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Optimal Dispatch of Regional Integrated Energy System Based on a Generalized Energy Storage Model

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ABSTRACT In view of the difficulties in optimal dispatch caused by diverse energy and various types of equipment in the regional integrated energy system(RIES), this paper established a generalized energy storage model by extracting the flexibility characteristics of cooling, heat, and electrical load based on abstract equivalence. Instead of reducing the accuracy of regulation, this modeling method can greatly simplify the information interaction between the energy dispatching center and energy consumers, thus cutting down the time of collaborative analysis calculations. With the scheduling characteristics of multiple types of flexible loads in day-ahead and intra-day time scales considered comprehensively, a multi-time-scale optimization scheduling model of RIES is established, which takes into account the economy of system operation and the demand response. The simulation results show that the proposed optimization model can fully tap the load-side scheduling potential, along with effectively reducing the computational complexity. Through the coordination of resources with different characteristics, the pressure of balancing energy supply and demand can be relieved, and the operating cost of the system can be minimized.

INDEX TERMS Regional integrated energy system (RIES), generalized energy storage model, multi-time-scale, optimal dispatch.

I. INTRODUCTION

The regional integrated energy system (RIES) integrates primary energies such as wind, solar, and natural gas, where collaborative optimization of cold, heat, electricity and gas between the supply and the demand side is realized [1], [2], which helps to optimize the energy structure and reduce dependence on traditional fossil energy. With the integration of multiple forms of energy, the types and numbers of equipment in RIES have increased dramatically, making it difficult to build regional optimization model to decide energy flow distribution. At present, most of the electric power, thermal, and gas systems in the world are discretely decision-making rather than globally optimized. The process of energy optimization and allocation involves the specific parameters and detailed information of each energy system, which is difficult for decision-making entities of other systems to obtain [3]–[5]. Therefore, a unified and standardized modeling method is needed to deal with equipment with similar characteristics in RIES, so as to make the optimization model easy to expand and to simplify the calculation process when the model is adapted to a larger system, which in fact, has important theoretical value and practical significance.

At present, modeling of integrated energy system is a hot issue in the energy optimization area, but most of the existing modeling methods are based on a specific regional energy system, and there is no unified definition of the typical architecture and modeling method of the integrated energy system. In [6], a two-stage iterative modeling method is implemented to capture multi-energy network limits and uncertainty. In [7], an electric-thermal coupling dispatching model is established to realize the full utilization of electrical and thermal energy, so as to reduce the operating cost of the microgrid. Further, a hybrid energy sharing framework of a heat-electricity integrated energy system is proposed in [8] to facilitate energy sharing and improve system flexibility. Since the integrated energy system involves multiple energy conversion equipment, energy transmission networks, and mutually coupled energy consumption patterns [9], it is necessary to take into account the non-linear characteristics of each unit,

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the complex topology of the energy network, and operation constraints at the same time [10]–[12]. Additionally, when the scale of the system needs to be expanded or reduced, it is intractable to add or reduce components based on the integrated model, so the existing unified modeling method is difficult to be applied to large-scale systems.

So far, traditional energy storage has not been widely used due to its high cost, long investment period, and many other restricted factors [13]. In the background of the intelligent and digital development of power grids, regulating energy consumption behavior of the demand side by direct control [14], [15] or economic means [16]–[18] can also achieve the same effect as energy storage which transfers energy across time periods. In order to dig deeper into the dispatching value of electricity, heat/cooling, and gas loads on the demand side, plenty of research on integrated energy coordination control and dispatching optimization considering demand response has been conducted to realize the optimal utilization of various energy resources. In [19], an elastic demand side response model in the electric-thermal coupling system is established to optimize the load scheduling, showing significant effect in cutting down the system operating cost and improving the absorption capacity of PVs. Reference [20] deals with the problem of optimal scheduling of integrated energy system by characterizing the effect of demand response and some other uncertainties through a risk-constrained two-stage stochastic programming model. However, the above-mentioned papers neglect the coordination of integrated energy load response characteristics and the system scheduling on the time scale. To this end, a multi-time scale flexible resources coordination optimization scheme is presented in [21], which considers the smart loads' participation and presents a multi-time-scale power dispatch model that considers coordination and interaction between resources and electrical loads. In [22], a multi-time scale scheduling framework is proposed for integrated electricity and natural gas system at a distribution level. However, the potential of the integrated demand response of cooling/heat load and electrical load is neglected. Therefore, how to coordinate the scheduling of different time scales considering the error of weather and load prediction, energy response characteristics and adjustment ability [23]–[25], along with scheduling cost of flexible loads needs further analysis and research.

Considering the deficiency of existing research on modeling method and optimal dispatching of RIES, this paper explores demand response potential based on the analysis of the energy consumption characteristics of cooling, heat, and electrical loads. Flexible resources on the demand side which can change the energy space-time distribution are categorized as generalized energy storage (GES), and the analogue energy storage model is presented. By optimizing the energy production and utilization of each period, full use of the low-cost energy, reduction of the energy demand peak [26], and improvement of the economy and stability of the system operation can be realized on the premise that the each equipment works within its capacity limit.

As a specific contribution, this paper proposes a multi-time scale optimal dispatching method for the electric-thermal coupling system, taking the integrated demand response into consideration. To do so, the scheduling model of RIES for day-ahead period and intra-day period has been established respectively in detail. The following part of this paper is organized as follows. Section II presents the modeling method of generalized energy storage. Then the detailed model for cooling/heat and electrical loads is established in Section III. In Section IV, the optimal dispatching model is proposed with the objective of minimizing the systematic operation costs, and its effectiveness is thus verified by case studies in Section V. Finally, Section VI concludes the findings.

II. GENERALIZED ENERGY STORAGE MODEL

There are multiple types of loads with different physical forms and energy consumption characteristics in the integrated energy system. For the energy dispatching center, it is more concerned about the overall load response potential of the distribution network and load aggregators. In the process of energy dispatch, the effect of peak shaving and valley filling which is similar to the energy storage can be achieved by optimizing the demand amount and demand time of the controllable load. Therefore, according to the concept of abstract equivalence, the controllable load in the integrated energy system can be viewed as an equivalent group for energy storage modeling by replacing their actual physical parameters with abstract unified features or virtual parameters.

Different types of energy storage devices share similarities in working characteristics and can usually be evaluated by indices such as charging/discharging power, switching state, charging/discharging time, and state of charge (SOC). The charging/discharging power directly reflects the equivalent power of the energy storage participating in RIES scheduling and is closely related to the state of the equipment switching sequence. The charging/discharging time determines the sustainable response capability of energy storage resources. Based on the concept of SOC for battery, state of energy (SOE) is presented to measure the remaining energy of energy storage and the remaining schedulable power of controllable loads, reflecting the real-time reserve quota of the equipment and its responsiveness of the current stage. In this paper, the electrochemical battery, flexible electrical loads, and flexible thermal loads of RIES are major components of GES. By mapping the concepts of battery, indices applicable to GES are defined. The related description of GES working characteristic indices is shown in Tab. 1.

Different kinds of GES equipment exhibit similar external characteristics, in this way, a dynamic general model of GES can be established. This modeling method is no longer limited to the specific physical properties and parameters of certain equipment. With more abstract parameters used to replace single physical parameter or combined parameters, a unified standardized model is presented to reduce the calculating pressure brought about by differences in large-scale load groups. The dynamic general model of GES can be

TABLE 1. Performance index of GES.

Energy Storage Device	Performance Index	Related Description
Electrochemical Battery	Charging/ Discharging power	adjustable power involved in power dispatch
	Switching state	depends on whether or not to participate in power dispatch
	Charging/ Discharging time	related to equipment parameters
	State of energy(SOE)	ratio of residual capacity to rated capacity
Flexible Electrical Loads	Charging/ Discharging power	adjustable power involved in demand response
	Switching state	depends on whether or not to participate in demand response
	Charging/ Discharging time	related to energy use pattern
	State of energy(SOE)	expression of the current response quantity and the maximum response quantity
Thermal Loads	Charging/ Discharging power	differentials between transient power and steady power
	Switching state	depends on whether or not to participate in demand response
	Charging/ Discharging time	related to the temperature change rate of the medium
	State of energy(SOE)	expression of the body sensing temperature and the comfort zone of users

expressed as:

$$\begin{cases} S_{\mathrm{OE}}^{t} = f(X_{\mathrm{GES}}^{t}) \\ s.t.\ S_{\mathrm{OE}}^{\min} \le S_{\mathrm{OE}}^{t} \le S_{\mathrm{OE}}^{\max} \end{cases} \tag{1}$$

where S_{OE}^{t} stands for the energy state of GES at time t; X_{GES}^{t} represents physical variables that reflect energy state of GES at time t; $S_{\mathrm{OE}}^{\max}$ and $S_{\mathrm{OE}}^{\min}$ are the upper and lower limit of energy state respectively.

Based on this general model, the lower-level equipment only needs to upload its state of energy(SOE) and the amount of its schedulable energy to the upper-level dispatching center after local calculation, which can improve the compatibility of flexible loads participating in systematic energy scheduling, and significantly reduce the amount of communication and optimization calculation between the upper and lower levels by eliminating unnecessary information.

III. ENERGY STORAGE MODEL FOR COOLING, HEAT AND ELECTRICAL LOADS

Typical flexible electrical loads such as washing machines and electric vehicles have the characteristics of adjustable or transferable demand elasticity and can usually actively participate in demand response to ensure the stability of system operation. DLC loads such as electric water heaters, air conditioners, etc. and controllable cooling/heat loads show preferable demand response potential due to their energy conversion and storage characteristics. The action of classifying them into the same category of modeling can help increase the flexibility of coupling utilization of energy and simplify the complexity of model solution. Therefore, in order to make full use of the above-mentioned GES resources and effectively incorporate them into the optimal operation of RIES, a GES model for flexible electrical loads which include transferable loads and interruptible loads, and a GES model for thermal loads which include DLC loads and controllable cooling/heat loads are established successively. Through the integration of various flexible resources into GES, a unified mathematical model is used to participate in optimal scheduling to achieve rapid and reasonable allocation of system resources.

A. GES MODEL FOR FLEXIBLE ELECTRICAL LOADS

The transferable load refers to a type of loads of which the electricity consumption behavior is transferred from the period when the electricity price is high to the period when the electricity price is low due to the consideration of electricity prices, but its electricity consumption behavior will still occur and the total electricity consumption remains unchanged. Combined with the transferable load characteristics, its state of energy can be expressed as:

$$S_{\mathrm{OE,SL}}^{t} = \begin{cases} \left| \dfrac{\sum P_{\mathrm{SL}}^{t}}{P_{\mathrm{SL}}^{\max}} \right|, & t \in T_{\mathrm{d}} \\ 0, & t \notin T_{\mathrm{d}} \end{cases} \tag{2}$$

where $S_{\mathrm{OE,SL}}^{t}$ stands for the energy state of the transferable load at time t; P_{SL}^{t} represents the amount of power transferred at time t; when the power consumption of the transferable load at time t is switched to other periods, P_{SL}^{t} represents a positive number, while the power consumption of the transferable load is switched to time t, P_{SL}^{t} represents a negative number, thus $\sum P_{\mathrm{SL}}^{t}$ indicates the amount of power transferred from the start point of the day to time t; T_{d} is the time set of transferable load participating in the demand response; $P_{\mathrm{SL}}^{\max}$ is the maximum transferred power of the transferable load.

An electric boiler is a heating device that can convert electricity into heat. This paper believes that the electric boiler configured on the load side according to the interruptible strategy is an interruptible and adjustable electrical load in RIES. For the thermal system, the thermal output of the interruptible electric boiler also can be viewed as an adjustable thermal load. During the abandonment period, the load-side electric boiler is connected to the grid and outputs heat while consuming electricity, thereby reducing the equivalent heat load in the thermal system and relieving the supply pressure of the heating network; during the non-abandonment period, the electric boiler stops running and no longer affects the equivalent thermal load. Combined with the operating characteristics of the electric boiler as an interruptible load, its state of energy can be expressed as:

$$S_{\mathrm{OE,IL}}^{t}=\begin{cases}\dfrac{P_{\mathrm{IL}}^{t}}{P_{\mathrm{IL}}^{\max}}, & t\notin T_{\mathrm{z}}\\ 0, & t\in T_{\mathrm{z}}\end{cases}\tag{3}$$

where $S_{\mathrm{OE,IL}}^{t}$ stands for the energy state of the interruptible load at time t; P_{IL}^{t} represents the amount of power interrupted at time t; $P_{\mathrm{IL}}^{\max}$ is the maximum interrupted power of the interruptible load, which can be calculated based on the maximum heating supply and heating efficiency; T_z is the time set of the interruptible load participating in the demand response.

B. GES MODEL FOR THERMAL LOADS

The electricity consumption of DLC loads is relatively flexible. When the electricity price is higher than its mental expectation, the electricity consumption of DLC loads can be reduced or even stopped, and the consumption is not continued during the rest of the time. Common DLC loads are air conditioners and water heaters. As a typical temperature-controlled household appliance, the air conditioner relies on the thermal inertia of the building envelope to show a charging or discharging behavior similar to that of an energy storage device, and short-term switching will not have a significant impact on consumer satisfaction. An air-conditioning thermodynamic model [27] is established based on the principle of thermodynamics:

$$T_{\mathrm{in}}^{t}=(T_{\mathrm{in}}^{t-1}-T_{\mathrm{out}}^{t}+\eta_{\mathrm{DLC}}P_{\mathrm{DLC}}^{t}\mathrm{R})e^{\frac{-\Delta t}{\mathrm{RC}}}+T_{\mathrm{out}}^{t}-\eta_{\mathrm{DLC}}P_{\mathrm{DLC}}^{t}\mathrm{R}\tag{4}$$

where T_{in}^{t} and T_{in}^{t-1} are the indoor temperatures at time t and time $t-1$ respectively; T_{out}^{t} is the outdoor temperature at time t; P_{DLC}^{t} represents the power consumption of the air conditioner at time t; η_{DLC} is the energy efficiency ratio of the air conditioner; R and C are the equivalent thermal resistance and equivalent heat capacity of the room respectively.

When RIES needs to shave peaks or fill valleys, the power consumption of the air conditioner can be increased or decreased by adjusting its setting temperature, so that the air conditioner is equivalent to be in the charging or discharging period as an energy storage. According to the air conditioner thermodynamic model, the remaining charging or discharging time of the air conditioner at time t can be expressed as:

$$\Delta t_{\mathrm{DLC}}^{t}=\mathrm{RC}\ln\frac{T_{\mathrm{in}}^{t-1}-T_{\mathrm{out}}^{t}+\eta_{\mathrm{DLC}}P_{\mathrm{DLC}}^{t}\mathrm{R}}{T_{\mathrm{set}}^{t}-T_{\mathrm{out}}^{t}+\eta_{\mathrm{DLC}}P_{\mathrm{DLC}}^{t}\mathrm{R}}\tag{5}$$

The energy state of the air conditioner corresponds to the indoor temperature, while the energy state of the water heater corresponds to the temperature of the water supply, both of which can be collectively referred to as the medium temperature. According to the current medium temperature and the upper and lower limits of the acceptable medium temperature, the energy state of the DLC load can be expressed as:

$$S_{\mathrm{OE,DLC}}^{t}=\frac{T_{\mathrm{medium}}^{\max}-T_{\mathrm{medium}}^{t}}{T_{\mathrm{medium}}^{\max}-T_{\mathrm{medium}}^{\min}}\tag{6}$$

where $S_{\mathrm{OE,DLC}}^{t}$ stands for the energy state of the DLC load at time t; $T_{\mathrm{medium}}^{\max}$ and $T_{\mathrm{medium}}^{\min}$ are the upper and lower limit of the acceptable medium temperature respectively. It can be recognized from (6) that the closer the value of $S_{\mathrm{OE,DLC}}^{t}$ is to 0.5, the larger the adjustable margin of the DLC load is, and the higher the consumer satisfaction is; while the closer its value is to 1 or 0, the smaller the adjustable margin of the DLC load is, and the lower the consumer satisfaction is.

The energy consumption characteristics of the controllable cooling/heat load are similar to that of the DLC load, except that the controllable cooling/heat load participates in the scheduling of the thermal system by coordinating with the heating equipment. By converting the traditional thermal load curve into a temperature range according to the consumer satisfaction range, the cooling/heat load is converted from a fixed value to a flexible value. As a result, the constraints of the traditional real-time balance of cooling/heat loads can be transformed into maintaining the indoor temperature of the heating area within a desired range, further increasing the energy storage capacity of the thermal system.

As a result, the main variables needed when various controllable resources from the demand side participate in scheduling as generalized energy storage are summarized, as shown in Tab. 2. The dispatching center can adjust the dispatching plan within the acceptable range of consumer satisfaction according to the flexible and controllable characteristics of the demand side or utilize economic means to guide consumers to selectively change their energy consumption behavior. Thus, the demand-side flexibility is increased, and the energy management of cooling, heat, and electrical loads is realized.

TABLE 2. Main variables of GES model.

Type of Load	Common Equipment	Main Variables
Transferable Load	washing machines, electric vehicles	transferred power P_{SL}^{t}
Interruptible Load	electric boilers	interrupted power P_{IL}^{t}
DLC Load	air conditioners, water heaters	medium temperature T_{medium}^{t}
Controllable Cooling/Heat Load	heating radiators	medium temperature T_{medium}^{t}

IV. MULTI-TIME SCALE ECONOMIC DISPATCHING MODEL OF RIES THAT INCLUDES THE GES MODEL

A. FRAMEWORK OF MULTI-TIME SCALE DISPATCHING OF RIES

Based on the forecast of renewable energy generation and uncontrollable load, an RIES collaborative dispatching framework based on day-ahead and intra-day time scale is presented in Fig.1 by comprehensively considering dynamic response characteristics of various dispatching resources. In the day-ahead scale, the complementary characteristics of electric-thermal coupling is utilized to optimize the coordination of heat and electricity. In the intra-day scale,

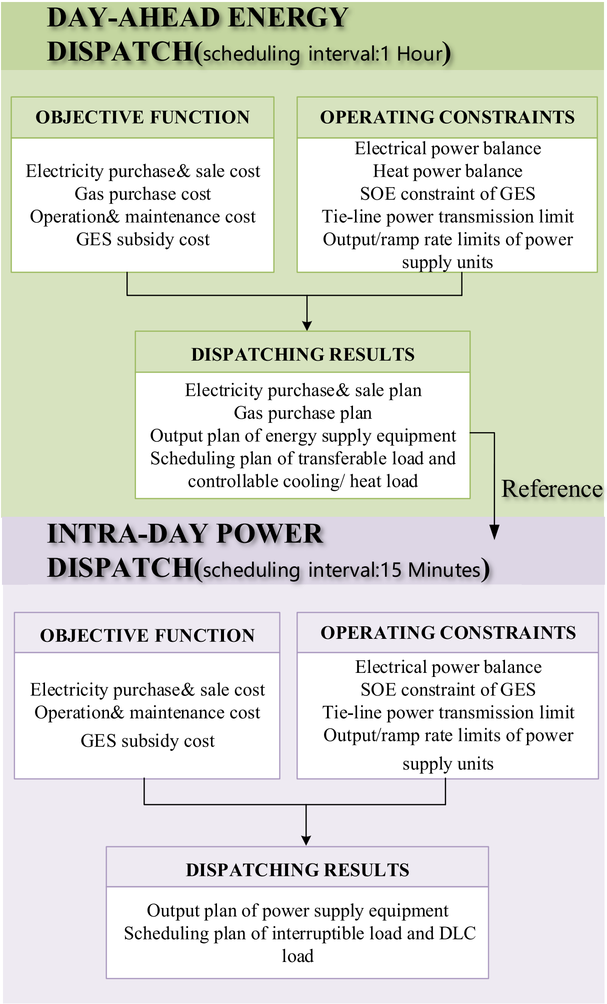


FIGURE 1. Structure of multi-time scale dispatching of RIES.

the fast responding characteristics of power equipment and the energy coupling characteristics of the electric boiler on the demand side is utilized to quickly eliminate the power fluctuation of RIES. Regarding the output of energy supply equipment in RIES and the amount of GES demand response as controllable variables, taking the minimum overall operating cost of RIES as the optimization goal, and comprehensively considering the electrical/heat power balance, equipment operating characteristics and the flexibility of GES participation in scheduling, a multi-time scale economic dispatching model of RIES that includes the GES model is presented to obtain the optimal scheduling plan of each supply equipment and the optimal demand response plan of GES.

The day-ahead heat-electricity coordinated scheduling is executed every 24 hours, and the unit scheduling interval is 1h. The goal of the day-ahead scheduling is to minimize the regional energy utilization costs which include the cost of power exchange between RIES and the external grid, the cost of purchasing gas from gas suppliers, the cost of operating and maintaining the energy supply equipment, and the subsidy cost of GES devices which participate in day-ahead demand response. Based on the short-term forecast data of renewable energy generation and integrated energy load, a dispatching plan for the following day is formulated. Since the thermal system has a large thermal inertia, the controllable cooling/heat load and the transferable load which need to be notified one day in advance are viewed as the day-ahead scheduling resources.

Further, on the basis of the day-ahead scheduling plan, the interruptible load and DLC load which possess faster response speed are viewed as the intra-day scheduling resources to assist the CHP units and battery in eliminating real-time fluctuations in wind and solar on the premise that the power distribution of the thermal system and the power exchanged by the tie line with the external grid remain unchanged. Intra-day power scheduling is executed every 1 hour, and the unit scheduling interval is 15 min. Since the thermal supply and tie-line power are fixed after the day-ahead scheduling, the goal of the intra-day scheduling is to minimize the regional electricity utilization costs which include the updated cost of power exchange, the cost of operating and maintaining the power supply equipment, and the subsidy cost of GES devices which participate in intra-day demand response. Based on the extended short-term forecast data of renewable energy generation and electrical load, a dispatching plan for the remaining time of the day is made.

B. OBJECTIVE FUNCTION OF DAY-AHEAD ENERGY DISPATCHING MODEL

The total operating costs of RIES in the day-ahead scheduling include the electricity purchase and sale cost $C_{\mathrm{ex}}^{\mathrm{power}}$, the gas purchase cost $C_{\mathrm{buy}}^{\mathrm{gas}}$, the operation and maintenance cost of the energy supply equipment $C_{\mathrm{om\_ah}}^{\mathrm{equi}}$, and the subsidy cost of GES $C_{\mathrm{dr\_ah}}^{\mathrm{load}}$ for participating in day-ahead demand response, which can be expressed as:

$$\begin{aligned}&\min(C_{\mathrm{ex}}^{\mathrm{power}}+C_{\mathrm{buy}}^{\mathrm{gas}}+C_{\mathrm{om\_ah}}^{\mathrm{equi}}+C_{\mathrm{dr\_ah}}^{\mathrm{load}})\\&=\sum_{t=1}^{24}\left(\frac{c_{\mathrm{buy}}^{t}+c_{\mathrm{sell}}^{t}}{2}P_{\mathrm{EX}}^{t}+\frac{c_{\mathrm{buy}}^{t}-c_{\mathrm{sell}}^{t}}{2}\left|P_{\mathrm{EX}}^{t}\right|\right)+\sum_{t=1}^{24}G_{\mathrm{CHP}}^{t}c_{\mathrm{gas}}\\&\quad+\sum_{t=1}^{24}[\sum_{i=1}^{N_{\mathrm{p}}}\delta_{i}^{t}f(P_{i}^{t})+\sum_{j=1}^{N_{\mathrm{h}}}\delta_{j}^{t}f(Q_{j}^{t})]+\sum_{t=1}^{24}(c_{\mathrm{SL}}P_{\mathrm{SL}}^{t}\\&\quad+c_{\mathrm{TL}}Q_{\mathrm{TL}}^{t})\end{aligned}\tag{7}$$

where P_{EX}^{t} stands for the power of the tie-line at time t; c_{buy}^{t} and c_{sell}^{t} are the purchase and sale prices of electricity at time t; G_{CHP}^{t} stands for the gas power purchased by CHP units from the natural gas supplier at time t; c_{gas} is the gas price; i and j are the label of power supply equipment and heat supply equipment respectively; N_{p} and N_{h} are the number of power supply equipment and heat supply equipment respectively; δ_{i}^{t} and δ_{j}^{t} represent the working status of each power supply equipment and heat supply equipment at time t; P_{i}^{t} and Q_{j}^{t} represent the output of each power supply equipment and heat supply equipment at time t; $f(P_i^t)$ and $f(Q_j^t)$ are the quadratic function of operation and maintenance cost of each power supply equipment and heat supply equipment respectively; P_{SL}^t and Q_{TL}^t are the electrical power transferred by the transferable load and the thermal power transferred by the controllable cooling/heat load respectively; c_{SL} and c_{TL} are the unit subsidy cost of the transferable load and the controllable cooling/heat load for demand response respectively.

C. OPERATING CONSTRAINTS OF DAY-AHEAD ENERGY DISPATCHING MODEL

The constraints of day-ahead energy dispatching model can be given as:

$$P_{\mathrm{WT}}^t + P_{\mathrm{PV}}^t + P_{\mathrm{CHP}}^t + P_{\mathrm{EX}}^t + \sum P_{\mathrm{GES\_ah}}^t = P_{\mathrm{LD\_ah}}^t \tag{8}$$

$$\sum P_{\mathrm{GES\_ah}}^t = P_{\mathrm{BS}}^t + P_{\mathrm{SL}}^t \tag{9}$$

$$Q_{\mathrm{CHP}}^t + \sum Q_{\mathrm{GES}}^t = Q_{\mathrm{LD}}^t \tag{10}$$

$$\sum Q_{\mathrm{GES}}^t = Q_{\mathrm{HS}}^t + Q_{\mathrm{TL}}^t \tag{11}$$

$$S_{\mathrm{OE,GES\_ah}}^{\min} \le S_{\mathrm{OE,GES\_ah}}^t \le S_{\mathrm{OE,GES\_ah}}^{\max} \tag{12}$$

where P_{WT}^t, P_{PV}^t and P_{CHP}^t stand for the output of wind turbines, photovoltaic and CHP units at time t; $\sum P_{\mathrm{GES\_ah}}^t$ represents the total charging/discharging power of GES participating in the day-ahead power scheduling; P_{BS}^t is the charging/discharging power of the battery storage at time t; $P_{\mathrm{LD\_ah}}^t$ is the forecast of systematic electrical load in the day-ahead stage at time t; Q_{CHP}^t is the heat power supply of CHP units at time t; $\sum Q_{\mathrm{GES}}^t$ represents the total charging/discharging heat power of GES participating in the thermal scheduling; Q_{HS}^t is the charging/discharging heat power of heat storage at time t; Q_{LD}^t is the forecast of systematic thermal load in the day-ahead stage at time t; $S_{\mathrm{OE,GES\_ah}}^t$ denotes the energy state of GES participating in the day-ahead scheduling at time t; $S_{\mathrm{OE,GES\_ah}}^{\max}$ and $S_{\mathrm{OE,GES\_ah}}^{\min}$ are the upper and lower limit of the energy state of GES respectively.

In (8)-(12), (8) represents the electrical power balance of RIES, and (10) represents the heat power balance of RIES; (9) and (11) indicate the components of GES participating in the day-ahead scheduling of power system and thermal system respectively; (12) stands for the SOE constraint of GES. Besides, other operating constraints such as tie-line power transmission constraints, output/ramp rate limits of power supply units also need to be met.

D. OBJECTIVE FUNCTION OF INTRA-DAY POWER DISPATCHING MODEL

The total operating costs of power system in the intra-day scheduling include the electricity purchase and sale cost $C_{\mathrm{ex}}^{\mathrm{power}}$, the operation and maintenance cost of the power supply equipment $C_{\mathrm{om\_in}}^{\mathrm{equi}}$, and the subsidy cost of GES $C_{\mathrm{dr\_in}}^{\mathrm{load}}$ for participating in intra-day demand response, which can be expressed as:

$$\begin{aligned}
&\min(C_{\mathrm{ex}}^{\mathrm{power}} + C_{\mathrm{om\_in}}^{\mathrm{equi}} + C_{\mathrm{dr\_in}}^{\mathrm{load}}) \\
&\quad = \sum_{t=1}^{24} \left(\frac{c_{\mathrm{buy}}^t + c_{\mathrm{sell}}^t}{2} P_{\mathrm{EX}}^t + \frac{c_{\mathrm{buy}}^t - c_{\mathrm{sell}}^t}{2} \left| P_{\mathrm{EX}}^t \right| \right) \\
&\qquad + \sum_{t=1}^{24} \delta_{\mathrm{BS}}^t f(P_{\mathrm{BS}}^t) + \sum_{t=1}^{24} (c_{\mathrm{IL}} P_{\mathrm{IL}}^t + c_{\mathrm{DLC}} P_{\mathrm{DLC}}^t)
\end{aligned} \tag{13}$$

where δ_{BS}^t represents the working status of battery storage at time t; $f(P_{\mathrm{BS}}^t)$ is the quadratic function of operation and maintenance cost of battery storage; c_{IL} and c_{DLC} are the unit subsidy cost of the interruptible load and the DLC load for demand response respectively; P_{IL}^t and P_{DLC}^t are the electrical power responded by the interruptible load and the DLC load respectively.

E. OPERATING CONSTRAINTS OF INTRA-DAY POWER DISPATCHING MODEL

The constraints of intra-day power dispatching model can be given as:

$$P_{\mathrm{WT}}^t + P_{\mathrm{PV}}^t + P_{\mathrm{CHP}}^t + P_{\mathrm{EX}}^t + \sum P_{\mathrm{GES\_in}}^t = P_{\mathrm{LD\_in}}^t \tag{14}$$

$$\sum P_{\mathrm{GES\_in}}^t = \sum P_{\mathrm{GES\_ah}}^t + P_{\mathrm{IL}}^t + P_{\mathrm{DLC}}^t \tag{15}$$

$$S_{\mathrm{OE,GES\_in}}^{\min} \le S_{\mathrm{OE,GES\_in}}^t \le S_{\mathrm{OE,GES\_in}}^{\max} \tag{16}$$

where $\sum P_{\mathrm{GES\_in}}^t$ represents the total charging/discharging power of GES participating in the intra-day power scheduling; $P_{\mathrm{LD\_in}}^t$ is the forecast of systematic electrical load in the intra-day stage at time t; $S_{\mathrm{OE,GES\_in}}^t$ denotes the energy state of GES participating in the intra-day scheduling at time t; $S_{\mathrm{OE,GES\_in}}^{\max}$ and $S_{\mathrm{OE,GES\_in}}^{\min}$ are the upper and lower limit of the energy state of GES respectively.

In (14)-(16), (14) represents the electrical power balance of RIES; (15) indicates the components of GES participating in the intra-day scheduling of power system; (16) stands for the SOE constraint of GES.

F. SOLUTION TO THE MODEL

The day-ahead and intra-day scheduling models presented are both mixed integer linear programming (MILP) models. The optimization subjects include the output of the energy supply equipment, the dispatching power and the energy state of GES, the power exchanged between the region and the grid, and the gas purchased from the natural gas company. Based on the YALMIP platform in MATLAB, the controllable variables can be optimized under the condition of satisfying the operating constraints to achieve the optimal solution of the objective function by invoking commercial solvers such as CPLEX/GUROBI/LINGO.

V. CASE STUDIES

To illustrate the GES model and employ it to the optimal dispatching problem, an integrated energy test system is used to

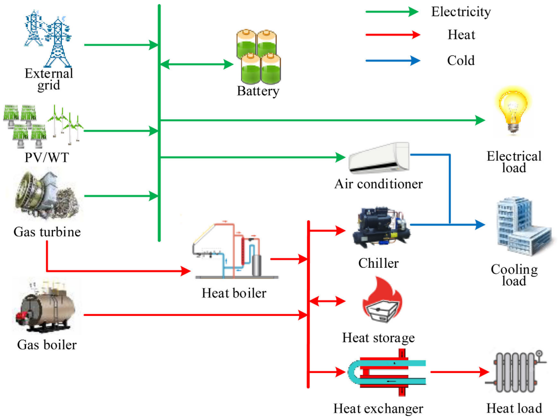


FIGURE 2. Structure of RIES.

demonstrate the proposed approach. As shown in Fig.2, RIES consists of renewable energy, CHP units, electricity/heat storage device, and multiple energy loads. The parameters of the energy supply equipment in the system are shown in Tab. 3, where P_M is the rated power; P_{max} means maximum power and P_{min} is minimum power. Output curves of wind turbines and photovoltaic, and electricity/heat load curves in a typical summer day are obtained from the historical forecast data. The maximum response amount of the transferable load, the DLC load, and the controllable cooling/heat load account for 15% of the original load, and the maximum response amount of the interruptible load accounts for 10% of the original load. The natural gas price is 4.2 cents/kWh after unit conversion, and Tab.4 shows the TOU electricity price.

TABLE 3. Relevant parameters of energy supply equipment.

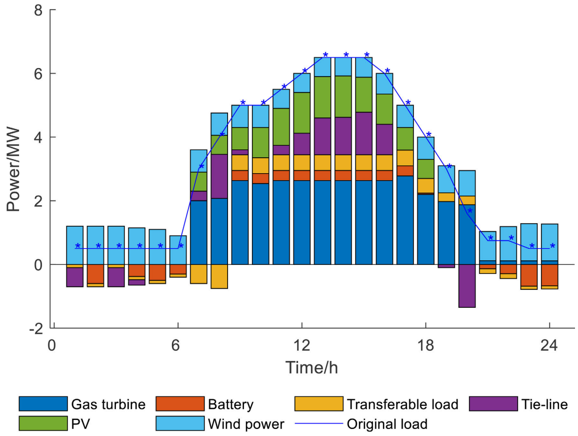
The equipment parameters	P_M/MW	P_{max}/MW	P_{min}/MW
Gas turbine	4.0	4.2	0.5
Gas boiler	4.0	4.0	0.5
Battery	0.8	0.5	-0.6
Heat storage	1.2	0.8	-0.9
Tie-line	—	2.0	-2.0

TABLE 4. TOU electricity price.

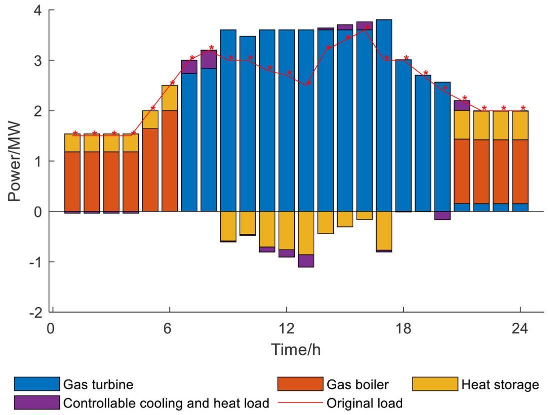
	Peak period (9h-12h, 15h-19h)	Flat period (7h-8h,13h-14h,20h-22h)	Valley period (1h-6h, 23h-24h)
Power purchase (cents/kWh)	8.6	7.2	5.5
Power sale (cents/kWh)	7.9	5.7	3.4

A. DISPATCH RESULT ANALYSIS

The results of day-ahead scheduling of RIES are shown in Fig. 3. In the day-ahead optimization stage, the power system and the thermal system jointly participate in energy scheduling. It is verified that the GES modeling method proposed in this paper can obtain consistent results with traditional flexible load modeling methods. It can be seen that the transferable load is transferred in when the systematic load is light (such as 4:00-8:00 and 21:00-24:00), and it is transferred out when the systematic load is heavy (such as 9:00-20:00) to achieve the effect of peak shaving and valley filling.



(a) power system



(b) thermal system

FIGURE 3. Day-ahead scheduling results of RIES.

In addition, the coordinated dispatch of the integrated heat and power energy system is conducive to promoting wind power consumption. It can be seen from Fig. 3(a) that from 21:00 to 6:00 of the next day, the wind power generation is high. During this period, the gas turbine is almost out of work, and the gas boilers and heat storage tanks in the thermal system come into use to meet the thermal demand. During the period from 7:00 to 20:00, which is the peak of power demand, the gas turbines with lower operating costs participate in the energy supply of power system and thermal system at the same time. In the period of low thermal demand, as shown in Fig. 3(b), the heat storage tank and the controllable heat load are used for energy storage and consumption. Therefore, the coordinated regulation of power and heat can effectively relieve the pressure of balancing energy supply and demand, as well as improve the operating economy of RIES and the rate of wind power consumption.

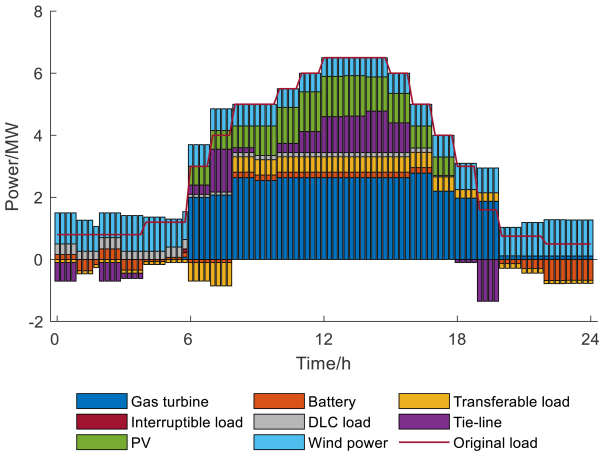


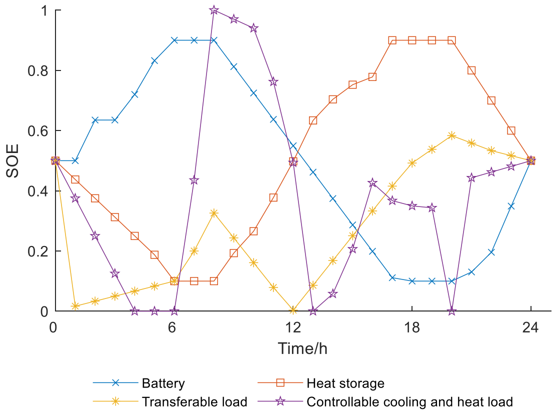
FIGURE 4. Intra-day scheduling results of power system.

The results of intra-day scheduling of RIES are shown in Fig. 4. In the intra-day optimization stage, only equipment with rapid adjustments in the power system participates in the scheduling. That is, on the premise that the transmission power of the tie-line and the transferred power of the transferable load are consistent with the day-ahead results, the real-time changes of wind power are eliminated by adjusting the output of the gas turbine and invoking the rest of GES to ensure the real-time balance of supply and demand in the power system. It can be noticed that the DLC load is flexibly invoked during the intra-day stage, effectively suppressing some power fluctuations in a shorter time scale. In addition, since the change in the output of the gas turbine will affect the supply and demand in thermal system, the interruptible load, such as the electric boiler, can also function as eliminating the changes in thermal power in time. By comparing the results of day-ahead and intra-day scheduling, it is obvious that intra-day scheduling can effectively trace real-time power fluctuations in the demand side and renewable energy generation, thus comprehensively reducing the cost of power regulation and improving the economy of system operation.

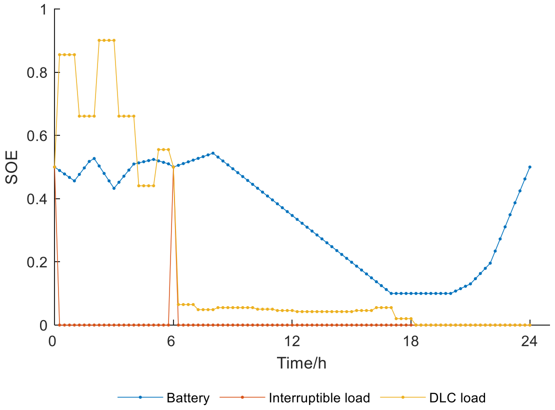
The demand side response can not only reduce electricity consumption, but also has a great impact on the reduction of operating cost of RIES. Tab. 5 shows the operating costs of electric-thermal coupling RIES with and without the demand response in the day-ahead scheduling and the final operating costs obtained after intra-day scheduling with demand response. It can be concluded that the total cost has been reduced after the adoption of demand side response. As can be seen in Tab. 5, the main reduction of operation cost comes from the power exchange cost, benefiting from the adjustment of energy storage output and the shaving of peak load. So far, the economic efficiency of the proposed approach is roundly proved.

TABLE 5. Operating costs of RIES.

Dispatch strategy	Gas cost /dollars	Power exchange cost /dollars	Maintenance cost /dollars	Subsidy cost /dollars	Total cost /dollars
Day-ahead scheduling without DR	4214.9	2045.9	10.6	—	6275.9
Day-ahead scheduling with DR	4889.3	419.6	10.7	49.0	5373.3
Intra-day scheduling with DR	4891.6	419.6	10.7	60.6	5386.4



(a) SOE of GES participating in the day-ahead scheduling



(b) SOE of GES participating in the intra-day scheduling

FIGURE 5. SOE of GES.

B. METHOD EFFICIENCY ANALYSIS

The SOE of GES can directly reflect the current response behavior of various energy storage devices and flexible loads, as well as their response capabilities of the next period. The hourly SOE changes of the transferable load and controllable heat load that participate in the day-ahead scheduling, along with the interruptible load and DLC load that participate in the intra-day scheduling are shown in Fig. 5.

It can be concluded that the electrical load is significantly reduced in the peak period when the proposed approach is adopted, i.e., part of the transferrable load is shifted to the valley period when the electricity price is much lower, which reduces the power generation of gas turbine and is conducive to the reduction of operating cost. During 1:00-6:00, the system is in the valley period, under the influence of the demand side, the consumption of electrical and controllable cooling/heat load at this stage increases slightly, resulting in the full utilization of wind power generation.

As for the working state of the battery in the day-ahead dispatch, due to the low initial capacity of the battery, the battery is charged during the valley period when the electricity price is low; during the period of 8:00-17:00, the power system is in peak period, and the electricity price is relatively high. Therefore, according to the scheduling strategy, the battery needs to be discharged to reduce the amount of electricity purchased. Since in the peak period the battery has released much electric power, and its SOE has almost reached its lower limit, it turns into the charging mode around 18:00 when the electricity price is relatively low. The working state of the battery in the intra-day dispatch is similar to before, but the charging power is reduced with the participation of DLC load in demand response, which helps to extend battery life. As for the working state of heat storage, it can be clearly seen that the heat storage is releasing heat to meet thermal needs at the interval time of 0:00-6:00 and 19:00-24:00, when gas turbine is out-of-work. In the rest of time, the heat storage is storing redundant heat produced by gas turbine when the systematic thermal load is low.

In order to verify the superiority of the GES modeling method proposed in this paper in terms of computational efficiency, the state sequence model built for multiple types of flexible loads in [28] is used for comparison. The optimal operation programs based on both modeling methods of RIES are run in MATLAB under the same simulation scenario. The computational efficiency of the mentioned modeling methods is compared from the number of iterations and the calculation time, as shown in Tab. 6.

TABLE 6. CPU time of different modeling methods.

Modeling method	Scheduling stage	Number of iterations	Calculating time/s
Traditional state sequence model	Day-ahead	2077	11.867
	Intra-day	725	13.953
GES model proposed	Day-ahead	1154	6.592
	Intra-day	393	7.542

The calculation time of the GES modeling method for multi-type of flexible loads proposed in this paper is almost half of the traditional state sequence modeling method with the simulation accuracy guaranteed. This is because the proposed method unifies the schedulable equipment with energy transferable characteristics in RIES from the perspective of dispatching center, which shows distinguished convergence performance, as well as reduces redundant information interaction and complex calculations effectively, thus saving much simulation time.

VI. CONCLUSION

An optimal dispatching approach considering integrated demand response is put forward for the electric-thermal coupling system in this paper. Simulation was carried out to verify the effectiveness of the proposed approach. Some useful conclusions can be summarized as follows.

(1) Based on the theory of abstract equivalence, the flexible feature of the controllable cooling, heat and electrical load are described in the form of GES and the unified model of the adjustable resources in RIES is completed. It is verified that the proposed method can not only accurately model the energy storage and the controllable load in a unified form, but also effectively reduce the computational complexity, which makes up for the shortcomings of traditional method in describing the flexible characteristics of the controllable load in the large-scale system scenario.

(2) A multi-time scale economic dispatching model of RIES considering integrated demand response is established to provide an effective approach for the energy flow analysis and optimization of RIES. The simulation results show that the effective utilization of integrated energy demand response can improve the matching degree of electricity, heat/cold and natural gas production with various energy consumption, and the economy and operating efficiency of the system is finally improved.

However, in this paper, the flexibility of heat network and gas pipelines had not been considered, resulting in certain limitation in the application of the proposed method. Further research will be carried out to address the deficiency in the near future.

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