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# Integrated Energy System Optimization Based on Standardized Matrix Modeling Method

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**Abstract:** Aiming at the optimization of an integrated energy system, a standardized matrix modeling method and optimization method for an integrated energy system is proposed. Firstly, from the perspective of system engineering, the energy flow between energy conversion devices is used as a state variable to deal with nonlinear problems caused by the introduction of scheduling factors, and a standardized matrix model of the integrated energy system is constructed. Secondly, based on the proposed model, the structural optimization (i.e., energy flow structure and equipment type), design optimization (i.e., equipment capacity and quantity), and operation optimization for the integrated energy system can be achieved. The simulation case studies have shown that the proposed integrated energy system standardized matrix modeling method and optimization method are both simple and efficient, and can be effectively used to decide the system components and their interconnections, and the technical characteristics and daily operating strategy of the system components.

**Keywords:** integrated energy system; standardized matrix modeling; structural optimization; design optimization; operation optimization; renewable energy

## 1. Introduction

Traditional energy system planning usually only concerns a single energy system (such as cooling, heat, electricity, and natural gas) and cannot jointly optimize resources of each energy system, and therefore the overall energy resource utilization efficiency is low [1]. Regarding this problem, researchers proposed the concept of an integrated energy system in conjunction with distributed clean energy [2–4]. The integrated energy system is couples multiple energy sources, such as cooling, heat, electricity, hot water, and natural gas, to form a physical system for comprehensive conversion and utilization of multiple energy sources. It can fully utilize the complementary and synergistic effects of different forms of energy, and thus realize the optimal allocation of resources of different energy systems in a wider range and improve the flexibility and reliability of system operation, distributed clean energy consumption capacity, and system comprehensive efficiency [5]. Kong et al. used the pattern search method and penalty function to optimize the operation strategy of distributed cogeneration system with minimum annual operating cost as the objective function [6]. Based on the mixed integer linear programming theory, with minimum daily operating cost as the objective function, Bischi et al. constructed an operation planning model for distributed cogeneration system, considering energy price, operation & maintenance cost, start–stop loss, ambient temperature, and other related factors [7]. Facci et al. analyzed the conventional "following the thermal load, FTL" and "following the electric load, FEL" modes of distributed cogeneration system, and proposed a dynamic programming model for system operation optimization [8]. Huang Zishuo et al. analyzed the influencing factors of the comprehensive energy efficiency of multi-energy complementary distributed energy system, and taking the summer operating conditions as an example, the comprehensive energy efficiency levels under several typical configurations were listed [9]. Ren Hongbo et al. discussed the research progress of design optimization of distributed cogeneration system, and proposed a hierarchical framework for system optimization consisting of structural optimization, design optimization, and operation optimization [10]. Compared with the distributed cogeneration system, the integrated energy system optimization will be one of the main topics of current and future energy system engineering research due to the inherent diversity and complexity of the integrated energy system. In addition, although a large number of articles have discussed the design optimization and operation optimization of distributed cogeneration systems, few papers have studied their standardized modeling methods [11,12]. Based on the scheduling factors, Chicco and Mancarella proposed a modeling technique for automatically generating coupling matrices for small-scale cooling, heat, and electricity triple-supply system [13]; however, the integrated energy system planning model established is nonlinear due to the scheduling factors involved, and it will be too complex for a large-scale integrated energy system. Almassalkhi and Towle proposed a linear modeling method for the integrated energy system with an energy "input-storage-conversion-storage-output" structure [14]. However, this modeling method can only deal with the integrated energy system in the form of fixed structure. At present, it is of great significance to study a computerized standardized modeling method for the integrated energy system, which is applicable to different structural forms.

In the paper, an effective and efficient standardized matrix modeling method and optimization method for the integrated energy system is proposed to solve the existing problems described above. The remainder of the paper is organized as follows. In Section 2, the basic theory of standardized matrix modeling method for the integrated energy system is introduced, and subsequently our proposed optimization method is described in Section 3. The related simulation case studies of the proposed approach are presented in Section 4, followed by the conclusions in Section 5.

## 2. Integrated Energy System Standardized Matrix Modeling

The integrated energy system is a system that integrates multiple energy inputs, multiple energy outputs, and multiple energy conversion devices, seen in Figure 1. Comprehensive and accurate system definition and scientific physical structure description are the bases for system modeling and optimization planning of the integrated energy system.

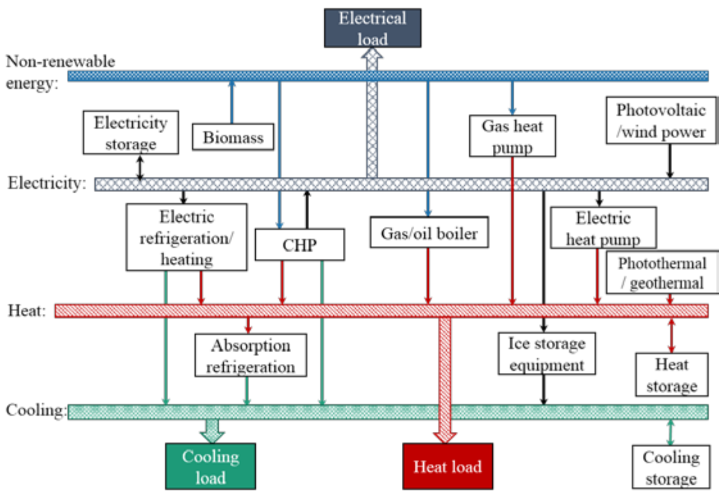


**Figure 1.** Schematic diagram of the integrated energy system.

Note: CHP is the abbreviation of the combined heat and power system; PV is the the abbreviation of the photovoltaic power.

The integrated energy system is a regional energy internet, as shown in Figure 1. From the perspective of system engineering, the integrated energy system can be composed of the following four subsystems.

① External energy supply subsystem

The external energy supply subsystem supports the operation of the entire integrated energy system, supplying primary nonrenewable energy (natural gas, fuel oil, and coal) and secondary energy (main grid power supply) for the entire system operation demand, and ensures the energy security for the entire system operation.

② Energy conversion subsystem

The first category of the energy conversion subsystem is a small-scale renewable energy power generation system including photovoltaic power generation, small wind power and small hydropower generation. The second category of the energy conversion subsystem is a cogeneration or a combined cooling, heat, and electric production system with an internal combustion engine, gas turbine, microgas turbine, fuel cell, and Stirling engine as prime movers, respectively. The third category of the energy conversion subsystem is the auxiliary energy conversion system, such as gas/oil boilers and energy storage equipment. The primary and secondary energy sources are efficiently converted into multiple forms of energy required by end users in a variety of ways by the energy conversion subsystem.

③ Energy transmission network

The energy transmission network (including the power grid, the heating network, and the cooling network) efficiently and reasonably transmits the energy generated by each energy conversion subsystem to each end user who needs different forms of energy.

④ User terminal Subsystem

The user terminal subsystem is a system that ultimately consumes the energy produced by the energy conversion subsystem. On the demand side, multiple types of users (such as resident users, factories, shopping malls, office buildings, hospitals, etc.) can be integrated into the same energy supply system to achieve load averaging through complementarity and interaction among users.

### 2.1. Energy Conversion Equipment Model

The conversion characteristics of various energy conversion devices are as follows.

The model of the combined heat and power (CHP) system with internal combustion engine, gas turbine, microgas turbine, fuel cell, and Stirling engine is as follows

$$\begin{bmatrix} v_{out,1} \\ v_{out,2} \end{bmatrix} = \begin{bmatrix} \eta_{\mathrm{Q}} \\ \eta_{\mathrm{W}} \end{bmatrix} [v_{in,1}] \tag{1}$$

where $\eta_{\mathrm{Q}}$ and $\eta_{\mathrm{W}}$ are the heat generation and electricity production efficiency of CHP equipment, respectively.

The model of gas/oil boiler is as follows

$$[v_{out}] = [\eta_{\mathrm{AB}}][v_{in}] \tag{2}$$

where $\eta_{\mathrm{AB}}$ is the boiler heat production efficiency.

The model of the electric refrigeration equipment is as follows

$$[v_{out}] = [\eta_{\mathrm{c}}][v_{in}] \tag{3}$$

where $\eta_{\mathrm{C}}$ is the performance coefficient for electric refrigeration equipment.

The model of the electric heating equipment is as follows

$$[v_{out}] = [\eta_{\mathrm{H}}][v_{in}] \tag{4}$$

where $\eta_{\mathrm{H}}$ is the performance coefficient of the electric heating equipment.

The model of the absorption refrigeration equipment is as follows

$$[v_{out}] = [\eta_{\mathrm{R}}][v_{in}] \tag{5}$$

where $\eta_{\mathrm{R}}$ is the performance coefficient of the absorption refrigeration equipment.

The model of the energy storage equipment is as follows.

In addition to charging and discharging behavior, energy storage also includes the change in the internal state of charge (SOC):

$$[\Delta E] = \begin{bmatrix} \eta_{\mathrm{CH}} \\ -1/\eta_{\mathrm{DS}} \end{bmatrix}^{T} \begin{bmatrix} v_{in} \\ v_{out} \end{bmatrix} \tag{6}$$

where $\eta_{\mathrm{CH}}$ is the charging efficiency; $\eta_{\mathrm{DS}}$ is discharging efficiency; $\Delta E$ is the change in the internal state of charge (SOC).

The energy storage state of the energy storage device at time $t$ is

$$E(t) = E(t-1) + \Delta E(t) \tag{7}$$

Note: the mathematical model of energy storage used at this stage is an idealized model of heat storage, cooling storage and electricity storage equipment.

### 2.2. Integrated Energy System Model

Computerized standardization modeling of the power system is an important foundation for power system automation. Similarly, computerized standardized modeling of the integrated energy system is an important foundation for future multi-energy system automation. The integrated energy system (seen in Figure 2) is a two-port network with multiple energy inputs $V_{in}$ and multiple energy outputs $V_{out}$. The energy conversion link between $V_{in}$ and $V_{out}$ can be represented by a coupling matrix $C$.

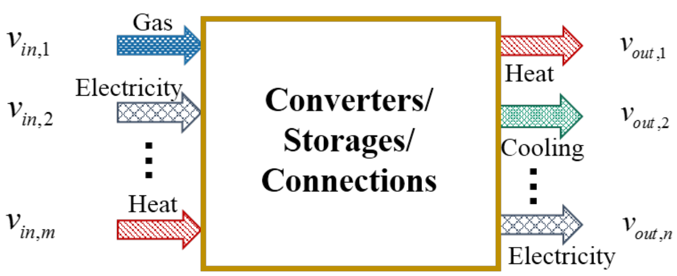


**Figure 2.** Standardized matrix modeling method of the integrated energy system.

$$V_{out} = CV_{in} \tag{8}$$

$$\text{i.e.,} \begin{bmatrix} v_{out,1} \\ v_{out,2} \\ \cdots \\ v_{out,n} \end{bmatrix} = \begin{bmatrix} c_{11}, c_{12}, \ldots, c_{1m} \\ c_{21}, c_{22}, \ldots, c_{2m} \\ \cdots \\ c_{n1}, c_{n2}, \ldots, c_{nm} \end{bmatrix} \begin{bmatrix} v_{in,1} \\ v_{in,2} \\ \cdots \\ v_{in,m} \end{bmatrix} \tag{9}$$

The coupling matrix $C$ is used to describe the conversion characteristics of different types of energy conversion devices.

The energy transmission network of the integrated energy system includes a power grid, heat network, cooling network, and natural gas network, as shown in Figure 1. A standardized matrix model (seen in Equation (9)) can be constructed using the energy flow between energy conversion devices as a state variable, seen in Figure 3. Since the relationship between any two energy flows is linear, there is no need to introduce a scheduling factor as decision variable. The standardized matrix modeling method proposed in the paper deals with nonlinear problems caused by the introduction of scheduling factors, which provides a new perspective for multi-energy system flexibility analysis and optimization.

$$\begin{bmatrix} E_{\mathrm{IES}}^{\mathrm{c}} \\ E_{\mathrm{IES}}^{\mathrm{h}} \\ E_{\mathrm{IES}}^{\mathrm{e}} \\ \Delta E_{\mathrm{c}} \\ \Delta E_{\mathrm{h}} \\ \Delta E_{\mathrm{e}} \end{bmatrix} = \begin{bmatrix} \eta_{\mathrm{C}}, & \eta_{\mathrm{R}}, & 0, & 0, & 0, & 0, & 0, & 0, & 0, & -1, & 1, & 0, & 0, & 0, & 0 \\ 0, & -1, & \eta_{\mathrm{AB}}, & \eta_{\mathrm{Q}}, & \eta_{\mathrm{H}}, & 1, & 0, & 0, & 0, & 0, & 0, & -1, & 1, & 0, & 0 \\ -1, & 0, & 0, & \eta_{\mathrm{W}}, & -1, & 0, & 1, & 1, & 1, & 0, & 0, & 0, & 0, & -1, & 1 \\ 0, & 0, & 0, & 0, & 0, & 0, & 0, & 0, & 0, & \eta_{\mathrm{CH,c}}, & -/\eta_{\mathrm{DI,c}}, & 0, & 0, & 0, & 0 \\ 0, & 0, & 0, & 0, & 0, & 0, & 0, & 0, & 0, & 0, & 0, & \eta_{\mathrm{CH,h}}, & -/\eta_{\mathrm{DI,h}}, & 0, & 0 \\ 0, & 0, & 0, & 0, & 0, & 0, & 0, & 0, & 0, & 0, & 0, & 0, & 0, & \eta_{\mathrm{CH,e}}, & -/\eta_{\mathrm{DI,e}} \end{bmatrix} \begin{bmatrix} E_{\mathrm{c}} \\ H_{\mathrm{h}} \\ F_{\mathrm{AB}} \\ F_{\mathrm{CHP}} \\ E_{\mathrm{h}} \\ S_{\mathrm{h}} \\ E_{\mathrm{i}} \\ S_{\mathrm{e}} \\ W_{\mathrm{e}} \\ V_{\mathrm{c,in}} \\ V_{\mathrm{c,out}} \\ V_{\mathrm{h,in}} \\ V_{\mathrm{h,out}} \\ V_{\mathrm{e,in}} \\ V_{\mathrm{e,out}} \end{bmatrix} \quad (10)$$

where $E_{\mathrm{c}}$ is the amount of electricity supplied to the electrical refrigeration equipment; $H_{\mathrm{h}}$ is the amount of heat supplied to the absorption refrigeration equipment; $F_{\mathrm{AB}}$ is the amount of fuel supplied to the boiler equipment; $F_{\mathrm{CHP}}$ is the amount of fuel supplied to the combined heat and power (CHP) system; $E_{\mathrm{h}}$ is the amount of electricity supplied to the electric heating equipment; $S_{\mathrm{h}}$ is the heat generated by photothermal/geothermal energy; $E_{\mathrm{i}}$ is the amount of power supplied by the main power grid; $S_{\mathrm{e}}$ is the amount of electricity generated by photovoltaics; $W_{\mathrm{e}}$ is the amount of electricity generated by wind power; $V_{\mathrm{c,in}}$ is the amount of cooling that is charged to the cooling storage equipment; $V_{\mathrm{c,out}}$ is the amount of cooling that is discharged by the cooling storage equipment; $V_{\mathrm{h,in}}$ is the heat that is charged to the heat storage equipment; $V_{\mathrm{h,out}}$ is the heat that is discharged by the heat storage equipment; $V_{\mathrm{e,in}}$ is the amount of electricity that is charged to the power storage device; $V_{\mathrm{e,out}}$ is the amount of electricity that is discharged by the power storage device; $E_{\mathrm{IES}}^{\mathrm{c}}$ is the total amount of cooling delivered to the end user through cooling network; $E_{\mathrm{IES}}^{\mathrm{h}}$ is the total amount of heat delivered to end user through heat network; and $E_{\mathrm{IES}}^{\mathrm{e}}$ is the total amount of electricity delivered to end user through power network.

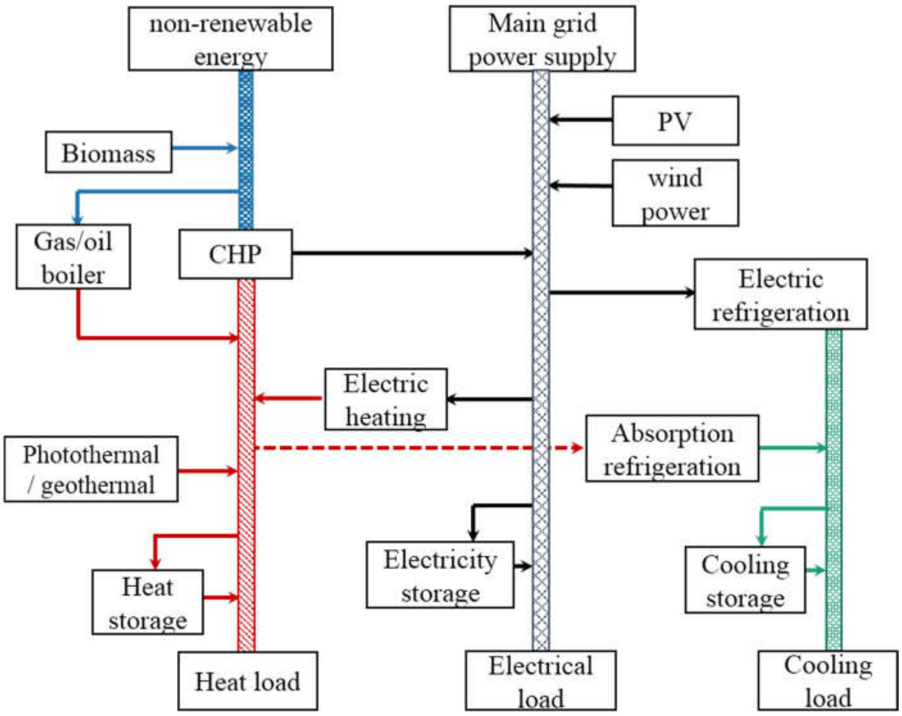


**Figure 3.** Physical structure description of the standardized matrix model for the integrated energy system.

## 3. Integrated Energy System Optimization

The optimization decision-making process of the integrated energy system is a complex system problem, which depends to a large extent on the decision-maker's preferences and the optimization purposes. From the time scale, the optimization of the integrated energy system can be divided into three levels: long-term strategic optimization (strategic planning), medium-term tactical optimization (tactical planning), and short-term operational optimization (operational planning), seen in Figure 4.

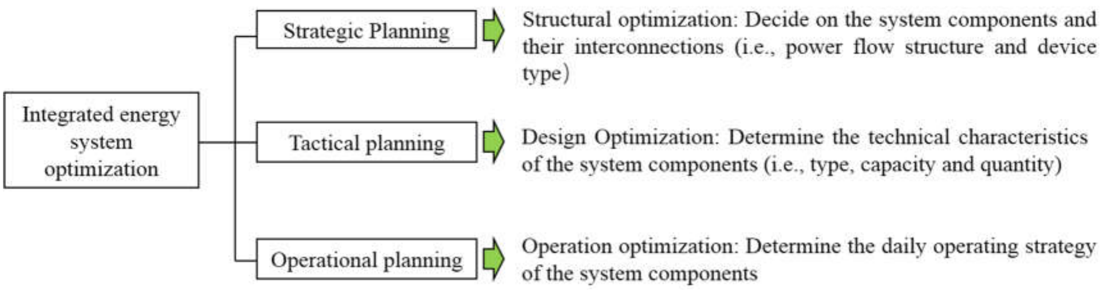


**Figure 4.** Optimization decision process of integrated energy system.

To briefly illustrate the use of the integrated energy system standardized matrix model, the following assumptions are made.

① Only the cooling network, heat network, power network, and natural gas network are considered in the energy transmission network, which are closely related to the energy conversion equipment configuration.

② The dissipation effect of pipelines and transmission lines during energy transmission is ignored.

③ The character and efficiency of the energy conversion equipment is constant under off-design conditions.

### *3.1. Structural Optimization of Integrated Energy System*

The purpose of structural optimization of the integrated energy system is to decide on the system components and their interconnections (i.e., energy flow structure and equipment type). As a complex energy utilization system, not only should the connection between the physical boundary of the integrated energy system and the environment, policies, and economic boundaries be considered, but also the interaction and coupling of energy flows, such as cooling, heat, and electricity, should be considered in the integrated energy system. At the same time, the interdependence among various links of production capacity, energy conversion, energy storage, and energy utilization, should be considered in the integrated energy system.

(1) Optimization target

Three categories of indicators (i.e., economics, energy saving, and environmental protection) can be selected as optimization target.

1) Economics

The total amount of annual heat, cooling, and electricity supply is selected as an economic evaluation index.

$$E_{\mathrm{IES}}^{\mathrm{h}} + E_{\mathrm{IES}}^{\mathrm{c}} + E_{\mathrm{IES}}^{\mathrm{e}} \tag{11}$$

2) Energy saving

The total amount of annual nonrenewable energy consumption is selected as an energy-saving evaluation index.

$$Q_{\mathrm{IES}} = (F_{\mathrm{AB}} + F_{\mathrm{CHP}} - B_{\mathrm{f}})\theta_{\mathrm{f}} + (E_{\mathrm{c}} + E_{\mathrm{h}} + E_{\mathrm{IES}}^{\mathrm{e}} - \eta_{\mathrm{W}} F_{\mathrm{CHP}} - S_{\mathrm{e}} - W_{\mathrm{e}})\theta_{\mathrm{e}} \tag{12}$$

where $\theta_{\mathrm{f}}$ is the converted standard coal coefficient of fossil fuel, which is 1 for natural gas. $\theta_{\mathrm{e}}$ is the converted standard coal coefficient of power supply by State Grid, which is 1.95 when thermal power accounts for 75% of the total power production.

3) Environmental protection

Annual $CO_2$ emissions of the integrated energy system include $CO_2$ emissions from natural gas and $CO_2$ emissions from system outsourcing electricity. The total amount of annual $CO_2$ emissions is selected as an environmental protection evaluation index.

$$E_{\mathrm{IES}}^{\mathrm{CO_2}} = [(F_{\mathrm{AB}} + F_{\mathrm{CHP}} - B_{\mathrm{f}})\theta_{\mathrm{f}} + (E_{\mathrm{c}} + E_{\mathrm{h}} + E_{\mathrm{IES}}^{\mathrm{e}} - \eta_{\mathrm{W}} F_{\mathrm{CHP}} - S_{\mathrm{e}} - W_{\mathrm{e}})\theta_{\mathrm{e}}]\varphi \tag{13}$$

where $\varphi$ is the carbon emission factor of natural gas.

Therefore, considering the economic, energy-saving, and environmental indicators, the system's annual comprehensive energy efficiency is used as the optimization target:

$$\eta = \frac{E_{\mathrm{IES}}^{\mathrm{h}} + E_{\mathrm{IES}}^{\mathrm{c}} + E_{\mathrm{IES}}^{\mathrm{e}}}{Q_{\mathrm{IES}}} \tag{14}$$

$E_{\mathrm{IES}}^{\mathrm{c}}$ is the total amount of cooling delivered to the end user through cooling network and $E_{\mathrm{IES}}^{\mathrm{c}}$ can be calculated by the integrated energy system standardized matrix model, as follows.

$$E_{\mathrm{IES}}^{\mathrm{c}} = [\eta_{\mathrm{C}}][E_{\mathrm{c}}] + [\eta_{\mathrm{R}}][H_h] \tag{15}$$

$E_{\mathrm{IES}}^{\mathrm{h}}$ is the total amount of heat delivered to end user through heat network and $E_{\mathrm{IES}}^{\mathrm{h}}$ can be calculated by the integrated energy system standardized matrix model as follows.

$$E_{\mathrm{IES}}^{\mathrm{h}} = -[H_{\mathrm{h}}] + [\eta_{\mathrm{AB}}][F_{\mathrm{AB}}] + [\eta_{\mathrm{Q}}][F_{\mathrm{CHP}}] + [\eta_{\mathrm{H}}][E_{\mathrm{h}}] + [S_{\mathrm{h}}] \tag{16}$$

$E_{\mathrm{IES}}^{\mathrm{e}}$ is the total amount of electricity delivered to end user through power network and $E_{\mathrm{IES}}^{\mathrm{e}}$ can be calculated by the integrated energy system standardized matrix model as follows.

$$E_{\mathrm{IES}}^{\mathrm{e}} = [E_{\mathrm{i}}] + [S_{\mathrm{e}}] + [W_{\mathrm{e}}] + [\eta_{\mathrm{W}}][F_{\mathrm{CHP}}] - [E_{\mathrm{h}}] - [E_{\mathrm{c}}] \tag{17}$$

The ratio of the total amount of cooling provided by the electrical refrigeration equipment to the total cooling demand by end users is as follows.

$$\alpha = \frac{\eta_{\mathrm{C}} E_{\mathrm{c}}}{E_{\mathrm{IES}}^{\mathrm{c}}} \tag{18}$$

The ratio of the total amount of heat provided by electric heating equipment to the total heat demand by end users is as follows.

$$\beta = \frac{\eta_{\mathrm{H}} E_{\mathrm{h}}}{E_{\mathrm{IES}}^{\mathrm{h}}} \tag{19}$$

The ratio of the total fuel consumption by the gas/oil boiler to the total fuel consumption by CHP equipment is as follows.

$$x = \frac{F_{\mathrm{AB}}}{F_{\mathrm{CHP}}} \tag{20}$$

The ratio of the total cooling demand by end users to the total electricity demand by end users is as follows.

$$y = \frac{E_{\mathrm{IES}}^{\mathrm{c}}}{E_{\mathrm{IES}}^{\mathrm{e}}} \tag{21}$$

The ratio of the total heat demand by end users to the total power demand by end users is as follows.

$$z = \frac{E_{\mathrm{IES}}^{\mathrm{h}}}{E_{\mathrm{IES}}^{\mathrm{e}}} \tag{22}$$

The ratio of the total amount of the equivalent standard coal of biomass, photovoltaic, and wind power energy to the total power demand by end users is as follows.

$$u = \frac{B_{\mathrm{f}}\theta_{\mathrm{f}} + (S_{\mathrm{e}} + W_{\mathrm{e}})\theta_{\mathrm{e}}}{E_{\mathrm{IES}}^{\mathrm{e}}} \tag{23}$$

At this point, a dimensionless system annual comprehensive energy efficiency expression can be obtained as follows.

$$\eta = \frac{1 + y + z}{w(1+x)\theta_{\mathrm{f}} + \left(\frac{\beta z}{\eta_{\mathrm{H}}} + \frac{\alpha y}{\eta_{\mathrm{C}}} + 1 - w\eta_{\mathrm{W}}\right)\theta_{\mathrm{e}} - u} \tag{24}$$

where $w = \frac{1}{x\eta_{\mathrm{AB}} + \eta_{\mathrm{Q}}}\left(\frac{1-\alpha}{\eta_{\mathrm{C}}} y + z - z\beta\right) = \frac{F_{\mathrm{CHP}}}{E_{\mathrm{IES}}^{\mathrm{e}}}$, which indicates the ratio of the total amount of fuel consumed by the CHP device to the total power demand by end users.

Finally, the optimization function with the system annual comprehensive energy efficiency as the optimization target is as follows.

$$\eta = f(\alpha, \beta, x, y, z, u) \tag{25}$$

where the variable $x, \alpha, \beta$ represents the system configuration scheme; the variable $y, z$ represents the total cooling, heat, and electricity demand structure of the regional end users; $u$ represents the local renewable energy utilization.

The schematic diagram of the structural optimization of integrated energy system is shown in Figure 5.

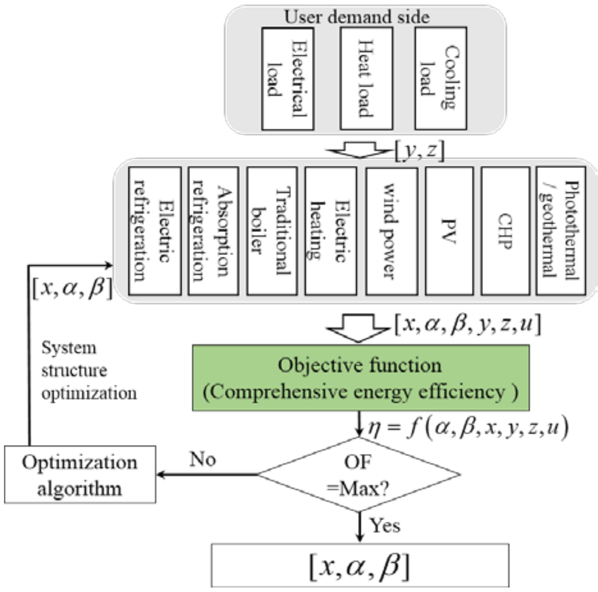


**Figure 5.** The schematic diagram of the structural optimization of integrated energy system.

### *3.2. Design Optimization of Integrated Energy System*

The purpose of the design optimization is to determine the technical characteristics of the system components (i.e., type, capacity, and quantity).

In order to improve the energy supply reliability of the integrated energy system, it can be designed as a regional distributed energy interconnection network, as seen in Figure 6. On the basis of meeting the total cooling, heat, and electricity demand of regional end users, it is recommended to select two or more devices for the same type of the energy conversion equipment, which are operated in parallel to further improve the comprehensive energy efficiency (i.e., improve equipment operating efficiency by increasing the partial load rate of equipment through operating in parallel) and the energy supply reliability of the system.

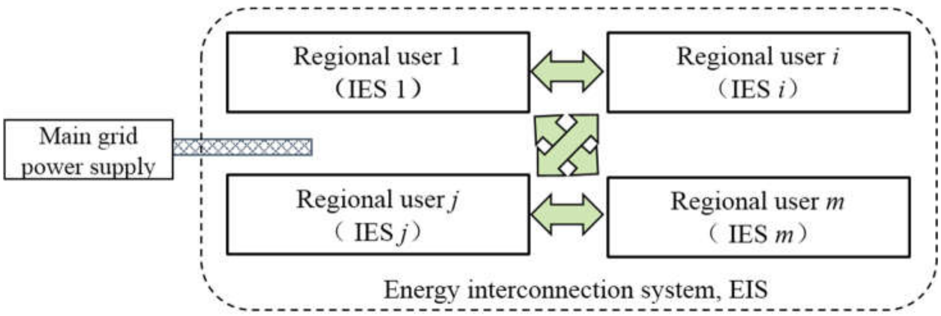


**Figure 6.** A regional distributed energy interconnection network.

### *3.3. Operation Optimization of Integrated Energy System*

The purpose of the operation optimization is to determine the daily operating strategy of the system components. The operation optimization study of the integrated energy system is to optimize the short-term operation for a given system on the basis of meeting the energy demand by end users and determine the quantity of hourly energy production and the external purchased energy, as shown in Figure 7.

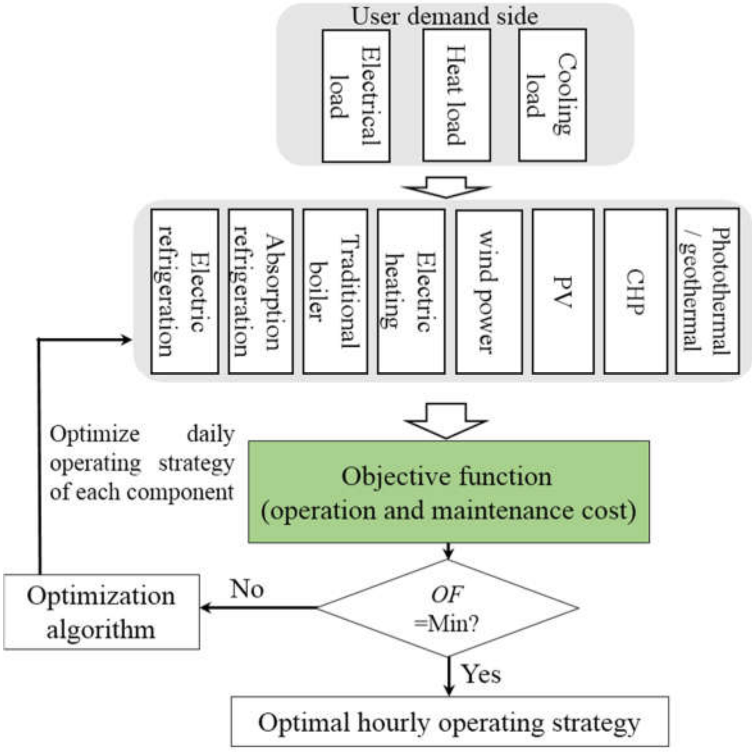


**Figure 7.** The schematic diagram of the operation optimization of integrated energy system.

Finally, aiming at the regional integrated energy system operation optimization and taking the operation and maintenance costs as the objective function, the optimal operation planning of the regional integrated energy system is carried out, to optimize the hourly operation strategy for each equipment unit. The related objective function is as follows.

$$\min \sum_{t=1}^{T} \sum_{i=1}^{M} P_{i,t} F_{i,t} \tag{26}$$

where $P_{i,t}$ is the price of $i$-th input energy at time period of $t$, $M$ is the total types of external purchased energy of the integrated energy system, and $F_{i,t}$ is the external purchased quantity of $i$-th input energy at time period of $t$.

## 4. Results and Analysis

The proposed modeling method and optimization method is implemented by M language based on the MATLAB software.

### *4.1. Simulation Case Study for Structural Optimization*

The structural optimization is to decide on the system components and their interconnections (i.e., power flow structure and device type) and the key is to determine the power flow structure and device type with long-term economics, energy savings, and environmental protection, to build an energy-efficient system, according to the total annual cooling, heat, and electricity demand of regional end users. Before implementing system structural optimization, the following assumptions are made.

① The ratio of the total cooling demand by end users to the total electricity demand by end users is $y = 0.3$.

② The ratio of the total heat demand by end users to the total power demand by end users is $z = 0.4$.

③ From Equation (24), we can see that, the relationship between local renewable energy utilization and comprehensive energy efficiency is relatively determined, and local renewable energy utilization is usually limited by local natural environmental resources and energy policy conditions, and here assume $u = 0.2$.

④ The current technical level of energy conversion equipment is shown in Table 1.

**Table 1.** Typical combined heat and power (CHP) system power generation and heat generation characteristics.

| Type | Power Generation Efficiency | Heat Generation Efficiency | Total Efficiency |
|---|---|---|---|
| Fuel cell | 0.45 | 0.30 | 0.75 |
| Internal combustion engine | 0.40 | 0.40 | 0.80 |
| Gas turbine | 0.35 | 0.45 | 0.80 |
| Steam turbine | 0.30 | 0.50 | 0.80 |

The technical level reference value of the remaining common energy conversion equipment is as follows $\eta_H = 3$, $\eta_R = 1$, $\eta_C = 3.5$, $\eta_{AB} = 0.90$.

According to the above assumptions, the optimization objective function of the system can be simplified as $\eta = f(\alpha, \beta, x)$. The genetic algorithm (GA) [15] and particle swarm optimization (PSO) are chosen as optimization algorithms to search for the optimal annual comprehensive energy efficiency, respectively. The related parameters of the PSO algorithm and GA algorithm are set as described previously [16,17], seen in Table 2. The system optimization results are shown in Table 3, in which the integrated energy system includes a CHP system based on a fuel cell, an internal combustion engine, a gas turbine, and a steam turbine marked as system 1, system 2, system 3, and system 4, respectively.

**Table 2.** Related parameters of the PSO algorithm and GA algorithm.

| Parameter | Value |
|---|---|
| Population size (GA & PSO) | 80 |
| Number of iterations (GA & PSO) | 60 |
| Acceleration constant $c1$ and $c2$ (PSO) | 1.2 |
| Cross probability (GA) | 0.35 |
| Mutation probability (GA) | 0.30 |

**Table 3.** System optimization results.

| | $x$ | | $a$ | | $\beta$ | | Comprehensive Energy Efficiency | |
|---|---|---|---|---|---|---|---|---|
| **Optimization Interval** | [0,+∞) | | [0,1] | | [0,1] | | | |
| **Optimization Algorithm** | **GA** | **PSO** | **GA** | **PSO** | **GA** | **PSO** | **GA** | **PSO** |
| system1 | 0.0026 | 0 | 0.1657 | 0 | 0.0188 | 0 | 0.8299 | 0.8350 |
| system 2 | 0.0003 | 0 | 0.1528 | 0 | 0.0609 | 0 | 0.7951 | 0.7963 |
| system 3 | 0.0607 | 0 | 0.9108 | 1 | 0.7094 | 1 | 0.7749 | 0.7808 |
| system 4 | 0.1683 | 0 | 0.9005 | 1 | 0.9606 | 1 | 0.7759 | 0.7808 |

From Table 3, it can be seen that the PSO algorithm can search for the optimization target more effectively than the GA algorithm under the same population size and number of iterations. When the regional end user's cooling/heat/electricity requirements, renewable energy resource utilization, and energy conversion equipment technology level are determined (as described in the above assumptions), the integrated energy system using only the CHP system with a fuel cell as the prime mover and the absorption refrigeration equipment to supply energy will have the best comprehensive energy efficiency; the comprehensive energy efficiency can reach 83.5%.

The optimal comprehensive energy efficiency of the integrated energy system varies with the demands for cooing, heat, and electricity on the user side, as shown in Figures 8–10.

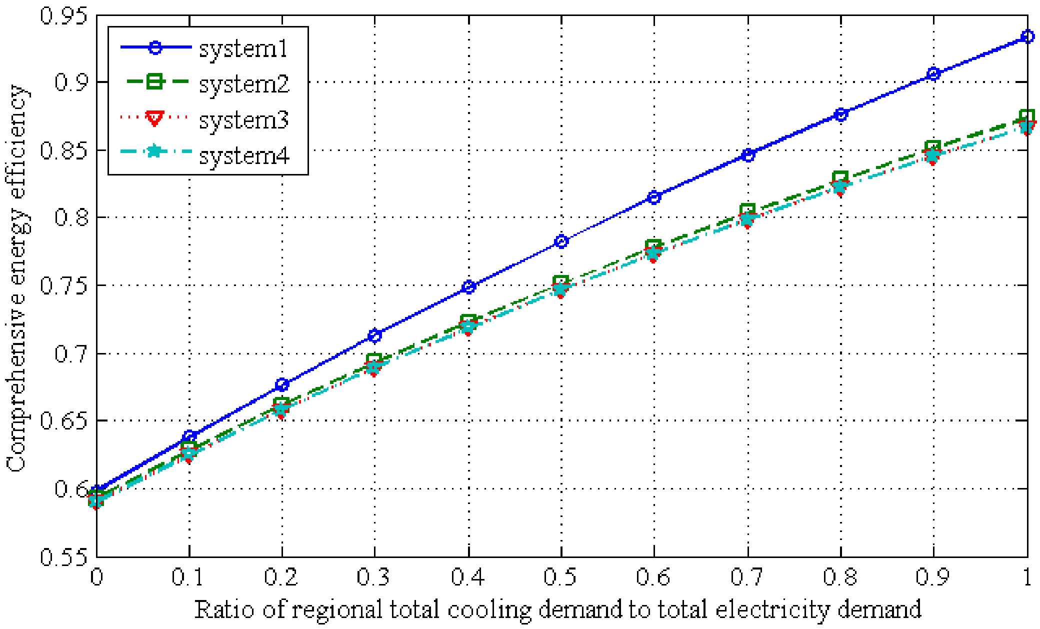


**Figure 8.** The variation of optimal comprehensive energy efficiency with $y$.

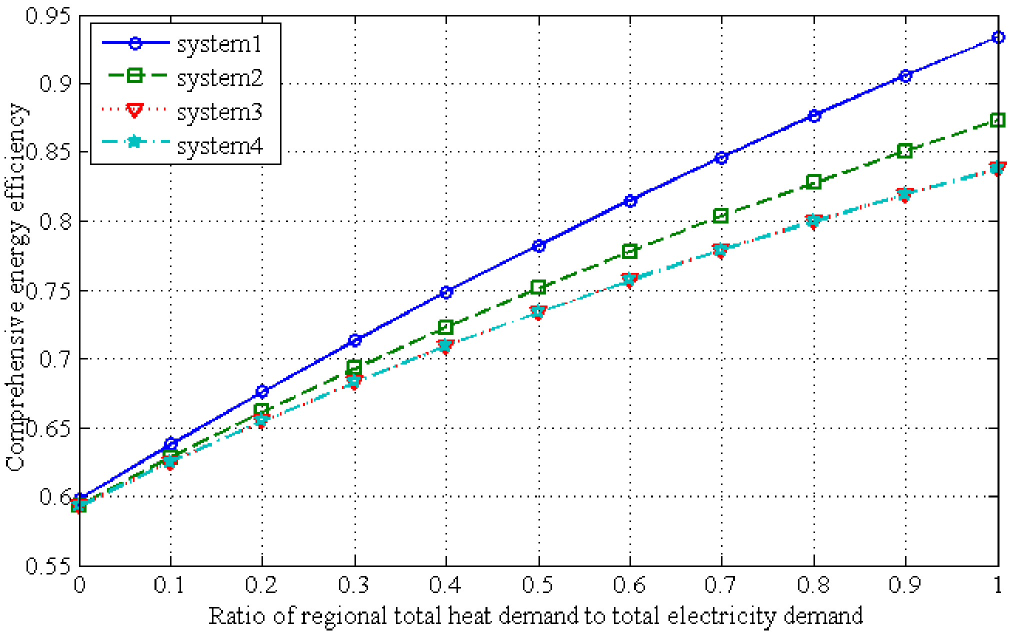


**Figure 9.** The variation of optimal comprehensive energy efficiency with $z$.

From Figures 8–10, as $y$ and $z$ increase, the optimal comprehensive energy efficiency of the integrated energy system gradually increases and the integrated energy system using the CHP system with a fuel cell as the prime mover will have the best comprehensive energy efficiency compared with the integrated energy system using CHP systems with an internal combustion engine, gas turbine, or steam turbine as the prime mover.

The simulation case study for structural optimization has shown that the proposed integrated energy system standardized matrix modeling method and optimization method can be effectively used to decide the system components and their interconnections, i.e., energy flow structure and equipment type.

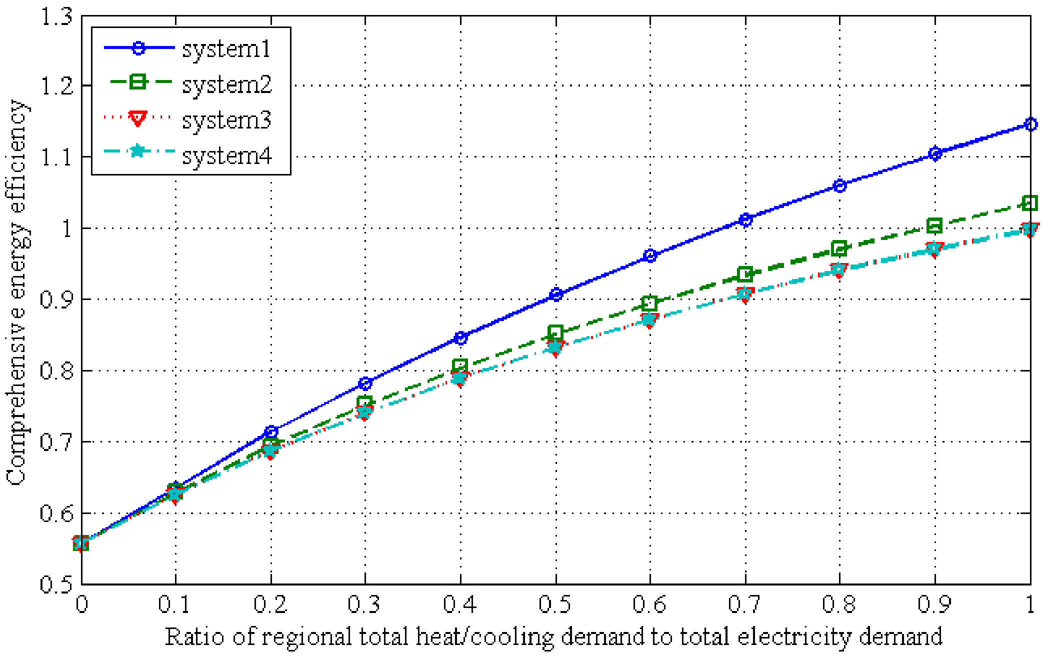


**Figure 10.** The variation of optimal comprehensive energy efficiency with both *y* and *z*.

*4.2. Simulation Case Study for Operation Optimization*

In order to test the effectiveness of the integrated energy system standardization modeling method and operation optimization method proposed in the paper, a simulation case study, which is described previously [13,18], is used to validate. The system consists of a back pressure operated CHP equipment, an auxiliary boiler (AB), an absorption refrigeration equipment (CERG), and an electric refrigeration equipment (WARG). The application case is a typical regional cooling, heat, and electricity triple supply system, and the physical structure description of the linear programming model for this integrated energy system is shown in Figure 11.

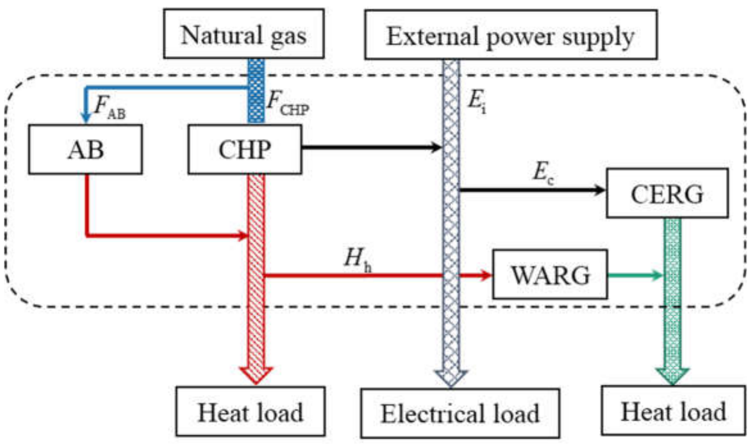


**Figure 11.** A typical regional cooling, heat, and electricity triple supply system.

The conversion character of each equipment of the system is shown in Table 4.

**Table 4.** Conversion characteristics of each equipment.

| No. | Type | Parameter | Capacity/kW |
|---|---|---|---|
| 1 | CHP | $\eta_W = 0.3$ | 120 |
| | | $\eta_Q = 0.4$ | 160 |
| 2 | AB | $\eta_{AB} = 0.8$ | 400 |
| 3 | CERG | $\eta_C = 3$ | 300 |
| 4 | WARG | $\eta_R = 0.7$ | 300 |

At this point, the integrated energy system linear programming matrix model (Equation (10)) can be scaled to

$$\begin{bmatrix} E^{c}_{\mathrm{IES}} \\ E^{h}_{\mathrm{IES}} \\ E^{e}_{\mathrm{IES}} \end{bmatrix} = \begin{bmatrix} \eta_C, \eta_R, 0, 0, 0 \\ 0, -1, \eta_{AB}, \eta_Q, 0 \\ -1, 0, 0, \eta_W, 1 \end{bmatrix} \begin{bmatrix} E_c \\ H_h \\ F_{AB} \\ F_{CHP} \\ E_i \end{bmatrix} \quad (27)$$

Among them, the hourly demands for regional end users such as cooling, heat, and electricity are shown in Figure 12.

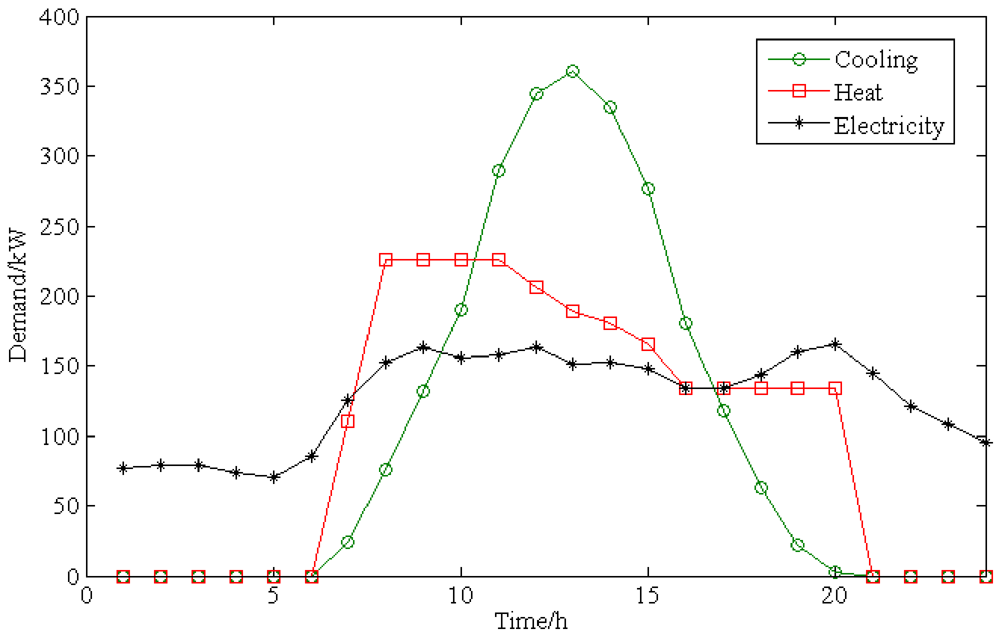


**Figure 12.** The hourly energy demands for regional end users.

In addition, the gas price of natural gas is 40 Euro/MWh and kept constant. The hourly price of external purchased electricity is shown in Figure 13.

Then, the optimization target is as follows.

$$OF = \sum_{t=1}^{24} E_{i,t} P_{e,t} + F_{AB,t} P_{g,t} + F_{CHP,t} P_{g,t} \quad (28)$$

The constraints of regional energy supply and demand balance are as follows.

$$\eta_C E_{c,t} + \eta_R H_{h,t} \geq E^{c}_{\mathrm{IES},t} \quad (29)$$

$$-H_{h,t} + \eta_{AB} F_{AB,t} + \eta_Q F_{CHP,t} \geq E^{h}_{\mathrm{IES},t} \quad (30)$$

$$-E_{c,t} + \eta_W F_{CHP,t} + E_{i,t} \geq E^{e}_{IES,t} \tag{31}$$

The constraints of conversion characteristics of each equipment are as follows.

$$0 \leq \eta_{AB} F_{AB,t} \leq 400 \tag{32}$$

$$0 \leq \eta_Q F_{CHP,t} \leq 160 \tag{33}$$

$$0 \leq \eta_C E_{C,t} \leq 300 \tag{34}$$

$$0 \leq \eta_R H_{h,t} \leq 300 \tag{35}$$

The optimization algorithm of fmincon at MATLAB can be taken as the solver to obtain the hourly operating strategy of the system components; the results can be seen in Figure 14.

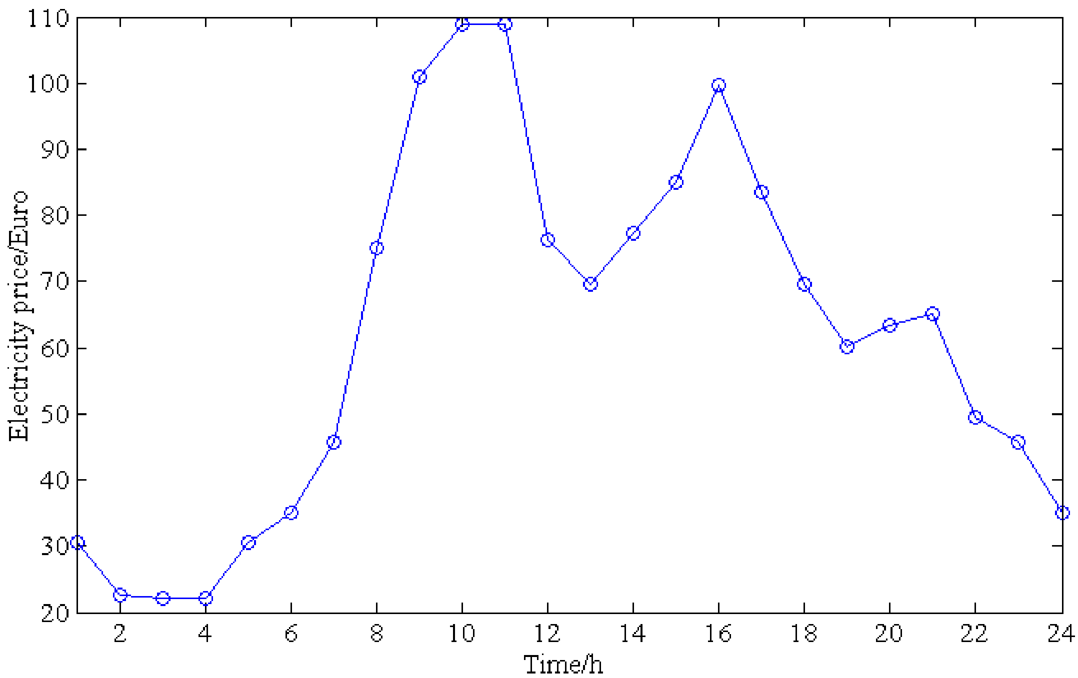


**Figure 13.** The hourly price of external purchased electricity.

Figure 14 shows the optimal hourly operation strategy of each equipment of the regional system obtained by the proposed integrated energy system standardized matrix modeling method and optimization method. In the 0–6 h phase, due to the lower electricity price, the electricity demand of the regional end users is entirely supplied by the external purchased electricity. After this, as the electricity price is higher than the natural gas price, and to meet the cooling, heat, and electricity demands of the regional end users, CHP equipment, auxiliary boiler (AB), absorption refrigeration equipment (CERG), electric refrigeration equipment (WARG), and the mode of externally purchasing electricity are in a cooperative optimization operation. In the 21–24 h period, the regional end users only have electricity demand, and the electricity price falls back. The electricity demand of the regional end users is all supplied by the external purchased electricity. The obtained optimal operation and maintenance cost within a day is in total 377.7725 Euro. From the comparison of calculation accuracy, the optimal operation and maintenance cost obtained previously [13] is 378.59 Euro, and the operation and maintenance cost obtained previously [18] is 377.90 Euro, indicating the accuracy and reliability of the proposed integrated energy system standardization modeling method and operation optimization method. From the comparison of calculation time, and the total calculation time of the proposed method is only 0.367053 s using a 4.0 GHz dual processor laptop, much better that of the nonlinear method proposed previously [9], which has a total calculation time of 22.7543 s using an Intel Core i7 2.60 GHz CPU and 8 GB RAM Desktop computer.

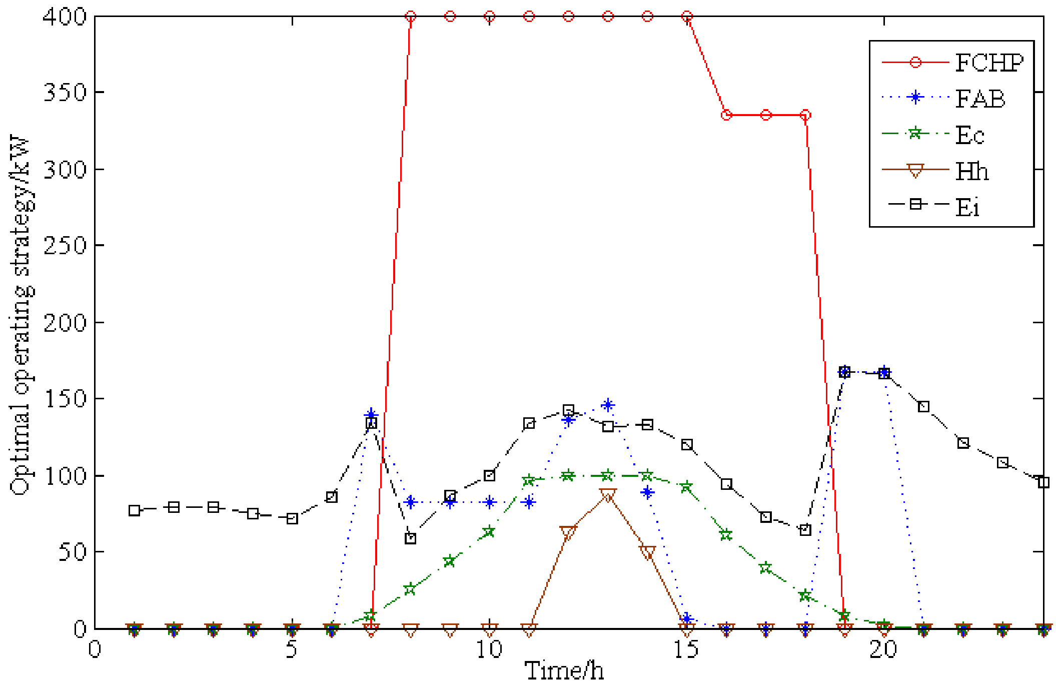


**Figure 14.** Optimal hourly operation strategy for each equipment of the regional system within a day.

The case study for operation optimization has shown that the proposed integrated energy system standardized matrix modeling method and optimization method can be effectively used to determine the hourly operating strategy of the system components.

## 5. Conclusions

The optimization of an integrated energy system has been carried out in the paper. Firstly, a standardized matrix modeling method for the integrated energy system is proposed by taking the energy flow between energy conversion devices as state variables to deal with nonlinear problems caused by the introduction of scheduling factors. Secondly, taking the comprehensive energy efficiency as objective function, the mathematical model for system structural optimization is established, and the optimal structure planning of the regional integrated energy system is carried out. In order to improve the energy supply reliability of the integrated energy system, it can be designed as a regional distributed energy interconnection network. On the basis of meeting the total cooling, heat, and electricity demand of regional users, it is recommended to select two or more devices for the same type of the energy conversion equipment, which are operated in parallel to further improve the comprehensive energy efficiency and reliability of the system. Finally, aiming at the regional integrated energy system operation optimization and taking the operation and maintenance cost as the objective function, the optimal operation planning of the regional integrated energy system is carried out, to optimize the hourly operation strategy of each equipment unit. The simulation case studies have shown that, the proposed modeling method and optimization method can be efficiently and effectively used to determine the system energy flow structure and equipment type, and the technical characteristics and hourly operating strategy of the system components.

In the future work, in order to make the proposed model more in line with the actual integrated energy system project, it is necessary to consider (i) the dissipation effect of pipelines and wire lines in the energy transmission process of the power grid, hot network, and cold network; (ii) the changes of the characteristics of the energy conversion equipment itself under variable operating conditions; and

(iii) various inertia links, such as rotational inertia, thermal inertia, and volume inertia. These are all issues that need to be solved in the near future.

**Author Contributions:** D.B. and Y.C. participated in data analysis and participated in the design of the study. X.L. and J.F. drafted the manuscript. Y.Y. and J.L. proposed the modeling method and optimization method. All authors gave final approval for publication.

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**Conflicts of Interest:** The authors declare no conflicts of interest.

## References

1. Li, J.; Niu, D.; Wu, M.; Wang, Y.; Li, F.; Dong, H. Research on Battery Energy Storage as Backup Power in the Operation Optimization of a Regional Integrated Energy System. *Energies* **2018**, *11*, 2990. [CrossRef]
2. Peng, K.; Zhang, C.; Xu, B. Progress and prospect of multi-energy cooperative energy system demonstration project. *Electr. Power Autom. Equip.* **2017**, *37*, 3–10.
3. AbstarAl Ghaithi, H.M.; Fotis, G.P.; Vita, V. Techno-economic assessment of hybrid energy off-grid system—A case study for Masirah island in Oman. *Int. J. Power Energy Res.* **2017**, *1*, 103–116. [CrossRef]
4. Hammami, M.; Torretti, S.; Grimaccia, F.; Grandi, G. Thermal and Performance Analysis of a Photovoltaic Module with an Integrated Energy Storage System. *Appl. Sci.* **2017**, *7*, 1107. [CrossRef]
5. Ge, S.; Li, J.; Liu, H.; Sun, H.; Wang, Y. Research on Operation–Planning Double-Layer Optimization Design Method for Multi-Energy Microgrid Considering Reliability. *Appl. Sci.* **2018**, *8*, 2062. [CrossRef]
6. Kong, X.; Wang, R.; Li, Y. Optimial operation of a micro-combined cooling, heating and power system. *J. Shanghai Jiao Tong Univ.* **2008**, *42*, 365–369.
7. Bischi, A.; Taccari, L.; Martelli, E. A detailed MILP optimization model for combined cooling, heat and power system operation planning. *Energy* **2014**, *74*, 12–26. [CrossRef]
8. Facci, A.L.; Andreassi, L.; Ubertini, S. Optimization of CHCP (combined heat power and cooling) systems operation strategy using dynamic programming. *Energy* **2014**, *66*, 387–400. [CrossRef]
9. Huang, Z.; Yu, H.; Peng, Z. Energy efficiency level of multi-complement distributed energy system and its influencing factors. *HVAC* **2017**, *47*, 23–28.
10. Ren, H.; Wu, Q. Study on design optimization of distributed cogeneration system. *Therm. Power Gener.* **2017**, *46*, 11–16.
11. Zhou, Z.; Liu, P.; Li, Z.; Ni, W. An engineering approach to the optimal design of distributed energy systems in China. *Appl. Therm. Eng.* **2013**, *53*, 387–396. [CrossRef]
12. Wang, M.; Mu, Y.; Jiang, T.; Jia, H.; Li, X.; Hou, K.; Wang, T. Load curve smoothing strategy based on unified state model of different demand side resources. *J. Mod. Power Syst. Clean Energy* **2018**, *6*, 540–554. [CrossRef]
13. Chicco, G.; Mancarella, P. Matrix modelling of small-scale trigeneration systems and application to operational optimization. *Energy* **2009**, *34*, 261–273. [CrossRef]
14. Almassalkhi, M.R.; Towle, A. Enabling City-scale Multi-energy Optimal Dispatch with Energy Hubs. In Proceedings of the Power Systems Computation Conference (PSCC), Genoa, Italy, 20–24 June 2016; IEEE: New York, NY, USA, 2016; pp. 1–7.
15. Chui, K.T.; Lytras, M.D.; Visvizi, A. Energy Sustainability in Smart Cities: Artificial Intelligence, Smart Monitoring, and Optimization of Energy Consumption. *Energies* **2018**, *11*, 2869. [CrossRef]
16. Ying, Y.; Gao, Y.; Li, S. Nonlinear steady-state model based gas turbine health status estimation approach with improved particle swarm optimization algorithm. *Math. Probl. Eng.* **2015**, *2015*, 940757. [CrossRef]
17. Li, Y.G.; Ghafir, M.F.A.; Wang, L. Nonlinear multiple points gas turbine off-design performance adaptation using a genetic algorithm. *J. Eng. Gas Turb. Power* **2011**, *133*, 071701. [CrossRef]
18. Wang, Y.; Kang, C.; Yang, J. Standardized Matrix Modeling of Multiple Energy Systems. *IEEE Trans. Smart Grid* **2018**, in press. [CrossRef]