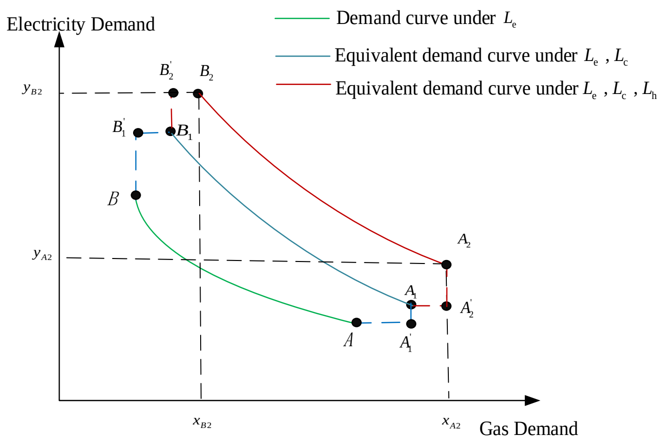

Fig 5 Schematic diagram of ACI under multi-energy complementary energy supply mode

The diagram of ACI is shown in Fig.5. Curve AB is pure electricity load. Vertical lines BB_1' and B_1B_2' indicate equivalent electricity when the system prefers to use electricity to supply the cooling and heating load. Horizontal lines $B_1'B_1$ and $B_2'B_2$ indicate the equivalent natural gas required to satisfy the rest load. If the electric refrigeration and heating device can fully meet the load, the horizontal line does not exist. Horizontal lines AA_1' and A_1A_2' indicate equivalent gas when the system prefers to use gas to supply the load. Vertical lines $A_1'A_1$ and $A_2'A_2$ indicate the equivalent electricity required to satisfy the rest load. If the gas can fully meet the cooling and heating load, the vertical line does not exist.

The demand interval of power and natural gas of the DES is [y_{A2},y_{B2}] and [x_{A2},x_{B2}] respectively. However, it is worth noting that because of the interaction between electricity and natural gas demand, the interval can only be adjustable on curve A_2B_2.

4.2.2 Case II: Multi-energy complementary supply mode with ESE

Adding ESE in DES will change the demand and supply balance constraints in Formulas (18-20).

$$E_{\text{in}}(t)+E_{\text{g-e}}(t)+D_{\text{e}}(t)=L_{\text{e}}(t)+E_{\text{e-h}}(t)+E_{\text{e-c}}(t)+S_{\text{e}}(t) \tag{18}$$

$$H_{\text{g-h}}(t)+H_{\text{e-h}}(t)+D_{\text{h}}(t)=L_{\text{h}}(t)+H_{\text{h-c}}(t)+S_{\text{h}}(t) \tag{19}$$

$$C_{\text{e-h}}(t)+C_{\text{h-c}}(t)+D_{\text{c}}(t)=L_{\text{c}}(t)+S_{c}(t) \tag{20}$$

E_{in} and $E_{\text{g-e}}$ are no longer complementary because of uncertain energy storage strategies. The multi-objective functions are in Formulas (21-22).

$$\begin{cases} \max \quad Q_{\text{E}}(t) \\ \max \quad Q_{\text{G}}(t) \end{cases} \tag{21}$$

$$\begin{cases} \min \quad Q_E(t) \\ \min \quad Q_G(t) \end{cases} \tag{22}$$

The constraints include energy balance in Formulas 18-20 and static limits of each element in Formula 17.

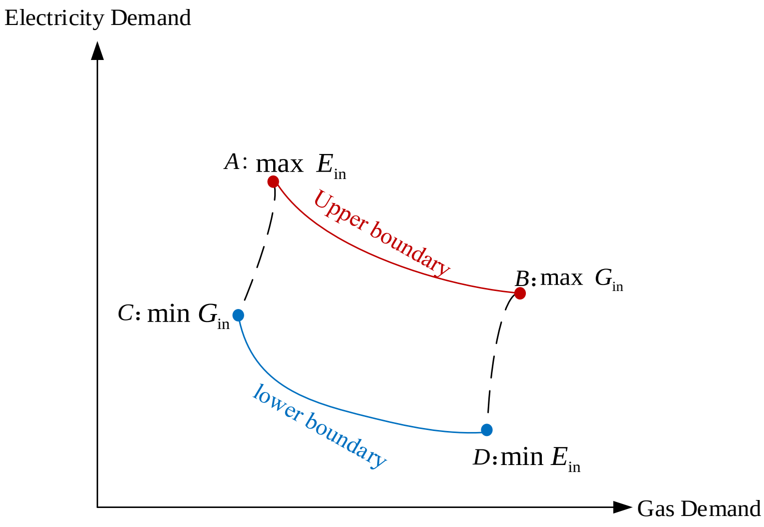

Fig 6 ACI with ESE

The curves AB and CD are the Pareto fronts, which form the upper and lower boundaries of the ACI, as shown in Fig. 6. The curves AC and CD respectively represent the maximum and minimum boundaries of electricity demand when the natural gas demand is $[x_C, x_A]$ and $[x_D, x_B]$. These four curves form the ACI, which is a plane on a two-dimensional space.

4.3 Impact of economic constraints

Economic constraints mainly narrow ACI interval by affecting energy output ratio of different devices and operation strategies of energy storage.

4.3.1 ACI under economic constraints in case I

Considering the economic constraints, DES tends to reduce electricity demand and use the CCHP system and gas boilers to meet the load during the peak periods of electricity prices, and tends to use electric boilers and air conditioning during the valley periods of electricity prices. Therefore, the upper boundary of electricity demand moves down, and the lower boundary of natural gas demand moves up during the peak period, vice versa.

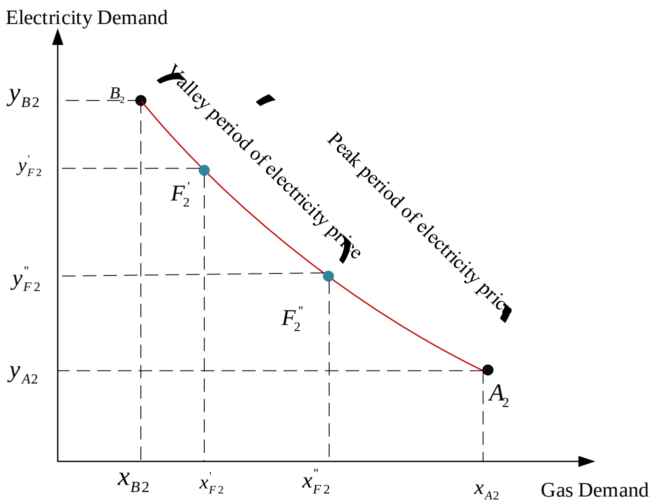

Fig. 7 The impact of economic constraints on the typical case I

As shown in Fig. 7, the ACI will be reduced to a part of the original curve. During peak periods, the electricity demand interval is reduced to [y_{A2}, y'_{F2}], and the gas demand interval is reduced to [x_{A2}, x'_{F2}]. The ACI is reduced to curve A_2F_2’. During valley periods, the electricity demand interval is reduced to [y_{B2}, y''_{F2}], and the gas demand interval is reduced to [x_{B2}, x''_{F2}]. The ACI is reduced to curve B_2F_2”.

4.3.2 ACI under economic constraints in case II

Considering economic constraints, ESE tends to release energy during peak periods, vice versa. Therefore, during peak periods, the upper boundary of electricity demand moves down and the lower boundary of natural gas demand moves up, vice versa. The ACI is reduced to only a part of the original two-dimensional plane. As shown in Fig. 8, the ACI is reduced from the original plane ABCD to A'B'C'D'.

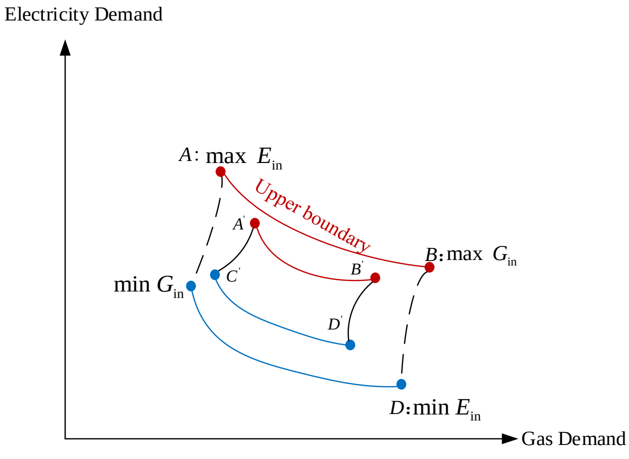

Fig. 8 The impact of economic constraints on typical case II

5. Dynamic evaluation of ACDES

The spatial dimension is required to realize dynamic evaluation of ACDES. The optimization method mentioned in section 4.1 is used in dynamic evaluation because the coupling of DES becomes more complex. The key to dynamic evaluation is to acquire the operating status of initial points and dynamic constraints. Thus, the ACDES will be dynamically evaluated from different initial states, including unknown initial state, fixed initial state, uncertain initial state.

5.1 Unknown initial state

In an unknown initial state, to obtain the adjustable capacity interval is to obtain the union of energy demand for UESS under all possible operating states. A schematic diagram is used to explain the evaluation method as is shown in Fig. 9. Curves 1, 2,…,*n* represent different energy demand for UESS under different operational strategies. At any time in the evaluation cycle, as long as there is an operational strategy to allow the energy demand to reach the upper or lower boundary, this demand is the maximum or minimum value. Therefore, the quantification of the ACI in the operation cycle is to identify the envelope of energy demand under all operational strategies, as shown by the red and black solid lines in Fig. 9.

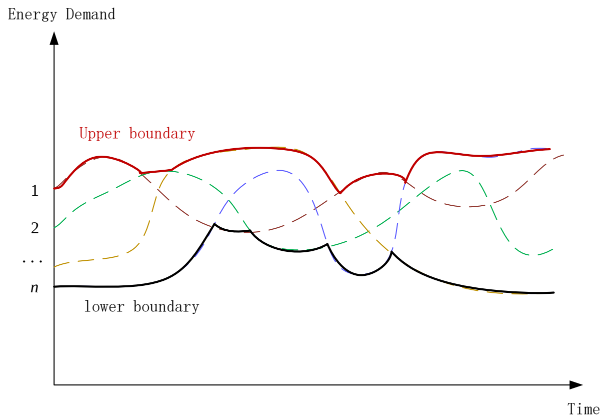

Fig. 9 A schematic diagram of the energy demand interval of DES

Under unknown initial states, since the interval at time t is the union of energy demand under all operational strategies, there is no need to consider dynamic constraints of influencing factors. The ACI can be obtained by evaluating the interval at each single time and then superimposing them on the time dimension.

In typical cases I and II in section 4, the constraints are constant, given in Formulas 15-16 and Formulas 21-22. In case I, the ACI is extended from a curve on a two-dimensional plane at a single time to a surface on a three-dimensional space in a continuous-time dimension, illustrated in Fig. 10. In case II, the ACI is extended from a surface on a two-dimensional space to geometry on a three-dimensional space, given in Fig. 11.

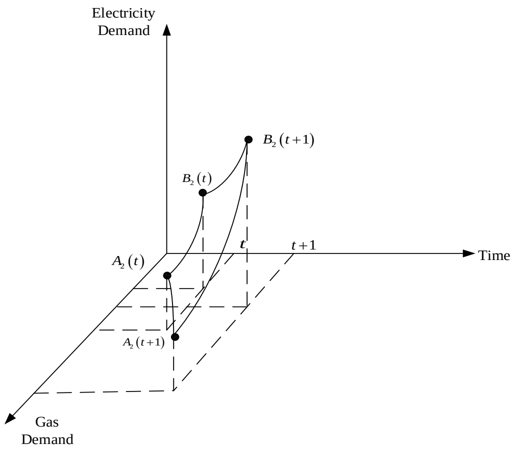

Fig. 10 Schematic diagram of recursive ACI in case I

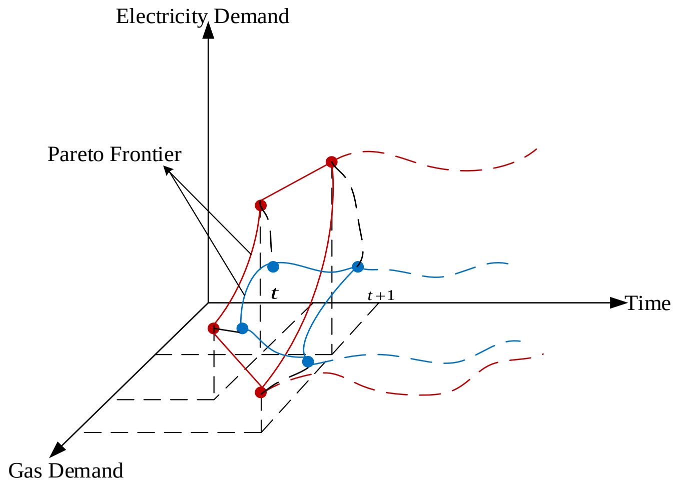

Fig. 11 Schematic diagram of recursive ACI in case II

5.2 Known initial state

When the initial state of DES is known, sequential recurrence can be divided into two cases, as given in Fig. 12. One is recurrence from the fixed initial state, from t to time t+1, and the other is recurrence from the uncertain initial state, from t+1 to t+2.

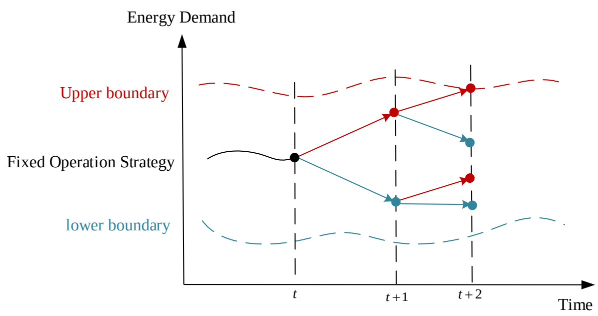

Fig. 12 ACI for postponing sequential time from time t

The optimization objectives of the two initial states are the same, with the difference in the dynamic constraints.

1) When the interval at time t+1 recurs from the fixed time t, the state of each device at time t is treated as a known boundary condition and substituted into the constraint condition at time t+1. The constraints at time t+1 include energy balance constraints in Formula 23, static constraints in Formula 24 and dynamic constraints in Formula 25.

$$s.t.\quad \sum_{\beta} Q_i^{\beta}\left(t+1\right)=\sum_{\gamma} Q_i^{\gamma}\left(t+1\right), i\in\left\{E,H,C\right\} \tag{23}$$

$$\begin{aligned} s.t.\quad & P_{w,\min} < P_w(t+1) < P_{w,\max} \\ & \alpha_i^{\mathrm{c}}(t+1)+\alpha_i^{\mathrm{d}}(t+1)=1,\quad \alpha_i^{\mathrm{c}}(t+1),\ \alpha_i^{\mathrm{d}}(t+1)\in\left\{0,1\right\} \end{aligned} \tag{24}$$

$$\begin{aligned} s.t.\quad & \left|P_w(t+1)-P_w(t)\right| < \upsilon_w \\ & S_{i,\min} < S_i(t)+P_{\mathrm{c},\max}(t+1) < S_{i,\max} \\ & S_{i,\min} < S_i(t)-P_{\mathrm{d},\max}(t+1) < S_{i,\max} \end{aligned} \tag{25}$$

2) When the interval at time t+2 recurs from the unknown state at time t+1, the state of each device at time t+1 is not fixed value but an interval. Therefore, as long as there is a state in the interval of time t+1 which allows the output of device at time t+2 to satisfy the constraints, the ACI at time $t+2$ can be obtained. The constraints at time $t+2$ include energy balance constraints in Formula 26, static constraints in Formula 27 and dynamic constraints in Formula 28.

$$s.t.\quad \sum_{\beta} Q_i^{\beta}\left(t+2\right)=\sum_{\gamma} Q_i^{\gamma}\left(t+2\right), i\in\left\{E,H,C\right\} \tag{26}$$

$$\begin{aligned} s.t.\quad & P_{w,\min} < P_w(t+2) < P_{w,\max} \\ & \alpha_i^{\mathrm{c}}(t+2)+\alpha_i^{\mathrm{d}}(t+2)=1,\quad \alpha_i^{\mathrm{c}}(t+2),\ \alpha_i^{\mathrm{d}}(t+2)\in\left\{0,1\right\} \end{aligned} \tag{27}$$

$$\begin{aligned} s.t\quad & \\ & \exists\, P_w(t+1)\in\left[P_{w,\min}(t+1),P_{w,\max}(t+1)\right],\ \left|P_w(t+2)-P_w(t+1)\right|<\upsilon_w \\ & \exists\, S_i(t+1)\in\left[S_{i,\min}(t+1),S_{i,\max}(t+1)\right],\ S_{i,\min}<S_i(t+1)+P_{\mathrm{c},\max}(t+2)<S_{i,\max} \\ & \exists\, S_i(t+1)\in\left[S_{i,\min}(t+1),S_{i,\max}(t+1)\right],\ S_{i,\min}<S_i(t+1)-P_{\mathrm{d},\max}(t+2)<S_{i,\max} \end{aligned} \tag{28}$$

It is worth noting that, as the output state of each device at time t+1 is an interval, the impact of dynamic constraints on the ACI at time t+2 will be reduced, and the interval will expand at time t+2 and continue to expand in the subsequent time period. If the subsequent time period is long enough, the ACI can be extended to the upper and lower boundaries of the interval when the initial state is unknown.

5.3 Recursive method considering economic constraints

In Section 4, the impact of economic constraints on the ACI at a single time is analyzed. In practical operation and scheduling of DES, the total operating cost is usually constrained over a period of time. Therefore, it is necessary to find all operational strategies that meet the economic constraints in original feasible strategies. The ACI of energy demand for UESS is the aggregation of energy demand corresponding to all operational strategies that meet economic constraints.

We use optimization algorithms to find the upper and lower boundaries of the adjustable interval. According to the different economic constraints, it can be divided into the following two categories.

1) If the allowed cost (CO_{st}) is greater than the minimum operating cost (CO_{best}) required for the optimal economic operation of DES in Formula 29, the adjustable interval method is similar to the method in Section 3.

$$CO_{\mathrm{st}} \geq CO_{\mathrm{best}} \tag{29}$$

The optimization objective is Formulas (15-16) and Formulas (21-22). The economic constraints are added to the original constraints in Formulas 30-31.

$$CO = \sum_{i}\sum_{t=1}^{T} Q_{i,\text{in}}(t)\cdot \rho_i(t) \quad i\in\{E,G,H,\text{C}\} \tag{30}$$

$$s.t.\ \ 0 \le CO \le CO_{\max} \tag{31}$$

2) If Formula (29) is not satisfied, the optimal economic operation cannot meet the economic constraints. Therefore, there is no feasible operational strategies for DES, which means that the ACI does not exist.

If the operational strategy has been determined during time window 0-t_{co}, the ACI in the sequential time period is recursively determined by system state at t_{co}. The operating cost of the preceding time window is determined in Formula (32). Then, the operating cost available in the latter time window is shown in Formula (33).

$$CO(t_{co}) = \sum_{i}\sum_{t=1}^{t_{\text{co}}} Q_{i,\text{in}}(t)\cdot \lambda_i(t) \quad i\in\{E,G,H,\text{C}\} \tag{32}$$

$$CO_{\text{r}} = CO_{\max} - CO(t_{co}) \tag{33}$$

If CO_{r} is higher than CO_{best}, the ACI is calculated according to Formula (30-31). Otherwise, the ACI does not exist.

6 Case study

6.1 Case overview

This section uses an industrial park as an example to quantify the ACDES on a typical day. The cooling, heating and electricity load curves are shown in Fig.13, and the time step is 15 minutes.

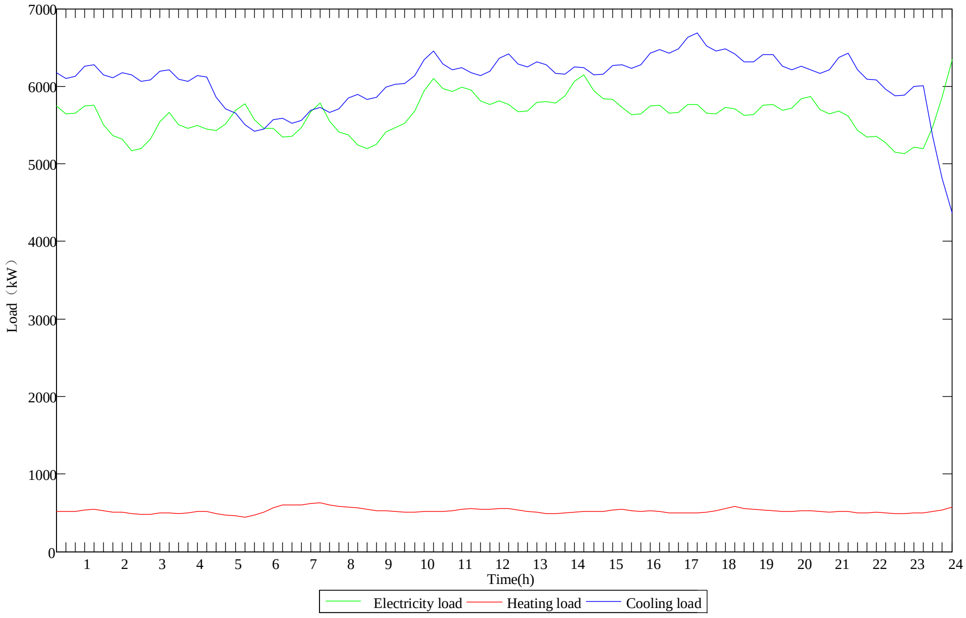

Fig. 13 Typical daily load curve

In DES, the two operating modes as are mentioned in section 4.2 are considered. In case I, the electricity load is supplied by the power grid and CCHP system, the heating load is supplied by CCHP system and gas boiler, and the cooling load is supplied by conventional refrigerators and lithium bromide refrigerators. Based on case I, case II adds ESE, such as batteries and cold storage pools. The devices and their parameters are shown in Table 1. Typical daily tariffs are shown in Table 2.

Tab. 1 Main devices and their parameters in the industrial park

Device	Rated capacity /MW·h	Rated power /MW	Efficiency	Case I	Case II
Gas Engine	5.7	5.7	Gas to Electricity：0.4	√	√
			Gas to Heat：0.45	√	√
Lithium bromide refrigerator	2.4	2.4	$COP_{h\text{-}c}$=1.2	√	√
Electric air conditioning	20	20	$COP_{e\text{-}c}$=4	√	√
Electric boiler	3.6	3.6	90%	√	√
Battery	20	2	0.9	×	√
Cooling storage tank	50	10	0.98	×	√

Tab. 2 Electricity price on typical days

	Time/h	Electricity Price/¥
Peak hour	14:00-21:00	0.36
Flat hour	8:00-13:00 22:00-23:00	0.67
Valley hour	1:00-7:00,24:00	1.07

6.2 ACIs in two typical cases

The single-time ACI and the overall ACI are shown in Fig.14-17.

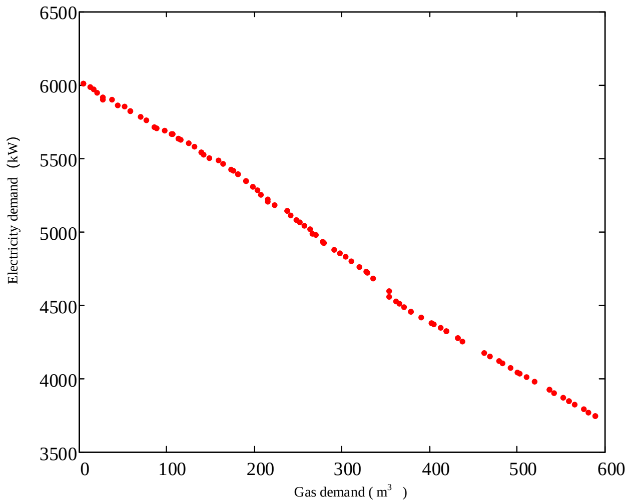

Fig. 14 ACI at single time node in case I

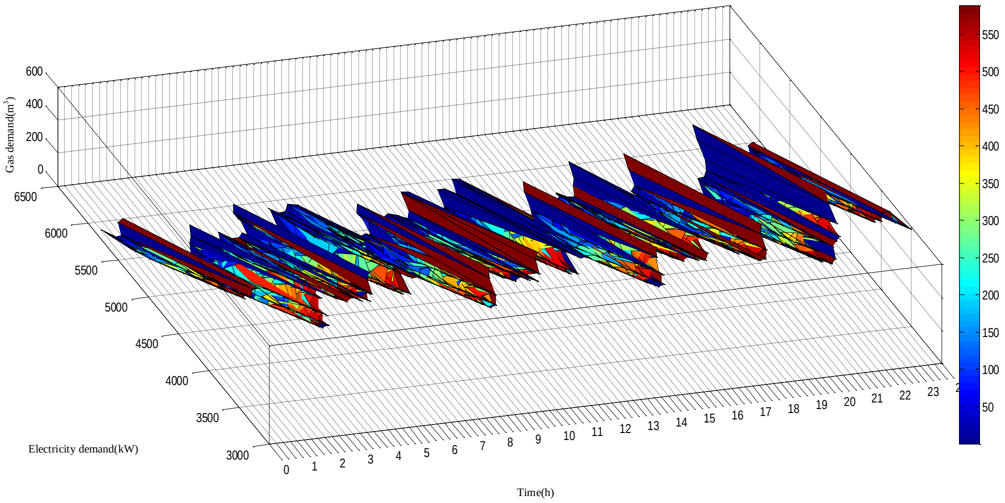

Fig. 15 Three-dimensional ACI in case I

In case I, electricity and natural gas demand for UESS is mutually restricted when DES is configured without ESE. The upper boundary of electricity demand corresponds to the lower boundary of the natural gas demand, vice versa. As shown in Fig. 14, the ACI at a single time is a line because of the negative linear correlation between the two energy demand. In addition, under two different operating modes of the CHP system, the demand relationship function of electricity and natural gas will change, manifested as the constant change in the linear function. Therefore, the ACI is not a straight line but a broken line with an inflexion point. When considering the time dimension, the ACI is a three-dimensional surface, as shown in Fig. 15. The color temperature indicates the demand for natural gas and shows a sloping and rising trend in the three-dimensional graph, which implies electricity demand decreases while natural gas demand increases.

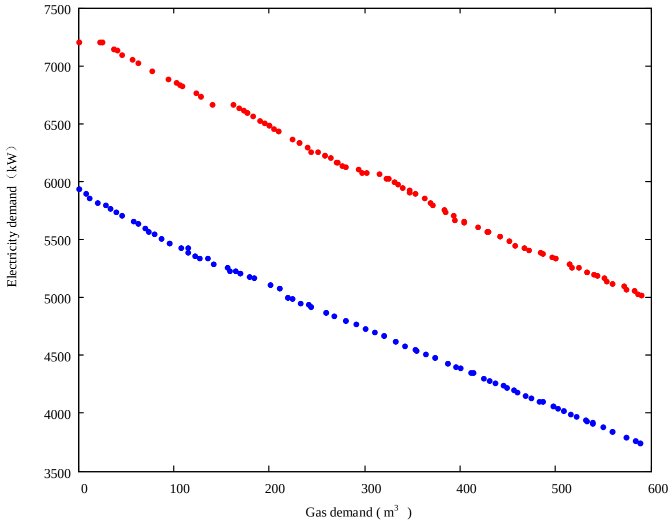

Fig. 16 ACI at a single time in case Ⅱ

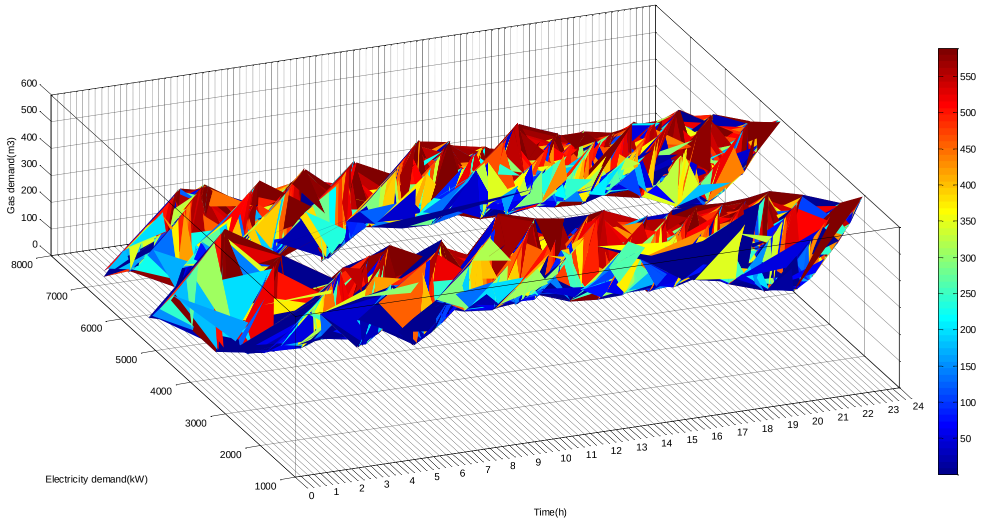

Fig. 17　Three-dimensional ACI in case Ⅱ

In case II, the size of ACI increases due to ESE. In addition, the demand for electricity and natural gas is not linearly correlated but interacts within a certain range. Considering the time dimension, the ACI becomes a three-dimensional space.

6.3 Recursion of ACI

The ACI changes over time due to the dynamic constraints of the devices, the recurrence analysis of the ACI under different initial states is carried out, as shown in Fig.18.

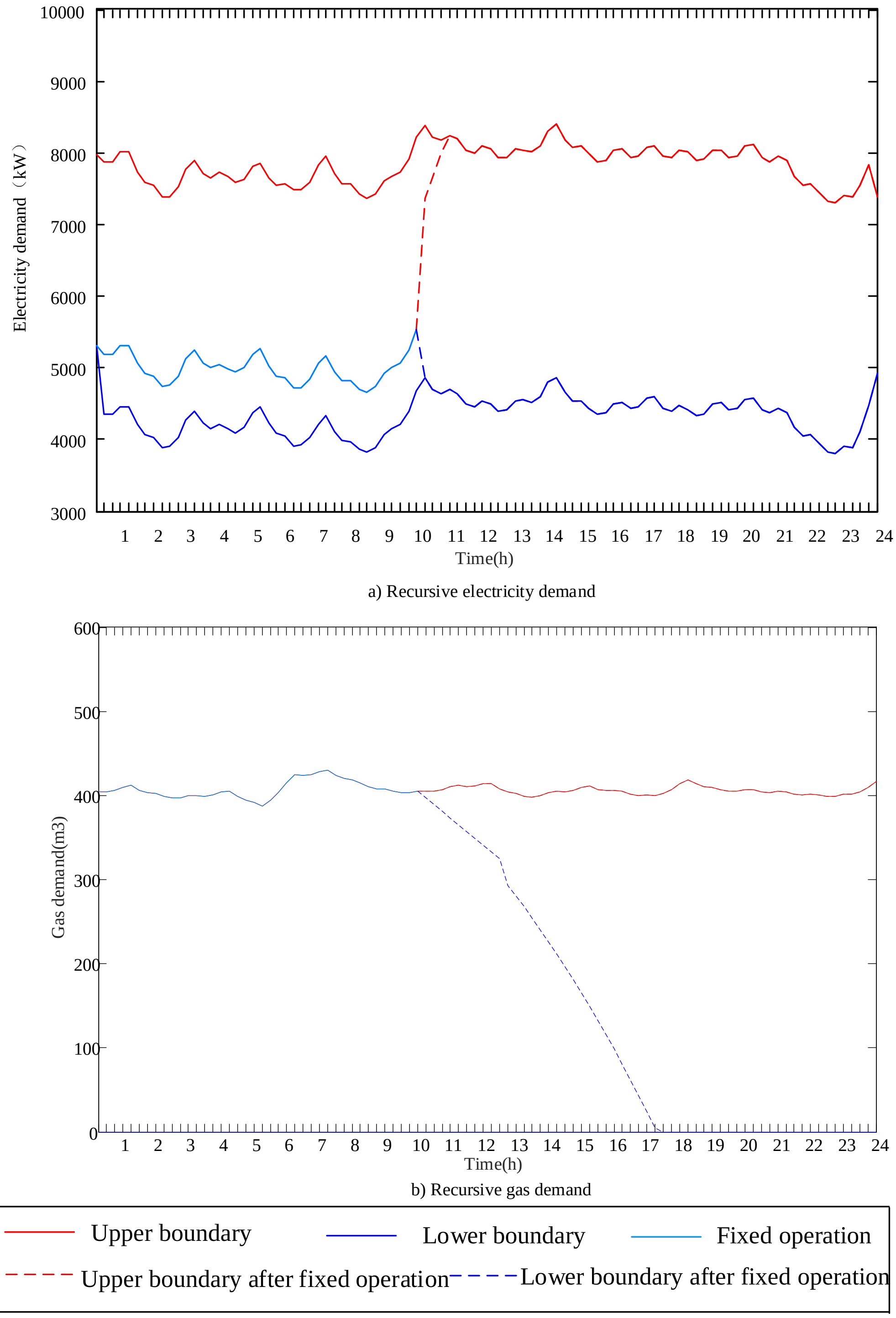

Fig 18 Recursion of ACI

In this case, DES originally operates according to a certain fixed strategy, i.e., no energy storage device is used, and the CCHP system operates in mode (i) from 0:00 to 10:00. The red and blue solid lines represent the ACI of electricity and natural gas when the initial state is unknown, which is the largest interval. The green solid lines represent that DES operates according to a certain fixed strategy from 0:00 to 10:00. At 10:15, the initial state is definite, and the ACI enlarges from the fixed value. After that, the initial state is an uncertain interval, its ACI continues to expand from the interval at 10:15. With the increase of the uncertainty of the initial state, the influence of the dynamic constraints is decreasing, so the duration of the dynamic constraints is relatively short. The impact time of dynamic constraints on ACI of electricity and nature gas last 30 minutes and 7hours. This is because the ramp rate constraints of power equipment are smaller than that of gas-fired units, and the impact of electric energy storage devices on the demand for natural gas is delayed.

6.4 Effect of economic constraints on ACI

As shown in Fig. 19, during the peak period from 13:00 to 17:00 and 18:00-21:00, the CCHP system is used to meet the load preferentially, and ESE releases more energy. Therefore, the upper boundary of the electricity demand moves downwards and the lower boundary of natural gas demand moves upwards. During the flat period from 8:00 to 13:00, ESE tends to store less energy, and only to meet the basic load in the subsequent period. Therefore, the upper boundary of the electricity demand also moves down. During the valley period from 1:00 to 7:00, the lower boundary of electricity demand moves up and the upper boundary of natural gas demand moves down.

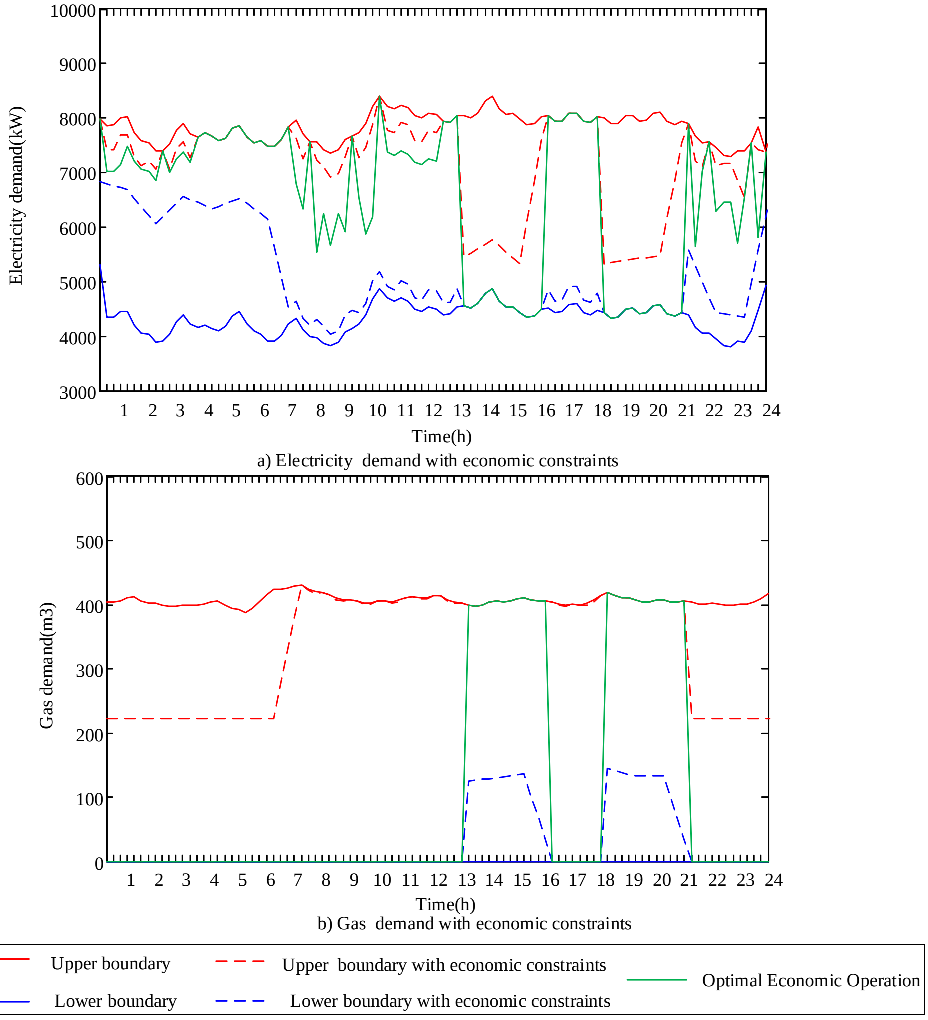

Fig. 19 ACI under economic constraints

Considering the overall economic constraints, the operational strategy of pre-sequence time will affect the ACI of latter time. The system runs with a fixed operational strategy during the period of 0-5:00, 0-10:00, 0-15:00, 0-20:00, and recurs the ACI in the following time.

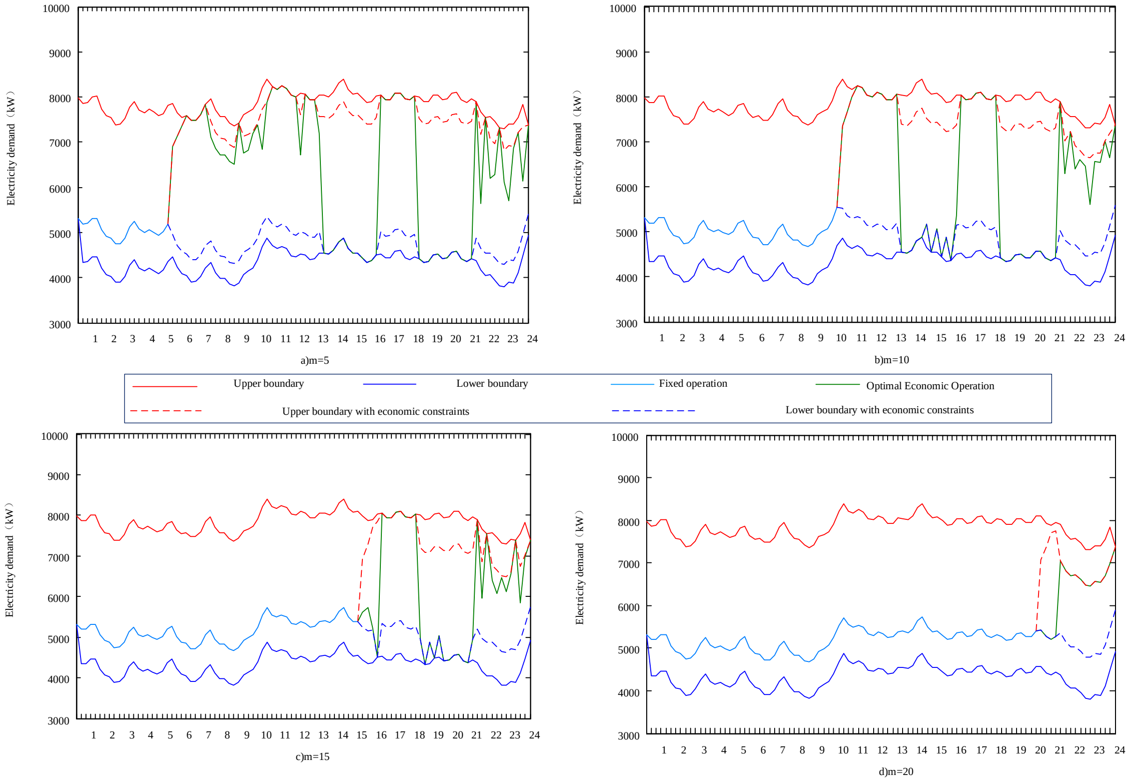

Fig. 20 Time series recurrence diagram of electricity ACI under economic constraints

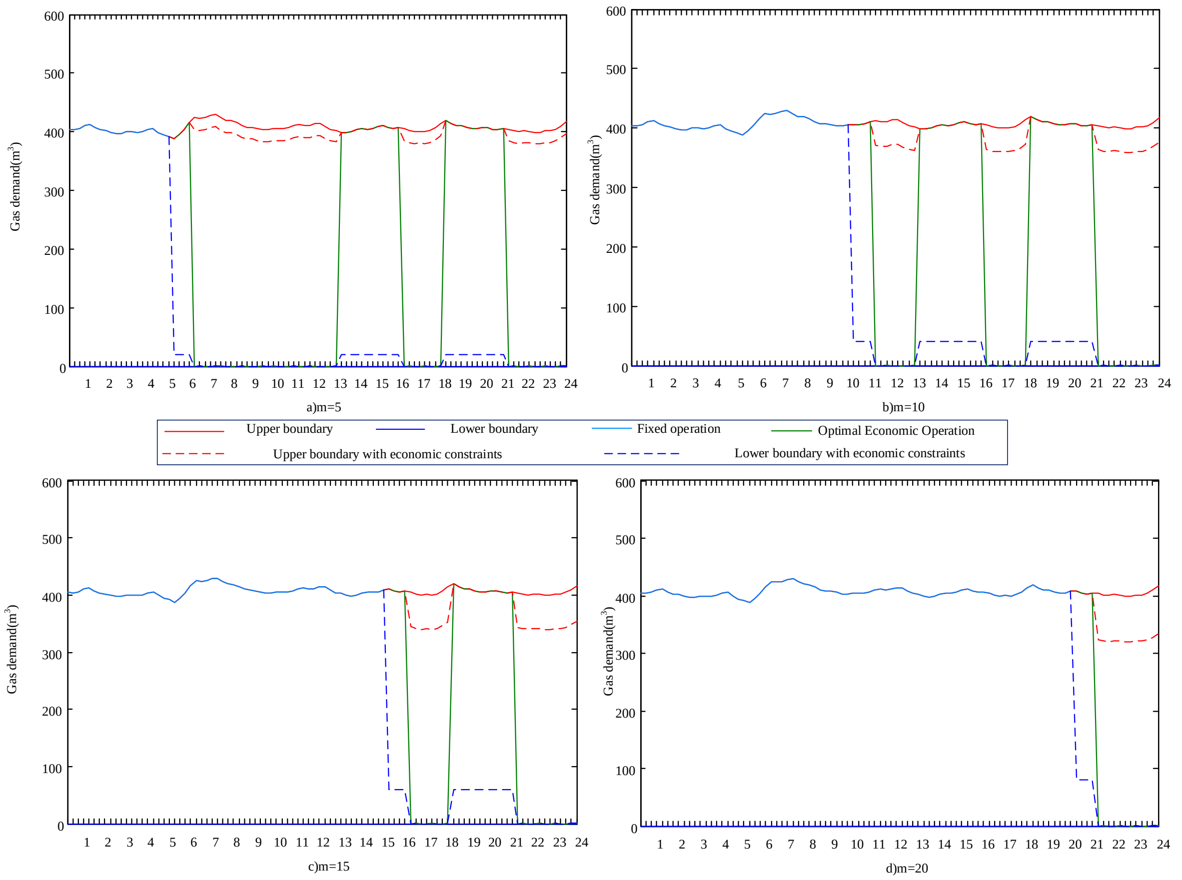

Fig. 21 Time series recurrence diagram of gas ACI under economic constraints

As shown in Figs. 20-21, economic constraints have a wider impact on the interval recurrence than the dynamic constraints of devices, and their duration lasts longer and even affects the whole operation period. In addition, the greater the value of m is, i.e., the longer the fixed strategy runs, the narrower of the ACI will be. Because the longer the fixed operation strategy runs, i.e., the smaller the expense balance in the latter time will be. The system is more inclined to choose the operation strategy with fewer costs during the subsequent period. Obviously, if the total economic constraints are too tight and the operation strategy in the preceding period is too loose, all operation strategies in the following periods may not meet the extreme situation of the economic constraints. Compared with natural gas, the ACI of electricity is narrowed more obviously, because electricity demand is more sensitive to the change of time-of-use prices. The adjustable range of natural gas changes slightly and until m=20 the interval of natural gas demand is greatly reduced.

6.5 Application of ACDES evaluation for UESS

As described in Section 2.2, the method is conducive to the rational planning and operation of UESS. This section takes the application of adjustable ability evaluation in the planning and maintenance of the upper power grid as an example.

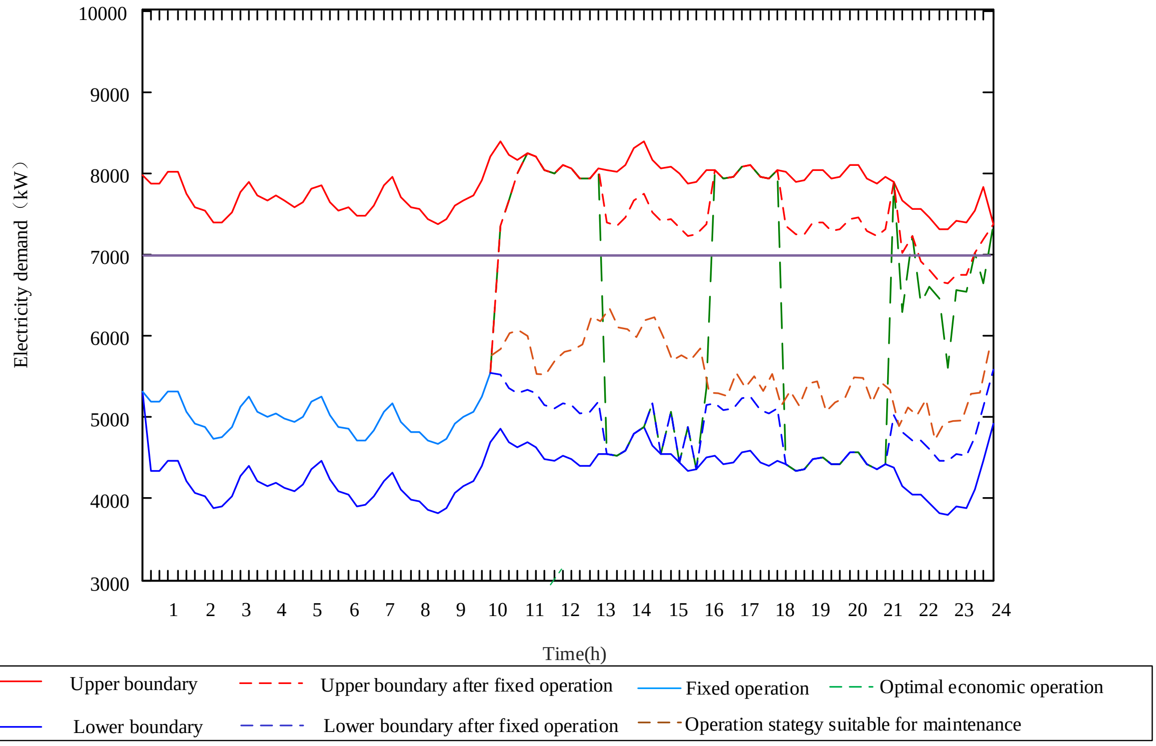

Fig .22 Application of ACDES evaluation for UESS

In this case, the power demand of DES does not exceed 9000kW in the assessment cycle. If the assessment is conducted in annual units, the maximum power supply capacity required by the power grid at this load node can be obtained, so as to guide the rational planning of the power grid.

The existing maintenance strategy is usually carried out when the load is low. However, due to the complex coupling relationship in DES, the load valleys of cold, heat and electricity often do not coincide, which leads to the power demand of the grid and the electrical load trough does not coincide. Therefore, it is difficult for the power grid to make maintenance plans.

In this case, it is assumed that DES originally operates according to a certain fixed strategy, i.e., no energy storage device is used, and CCHP system operates in mode (i). The power grid plans maintenance later this day at 10:00, and the maximum power supply is set as 6000kwh. Therefore, according to the green dotted line in Fig.22, if the power grid only implements time-of-use electricity prices, because the price of electricity in this area is lower than that of gas, DES is more inclined to use electricity to meet the load, and it cannot supply energy reliably during maintenance either, as shown by the green dotted line.

Therefore, it is necessary for the power grid to understand the ACDES. Through evaluating the lower boundary of the ACI, the power grid realizes that DES has enough margin to meet the maintenance schedule, as long as reasonable incentive measures are adopted. Thus, the power grid has formulated reasonable subsidies to fully utilize the ESE and CCHP units in DES, so that they can be overhauled as shown by the brown curve in Fig.22.

7 Conclusion

This paper has quantified the adjustable range of every influential factor in DES, revealed the mechanism of the interaction among the factors, and proposed a unified evaluation model for the ACDES. The model can realize the dynamic recursive analysis and reveal the influence of economic constraints on the ACDES. The conclusions drawn in this paper are as follows:

(1) Many factors in DES affect the ACDES. From the energy supply side, the multiple energy production and conversion devices realize the complementary substitution of multiple energy resources; renewable energy devices provide more energy sources; ESE realizes the transfer of energy at the time level. From the energy demand side, the terminal load participating in DR can be reduced or transferred.

(2) According to the connection relationship between the input and output ports of different devices, they are divided into two types: continuing relationship and juxtaposing relationship. When the relationship is the former, the maximum power limit of each input and output port should be considered; when the relationship is the latter, the balance between supply and demand sides should be considered.

(3) The recursion of ACI can be divided into three categories based on the initial state, i.e., unknown, definite value, and an uncertain interval. The influence duration of device dynamic constraints is relatively small and the influence of economic constraints is relatively big on the interval recursion.

(4) Economic constraints affect the ACI by affecting energy output ratio of different devices and the energy storage operation strategy. With economic constraints, the ACI shows a trend of reduction from the periphery to the centre.

Generally, the ACDES evaluation method is of great significance to the reliable planning and economic operation of UESS and DES. In the future, we will study， from the perspective of UESS, how to formulate energy prices or subsidies with the highest profit to mobilize the best use of DR in DES, and how to realize the optimal operation of DES while ensuring the ACDES.

Acknowledgements

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