Simulation Study of Integrated Smart Energy Systems

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***Abstract*—Concept of the integrated smart energy was introduced, and a typical integrated smart energy system was proposed and analyzed. Based on the mathematical modes of the main equipment of integrated smart energy systems, a simulation of the integrated smart systems including the monitoring screens, the simulation models, and the dispatching and control strategies based on a database centric architecture was constructed. Through the simulation study, the characteristics of the integrated smart system were analyzed, and some key problems were dug out to guide our future work.**

***Index Terms*—Energy, Modeling and Simulation, Integrated Smart Energy Systems, Dispatching and Control, Simulation Architecture**

I. INTRODUCTION

Energy is the basis of human survival and development, and also the lifeblood of the national economy. Improvement of the energy efficiency and the consumption of the clean energy have become an inevitable choice to solve the energy problem, and the contradiction between social development and environment protection. Breaking up the old mode that the different kinds of energy systems are planned, designed separately and operating independently, and realizing the integrated planning, designing and operating of the integrated energy systems is the trend of the future in the energy field [1].

At the beginning of this century, the United States, Europe, Japan and other developed countries have focused on the integrated energy system [2]. The United States Department of energy proposed a comprehensive energy system development plan in 2001 [3]. Energy Independence and Security Act (EISA) was enacted by United States in 2007. It is clear that the main energy supply system of the society must carry out integrated energy planning [4].in 2009, United States put the smart grid into the U.S. national strategy, the ultimate goal is to use new information technology to build a highly efficient, low investment, safe, flexible and integrated energy system [5]. Canada promulgated and implemented the community integrated energy system act, to promote the construction of more than 2000 community integrated energy systems [6] [7], In the EU Fifth Framework (FP5) [8], various forms of energy integrated optimization are placed in a prominent position, in the FP6 [9] and FP7 [10], related research on collaborative optimization of integrated energy system has been further deepened. The Japanese government announced emission reduction targets of the greenhouse gas in 2030 and 2050, and a project to build integrated energy systems covering the whole country, to realize the optimization of the energy structures and energy efficiency and promote the large-scale development of clean energy [11]. China has been launched a number of projects related to science and technology research and development of the integrated energy systems. The Chinese government is also working with the relevant agencies of other countries including Singapore, German and so on, to promote the integrated energy utilization technology, to establish a clean, safe, efficient, sustainable and comprehensive energy supply system and service system [12].

In this paper, the Integrated Smart Energy (ISE) system in China is introduced, and the concept of the ISE and the mathematical models of the main equipment of the ISE system is given. Then a simulation of the ISE system including the monitoring screens, the simulation models, and the dispatching and control strategies based on a database centric architecture was constructed. By this work, the characteristics of the ISE system were analyzed, and some key problems of development and management of it were proposed.

II. INTEGRATED SMART ENERGY

A. Concept of Integrated Smart Energy

For adapting to the development of China power sector reform and the development situation of international energy industry, the China State Power Investment Company (SPIC) had developed and proposed the concept of integrated smart energy as a new develop and operating mode of the multi-energy system based on the concept of integrated energy.

ISE is a smart and integrated solution of production, supply, transport and consumption of the community energy systems including multi kinds of energy, such as electricity, thermal, cold, gas and so on, for the energy users of a functional area such as an industrial park. ISE could not only fully meet the diverse need of energy users, but also innovative the energy consumption patterns and this can make the energy users achieving a more efficient usage of the energy. The Advantage of synergy of different energy will be played, and energy supplement will be optimized. The Energy integrated pipe gallery is used to optimize the energy transfer mode. Through the market mechanism and the information technology, the interaction between the supply and

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consumption could be achieved. The intelligent control platform may make collaborative operation of the energy source, energy grid and the energy load be easier to maximize the local consumption of the clean energy, and to provide users with efficient, flexible, convenient and economical energy supply and value-added services.

B. *Typical ISE System*

A typical ISE System of an industrial park in china, which includes electricity, heat, cold and other kind of energy, is shown in Fig 1. It clearly presents the multi energy flows ranging from production side to transport side, finally to consumption side of the ISE systems.

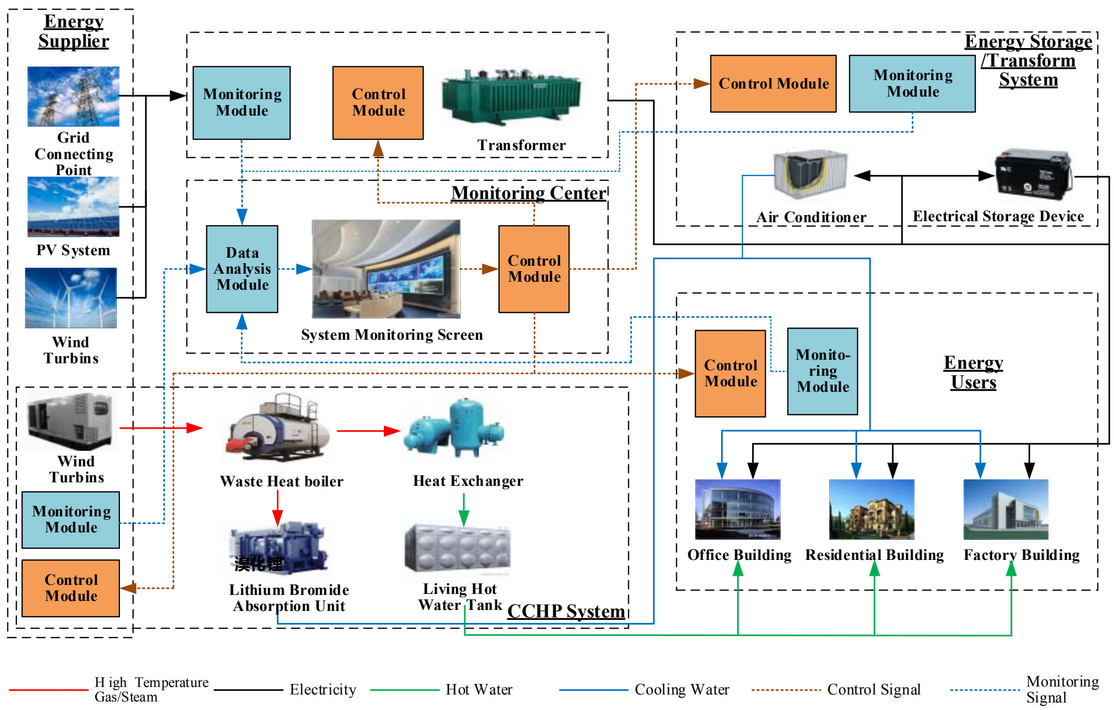


Figure 1. Typical ISE system

In the source side, the equipment producing the multi energy is included. The system is equipped with wind turbines and photovoltaic (PV) cells, to produce the clean power, and a Combined Cooling Heating and Power (CCHP) system based on micro turbines, waste heat boilers, and lithium bromide units, to provide power, heat and cold for users. Grid connecting devices are equipped, in order to ensure a greater demand of power in some operation conditions. In addition, the system is also equipped with electrical storage devices for peak load regulation of the system. Air conditioner is included to convert the electric into cold in power supply valley, so as to supplement the cooling capacity of the CCHP system. The integrated energy pipelines transport the electricity, heat water (or steam) and cold water. There are variety of typical energy users in the industrial park including factories, office buildings and residences. The core of ISE system is the operation monitoring center, which is composed with professional intelligent equipment and software. Through the energy management and control software deployed in the monitoring center and the field, the field data could be acquired so that monitoring and control of the system and equipment operation status will be achieved, and the energy dispatching instruction for production and consumption based on these status will be generated and optimized to make the ISE system operating most efficiently, smoothly and safely.

III. MODELS OF THE MAIN EQUIPMENT OF ISE SYSTEM

Mathematic models of some main equipment of ISE system including CCHP systems, PV cells, wind turbines, electricity storage devices and air conditioners are given as a basis of simulation modeling of the ISE system.

A. *CCHP Systems*

The CCHP is an energy generation system which includes heat engines, generators, heat recovery and cooling devices as a whole through a unified management of refrigeration, heating and power supply process. The micro turbine is the main equipment of the CCHP system, which consumes natural gas and produces electric power and waste heat. The use of waste heat can be realized by combination of the heat boiler, lithium bromide and heat exchanger, to produce thermal power and cooling power. If the heat loss of waste heat boiler is neglected, the mathematical model of the CCHP system can be written as [13]

$$\begin{cases} Q_{MT}(t) = P_{MT}(t)[1-\eta_{MT}(t)-\eta_{l}(t)]/\eta_{MT}(t) \\ Q_{H}(t)/COP_{H} + Q_{C}(t)/COP_{C} = Q_{MT}(t) \\ C_{gas}(t) = \Sigma[P_{MT}(t)/\eta_{MT}(t)]/LHV \end{cases} \tag{1}$$

Here, $Q_{MT}(t)$ is the heat of exhaust gas of micro turbines at time t; $P_{MT}(t)$ is the electric power of micro turbines at t,

$\eta_{MT}(t)$ is the generation efficiency of micro turbines at *t*, $\eta_l(t)$ is the heat loss coefficient of micro turbines at *t*, COP_H is the heating coefficient and COP_C is the cooling coefficient of CCHP systems, $C_{gas}(t)$ is the natural gas consumption at *t*, LHV is the low calorific value of natural gas, in $kW \bullet h / m^3$.

The generation efficiency of the micro gas turbine is related to the load characteristics of the unit, and the efficiency of the Capstone C65 is calculated as

$$\begin{aligned} \eta_{MT} &= 0.0753(P_{MT}/65)^3 - 0.3095(P_{MT}/65)^2 \\ &+0.4174(P_{MT}/65) + 0.1068 \end{aligned} \tag{2}$$

B. PV Cells

The PV cell is an energy conversion device which directly converts light energy into electric energy. The power output characteristics of PV cells can be expressed as [14]

$$P_{PV} = P_{base} H_0 [1 + g(t_{PV} - t_b)] / H_{base} \tag{3}$$

Here, P_{PV} is the power output of PV cells, P_{base} is the max power output of PV cells under the standard testing condition (the light intensity is 1000 W/m^2 , and the temperature is 25□), H_0 is the light intensity, g is the power-temperature coefficient, t_{PV} is the temperature of the PV cells, t_b is the reference temperature, and H_{base} is the light intensity under the standard testing condition.

C. Wind Turbines

Wind turbines can convert wind energy into electrical energy. The relationship between the output power of the wind turbine and the wind speed at the height of the blade can be written as follows [15]

$$P_{WTG} = 0.5 \rho A C_p(\lambda, \theta) V_W{}^3 \tag{4}$$

Here, ρ is the air density; A is the swept area, C_p is the efficiency coefficient, λ is the tip speed ratio, and

$$\lambda = R\omega_m / N_g V_W \tag{5}$$

Here, N_g is the gear ratio, V_W is the wind speed, R is the rotor radius, ω_m is the rotor speed, and θ is the propeller pitch angle According to (2), the active power output of wind turbine is related to the wind speed of 3 times. Therefore, due to the characteristics of wind speed, the output power of the wind farm can also fluctuate greatly.

D. Electricity Storage Devices

In the ISE system, through a reasonable charging and discharging control strategy of electricity storage devices and stabilized output power of PV cells, wind turbines and other clean energy, improve the utilization rate of PV cells, to ensure the stable power supply of the system. The mathematical model of electricity storage devices is [16]

$$\begin{cases} X_{SB}(t+1) = X_{SB}(t) + P_{SB}(t)\Delta t / E_{SB\max} \\ X_{SB}(t) = E_{SB}(t) / E_{SB\max} \end{cases} \tag{6}$$

Here, $X_{SB}(t)$ is the state of the charge at *t*, $P_{SB}(t)$ is the operating power at *t*. Devices operate in the charging state when $P_{SB}(t) > 0$, and in the discharging state when $P_{SB}(t) < 0$. $E_{SB}(t)$ is the capacity of the device at *t*, $E_{SB\max}$ is the rated capacity of the device, and Δt is the selected time interval.

E. Air Conditioners

In the ISE system, central air conditioners provide cooling energy as supplement of the CCHP system. Air conditioner can convert power to cold in the period of cold energy demand peak and electricity demand trough, so the surplus power can be transformed into the cooling load. The mathematical model of air conditioners can be written as

$$Q_{AC}(t) = P_{AC}(t) COP_{AC} \tag{7}$$

Here, $Q_{AC}(t)$ is the cooling power at t, $P_{AC}(t)$ is the power consumption at t, and COP_{AC} is the cooling coefficient of air conditioners.

IV. Simulation of ISE systems

According to the typical ISE system, based on the models of the main equipment of the system, a simulation model of the ISE systems is constructed in VPOWER software. Simulation architecture of the system is proposed to support the simulation test of the system models to achieve a complete simulation of the ISE system.

A. System simplification for modeling

Modeling of the typical ISE system shown in Fig. 1 is based on some reasonably simplification as follows.

- The effect of amplitude and phase angle adjustment process of the current and voltage in the grid mode switching is ignored so that the synchronization process between ISE system and grid outside of the industrial park can be seen as instantly completely.
- Assume that the consuming of the cool and heat is the simple heat transfer process. Under this assumption, in heating process the heat is transfer from system to users, and in cooling process, the heat is transfer from users to system. So the heat exchanger model can be used to simulate the heating or cooling process.
- The load demand curve and the clean energy output curve are preset so estimate problem of the load and clean energy need not be considered in simulation so that the simulation result is without uncertainty.
- The model of heat exchanger is used to simulate the characteristics of the lithium bromide units, the waste heat boilers and the other heater transfer or transform equipment not included in III.
- The electrical converters and the network energy loss are not considered in simulation.

B. Modeling and simulation environment

VPOWER is a multi-domain coupling simulation software developed by NEOSWISE Company of China, which can be used as modeling tool of the ISE system. There are two important tools included in the software, one is the modeling and simulation (M&S) environment, and the other is the human machine interface (HMI) tools. The former one provides basic module library of the electric/flow grid and equipment. A graphical modeling environment and a simulation engine are also integrated to support the coupling simulation of electricity and heat. The latter one provides a tool which can be used to configure monitor screens of ISE systems, and a separate engine to drive these screens.

To simulate the dispatch and control strategy of the ISE systems, we developed a dispatch and control simulation tools, which includes an algorithm library and a graphical modeling environment. In the modeling environment, the users can easily build a dispatch and control strategy through the combination and connection of the algorithm modules, and simulate the multi-energy management of the ISE system.

In order to simulate the ISE management system which consists of the energy management system (EMS) master station (monitoring center), supervisory control and data acquisition (SCADA) system and the field station, a runtime database (RTDB) was developed, which implemented the data interacting center of the monitoring software and the system models. Based on the RTDB, a simulation architecture of the ISE system is constructed which includes a monitoring workstation, a RTDB server and a system model server. Data interactions of the software deployed on different stations are achieved by using the TCP/IP protocol. The architecture is showed in Fig. 2.

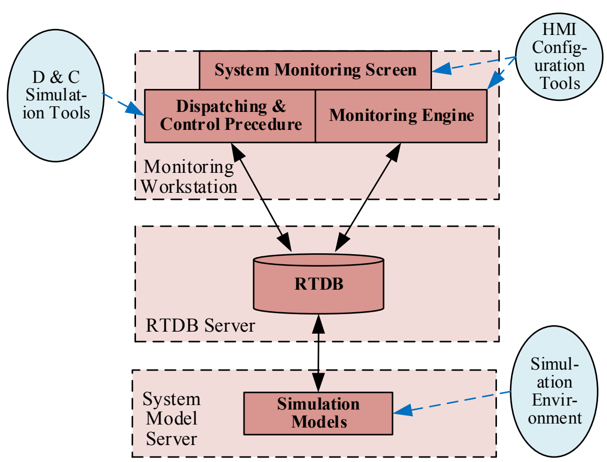


Figure 2. Simualtion architecture of ISE systems

Here RTDB server simulates the communication network of the data acquisition and control, and realizes the interface between the system model and data monitoring center, as well as between the dispatching and control procedure and the system model. Monitoring workstation simulates the operation of the monitoring center, on which the monitoring screen and the dispatch and control procedure are deployed. Dispatch and control procedure acquires data the system model feedback through RTDB server, then produces and sends the control instruction data to RTDB server. At the same time, the system operation data is acquired by the monitoring engine from the RTDB to drive the monitoring screens. System model server simulates the ISE system equipment and energy users in the field. The VPOWER simulation environment is deployed on the server and drives the ISE system models running. The models receive the control instruction data from the RTDB and feedback the runtime data of the system.

C. *Integrated modeling*

In VPOWER, we developed the CCHP module, PV module, wind turbine module, electrical storage module and air conditioner module using the user defined interface, based on the mathematical models given in III. According to typical system, a simulation model of the ISE system was built, and the model parameters was adjusted according to the specific circumstances of the equipment selection.

An industrial park in northern China is taken as the example for simulation. A 12 hours factory user and a 24 hours factory user of electricity, cold and heat, a residential user of electricity and heat, and an official user of electricity, cold and heat are set up. The system was simulated during 24 hours in summer. The energy customers load profiles, the wind speed curves and the light intensity curves are preset as the input conditions of the simulation. Some main parameters of the system are given in Table 1.

TABLE I. TABLE TYPE STYLES

System Parameters	Values
Voltage (Volt)	380
Maximum demand of power load (*kW*)	5000
Maximum demand of thermal load (*kW*)	2500
Maximum demand of cooling load (*kW*)	3500
Rated output power of the miro turbin (*kW*)	65
Heating coefficient of CCHP system	0.8
Cooling coefficient of CCHP system	0.8
Heat loss coefficent of CCHP system	0.1
PV cell area (m^2)	1000
Cooling coefficient of air conditioners	0.5

D. *Dispatching and Control Strategy*

Dispatching and control strategy is the core of ISE system operation. Taking a load following method as the basic strategy, considering the coupling relationship between multi energy based on the principle of maximizing the consumption of clean energy, a strategy of ordering power by heat is developed in simulation. The strategy is described follows:

Step1. Calculate power command of the CCHP according to current demand of the heating and cooling load, then control the gas intake and the working power of the micro turbines.

Step2. Calculate the power consumption of the air conditioner according the demand of the cooling load $Q_{C,dmd}(t)$ and the cooling power $Q_C(t)$ of the CCHP system, then control the output of the air conditioner. Put the air conditioner into operation when $Q_C(t) < Q_{C,dmd}(t)$.

Step3. Consideration the air conditioner consumption P_{AC} , calculate the power supply of the system $P_{\sup}$:

$$P_{\sup} = P_{MT} + P_{PV} + P_{WTG} \tag{8}$$

Here, P_{MT} is the power output of the CCHP system, P_{PV} is the power output of the PV cells, and P_{WTG} is the power output of the wind turbines, then calculates the demand of the power loads P_{dmd} :

$$P_{dmd} = P_{USER} + P_{AC} \tag{9}$$

Here, P_{USER} is the power demand of the users.

Step 4. Adjust the operation mode of the system through judging of the electric power distribution. When $P_{dmd} < P_{\sup}$, put the electrical storage devices into charging mode if the storage of ones is smaller than the capacity, otherwise switch system to the grid-connected mode to sell electricity outward. When $P_{dmd} \geq P_{\sup}$, put the electrical storage devices in to discharging mode if the storage of ones is greater than 0, otherwise switch system to the grid-connected mode to purchase electricity from external.

In order to better meet the requirement of power balance in the system, the temperature of the heating return pipe is controlled applying a PID algorithm, to make the gas injection be regulated, and the air conditioning power is regulated by controlling the temperature of the cooling return pipe.

E. Simulation and analysis

A simulation of the ISE system was built in the architecture given in IV, and a simulation rate of 10 times was set and 24 hours duration of the operation was simulated.

Fig. 3 gives the main page of the monitoring screens of the ISE system in simulation. Through the monitor screens, the main operating parameters such as power balance, gas consumption clean energy rate, energy output and consumption of the ISE system can be clearly understood, and the operation state of the system and the equipment included in it can be shown intuitively.

In order to analyze the operating state of the ISE system, comparison of the energy supply and consumption including the three kinds of energy during 24 hours is given in Fig. 4, Fig. 5 and Fig. 6.

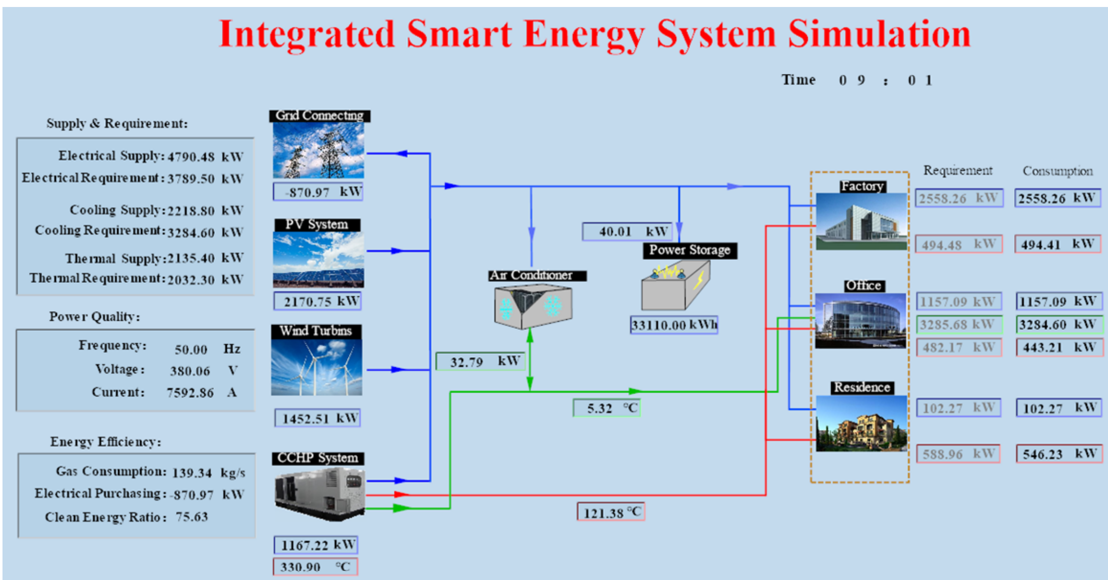


Figure 3. Monitoring Screen of ISE system

Fig. 4 shows the production (including the purchasing from grid) and the demand of users of the electrical power in the system. Negative purchasing power indicates that at this time the electrical power is flowing from the ISE system to the grid. We can see that whenever the electrical power is Instantaneous equilibrium, which is the power produced in the ISE system and the power purchasing from the grid always equals the power of demand by users.

From the Fig. 5 and Fig. 6, we can find some errors in the balance of heat and cold. This is mainly due to the resistance of cooling and heating system and the large time scale of heat conduction. A small amount of excess heat energy that the users can't consume has been dispersed trough the exhaust pipe, so the usage of the heat is not as efficient as conceived, and this is the main limit of the multi energy dispatching and control strategy applied in this study.

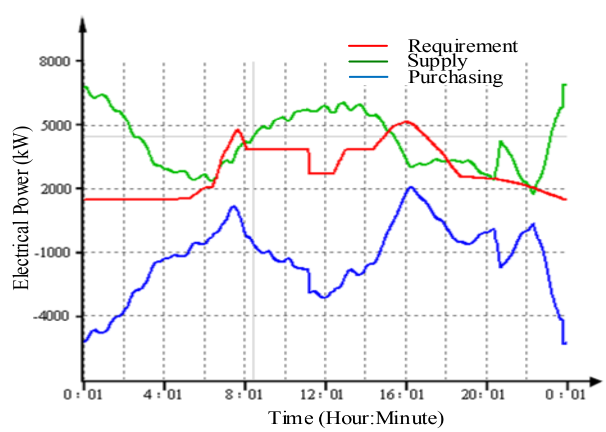
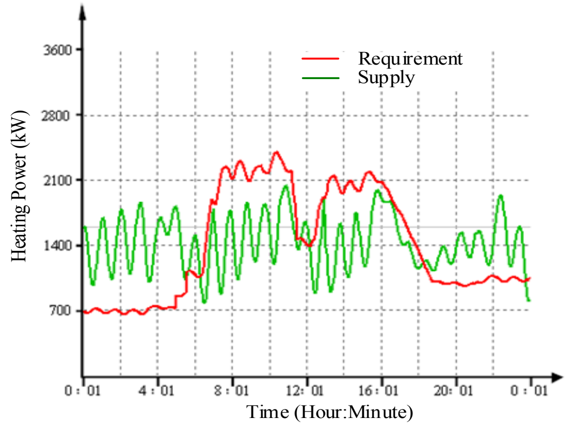
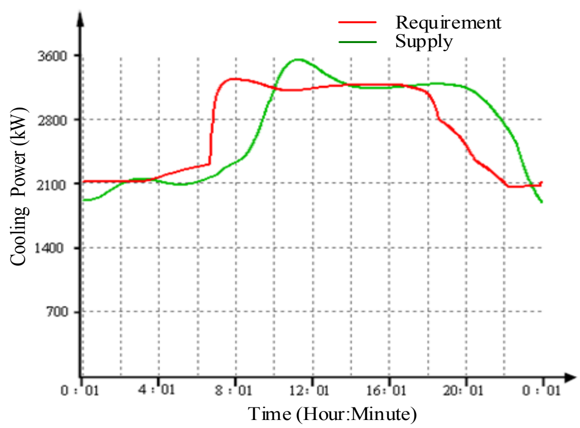


Figure 4. Suppliment and consumption of the eclectrical power in 24 hours



Figrue 5. Suppliment and consumption of the heati ng power in 24 hours



Figrue 6. Suppliment and consumption of the cooling power in 24 hours

From the simulation result, the main characteristics of the ISE system can be easily found. In ISE system, the energy distribution can be adjusted to guarantee the local consumption of energy, maximize the proportion of clean energy and improve the energy using efficiency. Some important problems of the ISE system had been dug out.

- The energy storage devices are important for the ISE systems, especially the clean energy is included.
- Dispatching and control strategy is the key point which determines the optimizing space of the system.
- In realistic, the forecasting and correction of the energy loads and clean energy production is a key problem of energy management.

V. CONCLUSION

Integrated smart energy system is a new energy production and usage mode in China. The efficiency and the energy-saving is better than the solutions of the old mode. Based on the mathematical models of the ISE systems, a simulation of it is built on the architecture proposed Compared with the previous mode that each kind of energy was managed and controlled Individually, our methods can better use of integrated energy optimization space to achieve an intelligence operation of the system. The simulation result has reflected the superiority of our method, and shown the characteristic of the ISE system. From the result some important problems were dug out. In the future work, these problems will be researched, and a simulation of high credibility will be developed based on this work.

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