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Operation Optimization of an Integrated Energy Service Provider with Ancillary Service Provision

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Abstract: During the transition towards a low carbon energy system, and as a result of the increasing penetration of renewable energy generation, ancillary services play an important role in ensuring the security and economics of power system operation. An integrated energy service provider (IESP), with the energy coupling and storage devices inside, can flexibly participate in electric energy markets and ancillary service markets. In this paper, a mixed-integer optimization problem is formulated to determine the optimal operating strategy for the IESP with ancillary service provision. First, the mathematical model of a regional integrated energy system (RIES) is established, including energy coupling devices and energy storage devices. Then, an optimization model for the IESP operation is formulated with the objective of maximizing daily operation profit, and the corresponding optimal capacity of ancillary service provision from the IESP is attained. Finally, case studies of an RIES are carried out to demonstrate the feasibility and effectiveness of the proposed method, and the impacts of the IESP with ancillary service provision on operational characteristics and economic benefits are analyzed.

Keywords: integrated energy service provider (IESP); regional integrated energy system (RIES); ancillary service; optimal operation strategy

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1. Introduction

As a result of the ever-increasing concerns about fossil energy consumption and environmental protection, many countries are exploring new modes of more efficient and sustainable energy utilization, with the aim of meeting various energy demands and improving the operation economics of energy systems [1,2]. Given this background, the so-called regional integrated energy system (RIES) has attracted widespread attention. In this system, multiple kinds of energy can be converted and stored to meet the demand of users in a cost-effective and highly efficient way [3,4]. Furthermore, as a result of the ever-evolving electricity market operation and the ever-increasing proportion of generation from renewable energy sources (RESs), an increasing number of demand-side resources or load aggregators that meet specified requirements are being encouraged to participate in the bidding-based electricity market operation, which can also provide demand response services or user-side ancillary services at a lower cost than generators [5,6].

In this context, as the operator of an RIES, the integrated energy service provider (IESP) has a large energy capacity and high scheduling flexibility to participate in the electric energy and ancillary service markets, thereby contributing to the secure and economic operation of the power system concerned. Furthermore, the provision of ancillary services will, in turn, increase the equipment utilization rate and reduce the operating costs of the IESP.

Existing publications about the IESP mainly focus on operation optimization [7,8], planning and renovation [9,10], integrated demand response (IDR) [11,12], and electricity energy market participation [13,14]. For the optimal operation of the RIES, in [7], a bi-directional flow model is established to show how the RIES enhances resilience in extreme conditions with the coordination of energy conversion and storage facilities, and a tri-level two-stage robust model is established to accommodate random outages; in [8], an operation optimization model is proposed considering the renewable energy consumption responsibility and carbon emission trading mechanism, so as to address the concern of renewable energy generation accommodation and emission reduction in the RIES operation. For the optimal planning and renovation of the RIES, in [9], a multi-scene optimal planning and renovation method of a park-level RIES is proposed, which models the working status of the RIES and considers the costs of investment, operation, and maintenance in the planning optimization model; in [10], with the objective of minimizing investment costs and network losses, the optimal locations of integrated energy stations are determined by the kernel density of the annual energy consumption of building groups, and the distribution of energy networks is optimized by finding the shortest path with the A-star search algorithm. Regarding the IDR during IESP operation, in [11], a pricing strategy of a multi-energy provider using a Stackelberg game-based bi-level programming model is proposed, in which the IDR-based energy optimization can help residential users manage their multi-energy loads and reduce the expected energy costs; in [12], a bi-level bidding and multi-energy retail price formulation method is presented based on the unified clearing of electricity and natural gas for an IESP considering multi-energy demand elasticity, which fully exploits the potential of IDR resources in improving economic benefits. In terms of the electricity market participation strategy of IESP, in [13], the optimal decision of the IESP in trans-province electricity trading is explored considering renewable portfolio standards and consumer preferences, which can promote the coordinated development of the electricity market, integrated energy services, and the renewable energy industry; in [14], a second-order cone model of day-ahead economic dispatch for a district IESP based on the electricity–gas market environment is presented, and is used to closely study the impact of the energy market environment on the operating strategy of the IESP.

In general, the existing research on IESPs mainly focuses on the interactions among multi-energy flows and the optimal scheduling of their equipment, but there are relatively few studies on the IESP potential in ancillary service provision. In [15], a scheduling model for service regulation of an RIES with energy storage systems is proposed, showing that the regulation flexibility of energy storage systems enables the IESP as a participant in the regulation market. In [16], an optimal planning model of an RIES considering the frequency regulation service is proposed, with the flexible electricity pricing model introduced to mitigate the tie-line power fluctuation. In [17], a day-ahead scheduling strategy for the RIES in joint energy and ancillary service markets is proposed, with the uncertainties in market prices and RES (Renewable Energy Source) output handled by the robust optimization approach. However, in [15–17], although the economic benefits from ancillary service provision are highlighted, there is a lack of analysis of the coordination relationship of the IESP's devices during the provision of ancillary services. Therefore, it is worth discussing the optimal operation of the IESP with participation in the electric energy and ancillary service markets. Specifically, the optimal operation strategy of the IESP to provide ancillary services needs to be studied, and the impact of ancillary services on the dispatching results of the IESP should also be explored.

Given this background, based on the characteristics of the equipment in an RIES, this paper proposes a mixed-integer optimization problem to determine the optimal operation strategy for the IESP. The major contributions of this paper are presented as follows:

(1) The operation mode of an IESP to provide ancillary services is studied. On this basis, the equipment model managed by the IESP is established, including energy coupling devices and energy storage devices.
(2) The ancillary service provision of the IESP is considered and the optimal operation strategy is determined. The optimization goal is to maximize the total operation profits of the IESP, and the corresponding optimal frequency regulation and spare ancillary service capacity that the IESP can provide is obtained.
(3) The changes in equipment scheduling before and after the ancillary service provision are compared and analyzed, providing useful guidance for the IESP's subsequent participation in the ancillary service market.

The rest of this paper is organized as follows. First, the operation mode and equipment model of an IESP are introduced. Then, aiming at the economical optimization, the optimal operation strategy of the IESP considering ancillary services is described. Next, case studies are presented, and the impact of the proposed strategy is analyzed. Finally, concluding remarks are presented.

2. Modeling of IESP's Operation

2.1. Operation Mode of IESP

The operation process of an IESP and its interaction with the markets are shown in Figure 1. In general, the IESP purchases energy from the electric energy and natural gas markets to supply load demands of users and provide ancillary services, through the optimized scheduling of the devices inside the RIES. Specifically, the IESP buys electricity from the electric energy market at the real-time price, provides electricity to its users with the time-of-use tariff, supplies other energy services to its users at fixed prices, and accepts fixed natural gas prices. Furthermore, in order to obtain additional benefits, the IESP participates in the ancillary service market when the prices are attractive and its pieces of equipment are idle. The IESP in this paper can be regarded as an integrated demand response provider, with the generator-like devices that produce electricity from other energy sources, the power-load-like devices that consume electricity, and the storage units that can flexibly release and store energy. Regarded as an energy hub, the IESP can increase its power output to the external network by increasing the output of generating units, reducing the consumption of load devices, discharging more from the electric storage, or charging less to the electric storage, and vice versa.

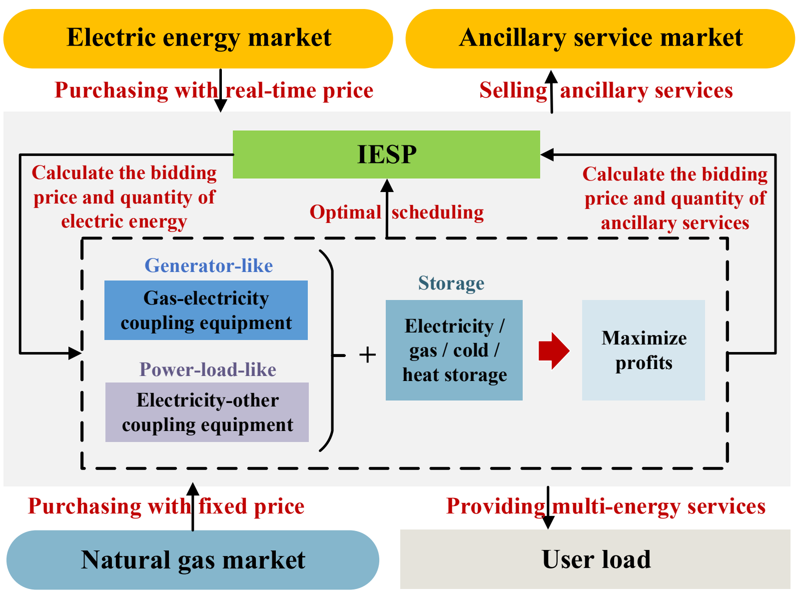

Figure 1. Operation of the IESP.

The ancillary services considered in this paper include frequency regulation and reserve services. The frequency regulation services provided by the IESP correspond to the AGC provided by the generator sets, in which the IESP adjusts its generation output or power load in seconds according to the instruction from the system operator. The provision of frequency regulation services requires that the IESP stands ready to offer the committed amount of capacity, meaning that the committed capacity will not participate in the electric energy market. Considering the response rate and the control precision of the devices, frequency regulation will only be provided by the electric storage units. For the reserve services, the IESP withholds a specified amount of capacity within 10 or 30 min when being commanded by the dispatcher, and keeps that capacity available for a few hours so as to address possible events such as a sudden load increase or system contingencies. The provision of reserve services requires the IESP to produce more and consume less power, with the coordination of all devices inside.

2.2. Modeling of Equipment in the IESP

The structure of the RIES studied in this paper is shown in Figure 2. The input of the RIES is mainly provided by the external power grid and natural gas network, and the output of the RIES is the users' load demand for electricity, heating, and cooling, in addition to the frequency regulation and reserve capacity provided to the ancillary service market. The devices in the RIES can be divided into two categories: energy coupling devices and energy storage devices. The energy coupling devices convert one type of energy into another type of energy, and include the electric boiler, which consumes electricity to produce heat; the electric chiller, which consumes electricity for refrigeration; the gas turbine, which burns gas to generate electricity; the gas boiler, which burns gas to generate heat; the absorption chiller, which converts heat to cold using LiBr or NH_3-H_2O; and the waste heat boiler, which collects heat in the flue gases from the combustion process of the gas turbine. The energy storage units can flexibly store and release energy to maintain the power balance, including electric storage, heat storage, and cold storage. The detailed modeling is given as follows.

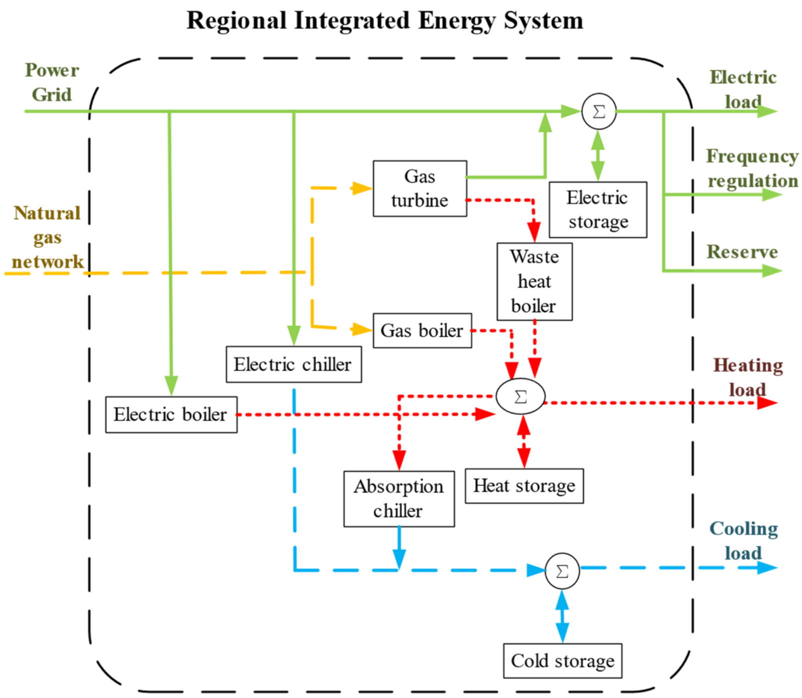

Figure 2. Structure of the RIES.

2.2.1. Energy Coupling Devices

1. Energy coupling constraints.

$$P_{i,t}^{\text{out}} = \eta_i P_{i,t}^{\text{in}},\ \forall i \in G^{\text{cou}} \tag{1}$$

where $P_{i,t}^{\text{out}}$ and $P_{i,t}^{\text{in}}$ are, respectively, the output and input power of the i-th energy coupling device at time t; η_i is the energy conversion efficiency of the i-th energy coupling device; G^{cou} is the collection of all the energy coupling devices.

2. Equipment power constraints.

$$0 \le P_{i,t}^{\text{out}} \le P_i^{\text{out,max}} \tag{2}$$

$$0 \le P_{i,t}^{\text{in}} \le P_i^{\text{in,max}} \tag{3}$$

where $P_i^{\text{out,max}}$ and $P_i^{\text{in,max}}$ are, respectively, the maximum output and input power of the i-th energy coupling device.

2.2.2. Energy Storage Devices

1. Energy storage state constraints.

$$S_{j,t+1}^{\text{store}} = \underbrace{(1-\delta_j^{\text{store}})S_{j,t}^{\text{store}}}_{\text{self}-\text{dissipation}} + \underbrace{P_{j,t}^{\text{charge}}\Delta t \cdot \eta_j^{\text{charge}}}_{\text{energy injected}} - \underbrace{P_{j,t}^{\text{discharge}}\Delta t / \eta_j^{\text{discharge}}}_{\text{energy withdrawn}} \tag{4}$$

$$S_{j,0}^{\text{store}} = S_{j,T}^{\text{store}}\ ,\forall j \in G^{\text{store}} \tag{5}$$

where $S_{j,t}^{\text{store}}$ is the state of charge (SOC) measured in MWh of the j-th energy storage unit at time t; δ_j^{store} is the loss rate of the j-th energy storage unit; η_j^{charge} and $\eta_j^{\text{discharge}}$ are, respectively, the efficiency of charging and discharging of the j-th energy storage unit; $P_{j,t}^{\text{charge}}$ and $P_{j,t}^{\text{discharge}}$ are, respectively, the charging and discharging power of the j-th energy storage unit; Δt is the time step in scheduling; T is the scheduling cycle; G^{store} is the collection of energy storage units.

Constraint (4) describes the charging and discharging process of the energy storage units, considering the energy loss during injection, withdrawal, and self-dissipation. Constraint (5) implies that the storage unit needs to restore its SOC at the end of the day, supposing that each operation day is identical.

2. Charging and discharging constraints.

Considering that energy storage devices cannot be charged and discharged at the same time, constraint (6) is required:

$$P_{j,t}^{\text{charge}} \cdot P_{j,t}^{\text{discharge}} = 0 \tag{6}$$

3. Power and capacity constraints.

$$0 \le P_{j,t}^{\text{discharge}} \le P_j^{\text{discharge,max}} \tag{7}$$

$$0 \le P_{j,t}^{\text{charge}} \le P_j^{\text{charge,max}} \tag{8}$$

$$S_j^{\text{store,min}} \le S_{j,t}^{\text{store}} \le S_j^{\text{store,max}} \tag{9}$$

where $P_j^{\text{discharge,max}}$ and $P_j^{\text{charge,max}}$ are, respectively, the maximum output and input power of the j-th energy storage unit; $S_j^{\text{store,min}}$ and $S_j^{\text{store,max}}$ are, respectively, the minimum and maximum SOC of the j-th energy storage unit.

Constraint (9) implies a margin constraint that the energy storage units cannot be fully charged or discharged, so that the regulation flexibility is guaranteed and the health of energy storage units such as batteries is protected.

3. Optimal Market Strategy for IESP

3.1. Objective Function

In this paper, the objective function is to maximize the economic benefit of the IESP operation as formulated by:

$$\max f^{\text{profit}} = f^{\text{income}} - f^{\text{cost}} \tag{10}$$

where f^{profit}, f^{income}, and f^{cost} are, respectively, the profit, total income, and total cost of the IESP.

3.1.1. IESP Income

The income of the IESP includes energy service income and ancillary service income:

$$f^{\text{income}} = f^{\text{energy}} + f^{\text{frequency}} + f^{\text{reserve}} \tag{11}$$

where f^{energy} is the income from supplying electricity, cooling, and heating to the users, $f^{\text{frequency}}$ is the income of frequency regulation, and f^{reserve} is the income of reserve services.

1. Energy supply income.

$$f^{\text{energy}} = \sum_{t=1}^{T} C_t^{\text{e}} P_t^{\text{load,e}} \Delta t + C^{\text{c}} \sum_{t=1}^{T} P_t^{\text{load,c}} \Delta t + C^{\text{h}} \sum_{t=1}^{T} P_t^{\text{load,h}} \Delta t \tag{12}$$

where $P_t^{\text{load,e}}$, $P_t^{\text{load,c}}$, and $P_t^{\text{load,h}}$ are, respectively, the electricity load, cooling load, and heating load of the users at time t; C_t^{e} is the electricity price at which the IESP sells to the users at time t, which is a time-of-use (ToU) tariff; C^{c} and C^{h} are, respectively, the price of the cooling and heating service, which is fixed during a day; the prices of energy services are in USD/MWh.

2. Frequency regulation service income.

$$f^{\text{frequency}} = f^{\text{fre,capacity}} + f^{\text{fre,mileage}} \tag{13}$$

$$f^{\text{fre,capacity}} = C^{\text{fre,capacity}} P^{\text{fre,capacity}} \tag{14}$$

$$f^{\text{fre,mileage}} = C^{\text{fre,mileage}} k^{\text{fre,mileage}} P^{\text{fre,capacity}} \tag{15}$$

where $f^{\text{fre,capacity}}$ is the capacity income of frequency regulation, which is determined by the withholding power $P^{\text{fre,capacity}}$; $f^{\text{fre,mileage}}$ is the mileage income of frequency regulation, which is determined by the mileage power (i.e., absolute movement of the regulating resources); the mileage power is assumed to be proportional to the withholding power with a ratio $k^{\text{fre,mileage}}$; $C^{\text{fre,capacity}}$ and $C^{\text{fre,mileage}}$ are, respectively, the prices of regulation capacity and regulation mileage in USD/MW.

3. Reserve service income.

Taking the upward reserve as an example, the formula for calculating the revenue of reserve services is as follows:

$$f^{\text{reserve}} = C^{\text{reserve}} P^{\text{reserve}} \tag{16}$$

where P^{reserve} is the power of reserve capacity provided by the IESP, C^{reserve} is the price of the reserve.

3.1.2. IESP Cost

The cost of the IESP includes the purchase cost of external energy and the maintenance cost of the devices:

$$f^{\text{cost}} = f^{\text{electricity}} + f^{\text{gas}} + f^{\text{maintenance}} \tag{17}$$

where $f^{\text{electricity}}$ is the cost of purchasing electricity from the grid; f^{gas} is the cost of purchasing gas from the natural gas network; $f^{\text{maintenance}}$ is the cost of the IESP equipment maintenance.

1. Electricity purchase cost.

$$f^{\text{electricity}} = \sum_{t=1}^{T} C_t^{\text{e,buy}} P_t^{\text{grid}} \Delta t \tag{18}$$

where $C_t^{\text{e,buy}}$ is the electricity purchase price from the grid at time t; P_t^{grid} is the electricity purchase power from the grid at time t.

2. Gas purchase cost.

$$f^{\text{gas}} = \sum_{t=1}^{T} C^{\text{g}} P_t^{\text{gas}} \Delta t \tag{19}$$

where C^{g} is the price of gas; P_t^{gas} is the power of gas consumption at time t.

3. Maintenance cost.

$$f^{\text{maintenance}} = \sum_{n \in G^{\text{equip}}} \sum_{t=1}^{T} C_n^{\text{m}} P_{n,t}^{\text{out}} \Delta t \tag{20}$$

where C_n^{m} is the maintenance price for the n-th equipment; $P_{n,t}^{\text{out}}$ is the output power of the n-th piece of equipment at time t; G^{equip} is the collection of all the equipment in the IESP.

3.2. Constraints

3.2.1. Constraints of Energy Conservation

Considering that the operation of the IESP involves multiple kinds of energy sources, its energy balance constraints include electricity, natural gas, heat, and cold as follows:

$$P_t^{\text{grid}} + P_t^{\text{ge,e}} + P_t^{\text{discharge,e}} = P_t^{\text{load,e}} + P_t^{\text{eh,e}} + P_t^{\text{ec,e}} + P_t^{\text{charge,e}} + P^{\text{reserve}}, \forall t \in \left[t^{\text{start}}, t^{\text{end}}\right] \tag{21}$$

$$P_t^{\text{grid}} + P_t^{\text{ge,e}} + P_t^{\text{discharge,e}} = P_t^{\text{load,e}} + P_t^{\text{eh,e}} + P_t^{\text{ec,e}} + P_t^{\text{charge,e}},\ \forall t \notin \left[t^{\text{start}}, t^{\text{end}}\right] \tag{22}$$

$$P_t^{\text{gas}} = P_t^{\text{gh,g}} + P_t^{\text{ge,g}} \tag{23}$$

$$P_t^{\text{hh,h,out}} + P_t^{\text{gh,h}} + P_t^{\text{eh,h}} + P_t^{\text{discharge,h}} = P_t^{\text{load,h}} + P_t^{\text{charge,h}} \tag{24}$$

$$P_t^{\text{hc,c}} + P_t^{\text{ec,c}} + P_t^{\text{discharge,c}} = P_t^{\text{load,c}} + P_t^{\text{charge,c}} \tag{25}$$

where $P_t^{\text{discharge,e}}$, $P_t^{\text{charge,e}}$, $P_t^{\text{discharge,h}}$, $P_t^{\text{charge,h}}$, $P_t^{\text{discharge,c}}$, and $P_t^{\text{charge,c}}$ are, respectively, the discharging and charging power of electricity, heat, and cold storage at time t; $P_t^{\text{load,e}}$, $P_t^{\text{load,h}}$, and $P_t^{\text{load,c}}$ are, respectively, the load demand of electricity, heat, and cold at time t; $P_t^{\text{ge,g}}$ and $P_t^{\text{ge,e}}$ are, respectively, the gas consumed and electricity produced by the gas turbine at time t; $P_t^{\text{eh,e}}$ and $P_t^{\text{eh,h}}$ are, respectively, the electricity consumed and heat produced by the electric boiler at time t; $P_t^{\text{ec,e}}$ and $P_t^{\text{ec,c}}$ are, respectively, the electricity consumed and cold produced by the electric chiller at time t; $P_t^{\text{gh,g}}$ and $P_t^{\text{gh,h}}$ are, respectively, the gas consumed and heat produced by the gas boiler at time t; $P_t^{\text{hh,h,out}}$ is the heating power of the waste heat boiler at time t; $P_t^{\text{hc,c}}$ is the cooling power of the absorption chiller at time t; t^{start} and t^{end} are, respectively, the start time and end time of the reserve services.

In addition, the heat sources of absorption chillers and waste heat boilers are mainly gas turbines, as follows:

$$k^{\mathrm{h}} P_t^{\mathrm{ge,e}} = P_t^{\mathrm{hh,h,in}} + P_t^{\mathrm{hc,h}} \tag{26}$$

where k^{h} is the electricity-to-heat ratio of the gas turbine; $P_t^{\mathrm{hh,h,in}}$ is the heat power consumed by the waste heat boiler at time t; $P_t^{\mathrm{hc,h}}$ is the heat power consumed by the absorption chiller at time t.

Furthermore, regardless of whether the IESP provides ancillary services, its original power purchase plan should not be changed; namely, buying electricity from the grid to provide ancillary services is not allowed. Therefore, the following constraint is required:

$$P_t^{\mathrm{grid}} = \widetilde{P}_t^{\mathrm{grid}} \tag{27}$$

where $\widetilde{P}_t^{\mathrm{grid}}$ is the electricity purchased from the grid at time t without considering the ancillary service provision.

3.2.2. Constraints of Line Capacity

The power on the energy transmission lines and natural gas pipelines is limited by the transmission capacity, as follows:

$$0 \le P_t^{\mathrm{grid}} \le P_t^{\mathrm{grid,max}} \tag{28}$$

$$0 \le P_t^{\mathrm{gas}} \le P_t^{\mathrm{gas,max}} \tag{29}$$

where $P_t^{\mathrm{grid,max}}$ is the maximum power of electricity purchased from the grid, $P_t^{\mathrm{gas,max}}$ is the maximum power of gas from the external gas network.

3.2.3. Constraints of Frequency Regulation Service

Considering that the frequency ancillary service requires high equipment responsiveness, it is provided by the electric storage equipment in the IESP, and is subject to the following constraints:

$$0 \le P_t^{\mathrm{discharge,e}} \le P^{\mathrm{discharge,e,max}} - P^{\mathrm{fre,capacity}} \tag{30}$$

$$0 \le P_t^{\mathrm{charge,e}} \le P^{\mathrm{charge,e,max}} - P^{\mathrm{fre,capacity}} \tag{31}$$

where $P^{\mathrm{discharge,e,max}}$ and $P^{\mathrm{charge,e,max}}$ are, respectively, the maximum discharging and charging power of the electric storage.

3.2.4. Constraints of Reserve Service

During the IESP operation, it is necessary to maintain the promised power margin of the reserve service at all times. Therefore, it is necessary to impose the following constraints on the operation of the IESP:

$$0 \le P^{\mathrm{reserve}} \le P^{\mathrm{reserve,max}} \tag{32}$$

where $P^{\mathrm{reserve,max}}$ is the maximum power of reserve capacity that can be provided by the IESP.

Specifically, the maximum power of reserve capacity that can be provided by the IESP is related to the power purchased from the grid and the operating state of the internal equipment when the reserve ancillary service is not considered. Therefore, it can be solved by constructing the following mathematical problem:

$$\text{obj. } P^{\mathrm{reserve,max}} = \max P^{\mathrm{reserve}} \tag{33}$$

$$\text{s.t. } P_t^{\text{grid}} + P_t^{\text{ge,e}} + P_t^{\text{discharge,e}} = P_t^{\text{load,e}} + P_t^{\text{eh,e}} + P_t^{\text{ec,e}} + P_t^{\text{charge,e}} + P^{\text{reserve}}, t \in [1,T] \quad \text{Constraints (1)–(9), (23)–(31)} \tag{34}$$

The above optimization problem obtains the maximum reserve capacity by changing the natural gas purchase and equipment operation schedule. At the same time, considering the influence of the energy storage capacity and charging/discharging power, the following constraints are required:

$$\begin{gathered} S_{j,t+1}^{\text{store}} \leq (1-\delta_j^{\text{store}})\hat{S}_{j,t}^{\text{store}} + P_j^{\text{charge,max}} \eta_j^{\text{charge}} \Delta t \\ S_{j,t+1}^{\text{store}} \geq (1-\delta_j^{\text{store}})\hat{S}_{j,t}^{\text{store}} - P_j^{\text{discharge,max}} / \eta_j^{\text{discharge}} \Delta t \\ \forall j \in G^{\text{store}} \end{gathered} \tag{35}$$

where $\hat{S}_{j,t}^{\text{store}}$ is the state of charge of the j-th energy storage equipment at time t when the IESP provides the maximal reserve service.

3.3. Optimal Operation Procedure of IESP

First, the IESP needs to predict the load demand of its users, in terms of electricity, cooling, heating, etc. Then, the maximum capacity of ancillary services that can be provided by the IESP is determined, including frequency regulation and reserve services. The IESP needs to continuously provide the proposed quantity of ancillary services during its operation, so it must carefully determine the maximum available ancillary capacity according to the scheduled operation plan, installed capacity, and ramping characteristics of the equipment. Finally, according to the price information from the energy markets, the IESP needs to comprehensively consider its income and costs to propose an operation plan with the best economic benefits.

The solution to the optimal market strategy of IESP can be summarized in the following steps:

(1) Obtain the IESP optimal operation schedule without providing ancillary services, and attain the power purchase plan.
(2) Maintain the original power purchase plan of the IESP and calculate the available maximal reserve capacity.
(3) Attain the IESP optimal operation scheme with ancillary service provision, with the maximum reserve service constraint respected.

4. Numerical Example and Results

4.1. Numerical Example

To demonstrate the effectiveness of the proposed strategy, cases of an IESP and its industrial park users in eastern China are presented. Taking a typical summer day as an example, the users demand for electricity, cooling, and heating, as shown in Figure 3. The equipment coordination relationship is shown in Figure 2, and the technical parameters of the devices are shown in Table 1. Moreover, the frequency regulation and reserve service provisions are considered to improve the economic benefits of the IESP, and the relevant parameters are shown in Table 2. In addition, since the power generation scale of the IESP is smaller than that of conventional generators, it can hardly affect the price of the electric energy and ancillary service markets. Therefore, the IESP can only determine its bidding quantity in the markets. The price at which the IESP purchases from the electric energy market is simulated by the real-time electricity price, and the price at which the IESP sells electricity to users is simulated by the time-of-use tariff, as shown in Figure 4. Other parameters involved, such as prices of energy services and parameters of the external energy network, are shown in Table 3.

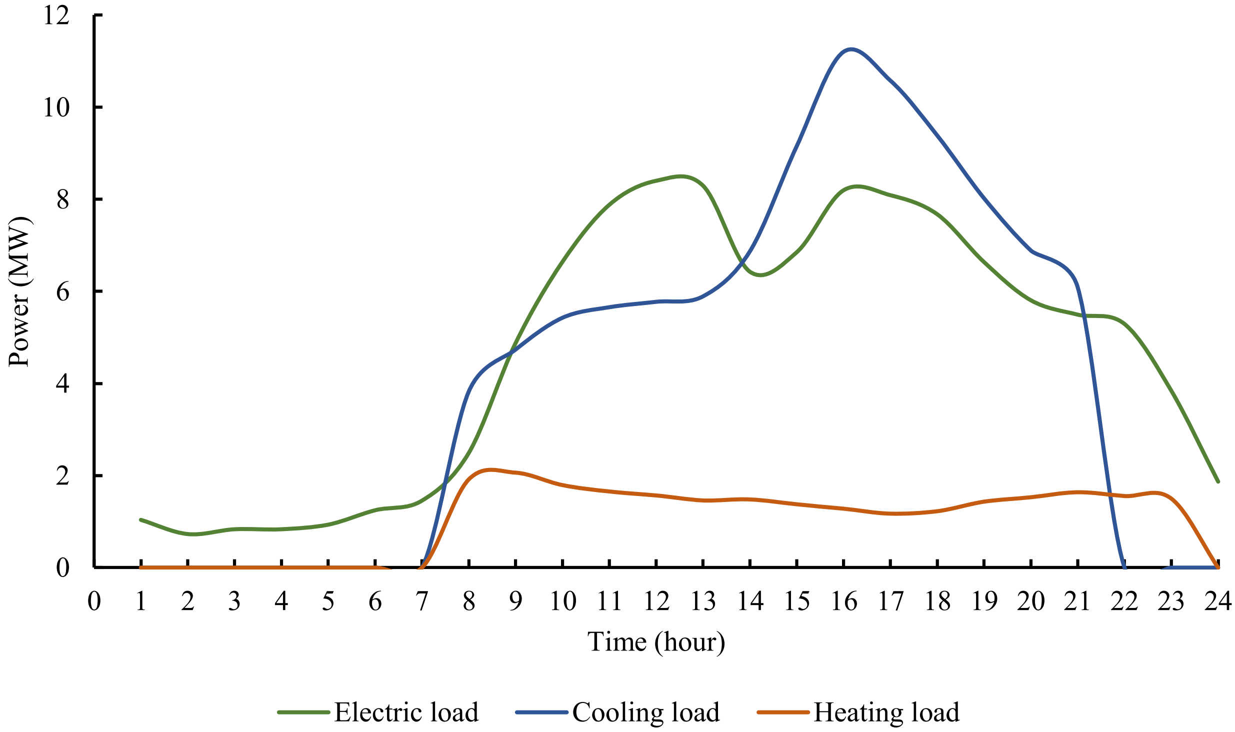

Figure 3. Load demand of an industrial park in a typical summer day.

Table 1. Device parameters.

Equipment	Installed Capacity	Efficiency	Maintenance Price
Gas turbine	10 MW	0.427 (gas-electricity) 0.458 (waste heat)	9.46 USD/MWh
Absorption chiller	8 MW	0.8	1.26 USD/MWh
Waste heat boiler	2 MW	0.9	0.47 USD/MWh
Gas boiler	2 MW	0.93	0.63 USD/MWh
Electric boiler	2 MW	0.95	0.79 USD/MWh
Electric chiller	8 MW	3.5	0.80 USD/MWh
Electric storage	10 MW, 20 MWh	$\eta^{\text{charge}} = \eta^{\text{discharge}} = 0.95,\ \delta^{\text{store}} = 0.01$	11.04 USD/MWh
Cold storage	2 MW, 10 MWh	$\eta^{\text{charge}} = \eta^{\text{discharge}} = 0.85,\ \delta^{\text{store}} = 0.01$	0.78 USD/MWh
Heat storage	2 MW, 10 MWh	$\eta^{\text{charge}} = \eta^{\text{discharge}} = 0.90,\ \delta^{\text{store}} = 0.01$	1.25 USD/MWh

Table 2. Ancillary service parameters.

Parameter	Value
Capacity price for reserve ancillary services	250 USD/MW
Actual start time of reserve ancillary services	18:00
Actual end time of reserve ancillary service	19:00
Capacity price for frequency ancillary services	100 USD/MW
Mileage price for frequency ancillary services	15 USD/MW
Mileage factor for frequency ancillary services	10

Two scenarios are considered for comparison and analysis:

(1) Scenario 1: IESP optimal operation without ancillary service provision.
(2) Scenario 2: IESP optimal operation with ancillary service provision.

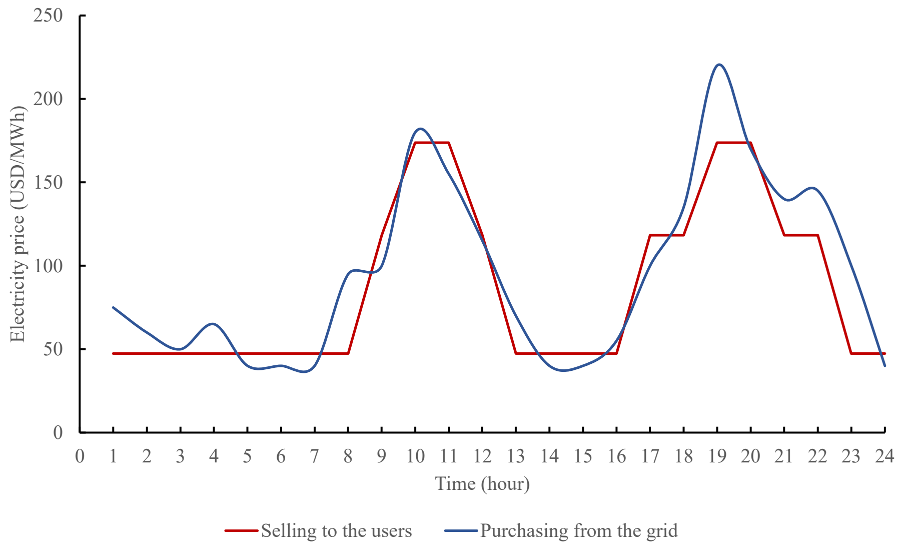

Figure 4. Electricity prices.

Table 3. Prices of energy services and parameters of the external energy network.

Parameter	Value
Price of heating service	80 USD/MWh
Price of cooling service	80 USD/MWh
Price of purchasing natural gas	70 USD/MWh
Maximum power purchased from the natural gas network	12 MW
Maximum power purchased from the external power grid	8 MW

4.2. Simulation Results

4.2.1. Operation Results

The optimal operation results of the IESP in Scenarios 1 and 2 are shown in Figures 5–8. The power balance, gas balance, cold balance, and heat balance are respectively presented for the two scenarios. The positive bars in the figures represent the power of energy produced, the negative bars represent the power of energy consumed, and the curve represents the user's energy load.

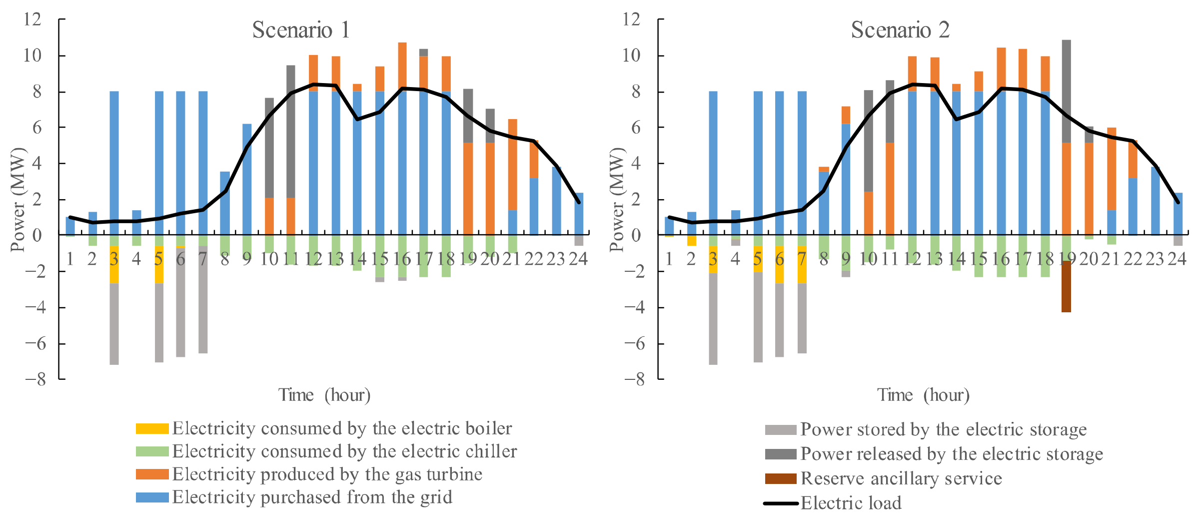

Figure 5. Power balance.

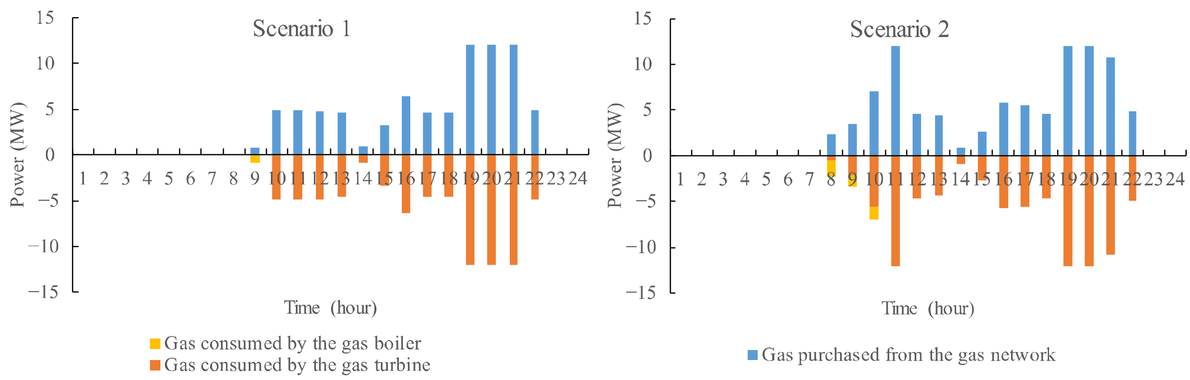

Figure 6. Gas balance.

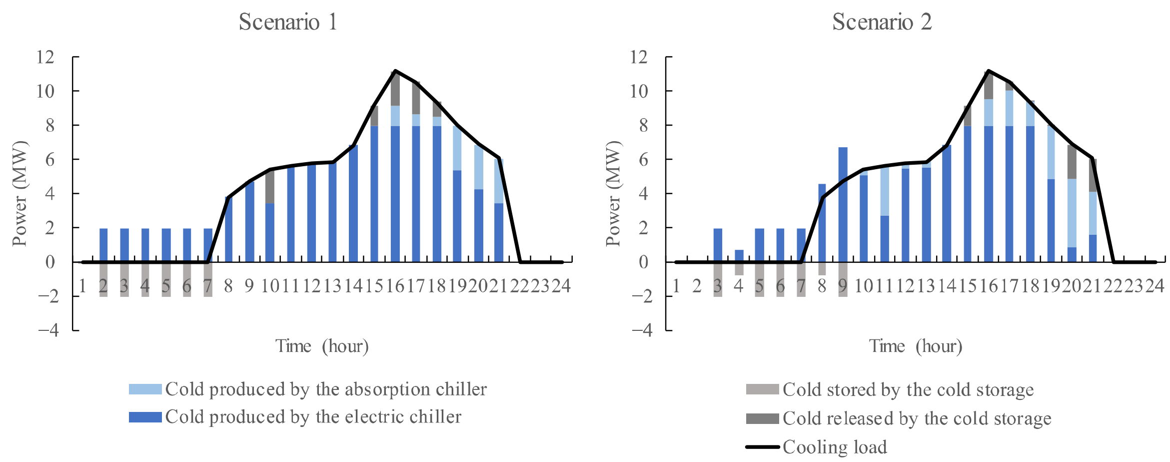

Figure 7. Cold balance.

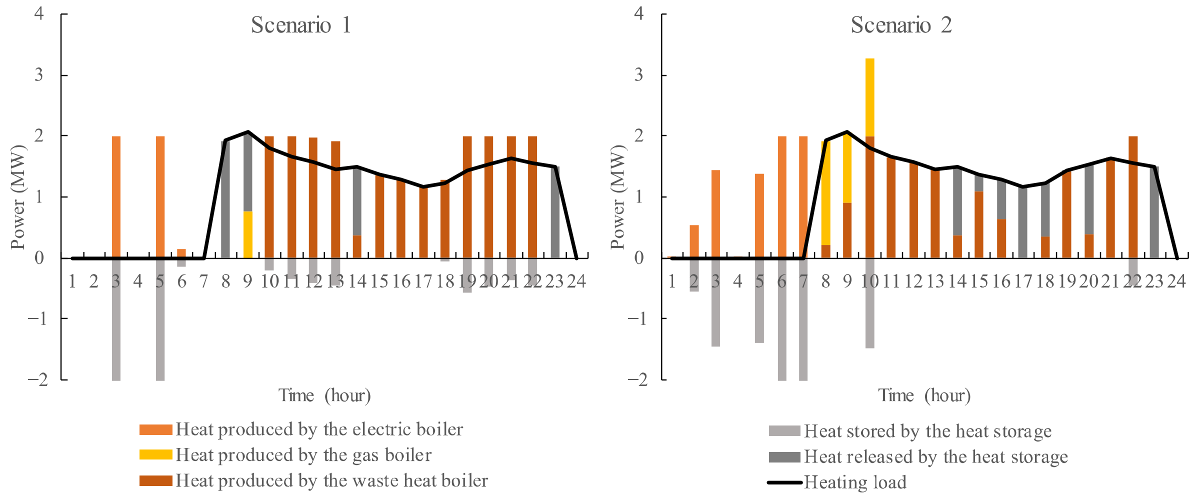

Figure 8. Heat balance.

The subplots in the left-hand side of Figures 5–8 show that, when the IESP in Scenario 1 does not provide ancillary services, its optimal operation result is mainly affected by the electricity price. When the electricity price is low (e.g., 0:00–8:00), the IESP purchases electricity from the grid and charges the electric storage unit; when the electricity price is high (e.g., 10:00–12:00, 19:00–21:00), the IESP reduces the purchase from the grid and supplies electricity demand with the power generation of gas turbines and the discharge of the electric storage unit. Natural gas consumption follows the operation of gas turbines. In addition, the waste heat generated by the gas turbine is utilized by the waste heat boiler to supply the heating load. The cooling load of users is mainly supplied by the electric chiller, which is advantageous in economic terms due to its high cooling efficiency. Furthermore, energy storage units, such as electricity, cold, and heat, are used to varying degrees during the operation of the IESP to play a role in the flexible operation of the system.

The subplots in the right-hand side of Figures 5–8 show that the optimal operation scheme of the IESP in Scenario 2 is changed compared with that in Scenario 1 due to the provision of ancillary services. The results show that 2.38 MW of frequency regulation service is provided, withholding 2.38 MW of output capacity of the electric storage unit for the whole day; and 2.83 MW of reserve capacity is provided from 19:00 to 20:00, which is mainly supplied by discharging the electric storage. The operation plans of all devices are adjusted slightly to coordinate with the change. On the premise of not changing the power purchase plan, the IESP provides ancillary services by changing the natural gas purchase plan and the operation schedule. The most notable changes include an increase in the natural gas purchase and the adjustments to the operation plan of energy storage units. In general, devices using natural gas operate more frequently, the operating hours of cold storage and heat storage units increase, and the operating power of the electric storage unit decreases.

Furthermore, Figure 9 shows the difference in the storage states of different energy storage units in different scenarios. In Scenario 2, 2.38 MWh of electric storage capacity is retained to ensure that the IESP can provide the committed frequency regulation capacity when required. Hence, the available energy supply of the electric storage unit is reduced. Consequently, the usages of cold storage and heat storage units are increased to fulfill the demands of users. Due to the high cooling load demand and low heating load demand of the users, the usage of the cold storage unit is already high in Scenario 1; therefore, during the optimization in Scenario 2, a shift appears in the charging and discharging of the cold storage unit. Regarding the heat storage unit, since its usage in Scenario 1 is low, the optimization in Scenario 2 greatly increases its usage to cooperate with other devices in the RIES to provide reserve services.

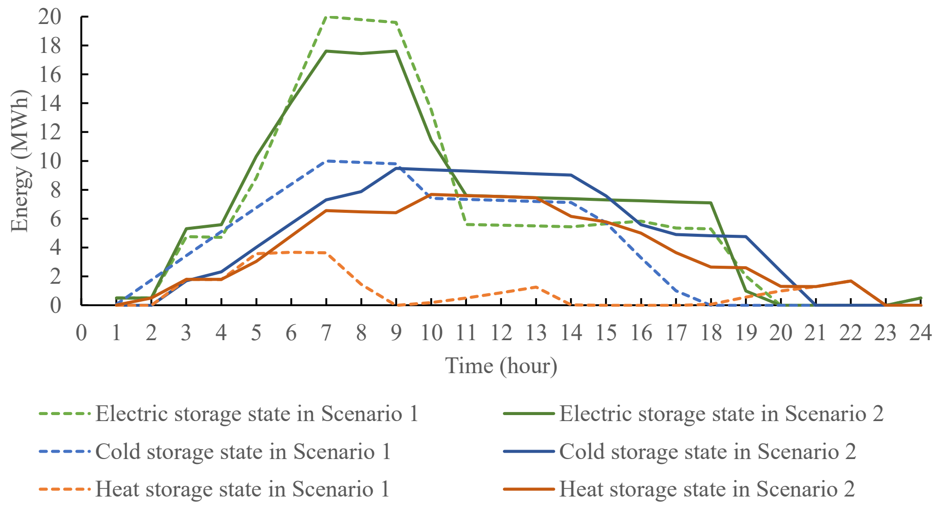

Figure 9. Operation of energy storage equipment.

4.2.2. Economic Results

Table 4 shows the economic results of the IESP's operation in the two scenarios. When the IESP provides ancillary services in Scenario 2, compared with no ancillary service provision in Scenario 1, its total income increases by 6.08% (from USD 21,452.31 to USD 22,756.79) and its total cost increases by 1.54% (from USD 14,690.90 to USD 14,917.25), finally resulting in an increase of 15.95% in the profit (from USD 6761.41 to USD 7839.53). Specifically, with ancillary service provision, the energy supply income of the IESP does not change, and the increase in income is mainly due to the provision of frequency regulation and reserve services. Moreover, the increase in cost is mainly due to the cost of purchasing more natural gas. Generally speaking, during the daily operation process of the IESP, if some equipment is idle and the price of ancillary services is appropriate, the IESP tends to increase the purchase of natural gas and leaves its power purchase plan unchanged, and adjusts the operation plan of its energy coupling and storage equipment to provide ancillary services.

Table 4. Economic comparison.

Items (In USD)	Scenario 1	Scenario 2
Total income	**21,452.31**	**22,756.79**
Electricity income	11,523.88	11,523.88
Cooling income	7957.66	7957.66
Heating income	1970.78	1970.78
Frequency ancillary service income	0	596.20
Reserve ancillary services income	0	708.27
Total cost	**14,690.90**	**14,917.25**
Electricity purchase cost	8147.80	7524.52
Gas purchase cost	5642.56	6504.81
Maintenance cost	900.54	887.92
Total profit	**6761.41**	**7839.53**

5. Conclusions

This paper presents an optimization model to determine the optimal operation strategy for an IESP with ancillary service provision. First, a mathematical model is established for the energy coupling devices and energy storage devices in the IESP. On this basis, the optimal operation schedule of the equipment is obtained considering frequency regulation and reserve services, and the optimal capacity of frequency regulation and the reserve is determined. The case study compares and analyzes the optimal operation results with and without ancillary service provision, and the simulation results show that:

(1) In terms of operation, when the IESP provides ancillary services, it increases the consumption of natural gas and the use of related energy coupling devices, increases the use of heat and cold storage units, and reduces the use of the electric storage unit to improve its capability of providing ancillary services.
(2) In terms of economic benefits, when the IESP provides ancillary services, the income from ancillary services is higher than the cost from the increase in natural gas consumption, with other income and costs basically unchanged. Hence, the profit of the IESP operation in a typical day is increased.

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