sustainability

MDPI

Article

Optimal Energy Configuration of Integrated Energy Community Considering Carbon Emission

Jiangping Liu [1], Jianghong Nie [1], Xue Cui [2,*], Peng Liu [2,*], Pingzheng Tong [2] and Xue Liu [2]

[1] Hubei Power Exchange Center, Wuhan 430077, China; 13378770329@163.com (J.L.); 13317139492@163.com (J.N.)
[2] School of Electrical Engineering and Automation, Wuhan University, Wuhan 430072, China; 2019302070317@whu.edu.cn (P.T.); 2020302191040@whu.edu.cn (X.L.)
* Correspondence: xue_cui_whu@163.com (X.C.); liupwhu@163.com (P.L.)

Abstract: An integrated energy community with a distributed utilization of renewable energy and complementary electricity–gas–cold–heat integrated energy will play an important role in energy conservation and emission reduction. In addition, compared with traditional thermoelectric power equipment, solid oxide fuel cells have many advantages, such as a high energy utilization rate, good waste heat quality, and low carbon emissions. Therefore, the SOFC-based multi-energy and energy storage sharing operation model of an integrated energy community with an electricity–gas–cooling–heat integrated energy system is constructed, and a bi-objective optimal configuration model considering the carbon emission index is established. Considering the economic objective of the smallest annual total operating cost as the most important objective in optimizing the planning model, the ε-constraint method is used to transform the environmental objective function with the smallest annual total carbon emission into a constraint condition under the decision making of an economic single objective function, and then the planning model is linearized and solved by using the Big-M method and the McCormick relaxation method. By calculating and analyzing the energy allocation results in five scenarios, the effectiveness and rationality of the model built in this article are verified. At the same time, the calculation example analysis results show that as the ε value decreases, the energy configuration of the integrated energy community will shift from natural gas to clean energy. From this perspective, the energy equipment configuration and operating costs will increase. However, the heat storage system and power storage system sharing can effectively reduce the energy allocation capacity and costs.

Keywords: carbon emission; integrated energy community; solid oxide fuel cell; bi-objective optimization; optimal configuration

Citation: Liu, J.; Nie, J.; Cui, X.; Liu, P.; Tong, P.; Liu, X. Optimal Energy Configuration of Integrated Energy Community Considering Carbon Emission. *Sustainability* **2024**, *16*, 728. https://doi.org/10.3390/su16020728

Academic Editors: Kh Md Nahiduzzaman, Yuanshi Zhang, Amin Mohammadpour Shotorbani and Yahya Naderi

Received: 11 November 2023
Revised: 7 January 2024
Accepted: 10 January 2024
Published: 15 January 2024

1. Introduction

With the continuous development of distributed energy systems, the decentralized utilization of renewable energy [1] and the comprehensive energy complementarity of electricity, gas, cold, and heat [2] have received extensive attention and research. Furthermore, rich energy management mechanisms and multiple energy investment and operation business models have been derived.

The planning problem of an integrated energy community's energy often takes the life cycle cost as the objective function of decision making, including the investment cost, the maintenance cost, and the operational costs. The decision variable is the planning capacity of a community's energy equipment. The optimization planning is related to historical load data, demand status, and energy price. Due to the nonlinear characteristics of internal combustion engines, gas turbines, and other equipment in integrated energy equipment, heuristic intelligent algorithms are commonly used in integrated energy system planning to solve a model. Reference [3] proposes a distributed evolutionary algorithm for collaborative optimization planning of building and regional integrated energy systems. Based on the investment constraints of different energy equipment, Reference [4] established an integrated energy optimal allocation model and combined the Strength Pareto Evolutionary Algorithm 2 (SPEA2) algorithm and the Technology for Order Preference by Similarity to an Ideal Solution (TOPSIS) method to optimize the model. In Reference [5], a model optimization method based on an improved co-evolutionary algorithm is proposed for the economic and reliability optimization planning of integrated energy systems. In Reference [6], considering the utility of decision makers, a multi-objective scheduling model of an energy system in an integrated energy community was proposed, and an improved chicken swarm optimization algorithm based on Lévy flight was used to quickly solve the proposed mixed-integer nonlinear programming model. Reference [7] proposes a new distributed energy system that takes into account multiple energy scenarios of cold, heat, and electricity and solves for the energy allocation and optimal operation of the integrated energy community based on a two-stage collaborative optimization method combining the NSGA-II and TOPSIS methods.

Heuristic intelligent algorithms are often used to solve nonlinear programming problems with nondeterministic polynomials, but some experts and scholars have modeled the planning problem of integrated energy systems as a mixed-integer linear programming problem to solve. In Reference [8], a mixed-integer linear programming model was used to solve the optimal planning model of a power and natural gas regional integrated energy system based on the coupling of a combined cooling, heating, and power (CCHP) system with the minimum total investment and operating cost as the objective functions. In Reference [9], a joint optimization model of the planning and operation of a user-side integrated energy system with multiple network nodes was constructed, which was described as a mixed-integer linear programming model. Reference [10] compared the effects of mixed-integer linear programming and robust optimization in the planning and operation of Swedish building integrated energy systems. Reference [11] proposed an island integrated energy system with a distributed solar–biogas energy supply and described its planning model as a two-stage mixed-integer linear programming problem, in which the relevant nonlinear constraints were piecewise linearized and the large-scale scenario problem was decomposed and solved by the Benders decomposition method, and the results show that the complementarity of solar energy and biogas can be used to meet the multiple energy needs of households. In Reference [12], the flexible operation of combined heat and power (CHP) resources was considered in the integrated energy system. In order to describe the power generation expansion model of the integrated energy system as a mixed-integer linear programming problem, the cost function and constraints of CHP resources were linearized in this paper.

Based on the current research, the optimization planning problem of an integrated energy community is often solved by a heuristic intelligent algorithm. This is because the output characteristics and constraint conditions of energy equipment, such as gas turbines and internal combustion engines, in integrated energy systems are nonlinear. However, compared with mixed-integer programming, heuristic intelligent algorithms have problems such as their long solution time and susceptibility to falling into local optimization. Although mixed-integer nonlinear programming has been partially studied, its development and solutions are not as mature as those of mixed-integer linear programming. Therefore, some studies have chosen to linearize the nonlinear constraints in integrated energy community optimization planning so that the planning model is described as a mixed-integer linear programming model. Finally, a commercial solver is used for convenient solutions. In the selection of comprehensive energy community planning objectives, most of the literature considers planning economic objectives and technical objectives, and few studies consider energy conservation and emission reduction benefits and a community's carbon emissions as planning environmental objectives. The analysis also focuses on the economic and technical benefits provided by planning and operation, ignoring consideration and discussion of the environmental benefits of planning results.

The electricity–gas–cooling–heat multi-energy complementary integrated energy system is an important direction for the development of distributed energy systems in the future. Among them, the existing commonly used natural gas distributed energy generation equipment has problems such as its low energy efficiency and large carbon emissions. Compared with traditional equipment, such as microgas turbines, solid oxide fuel cells (SOFCs) have many advantages, such as their high energy utilization rate, good waste heat quality, and low carbon emissions. Therefore, it is of practical significance to study the optimization planning method of an electricity–gas–cooling–heat community integrated energy system based on SOFCs. Based on the above problems, a shared operation mode and integrated energy management strategy of the integrated energy community are proposed, which can achieve the unified deployment and control of electricity, gas, cold, and heat energy sources. The model utilizes solid oxide fuel cells (SOFCs) as the core equipment, which have high energy efficiency, good waste heat utilization, and a low carbon footprint. The paper also develops a dual-objective optimal configuration model that considers both economic and environmental factors and aims to minimize the total planned cost and carbon emissions of the community's energy system. The paper applies the ε-constraint method to transform the multi-objective problem into a single-objective problem and uses the Big-M method [13] and the McCormick relaxation method [14] to linearize the nonlinear constraints, which simplifies the solution process and improves the computational efficiency. The paper conducts a case study based on actual project data to demonstrate the effectiveness and rationality of the proposed method and model and shows that they can significantly reduce the energy costs and carbon emissions of the community. The paper provides a practical and innovative solution for the optimization planning of the integrated energy community based on SOFCs and contributes to the research and development of a sustainable and clean-energy future.

2. Integrated Energy Community Energy System Modeling

2.1. Integrated Energy Community's Energy System Structure

The shared operation architecture of the integrated energy community is shown in Figure 1. In the electricity–gas–cold–heat integrated energy community, natural gas is used as the input fuel of the solid oxide fuel cell, and each building contains an integrated energy load demand, including an electric load, heat load, and cold load. Electrical energy is first supplied by the SOFC and a clean energy power station; heat energy is supplied by the SOFC and heat pump; and cold energy is supplied by an absorption chiller and an electric chiller. At the same time, the community is configured with a power storage system and a heat storage system. The power storage system and heat storage system are invested in and allocated by community energy operators and shared in the integrated energy community. When there is a gap or surplus in the building load demand in the integrated energy community, the energy management system of the integrated energy community is uniformly deployed, and priority is given to integrated energy sharing with other buildings in the community. When there is still a gap or surplus in the load demand of the building after sharing, it interacts with the power grid, and the integrated energy community purchases electricity from the power grid or sells electricity to the power grid.

The energy conversion relationship between the various pieces of equipment is shown in Figure 1. The demand for electricity in the building is preferentially met by the SOFC with wind power/photovoltaic power. When there is excess electricity in the building, the integrated energy community's energy management system first checks whether other buildings have insufficient electricity. If there is insufficient electricity in other buildings, the building will supply excess electricity to other buildings. If there is still excess electricity after supplying power to other buildings, the state of charge of the storage system will be checked. If there is no shortage of electricity in the other buildings, whether the community's power storage system reaches the maximum state of charge will be checked. If the storage system reaches the maximum state of charge, the building will sell the excess electricity; otherwise, the excess electricity will be given, as a priority, to community's storage system charging. When there is insufficient power in the building, the integrated energy community's energy management system first checks whether there is excess power in other buildings. If there is excess power in other buildings, other buildings will supply excess power to the building. If there is still insufficient power in the building after the supply of other buildings, then the state of charge of the power storage system will be checked. If there is no excess power in the other buildings, then whether the community's power storage system reaches the minimum state of charge will be checked. If the power storage system reaches the minimum state of charge, the building will purchase power from the power grid to supplement the power supply. Otherwise, the required power will be preferentially supplied by the community's power storage system.

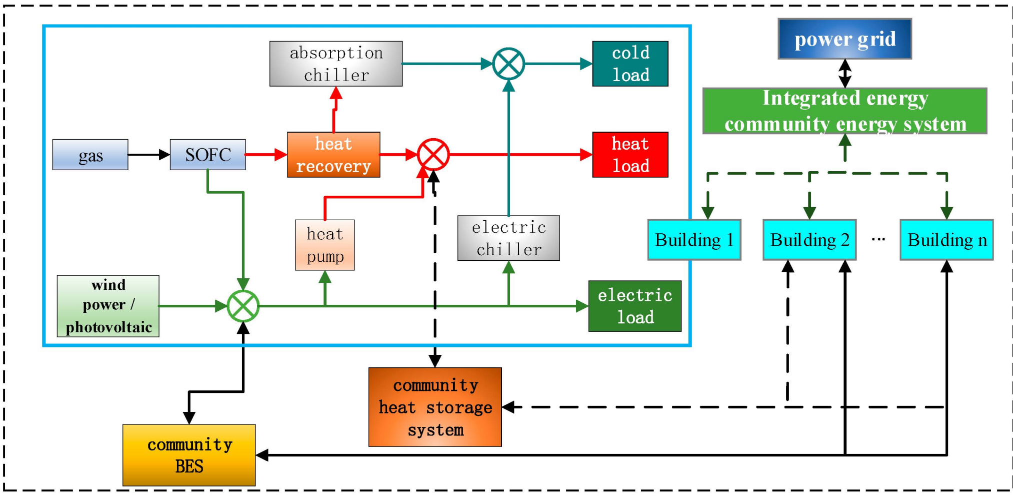

Figure 1. Integrated energy community's shared operation architecture.

The heat load demand of the building is preferentially satisfied by the heat energy and heat pump after SOFC heat recovery. When there is excess heat after SOFC heat recovery, the excess heat energy is stored in the community's heat storage system until the heat storage system reaches the maximum heat storage state. When there is a heat demand gap in the community, the heat energy in the community's heat storage system can be called upon to meet the heat load demand. The heat energy consumed by the absorption chiller comes from the heat energy generated after SOFC heat recovery. The heat energy generated by the heat pump is not used as the heat energy input of the absorption chiller and is only used to meet the heat load demand of the building. The cooling load demand of the building is met by the electric chiller and the absorption chiller.

2.2. Mathematical Model

2.2.1. Distributed Renewable Energy Model

The main factor affecting the output power of wind power generation is wind speed. The output model of distributed wind power generation is as follows [15]:

$$P_{WT} = \begin{cases} 0, \quad 0 \le v \le v_i \;\; or \;\; v_o \le v_i \\ P_{WT}^r \frac{v - v_i}{v_r - v_i}, \quad v_i < v < v_r \\ P_{WT}^r, \quad v_r \le v \le v_o \end{cases} \tag{1}$$

In the formula, P_{WT} is the output power of the wind power generation, P_{WT}^r is the rated output power of the wind power generation, v is the current wind speed, v_i is the cut-in wind speed, v_o is the cut-out wind speed, and v_r is the rated wind speed.

Photovoltaic power generation is mainly achieved by photovoltaic panels absorbing energy from the sun. The power of photovoltaic power generation can be obtained according to the light intensity of the real-time weather and the parameters of the photovoltaic panels themselves. The output model of distributed photovoltaic power generation is as follows [16]:

$$P_{PV} = \begin{cases} P_{PV}^{r} \frac{I}{I_r} &, I \leq I_r \\ P_{PV}^{r} &, I > I_r \end{cases} \tag{2}$$

In the formula, P_{PV} is the photovoltaic power generation output power, P_{PV}^{r} is the photovoltaic power output rated active power, I is the intensity of illumination, and I_r is the rated light intensity.

According to Formulas (1) and (2), it can be seen that the real-time output power and configuration capacity of distributed wind power and photovoltaic power generation are linear in the range of conventional weather. In the energy planning process of the integrated energy community, for simplicity, the formula shown in Formula (3) is used to replace the output formula of distributed renewable energy.

$$P_{DG}(t) = \eta_{DG}(t) \cdot P_{DG} \tag{3}$$

In the formula, $\eta_{DG}(t)$ is the power generation per unit of distributed renewable energy at time t, that is, the power generation coefficient per unit of photovoltaic or wind power, and can be obtained from historical power generation data. P_{DG} is the planning capacity of distributed renewable energy, and $P_{DG}(t)$ is the output wind power or the photovoltaic power generation at time t in the planning process.

2.2.2. SOFC Model

Compared with other natural-gas-distributed energy power generation equipment, SOFCs have the advantages of high power generation efficiency, high waste heat quality, no vibration, a low level of noise, a wide range of fuel selection, green environmental protection, and so on. In this paper, natural gas is used as the fuel input of the SOFC, and the output electric power and thermal power of the SOFC can be expressed by Formulas (4) and (5) [17,18].

$$E_{SOFC} = \eta_{SOFC} \cdot Q_{NG} \tag{4}$$

$$H_{SOFC} = \delta_{SOFC} \cdot E_{SOFC} \tag{5}$$

In the formula, Q_{NG} is the natural gas consumption of the SOFC, η_{SOFC} is the electrical efficiency of the SOFC, E_{SOFC} is the electrical power output of the SOFC, and δ_{SOFC} is the output thermoelectric ratio of the SOFC, which can be obtained by dividing the output thermal efficiency of the SOFC by the output electrical efficiency. H_{SOFC} is the output thermal power of the SOFC.

2.2.3. Power Storage System Model

The characteristics of the storage system include the state of charge, the capacity of the storage device, the charge and discharge efficiency, and so on. The mathematical model of the storage device is as follows [19]:

$$SOC(t) = SOC(t-1) + \left(\frac{Q_{cha} \cdot \mu_{cha}}{E_{BES}} - \frac{Q_{discha}}{\mu_{discha} \cdot E_{BES}}\right) \cdot \Delta t \tag{6}$$

In the formula, $SOC(t)$ is the state of charge of the power storage system, E_{BES} is the device configuration capacity of the power storage system, Q_{cha} is the charging power of the storage system, μ_{cha} is the charging efficiency of the power storage system, Q_{discha} is the discharge power of the power storage system, and μ_{discha} is the discharge efficiency of the power storage system.

2.2.4. Heat Storage System Model

The mathematical model of the heat storage system is similar to that of the power storage system. The model is as follows:

$$SOC^{HS}(t) = SOC^{HS}(t-1) + \left(\frac{Q_{cha}^{HS} \cdot \mu_{cha}^{HS}}{E_{HS}} - \frac{Q_{discha}^{HS}}{\mu_{discha}^{HS} \cdot E_{HS}}\right) \cdot \Delta t \tag{7}$$

In the formula, $SOC^{HS}(t)$ is the heat storage state of the heat storage system, E_{HS} is the device configuration capacity of the heat storage system, Q_{cha}^{HS} is the charging power of the heat storage system, μ_{cha}^{HS} is the charging efficiency of the heat storage system, Q_{discha}^{HS} is the heat release power of the heat storage system, and μ_{discha}^{HS} is the heat release efficiency of the heat storage system.

2.2.5. Electric Heat Pump Model

In an intelligent energy community, when the waste heat recovered by the SOFC is not enough to meet the heat load demand, the electric heat pump can be used as a supplement of heat energy. The electric heat pump relies on the input of electrical energy to drive the equipment and output heat energy. Its heating coefficient depends on the ratio of the output heat power to the input electrical power. The heating formula of the heat pump can be expressed by Equation (8).

$$H_{HP} = \eta_{HP} \cdot E_{HP} \tag{8}$$

In the formula, E_{HP} is the electrical power consumed by the electric heat pump, and H_{HP} is the thermal power output by the electric heat pump.

2.2.6. Electric Refrigerator Model

In a smart energy community, the electric refrigerator can be used to meet the cooling load demand of the community. The electric refrigerator relies on the input of electrical energy to drive the equipment and output cold energy. The refrigeration coefficient depends on the ratio of the output cold power to the input electrical power. The refrigeration formula of the electric refrigerator can be expressed by Equation (9).

$$C_{EC} = \eta_{EC} \cdot E_{EC} \tag{9}$$

In the formula, E_{EC} is the electrical power consumption of the electric refrigerator, and C_{EC} is the output cold power of the electric refrigerator.

2.2.7. Absorption Refrigerator Model

In an integrated energy system equipped with an SOFC, in order to efficiently utilize the thermal power after the SOFC heat recovery, it can be used as a source of refrigeration energy for the absorption chillers and to meet the cooling load requirements of a smart energy community. The refrigeration coefficient of the absorption refrigerator depends on the ratio of the output cooling power to the input heat power. The refrigeration formula of the absorption refrigerator can be expressed by Formula (10).

$$C_{AC} = \eta_{AC} \cdot H_{AC} \tag{10}$$

In the equation, H_{AC} is the heat power consumption of the absorption refrigerator. C_{AC} is the output cold power of the absorption refrigerator.

3. Dual-Objective Optimal Configuration Model of Integrated Energy Community

3.1. Objective Function

In this paper, the two objectives are evaluated from economic and environmental perspectives. In an integrated energy community, including electrical, gas, cold, and heat energy, the impact of carbon emissions should be considered in particular. Therefore, the annual total operating cost and annual carbon emissions are selected as the optimal allocation objectives of the integrated energy community.

3.1.1. Total Annual Operating Costs

The minimum annual total operating cost is selected as the economic objective function to determine the configuration capacity of various pieces of energy equipment. The annual total operating cost includes the primary investment cost and the operation and maintenance costs of the power storage system, heat storage system, clean energy power station, solid oxide fuel cell system, heat pump, electric refrigerator, and absorption refrigerator. The cost of purchasing and selling electricity from the power grid and the cost of purchasing natural gas from the fuel cell are shown in (11).

$$\begin{aligned} \min C_{total} &= C_{BES} + C_{HS} + C_{PV} + C_{WT} + C_{SOFC} \\ &+ C_{HP} + C_{EC} + C_{AC} + C_{buy} - C_{sell} + C_{NG} \end{aligned} \tag{11}$$

In the formula, C_{total} is the total annual operating cost of the integrated energy community, including the investment cost of the power storage system, C_{BES}; the investment cost of the heat storage system, C_{HS}; the investment cost of the photovoltaic system, C_{PV}; the investment cost of the wind power system, C_{WT}; the investment cost of the solid oxide fuel cell system, C_{SOFC}; the investment cost of the heat pump, C_{HP}; the investment cost of the electric refrigerator, C_{EC}; the investment cost of the absorption chillers, C_{AC}; the cost of purchasing electricity from the grid, C_{buy}; the revenue from electricity sales to the grid, C_{sell}; and the fuel cost of purchasing natural gas, C_{NG}. The specific calculation formulas of the costs are as follows [20].

1. The investment cost of the power storage system:

$$C_{BES} = [\frac{r(1+r)^{n_{BES}}}{(1+r)^{n_{BES}} - 1} \cdot C_{BES}^{init} + C_{BES}^{OM}] \cdot E_{BES} \tag{12}$$

In the formula, r is the discount rate, n_{BES} is the life cycle of the power storage system, C_{BES}^{init} is the primary investment cost of the unit power storage system, C_{BES}^{OM} is the annual operation and maintenance costs of the unit power storage system, and E_{BES} is the configuration capacity of the power storage system.

2. The investment cost of the heat storage system;

$$C_{HS} = [\frac{r(1+r)^{n_{HS}}}{(1+r)^{n_{HS}} - 1} \cdot C_{HS}^{init} + C_{HS}^{OM}] \cdot E_{HS} \tag{13}$$

In the formula, r is the discount rate, n_{HS} is the life cycle of the heat storage system. C_{HS}^{init} is the unit investment cost of the heat storage system, C_{HS}^{OM} is the annual operation and maintenance costs of the unit heat storage system, and E_{HS} is the configuration capacity of the heat storage system.

3. The investment cost of the photovoltaic system;

$$C_{PV} = [\frac{r(1+r)^{n_{PV}}}{(1+r)^{n_{PV}} - 1} \cdot C_{PV}^{init} + C_{PV}^{OM}] \cdot P_{PV} \tag{14}$$

In the formula, n_{PV} is the life cycle of photovoltaic systems, C_{PV}^{init} is the primary investment cost of the unit photovoltaic system. C_{PV}^{OM} is the annual operation and maintenance costs of the unit photovoltaic system, and P_{PV} is the configuration capacity of the photovoltaic system.

4. The investment cost of the wind power system;

$$C_{WT} = [\frac{r(1+r)^{n_{WT}}}{(1+r)^{n_{WT}}-1} \cdot C_{WT}^{init} + C_{WT}^{OM}] \cdot P_{WT} \quad (15)$$

In the formula, n_{WT} is the life cycle of the wind power system, C_{WT}^{init} is the primary investment cost of the unit wind power system, C_{WT}^{OM} is the annual operation and maintenance costs of the unit wind power system, and P_{WT} is the configuration capacity of the wind power system.

5. The SOFC system's investment costs;

$$C_{SOFC} = [\frac{r(1+r)^{n_{SOFC}}}{(1+r)^{n_{SOFC}}-1} \cdot C_{SOFC}^{init} + C_{SOFC}^{OM}] \cdot P_{SOFC} \quad (16)$$

In the formula, n_{SOFC} is the life cycle of the solid oxide fuel cell system, C_{SOFC}^{init} is the unit investment cost of the solid oxide fuel cell system, C_{SOFC}^{OM} is the annual operation and maintenance costs of the unit solid oxide fuel cell system, and P_{SOFC} is the configuration capacity of the solid oxide fuel cell system.

6. The investment cost of the heat pump:

$$C_{HP} = [\frac{r(1+r)^{n_{HP}}}{(1+r)^{n_{HP}}-1} \cdot C_{HP}^{init} + C_{HP}^{OM}] \cdot P_{HP} \quad (17)$$

In the formula, n_{HP} is the life cycle of the heat pump, C_{HP}^{init} is the unit investment cost of the heat pump, C_{HP}^{OM} is the unit annual operation and maintenance costs of the heat pump, and P_{HP} is the configuration capacity of the heat pump.

7. The investment cost of the electric refrigerator:

$$C_{EC} = [\frac{r(1+r)^{n_{EC}}}{(1+r)^{n_{EC}}-1} \cdot C_{EC}^{init} + C_{EC}^{OM}] \cdot P_{EC} \quad (18)$$

In the formula, n_{EC} is the life cycle of the electric refrigerator, C_{EC}^{init} is the first investment cost of the unit electric refrigerator, C_{EC}^{OM} is the annual operation and maintenance costs of the unit electric refrigerator, and P_{EC} is the configuration capacity of the electric refrigerator.

8. The investment cost of the absorption chillers:

$$C_{AC} = [\frac{r(1+r)^{n_{AC}}}{(1+r)^{n_{AC}}-1} \cdot C_{AC}^{init} + C_{AC}^{OM}] \cdot P_{AC} \quad (19)$$

In the formula, n_{AC} is the life cycle of an absorption refrigerator, C_{AC}^{init} is the first investment cost of the unit absorption refrigerator, C_{AC}^{OM} is the annual operation and maintenance cost of the unit absorption chiller, and P_{AC} is the configuration capacity of the absorption refrigerator.

9. The cost of purchasing electricity from the grid:

$$C_{buy} = \sum_{\forall t} \lambda_{re}(t) \cdot P_{buy}(t) \cdot \Delta t \quad (20)$$

In the formula, $\lambda_{re}(t)$ is the power grid electricity purchase price over period t, $P_{buy}(t)$ is the community's electricity purchases from the grid over a period t, and Δt is the duration of the unit scheduling period.

10. Revenue from electricity sales to the grid:

$$C_{sell} = \sum_{\forall t} \lambda_{fit}(t) \cdot P_{sell}(t) \cdot \Delta t \tag{21}$$

In the formula, $\lambda_{fit}(t)$ is the on-grid price over a period t, and $P_{sell}(t)$ is the amount of electricity sold by the community to the grid over a period t.

11. The cost of purchasing natural gas:

$$C_{NG} = \sum_{\forall t} \lambda_{NG}(t) \cdot Q_{NG}(t) \cdot \Delta t \tag{22}$$

In the formula, $\lambda_{NG}(t)$ is the natural gas purchase unit price over a period t, and $Q_{NG}(t)$ is the purchase amount of natural gas over a period t.

3.1.2. Total Annual Carbon Emissions

The annual total carbon emissions are the objective function evaluated from the perspective of the environment. Clean energy generates almost no carbon emissions in the process of generating electricity. At the same time, in order to simplify the problem, the carbon emissions generated during the operation and maintenance of the energy equipment are not considered. Therefore, the calculation of the annual carbon emissions is mainly composed of two parts: the emissions of electricity purchased from the main power grid and the emissions generated by natural gas consumption, as shown in (23).

$$\min C_{CE} = \mu_{Grid} \cdot \sum_{\forall t} P_{buy}(t) \cdot \Delta t + \mu_{NG} \cdot \sum_{\forall t} Q_{NG}(t) \cdot \Delta t \tag{23}$$

In the formula, μ_{Grid} is the unit carbon emission coefficient of the power grid, and μ_{NG} is the unit carbon emission coefficient of natural gas.

3.2. Constraint Condition

According to the energy management strategy of the integrated energy community given in Section 2.1, the constraints of the integrated energy community's energy optimization configuration model include equipment state constraints, cold and heat energy balance constraints, the building's power state constraints, the community's power state constraints [21], the community's purchase and sale power constraints [22], the power storage system's state continuity constraints [23], and the heat storage system's state constraints.

1. The equipment's state constraints:

The equipment state constraint indicates that the available installation capacity of the planned energy production equipment is constrained by the planning upper limit, and the input of the heat pump, the electric refrigerator, and the absorption refrigerator must be lower than the corresponding installation capacity. At the same time, the energy conversion efficiency constraints of each piece of energy conversion equipment are also stipulated. Constraints (24) and (25) indicate that the clean energy scale that each building can plan to configure is limited. Constraint (26) indicates that the SOFC scale planned for each building is limited. Constraints (27) to (29) indicate that the operating power of the energy equipment must not exceed its configuration capacity. Constraint (30) represents the energy balance model of the electric heat pump. Constraint (31) represents the energy balance model of the electric refrigerator. Constraint (32) represents the energy balance model of the absorption refrigerator. Constraint (33) indicates that the operating power of the SOFC must not exceed its configuration capacity and must not be less than 30% of its configuration capacity to avoid the low-load operating conditions of the SOFC [24]. Constraints (34) and (35) represent the energy balance model of the SOFC. Constraints (36) and (37) indicate that in order to avoid drastic changes in the output of the SOFC, the difference in the output power of the SOFC at adjacent times is limited to 50% of the configuration capacity [24].

$$0 \leq P_{PV,n} \leq CA_{PV,n} \quad (24)$$

$$0 \leq P_{WT,n} \leq CA_{WT,n} \quad (25)$$

$$0 \leq P_{SOFC,n} \leq CA_{SOFC,n} \quad (26)$$

$$0 \leq E_{HP,n}(t) \leq P_{HP,n} \quad (27)$$

$$0 \leq E_{EC,n}(t) \leq P_{EC,n} \quad (28)$$

$$0 \leq H_{AC,n}(t) \leq P_{AC,n} \quad (29)$$

$$H_{HP,n}(t) = \eta_{HP,n} \cdot E_{HP,n}(t) \quad (30)$$

$$C_{EC,n}(t) = \eta_{EC,n} \cdot E_{EC,n}(t) \quad (31)$$

$$C_{AC,n}(t) = \eta_{AC,n} \cdot H_{AC,n}(t) \quad (32)$$

In the formula, $CA_{PV,n}$ is the upper limit of the configuration capacity of the photovoltaic system in building n, $CA_{WT,n}$ is the upper limit of the wind power system configuration capacity in building n, $CA_{SOFC,n}$ is the upper limit of the SOFC system configuration capacity in building n; $E_{HP,n}(t)$ is the electric power consumed by the heat pump of building n at time t, $E_{EC,n}(t)$ is the electric power consumed by the electric refrigerator of building n at time t, $H_{AC,n}(t)$ is the thermal power absorbed by the absorption chiller of building n at time t; $H_{HP,n}(t)$ is the thermal power generated by the heat pump of building n at time t, $\eta_{HP,n}$ is the heating efficiency of the heat pump in building n; $C_{EC,n}(t)$ is the cold power generated by the electric refrigerator of building n at time t, $\eta_{EC,n}$ is refrigeration efficiency of the electric refrigerator in building n; $C_{AC,n}(t)$ is the cold power generated by the absorption chiller of building n at time t, and $\eta_{AC,n}$ is the refrigeration efficiency of an absorption chiller for building n.

$$30\% \times P_{SOFC,n} \leq E_{SOFC,n}(t) \leq P_{SOFC,n} \quad (33)$$

$$E_{SOFC,n}(t) = \eta_{SOFC,n} \cdot Q_{NG,n}(t) \quad (34)$$

$$H_{SOFC,n}(t) = \delta_{SOFC,n} \cdot E_{SOFC,n}(t) \quad (35)$$

$$E_{SOFC,n}(t+1) - E_{SOFC,n}(t) \leq 50\% \times P_{SOFC,n} \quad (36)$$

$$E_{SOFC,n}(t) - E_{SOFC,n}(t+1) \leq 50\% \times P_{SOFC,n} \quad (37)$$

In the formula, $E_{SOFC,n}(t)$ is the electrical power output by the SOFC of building n at time t, $Q_{NG,n}(t)$ is the amount of natural gas consumed by building n at time t, $\eta_{SOFC,n}$ is the electrical efficiency of the SOFC for building n, $\delta_{SOFC,n}$ is the heat-to-electric output ratio of the SOFC for building n, and $H_{SOFC,n}(t)$ is the thermal power output of the SOFC of building n at time t.

2. The cold and hot energy balance constraints:

The cold and hot energy balance constraint indicates that the cold and hot power in each building in the community should be balanced under the community integrated energy management strategy proposed in this paper. Constraint (38) indicates the thermal power energy balance of building n. Constraint (39) indicates the cold power energy balance of building n. Constraint (40) indicates that the thermal power output by the SOFC consists of two parts.

$$H_{SOFC,n}^{use}(t) + H_{HP,n}(t) + H_{dis,n}(t) = H_{L,n}(t) + H_{AC,n}(t) \quad (38)$$

$$C_{EC,n}(t) + C_{AC,n}(t) = C_{L,n}(t) \quad (39)$$

$$H_{SOFC,n}^{use}(t) + H_{SOFC,n}^{waste}(t) = H_{SOFC,n}(t) \quad (40)$$

In the formula, $H_{L,n}(t)$ is the thermal load power demand of building n at time t, $C_{L,n}(t)$ is the cooling load power demand of building n at time t, $H_{dis,n}(t)$ is the thermal power obtained by building n from the heat storage system at time t, $H_{SOFC,n}^{use}(t)$ is the part of the thermal power output by the SOFC of building n at time t, and $H_{SOFC,n}^{waste}(t)$ is the part of the thermal power that is not utilized in the SOFC output of building n at time t.

3. The state constraints of the buildings' electric power:

The electric power state constraint of the buildings indicates the calculation method and state limit of the excess electric power and electric power shortage of each building in the community under the community integrated energy management strategy proposed in this paper. Constraints (41) and (42) represent the calculation method of the electric power excess and shortage of building n in a period t, respectively. Constraint (43) indicates that the two states of electric power excess and power shortage cannot appear at the same time. Constraint (44) indicates that the sum of the variables $P_{BD,n}^{pos}(t)$ and $P_{BD,n}^{neg}(t)$ is nonnegative.

$$P_{BD,n}^{pos}(t) = \begin{pmatrix} \eta_{PV,n}(t) \cdot P_{PV,n} + \eta_{WT,n}(t) \cdot P_{WT,n} + E_{SOFC,n}(t) \\ -P_{L,n}(t) - E_{HP,n}(t) - E_{EC,n}(t) \end{pmatrix} \cdot X_{BD,n}^{pos}(t) \tag{41}$$

$$P_{BD,n}^{neg}(t) = \begin{pmatrix} P_{L,n}(t) + E_{HP,n}(t) + E_{EC,n}(t) \\ -\eta_{PV,n}(t) \cdot P_{PV,n} - \eta_{WT,n}(t) \cdot P_{WT,n} - E_{SOFC,n}(t) \end{pmatrix} \cdot X_{BD,n}^{neg}(t) \tag{42}$$

$$X_{BD,n}^{pos}(t) + X_{BD,n}^{neg}(t) = 1 \tag{43}$$

$$P_{BD,n}^{pos}(t) \geq 0 \text{ , } P_{BD,n}^{neg}(t) \geq 0 \tag{44}$$

In the formula, $P_{BD,n}^{pos}(t)$ is the remaining amount of electrical power in building n at time t, $P_{BD,n}^{neg}(t)$ is the shortage of electrical power in building n at time t, $P_{PV,n}$ is the configuration capacity of the photovoltaic system in building n, $P_{WT,n}$ is the wind power configuration capacity of building n, and $\eta_{PV,n}(t)$ and $\eta_{WT,n}(t)$ are the amounts of power generated by the unit photovoltaic and unit wind power systems of building n at time t, respectively. $P_{L,n}(t)$ is the electrical load power demand of building n at time t. $X_{BD,n}^{pos}(t)$ represents the 0–1 variable of the residual state of electrical power in building n in time period t. Taking 1 means that there is an electrical power surplus in building n; otherwise, a value of 0 is obtained. $X_{BD,n}^{neg}(t)$ represents the 0–1 variable of the state of an electrical power shortage in building n during the period t. When 1 is taken, it indicates that there is insufficient electrical power in building n; otherwise, 0 is taken.

4. The community's electrical power state constraints:

The community's electrical power state constraint represents the calculation method and state limitation of an overall electrical power surplus and electrical power shortage in the community under the community integrated energy management strategy proposed in this paper. Constraints (45) and (46) represent the calculation method of an electrical power surplus and shortage in the community's building group in a period t, respectively. Constraint (47) indicates that the two states of electrical power surplus and power shortage cannot appear at the same time. Constraint (48) indicates that the sum of the variables $P_{CO}^{pos}(t)$ and $P_{CO}^{neg}(t)$ is nonnegative.

$$P_{CO}^{pos}(t) = (\sum_{n=1}^{N} P_{BD,n}^{pos}(t) - \sum_{n=1}^{N} P_{BD,n}^{neg}(t)) \cdot X_{CO}^{pos}(t) \tag{45}$$

$$P_{CO}^{neg}(t) = (\sum_{n=1}^{N} P_{BD,n}^{neg}(t) - \sum_{n=1}^{N} P_{BD,n}^{pos}(t)) \cdot X_{CO}^{neg}(t) \tag{46}$$

$$X_{CO}^{pos}(t) + X_{CO}^{neg}(t) \leq 1 \tag{47}$$

$$P_{CO}^{pos}(t) \geq 0 \text{ , } P_{CO}^{neg}(t) \geq 0 \tag{48}$$

In the formula, N is the total number of buildings in the community, $P_{CO}^{pos}(t)$ is the remaining amount of electrical power in the community's buildings at time t, $P_{CO}^{neg}(t)$ is the shortage of electrical power in the community's buildings at time t, and $X_{CO}^{pos}(t)$ represents the 0–1 variable of the residual state of electrical power in the community during a period t. When 1 is taken, it indicates that there is residual electrical power in the community's buildings; otherwise, 0 is taken. $X_{CO}^{neg}(t)$ represents the 0–1 variable of the state of an electrical power shortage in the community during the period t. When 1 is taken, it indicates that there is insufficient electrical power in building n; otherwise, 0 is taken.

5. The electricity purchase and sale's constraints in the community:

The community's power purchase and sale constraint represents the calculation method of the community's and external power grid's power purchases and sales under the community integrated energy management strategy proposed in this paper and its limited binary variable state constraint. Constraints (49) and (50) represent the calculation methods of power sales and power purchases over a period t, respectively. Constraints (51) and (52) represent the state constraints of the maximum state of charge and the minimum state of charge of the power storage system, respectively.

$$P_{sell}(t) = (P_{CO}^{pos}(t) - P_{cha}(t)) \cdot Y_{BES}^{\max}(t) \tag{49}$$

$$P_{buy}(t) = (P_{CO}^{neg}(t) - P_{dis}(t)) \cdot Y_{BES}^{\min}(t) \tag{50}$$

$$Y_{BES}^{\max}(t) \leq 2X_{CO}^{pos} \tag{51}$$

$$Y_{BES}^{\min}(t) \leq 2X_{CO}^{neg} \tag{52}$$

In the formula, $Y_{BES}^{\max}(t)$ represents the 0–1 variable of whether the community's power storage system reaches the maximum state of charge during a period t. When 1 is taken, it means that the power storage system reaches the maximum state of charge; otherwise, a value of 0 is obtained. $Y_{BES}^{\min}$ represents the 0–1 variable of whether the community's power storage system reaches the minimum state of charge during the period t. When 1 is taken, it means that the power storage system reaches the minimum state of charge; otherwise, a value of 0 is obtained. $P_{cha}(t)$ is the charging amount of the storage system over a period t, and $P_{dis}(t)$ is the discharge amount of the storage system over a period t. The calculation methods are as follows in (53) and (54).

$$P_{cha}(t) = (SOC_{\max} - SOC(t-1)) \cdot \frac{E_{BES}}{\mu_{cha}\Delta t} \tag{53}$$

$$P_{dis}(t) = (SOC(t-1) - SOC_{\min}) \cdot \frac{\mu_{dis}E_{BES}}{\Delta t} \tag{54}$$

In the formula, $SOC(t)$ is the state of charge of the community's power storage system at time t, $SOC_{\max}$ is the maximum state of charge of the power storage system, $SOC_{\min}$ is the minimum state of charge of the power storage system, μ_{cha} is the charging efficiency of the power storage system, and μ_{dis} is the discharge efficiency of the power storage system.

6. The continuity constraint of the state of charge of the storage system:

The continuity constraint on the state of charge of the power storage system represents the calculation method and state constraint of the state of charge of the power storage system under the community integrated energy management strategy proposed in this paper.

$$\begin{aligned} SOC(t) = \quad & SOC(t-1) \cdot (1 - Y_{BES}^{\max}(t) - Y_{BES}^{\min}(t)) + \tfrac{P_{CO}^{pos}(t)\mu_{cha}\Delta t}{E_{BES}}(1 - Y_{BES}^{\max}(t)) \\ & - \tfrac{P_{CO}^{neg}(t)\Delta t}{\mu_{dis}E_{BES}}(1 - Y_{BES}^{\min}(t)) + SOC_{\max}Y_{BES}^{\max}(t) + SOC_{\min}Y_{BES}^{\min}(t) \end{aligned} \tag{55}$$

$$SOC(t=0) = SOC(t=last) \tag{56}$$

$$SOC_{\min} \leq SOC(t) \leq SOC_{\max} \tag{57}$$

In the formula, Constraint (55) represents the calculation formula for the state of charge. Constraint (56) represents the energy conservation of the initial and final states of the community's power storage system. Constraint (57) indicates that the state of charge at any time is between the maximum state and the minimum state of charge.

7. The state constraints of the heat storage system:

The continuity constraint on the state of charge of the heat storage system represents the calculation method and state constraint of the state of charge of the heat storage system under the community integrated energy management strategy proposed in this paper. Constraint (58) represents the heat storage state calculation formula for the heat storage system. Constraint (59) represents that the two states of stored heat energy and released heat energy cannot appear at the same time. Constraint (60) represents the energy conservation of the initial and final states of the community's heat storage system. Constraint (61) represents that the heat storage state at any time is between the maximum and the minimum heat storage states.

$$\begin{aligned} SOC^{HS}(t) = \quad & SOC^{HS}(t-1) + \frac{\sum\limits_{n=1}^{N} H_{SOFC,n}^{waste}(t) \cdot \mu_{cha}^{HS} \Delta t}{E_{HS}} \cdot Y_{HS}^{cha}(t) \\ & - \frac{\sum\limits_{n=1}^{N} H_{dis,n}(t) \cdot \Delta t}{\mu_{discha}^{HS} \cdot E_{HS}} \cdot Y_{HS}^{discha}(t) \end{aligned} \tag{58}$$

$$Y_{HS}^{cha}(t) + Y_{HS}^{discha}(t) \leq 1 \tag{59}$$

$$SOC^{HS}(t=0) = SOC^{HS}(t=last) \tag{60}$$

$$SOC_{\min}^{HS} \leq SOC^{HS}(t) \leq SOC_{\max}^{HS} \tag{61}$$

In the formula, $SOC^{HS}(t)$ is the heat storage state of the community's heat storage system at time t, $SOC_{\max}^{HS}$ is the maximum heat storage state of the heat storage system, $SOC_{\max}^{HS}$ is the minimum heat storage state of the heat storage system, μ_{cha}^{HS} is the heat storage efficiency of the heat storage system, and μ_{discha}^{HS} is the heat release efficiency of the heat storage system. $Y_{HS}^{cha}(t)$ represents the 0–1 variable of whether the community's heat storage system is in the state of stored heat energy over a period t. When 1 is taken, it means that the heat storage system is in a state of stored heat energy; otherwise, a value of 0 is obtained. $Y_{HS}^{discha}(t)$ represents the 0–1 variable of whether the community's heat storage system is in a state of releasing heat energy over a period t. When 1 is taken, the heat storage system is in a state of releasing heat energy; otherwise, 0 is taken.

4. The Method of Solving the Model

4.1. ε-Constraint Method

The ε-constraint method is an effective method for dealing with multi-objective optimization decision making. Its core idea is to transform a multi-objective optimization decision-making problem into a single-objective optimization decision-making problem to solve. The specific method for implementing the ε-constraint method is to select the most important or the decision maker's most preferred objective function as the reserved objective function among the multiple objective functions of the optimization of the decision-making process. The reserved objective function is the objective function of the transformed single-objective optimization decision-making problem. The other objective functions are transformed into constraints of the single-objective optimization decision-making problem by adding a restriction domain ε_i [25]. The specific steps of the ε-constraint method are as follows:

Step 1: By minimizing the nth objective function (assuming that the decision-making problem is a minimization problem), $\overline{x}^*$ can be obtained, and then we set

$f_n(\overline{x}^*) = \min\limits_{x \in F} f_n(\overline{x})$, satisfying $f_i(\overline{x}) \le \varepsilon_i$, where $i = 1, 2, \ldots, m$, $i \ne n$; ε_i represents the estimation of the maximum value of the objective function.

Step 2: Different ε_i values are selected to repeat Step 1, and different optimization decision results are obtained until the problem decision maker thinks that a satisfactory decision solution has been found. In general, the following method can be used to determine the value range of ε_i to avoid the case of obtaining no solution: for each objective function, f_i, $i = 1, 2, \ldots, m$, if there is an optimal decision variable $\overline{x}_i^*$, make $f_i(\overline{x}_i^*)$ the minimum, then let $\varepsilon_i \ge f_i(\overline{x}_i^*)$, $i = 1, 2, \ldots, n-1, n+1, \ldots, m$, and $\varepsilon_i \le f_i(\overline{x}_n^*)$, $i = 1, 2, \ldots, n-1, n+1, \ldots, m$.

In the energy optimal allocation model of the integrated energy community constructed in this paper, the economic objective of minimizing the total annual operating cost is considered an important objective in the optimization planning model. Therefore, with the help of the idea of the ε-constraint method, a limit domain is added to the annual total carbon emission target, which is transformed into the constraint condition on the objective function of minimizing the total annual operating cost, so as to transform the multi-objective optimization decision in the integrated energy optimal allocation model into a single-objective optimization decision. The specific steps are as follows:

Step 1: By minimizing the economic objective, $C_{total}(X)$, an optimal decision variable, $X_1{}^*$, of $C_{total}(X)$ can be obtained, which can make $C_{total}(X_1{}^*) = \min C_{total}(X)$ and $C_{CE}(X) \le \varepsilon$, where ε is the maximum estimation of the objective function.

Step 2: Determine the value range of the limiting domain ε of the objective function of minimizing the total annual carbon emissions. For ε, it is necessary to satisfy both $\varepsilon \ge C_{CE}(X_2{}^*)$ and $\varepsilon \le C_{CE}(X_1{}^*)$. Therefore, the range of ε is $[C_{CE}(X_2{}^*), C_{CE}(X_1{}^*)]$.

Step 3: Select different ε values in the value interval $[C_{CE}(X_2{}^*), C_{CE}(X_1{}^*)]$, and repeat Step 1 until the problem decision maker finds a satisfactory decision solution.

4.2. Model Linearization

In Section 3, an integrated energy community energy optimal allocation model with (11) and (23) as objective functions and (24)–(61) as constraints is established. There are nonlinear terms in Equations (41), (42), (45), (46), (49), (50), (53)–(55), and (58). The model is a mixed-integer nonlinear programming problem, which cannot be solved directly by commercial solvers. Among them, the nonlinear terms in constraints (41), (42), (45), (46), (49), and (50) are constant variables multiplied by 0–1 variables. They can be linearized directly by the Big-M method, where M is a large constant. There are bilinear terms in Equations (53)–(55), and (58), which cannot be converted by the Big-M method. Therefore, the McCormick relaxation method is used to deal with bilinear terms.

For the bilinear terms in (53)–(55), the auxiliary variable is defined as Equation (62).

$$E(t) = SOC(t) \cdot E_{BES} \tag{62}$$

The McCormick relaxation method is used to transform Equation (62) into the constraints shown in Equations (63)–(66), and Equation (62) is substituted into Equations (53)–(55) so as to eliminate the bilinear term and obtain the linearized constraints.

$$E(t) \le SOC_{\min} \cdot E_{BES} + SOC(t) \cdot E_{BES}^{\max} - SOC_{\min} \cdot E_{BES}^{\max} \tag{63}$$

$$E(t) \le SOC_{\max} \cdot E_{BES} + SOC(t) \cdot E_{BES}^{\min} - SOC_{\max} \cdot E_{BES}^{\min} \tag{64}$$

$$E(t) \ge SOC_{\max} \cdot E_{BES} + SOC(t) \cdot E_{BES}^{\max} - SOC_{\max} \cdot E_{BES}^{\max} \tag{65}$$

$$E(t) \ge SOC_{\min} \cdot E_{BES} + SOC(t) \cdot E_{BES}^{\min} - SOC_{\min} \cdot E_{BES}^{\min} \tag{66}$$

For the bilinear term in (58), the auxiliary variable is defined as Equation (67).

$$E^{HS}(t) = SOC^{HS}(t) \cdot E_{HS} \tag{67}$$

The McCormick relaxation method is used to transform Formula (67) into the constraints shown in Formulas (68)–(71), and Formula (67) is substituted into Formula (58) so that the bilinear term is eliminated and the linearized constraints are obtained.

$$E^{HS}(t) \le SOC_{\min}^{HS} \cdot E_{HS} + SOC^{HS}(t) \cdot E_{HS}^{\max} - SOC_{\min}^{HS} \cdot E_{HS}^{\max} \tag{68}$$

$$E^{HS}(t) \le SOC_{\max}^{HS} \cdot E_{HS} + SOC^{HS}(t) \cdot E_{HS}^{\min} - SOC_{\max}^{HS} \cdot E_{HS}^{\min} \tag{69}$$

$$E^{HS}(t) \ge SOC_{\max}^{HS} \cdot E_{HS} + SOC^{HS}(t) \cdot E_{HS}^{\max} - SOC_{\max}^{HS} \cdot E_{HS}^{\max} \tag{70}$$

$$E^{HS}(t) \ge SOC_{\min}^{HS} \cdot E_{HS} + SOC^{HS}(t) \cdot E_{HS}^{\min} - SOC_{\min}^{HS} \cdot E_{HS}^{\min} \tag{71}$$

After transforming MINLP into mixed-integer linear programming by the Big-M method and the McCormick relaxation method, the commercial solver CPLEX [20] or GUROBI [26] can be used to solve it.

5. Example Analysis

5.1. Scene Setting

In order to evaluate the comprehensive benefits of energy sharing and sharing the power storage system and heat storage system in the integrated energy community, this paper sets up five scenarios based on whether to consider sharing, whether to consider a power storage system, and whether to consider a heat storage system, the data are presented in Table 1, where "$\surd$" means considered and "$\times$" means not considered. The definition of each scenario is as follows.

Table 1. Case scenario setting.

	Whether to Consider Power Storage	Whether the Power Storage Is Shared	Whether to Consider Heat Storage	Whether the Heat Storage Is Shared
Scenario 1	√	√	√	√
Scenario 2	√	√	√	×
Scenario 3	√	×	√	×
Scenario 4	√	√	×	×
Scenario 5	√	×	×	×

Scenario 1: The community's power storage system and the community's heat storage system are installed simultaneously in the integrated energy community, and the power storage system and the heat storage system are shared within the community.

Scenario 2: A power storage system is installed in the integrated energy community, and the power storage system is shared in the community; the buildings in the community are separately installed with heat storage systems, and the individually configured heat storage systems are not shared within the community.

Scenario 3: The buildings in the integrated energy community are separately equipped with a power storage system and a heat storage system, and the separately configured power storage system and heat storage system are not shared within the community.

Scenario 4: The integrated energy community does not consider the configuration of a heat storage system and installs a community power storage system, and the power storage system is shared within the community.

Scenario 5: The configuration of a heat storage system is not considered in the integrated energy community. The buildings in the community are separately installed with a power storage system, and the individually configured power storage system is not shared within the community.

5.2. Basic Parameters and Data

For the sake of simplicity, the typical curves of clean energy power generation and electric heating and cooling loads are used as the input data for the example planning process. The number of buildings in the community is set to be three. It is assumed that Building 1 and Building 3 are configured with photovoltaic systems based on clean energy, and Building 2 is configured with wind power based on clean energy. The typical daily unit clean energy power generation coefficient of clean energy configured by each building is shown in Figure 2. The typical daily load demand of each building is shown in Appendix A, Figures A1–A3. The typical daily electricity purchase price from the grid and the on-grid price sold to the grid are shown in Figure 3. The fuel of the SOFC is natural gas, and the unit price of natural gas in this example is CNY 0.254/kWh. In the example, the scheduling period is 1 h; that is, $\Delta t = 1$.

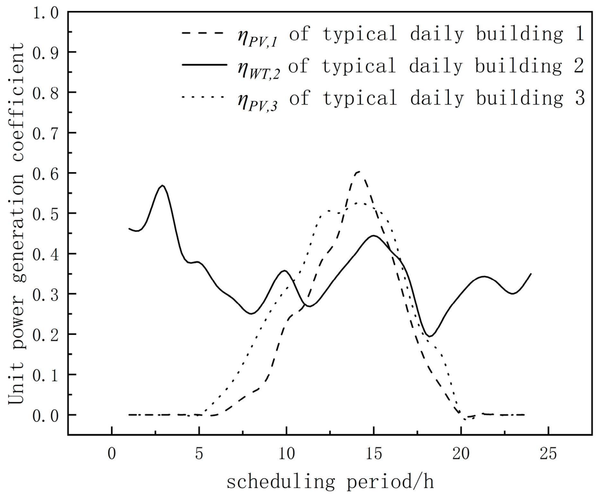

Figure 2. Coefficient of clean energy power generation per unit for a typical day.

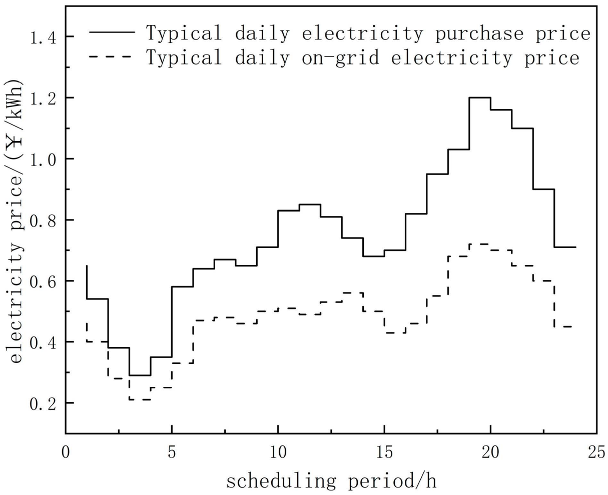

Figure 3. Typical daily electricity purchase price and on-grid electricity price.

It is assumed that the capacity-to-power ratio of the energy storage battery and the heat storage system is small enough to fully charge or discharge the energy storage system or the heat storage system between two continuous scheduling intervals. Other basic parameters are considered from economic, technical, and environmental perspectives and are listed in Appendix A, Table A1. The table contains parameters such as the primary investment costs of various pieces of energy equipment, the energy conversion efficiency of multi-energy equipment, and the carbon emission coefficient.

According to the actual project, the annual operation and maintenance costs of general energy equipment account for 1–5% of the cost of a single investment, and the situation is different according to the actual project. This paper assumes that the annual operation and maintenance costs of each piece of energy equipment are 2% of the investment costs. In addition, at present, the engineering life of a photovoltaic project is about 25–30 years, and the engineering life of a wind power project is lower than that of a photovoltaic project, about 20 years. The life of an energy storage project is shorter than that of photovoltaic and wind power projects. However, with the progress of technology, the life of an energy storage project will continue to increase in the future. For simplicity, this paper assumes that the life cycle of each piece of energy equipment is 20 years.

5.3. Result and Discussion

5.3.1. Analysis of Configuration Results under Different Restriction Domains, ε

In the fourth section of the model solution method, it is mentioned that different ε values are selected in the value range of the restricted domain, [$C_{CE}(X_2{}^*)$, C_{CE} $(X_1{}^*)$], and different optimization decision-making solutions can be obtained by repeating the transformed single-objective optimization solution process. The decision maker needs to select a satisfactory decision-making solution from different optimization decision-making solutions. Therefore, the energy equipment configuration under different ε values and the economic and environmental outcomes of the configuration results are analyzed in this section.

In order to obtain the value range of the limit domain [CCE (X2*), CCE (X1*)], the single-objective optimization decision-making processes for the economic target and the environmental target are carried out separately in the first scenario. The configuration result obtained by minimizing the annual total operating cost is shown in Table 2. Under the configuration result, the annual total operating cost of the integrated energy community is CNY 6.9130 million, the annual total carbon emission is 2708 tons, and the initial primary investment cost of all the energy equipment is CNY 101.21 million.

Table 2. Results of integrated energy optimization configuration obtained by minimizing total annual operating cost under Scenario 1.

Building	1	2	3
power storage/kWh		1270	
heat storage/kWh		2500	
clean energy/kW	5397	3100	0
SOFC/kW	375	0	450
heat pump/kW	0	844	30
electric refrigerator/kW	533	227	138
absorption refrigerator/kW	275	0	22

The configuration results obtained by minimizing the annual total carbon emissions as the objective function are shown in Table 3. Under this configuration result, the annual total operating cost of the integrated energy community is CNY 8.1564 million, the annual total carbon emissions are 1162 tons, and the initial primary investment cost of all the energy equipment is CNY 108 million.

Therefore, the value range of the restriction domain, ε, is [1162, 2708], and the unit is ton. The ε value represents the maximum estimation of the annual total carbon emissions of the integrated energy community. Different ε values are selected for optimization decision making, and the integrated energy equipment planning and configuration scheme under different carbon emissions expectations can be obtained. The annual total operating cost of the integrated energy community and the initial investment cost of energy equipment will also change with the change in the value of ε.

Table 3. Results of integrated energy optimization configuration obtained by minimizing total annual carbon emissions under Scenario 1.

Building	1	2	3
power storage/kWh		2500	
heat storage/kWh		909	
clean energy/kW	6166	3750	0
SOFC/kW	450	0	0
heat pump/kW	853	1103	882
electric refrigerator/kW	534	227	139
absorption refrigerator/kW	361	0	0

The trend of the annual total operating cost of the integrated energy community with the change in the value of ε is shown in Figure 4. With a decrease in the value of ε, that is, a reduction in the maximum estimated value of the annual total carbon emissions of the integrated energy community by the decision makers, the annual total operating costs gradually increase from CNY 6.9130 million when the ε value is 2708 tons to CNY 7.9547 million when the ε value is 1162 tons, and the annual total operating costs increase by 15.1%. At the same time, the annual total carbon emissions also decrease significantly, which indicates that the annual total operating costs and the annual total carbon emissions are inconsistent. When the decision makers have the demand for energy conservation and emission reduction, they need to increase the investment in energy equipment configuration and operation and exchange the investment of funds for environmental benefits.

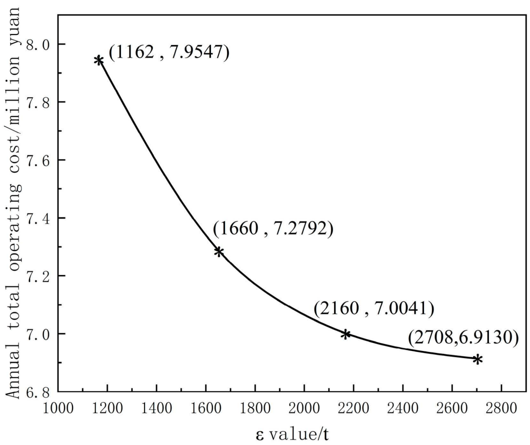

Figure 4. Annual total operating cost of integrated energy communities under different ε values.

For the sake of simplicity, only the results of the integrated energy optimization configuration of some labeled data points in Figure 4 are shown in Tables 4 and 5. It can be seen that when the value of ε decreases from 2708 tons to 1162 tons, the configuration capacity of the community power storage system increases from 1270 kWh to 2500 kWh, while the configuration capacity of the community heat storage system decreases from 2500 kWh to 1051 kWh, which corresponds to an increase in the configuration scale of the clean energy power station in the integrated energy community and a decrease in the configuration scale of the SOFC. At the same time, the configuration capacity of the heat pump and the electric refrigerator with electrical energy as the input energy in the integrated energy community also increases.

Table 4. Integrated energy optimization configuration results when the ε value is 2708 under the bi-objective optimization in Scenario 1.

Building	1	2	3
power storage/kWh		1270	
heat storage/kWh		2500	
clean energy/kW	5397	3100	0
SOFC/kW	375	0	450
heat pump/kW	0	357	516
electric refrigerator/kW	533	227	138
absorption refrigerator/kW	275	0	22

Table 5. Integrated energy optimization configuration results when the ε value is 1162 under the bi-objective optimization in Scenario 1.

Building	1	2	3
power storage/kWh		2500	
heat storage/kWh		1051	
clean energy/kW	6179	3750	0
SOFC/kW	428	0	0
heat pump/kW	853	804	89
electric refrigerator/kW	533	227	138
absorption refrigerator/kW	343	0	0

This shows that when the value of ε is reduced, decision makers have higher requirements for carbon emission reduction, and communities are expected to emit less carbon. The main energy sources of the community are the energy produced by the clean energy power station and the energy generated by the SOFC, which consumes natural gas. As clean energy, wind power and photovoltaic power are almost equivalent to zero carbon emissions in the process of producing electrical energy. As a fossil fuel, natural gas has a low carbon emission coefficient, but it will still produce a certain amount of carbon emissions. Then, driven by the goal of energy conservation and emission reduction, the planning and configuration of the integrated energy community will shift from natural gas to the clean energy of wind power and photovoltaic systems.

The main sources of the community's carbon emissions are the carbon emissions converted from the purchase of electricity from the power grid and the carbon emissions generated by the SOFC, which uses natural gas as fuel. Reducing carbon emissions must start with these two aspects. On the one hand, more wind power, photovoltaic power, and power storage systems are configured to reduce the interaction between the community and the power grid. On the other hand, fewer SOFCs are configured to minimize the consumption of natural gas while ensuring economic efficiency. In this process, decision makers also need to incur higher costs in exchange for environmental benefits.

5.3.2. Analysis of Energy Configuration Results in Different Scenarios

In the context of the example scenarios, five scenarios were established to assess the comprehensive benefits of energy sharing and sharing power storage and heat storage systems within the integrated energy community. The outcomes of the community's energy optimization configurations, derived by minimizing the total annual operating costs in Scenario 1, are presented in Table 2. Meanwhile, the optimization configurations for the integrated energy community in the other four scenarios, under the same objective function, are detailed in Table 6. And the capacity of power storage, heat storage, and clean energy configurations in comprehensive energy communities under different scenarios is shown in Figure 5.

Table 6. Results of integrated energy optimization configuration obtained by minimizing total annual operating cost under Scenarios 2, 3, 4, and 5.

	Scenario 2			**Scenario 3**			**Scenario 4**			**Scenario 5**		
Building	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
power storage/kWh		660		0	1018	0		2302		5000	1948	0
heat storage/kWh	2500	2500	1885	2500	2500	1886		/			/	
clean energy/kW	4553	3750	509	5008	2747	1000	5431	3731	0	6103	3262	1000
SOFC/kW	375	0	450	425	0	240	434	0	450	438	0	245
heat pump/kW	338	410	0	374	345	37	405	513	83	362	513	165
electric refrigerator/kW	518	227	102	533	227	100	533	227	133	533	227	138
absorption refrigerator/kW	80	0	350	275	0	192	0	0	75	0	0	75

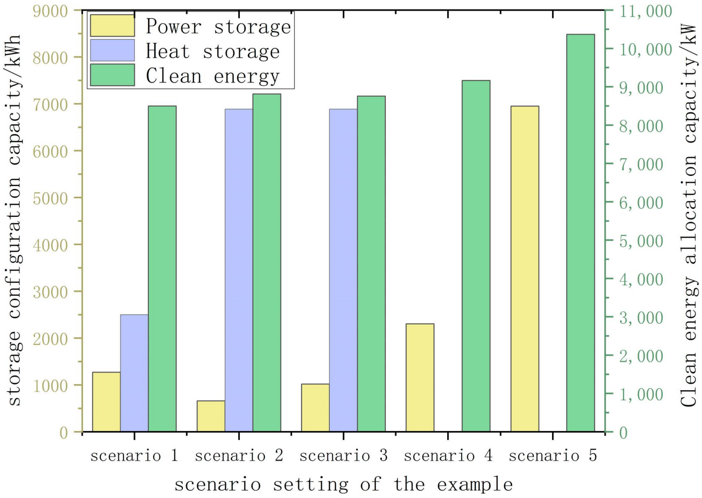

Figure 5. The storage and clean energy capacity of integrated energy community configuration results in different scenarios.

Scenario 2: The community power storage system is configured at 660 kWh, representing a 48% reduction compared to the 1270 kWh configuration in Scenario 1. Achieving savings in storage capacity is facilitated by individual thermal storage systems for each building. Simultaneously, the capacity of the community's heat storage system increases by 175.4%. The capacity of the SOFCs in each building remains unchanged, while adjustments are made to the configurations of solar and wind energy. This modification reflects the improved ability of each building to cater to its own electric heating and cooling load needs through separate thermal storage system configurations. The overall community clean energy configuration increases from 8498 kW to 8812 kW. The shared heat storage systems effectively mitigate the configuration capacity of the power storage and heat storage systems, thereby enhancing the overall community's energy utilization.

Scenario 3: The individually configured heat storage systems in each building exhibit almost identical capacities. Consequently, neither Building 1 nor Building 3 is equipped with a power storage system. Building 2 alone is furnished with a 1018 kWh power storage system, surpassing the 660 kWh storage system in Scenario 2 by 54.2%. This choice is influenced by the higher investment costs associated with electrical storage systems, rendering thermal storage systems more preferable in the absence of sharing. The communal sharing of power storage systems effectively diminishes the demand for power storage configurations, thus improving the utilization rate of power storage equipment.

Scenario 4: The capacity of the community's power storage system configuration reaches 2302 kWh, marking an 81.3% increase compared to that in Scenario 1. The overall clean energy deployment capacity also experiences a 7.8% increment. Building 3 continues to refrain from adopting clean energy, opting for a more stable SOFC. This strategic decision arises from the communal sharing conditions, where solar energy is more aligned with the community's overall planning needs in Building 1. The configuration of the thermal storage system effectively reduces the demand for a power storage system while enhancing the production and utilization efficiency of clean electrical energy.

Scenario 5: Each building independently configures a power storage system. The integrated energy community is equipped with a total power storage system capacity of 6948 kWh, marking a 202% increase over the 2302 kWh capacity in Scenario 4. Concurrently, the clean energy allocation capacity also sees a 13.1% increase. A comparative analysis between Scenarios 4 and 5 reaffirms that the community sharing model can effectively reduce the configuration capacity of the energy equipment and enhance its utilization rate.

5.3.3. Analysis of Economic and Environmental Benefits of Different Scenarios' Configurations

The total annual operating cost, the initial investment cost of integrated energy equipment, and the total annual carbon emissions of the integrated energy community under the five scenarios are shown in Figure 6.

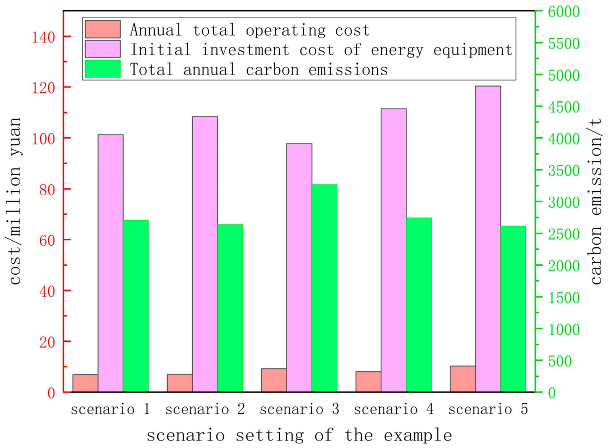

Figure 6. Cost and carbon emissions of integrated energy community configuration results in different scenarios.

Scenario 1: This is the baseline scenario, in which the community shares an electricity storage system and a heat storage system, and the goal of the optimal configuration is to minimize the total annual operating cost. The total annual operating cost, the initial investment cost of the energy equipment, and the total annual carbon emissions in this scenario are CNY 6.913, CNY 101.21 million, and 2708 tons, respectively, which is the lowest among the five scenarios.

Scenario 2: Each building is equipped with a separate thermal storage system, and the community shares a power storage system. The goal of optimizing the configuration is the same as in Scenario 1. In this scenario, the annual total operating cost, the initial one-time investment cost of the energy equipment, and the total annual carbon emissions are CNY 7.043 million, CNY 108.41 million, and 2638 tons, respectively. Compared with scenario 1, the operating cost and investment cost have increased, but carbon emissions have decreased because the expanded use of thermal storage systems has improved the community's energy efficiency.

Scenario 3: Each building is configured with a separate thermal storage system and a power storage system without sharing. The goal of optimizing the configuration is the same as in Scenario 1. In this scenario, the annual total operating costs, the initial one-time investment cost of the energy equipment, and the total annual carbon emissions are CNY 9.1947 million, CNY 97.741 million, and 3266 tons, respectively. Compared with scenario 2, the operating costs and carbon emissions have increased significantly, but the investment cost has been reduced. This is because each building can configure the most suitable energy equipment capacity according to its own electric, heating, and cooling load needs. There is no energy equipment margin, but this also reduces the sharing and exchange of energy, resulting in lower energy utilization efficiency.

Scenario 4: The community shares a power storage system and a heat storage system, but no heat storage system is configured. The goal of optimizing the configuration is the same as in Scenario 1. In this scenario, the annual total operating costs, the initial one-time investment cost of the energy equipment, and the total annual carbon emissions are CNY 8.1545 million, CNY 111.49 million, and 2745 tons, respectively. Compared with scenario 1, the operating costs and investment costs have increased, and the carbon emissions have also increased slightly. This is because the lack of thermal storage systems leads to the need for communities to configure more high-cost electricity storage systems. It also increases their dependence on SOFCs and reduces the proportion of clean electricity used.

Scenario 5: Each building is equipped with an independent power storage system. There is no sharing and no heat storage system. The goal of optimizing the configuration is the same as in Scenario 1. In this scenario, the total annual operating cost, the initial one-time investment cost of the energy equipment, and the total annual carbon emissions are CNY 10.1995 million, CNY 120.367 million, and 2615 tons, respectively. Compared with scenario 4, the operating cost and investment cost have increased significantly. However, the carbon emissions have decreased. This is because each building is equipped with more clean energy and power storage systems, which reduces the reliance on SOFC but also reduces the utilization and efficiency of the energy equipment.

From the above comparative analysis, it can be seen that the community sharing model can reduce the planning and configuration capacity of various pieces of energy equipment in the integrated energy community, improve the utilization rate and efficiency of the energy equipment, and balance the clean energy production efficiency and electric heating and cooling load demand of each building. While reducing the annual configuration cost and the initial investment cost of the energy equipment, it can also reduce the number of power purchases and sales with the power grid, improve the efficiency of natural gas energy use, reduce the carbon emissions of the integrated energy community, and achieve the role of energy conservation and emission reduction; the cost of a heat storage system is lower than that of a power storage system. The use of a power storage system with a heat storage system can effectively reduce the demand on the power storage system. The disadvantage is that the integrated energy community may rely more on natural gas and thermal energy systems, thereby reducing the use of clean energy. Relatively speaking, it may not be conducive to carbon emission reduction. Therefore, it is necessary to balance the economic cost of planning and configuration with the environmental benefits of energy conservation and emission reduction and comprehensively consider the optimal configuration of a power storage system and a heat storage system.

6. Conclusions

Based on the concept of sharing, this paper constructs a multi-energy and energy storage sharing operating model of an electricity–gas–cooling–heat integrated energy community containing solid oxide fuel cells (SOFCs) and proposes a unified energy management strategy for integrated energy communities that can be used. The unified optimization planning of energy in smart integrated energy communities achieves the purpose of improving energy utilization efficiency and reducing energy allocation costs. The main results and conclusions of this paper are as follows:

(1) A dual-objective optimal energy allocation model considering economic and environmental factors is established. In order to facilitate a rapid solution, the ε-constraint method is used to simplify the multi-objective problem into a single-objective problem, and the nonlinear constraints are linearized through the Big-M method and the McCormick relaxation method.

(2) The analysis results of the examples under the different scenarios show that as the value of ε decreases, the maximum estimate of the annual total carbon emissions of the integrated energy community by decision makers decreases. Along with this, the

annual total operating cost of the integrated energy community gradually decreases. Therefore, in this process, decision makers need to incur higher economic costs in exchange for environmental benefits. This reveals that decision makers can achieve a balance between carbon emission reduction and operating costs by adjusting the ε value and adjusting different energy configurations.

(3) The sharing of thermal storage systems and power storage systems can effectively reduce the configuration capacity and planning costs of comprehensive energy communities and improve energy utilization and energy equipment utilization. At the same time, the cost of thermal storage systems is lower than that of power storage systems, but the configuration is over-configured. Multiple heat storage systems are not conducive to the reduction carbon emissions from comprehensive energy sources. Therefore, in terms of energy allocation, it is necessary to comprehensively consider economic costs, energy conservation, and emission reduction to coordinate and optimize the configuration of power storage systems and heat storage systems.

Author Contributions: Formal analysis, J.L. and X.C.; investigation, J.N.; methodology, J.L. and P.L.; project administration, J.L. and X.C.; resources, J.N. and P.L.; software, P.L. and P.T.; supervision, J.L. and X.C.; validation, P.L. and P.T.; visualization, P.L.; writing—original draft, P.L. and P.T.; writing—review and editing, P.T. and X.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by National Natural Science Foundation of China, grant number 72174151, and the Hubei Electric Power Technical Service Project (SGDLJY00JSJS2310034).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: Authors Jiangping Liu and Jianghong Nie were employed by the company Hubei Power Exchange Center. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix A

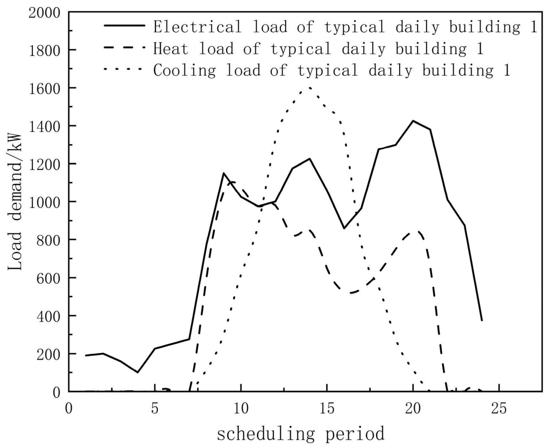

Figure A1. Typical daily load demand for Building 1.

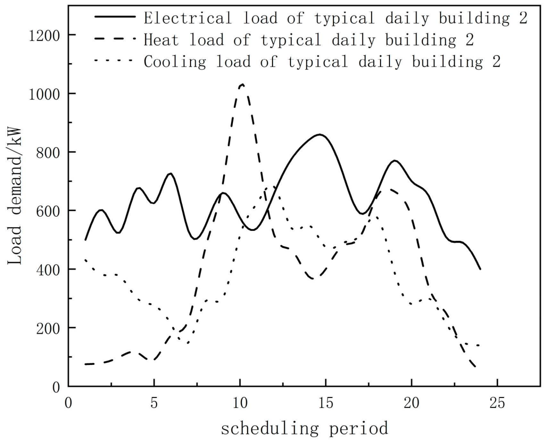

Figure A2. Typical daily load demand for Building 2.

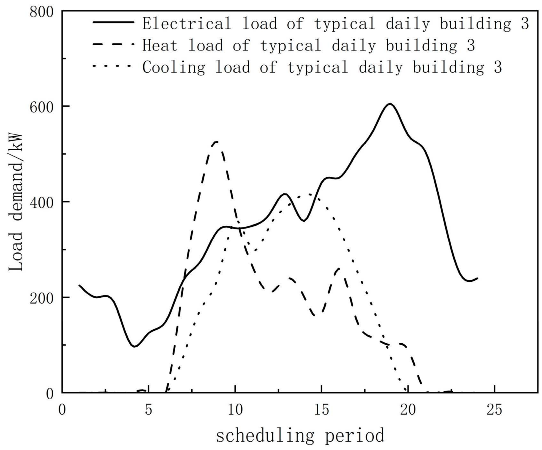

Figure A3. Typical daily load demand for Building 3.

Table A1. Basic examples of economic, technological, and environmental parameters.

	Parameter	Numerical Value	Unit
economic parameters	discount rate	5%	
	plant life cycle	20	year
	the primary investment cost of power storage system	1500	CNY/kWh
	primary investment cost of heat storage system	400	CNY/kWh
	primary investment cost of photovoltaic system	3500	CNY/kWp
	primary investment cost of wind power system	7500	CNY/kW
	the first investment cost of SOFC system	19,000	CNY/kW
	primary investment cost of heat pump	1275	CNY/kW
	the first investment cost of electric refrigerator	970	CNY/kW
	the first investment cost of absorption refrigerator	1200	CNY/kW
	charging efficiency of power storage system	88%	
	discharge efficiency of power storage system	88%	
	the maximum state of charge of the storage system	0.9	
	the minimum state of charge of the storage system	0.1	
	charging efficiency of heat storage system	88%	
	heat release efficiency of heat storage system	88%	
	the maximum heat storage state of the heat storage system	0.9	
	the minimum heat storage state of the heat storage system	0.1	
technical parameters	the upper limit of photovoltaic system planning in Building 1 the upper limit of photovoltaic system planning in Building 1	7500	kWp

Table A1. *Cont.*

	Parameter	Numerical Value	Unit
	the upper limit of wind power system planning in Building 2	3750	kW
	the upper limit of photovoltaic system planning in Building 3	1000	kWp
	the upper limit of SOFC system planning in buildings	450	kW
	the electrical efficiency of SOFC	45%	
	the output thermoelectric ratio of SOFC	80%	
	heat efficiency of heat pump	2	
	cooling efficiency of an electric refrigerator	3	
	refrigeration efficiency of absorption refrigerators	1	
environmental parameters	unit carbon emission coefficient of power grid	0.673	kg/kWh
	the unit carbon emission coefficient of natural gas	0.180	kg/kWh

References

1. El Bassam, N. Current distributed renewable energy in rural and urban communities. In *Distributed Renewable Energies for Off-Grid Communities*; Elsevier Inc.: Amsterdam, The Netherlands, 2021; pp. 297–326.
2. Liu, C.; Wang, H.; Wang, Z.; Liu, Z.; Tang, Y.; Yang, S. Research on life cycle low carbon optimization method of multi-energy complementary distributed energy system: A review. *J. Clean. Prod.* **2022**, *336*, 130380. [CrossRef]
3. Bucking, S.; Dermardiros, V. Distributed evolutionary algorithm for co-optimization of building and district systems for early community energy masterplanning. *Appl. Soft Comput.* **2018**, *63*, 14–22. [CrossRef]
4. Wang, Y.; Li, R.; Dong, H.; Ma, Y.; Yang, J.; Zhang, F.; Zhu, J.; Li, S. Capacity planning and optimization of business park-level integrated energy system based on investment constraints. *Energy* **2019**, *189*, 116345. [CrossRef]
5. Lin, Y.J.; Miao, S.H.; Yin, X.B. Optimal planning for economy and reliability of integrated energy system based on improved co-evolution algorithm. *Electr. Power Autom. Equip.* **2021**, *41*, 173–181.
6. Gao, J.; Gao, F.; Ma, Z.; Huang, N.; Yang, Y. Multi-objective optimization of smart community integrated energy considering the utility of decision makers based on the Lévy flight improved chicken swarm algorithm. *Sustain. Cities Soc.* **2021**, *72*, 103075. [CrossRef]
7. Liu, Z.; Guo, J.; Wu, D.; Fan, G.; Zhang, S.; Yang, X.; Ge, H. Two-phase collaborative optimization and operation strategy for a new distributed energy system that combines multi-energy storage for a nearly zero energy community. *Energy Convers. Manag.* **2021**, *230*, 113800. [CrossRef]
8. Chao, Q.; Xiaofeng, D.; Tong, J. Optimization planning of integrated electricity-gas community energy system based on coupled CCHP. *Power System Technol.* **2018**, *42*, 2456–2466.
9. Cui, Q.; Bai, X.; Dong, W.; Huang, B. Joint optimization of planning and operation in user-side multi-energy systems. *Proc. CSEE* **2019**, *39*, 4967–4981+5279.
10. Zhang, Y.; Campana, P.E.; Lundblad, A.; Zheng, W.; Yan, J. Planning and operation of an integrated energy system in a Swedish building. *Energy Convers. Manag.* **2019**, *199*, 111920. [CrossRef]
11. Li, C.; Yang, H.; Shahidehpour, M.; Xu, Z.; Zhou, B.; Cao, Y.; Zeng, L. Optimal planning of islanded integrated energy system with solar-biogas energy supply. *IEEE Trans. Sustain. Energy* **2019**, *11*, 2437–2448. [CrossRef]
12. Ko, W.; Kim, J. Generation expansion planning model for integrated energy system considering feasible operation region and generation efficiency of combined heat and power. *Energies* **2019**, *12*, 226. [CrossRef]
13. Liu, J.; Liu, S. Optimal distributed generation allocation in distribution network based on second order conic relaxation and big-m method. *Power Syst Technol.* **2018**, *42*, 2604–2611.
14. Zhang, C.; Kai, K.A.; Sheng, L.U.; Xinyu, Q.I.; Huang, Y.; Zhengtian, L.I. Economic scheduling of renewable energy storage plants with integrated thermal management of energy storage systems and battery life. *Energy Storage Sci. Technol.* **2021**, *10*, 1353.
15. Jiang, Z.; Liu, T.; Jiang, X.; Sheng, G. Reconfiguration of active distribution network considering DG and load uncertainty. *Electr. Meas. Instrum.* **2019**, *56*, 76–84.
16. Sun, J.; Hu, J.; Wei, F. Optimal power configuration of distributed generation operator considering cooperation of stakeholders. *Electr. Power Constr.* **2021**, *42*, 127–134.
17. Jing, R.; Wang, M.; Liang, H.; Wang, X.; Li, N.; Shah, N.; Zhao, Y. Multi-objective optimization of a neighborhood-level urban energy network: Considering Game-theory inspired multi-benefit allocation constraints. *Appl. Energy* **2018**, *231*, 534–548. [CrossRef]
18. Sun, W.; Chen, Z.; Zhang, Y.; Su, Z.; Sun, L. Economic day-ahead scheduling of sofc-based integrated tri-generation energy system using dynamic programming. *Proc. CSEE* **2022**, *42*, 7775–7784.
19. Rao, Y.; Cui, X.; Zou, X.; Ying, L.; Tong, P.; Li, J. Research on Distributed Energy Storage Planning-Scheduling Strategy of Regional Power Grid Considering Demand Response. *Sustainability* **2023**, *15*, 14540. [CrossRef]
20. CPLEX. *IBM ILOG CPLEX Optimization Studio V12.10*; IBM: New York, NY, USA, 2023.
21. AlSkaif, T.; Luna, A.C.; Zapata, M.G.; Guerrero, J.M.; Bellalta, B. Reputation-based joint scheduling of households appliances and storage in a microgrid with a shared battery. *Energy Build.* **2017**, *138*, 228–239. [CrossRef]

22. Van Der Stelt, S.; AlSkaif, T.; Van Sark, W. Techno-economic analysis of household and community energy storage for residential prosumers with smart appliances. *Appl. Energy* **2018**, *209*, 266–276. [CrossRef]
23. Mehrtash, M.; Capitanescu, F.; Heiselberg, P.K.; Gibon, T.; Bertrand, A. An enhanced optimal PV and battery sizing model for zero energy buildings considering environmental impacts. *IEEE Trans. Ind. Appl.* **2020**, *56*, 6846–6856. [CrossRef]
24. Zhao, N.; Gu, W. Low-carbon planning and optimization of the integrated energy system considering lifetime carbon emissions. *J. Build. Engg.* **2024**, *82*, 108178. [CrossRef]
25. Zhu, X.L.; Ding, S.; Zhu, W.L. An energy optimization model of iron and steel supply chain using ε-constraint method and interval linear programming approach. *J. Ind. Eng. Eng. Manag.* **2016**, *30*, 243–250.
26. GUROBI. *Gurobi Optimizer Reference Manual (Version 9.5)*; Gurobi Optimization, LLC: Beaverton, OR, USA, 2023.