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Research on the Optimal Operation of a Novel Renewable Multi-Energy Complementary System in Rural Areas

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Abstract: Sustainable development is an inevitable choice for the development of human society, and energy is closely related to sustainable development. Improving energy structure, increasing energy efficiency, and vigorously developing renewable energy are of great significance to the sustainable development of rural areas. Moreover, the establishment of a distributed multi-energy complementary system (MECS) using abundant renewable energy such as wind, solar, and biomass energy is an effective way to solve the rapid growth of rural power demand, weak rural power grids, and rural environmental pollution. This paper proposes a new type of Wind–Solar–Biomass–Storage MECS composed of wind power generation (WPG), photovoltaic power generation (PVG), biogas power generation (BPG) and energy storage system (ESS) and establishes a MECS optimization operation model with the goal of maximizing daily operating economic benefits, considering the characteristics of each power generation system and power demand characteristics. By using the multi-population genetic algorithm (MPGA), the simulation experiments of the MECS operation under four typical weather scenarios are carried out. The results show that the MECS can operate stably in different scenarios and achieve the goal of maximizing economic benefits, which verifies the feasibility of the MECS model. In addition, the simulation results are compared with the standard genetic algorithm (SGA), which shows the effectiveness of the optimization method. This paper takes Chinese rural areas as an example for research. The proposed MECS and optimal operation model are also applicable to developing countries with a high proportion of the rural population.

Keywords: multi-energy complementation system (MECS); optimal operation; renewable energy; multi-population genetic algorithm (MPGA); rural areas

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1. Introduction

Energy shortage and climate change are major challenges facing the world today [1]. Developing a low-carbon economy and completing an energy consumption structure dominated by clean energy consumption is an inevitable choice for achieving sustainable development [2]. In recent years, most countries have a deeper understanding of renewable energy and its impact on the ecological environment [3]. According to the "China Renewable Energy Development Roadmap 2050", the proportion of renewable energy power generation in China's power supply will reach 86% by 2050 [4]. Among many renewable energy sources, solar energy, wind energy, and water energy are the main substitutes for traditional energy [5]. These clean energy sources have received a lot of attention in the single energy system and multi-energy complementary system (MECS).

Rural areas are the key to economic growth in developing countries. In recent years, with the development of the rural economy and the improvement of residents' living standards, the demand for electricity in rural areas is growing rapidly, which puts forward higher requirements for energy supply [6]. Based on the data released by the "China Statistical Yearbook", during the ten years from 2009 to 2019, China's rural electricity consumption increased from 610.44 billion kWh to 948.29 billion kWh, with a growth

rate of 55% [7]. However, it is difficult to meet the growing demand for electricity in rural areas due to the aging and backward power facilities, weak power grid structure, and poor power supply capacity [8]. Large-scale transformation and upgrading of rural power grids will require huge investment and a long period of time. Moreover, large power grids have a high cost of power supply and a large transmission loss in remote areas [9]. At the same time, the biomass energy resources in rural areas are extremely rich, the annual amount of straw in rural areas is about 700 million tons, and the amount of livestock manure is also very large [7]. At present, the utilization of biomass energy in rural areas is mostly at the primary stage, such as the direct combustion of biomass energy and the direct irrigation of manure. Such utilization methods are not only inefficient but also cause serious environmental pollution [10]. Therefore, it has become a consensus to develop and utilize the abundant wind energy, solar energy, biomass energy, and other resources in rural areas according to local conditions, replace traditional fossil energy with renewable energy, reduce environmental pollution caused by energy consumption, and achieve sustainable development [11]. Meanwhile, the construction of a renewable MECS has become an important measure to ensure the reliable supply of rural energy, promote rural energy transition, and achieve sustainable development.

Due to the volatility and intermittency of wind and photovoltaic power generation, the reliability of single energy power generation is poor, and its development is restricted. In recent years, there is abundant literature on renewable energy MECSs represented by photovoltaic and wind power, including wind–solar [12], wind–solar–storage [13], wind–solar–hydro [14,15], wind–solar–thermal–hydro [16], wind–solar–diesel [17,18] and other different systems. However, compared with the mature energy categories of photovoltaics and wind power, although biomass energy has huge reserves, its application is not widespread. In order to promote the rational development and utilization of biomass energy, some scholars have conducted studies on the feasibility, environmental and economic benefits of biomass power generation (BPG) systems. Zhang et al. adopted an economic analysis method considering environmental benefits to study the large-scale farm BPG system. The results showed that the large-scale farm BPG system had greater environmental and higher economic benefits than coal-fired power generation [19]. Bernal et al. studied and calculated the relevant potential energy based on the biogas production process by anaerobic digestion of distiller's grains, and demonstrated that BPG can obtain environmental and energy benefits [20].

As hinted above, BPG has good economic and environmental benefits, but its application research in MECS is still rare. Unlike solar energy and wind energy, which have many different combination types with other energy sources, the current research on the combination of biomass energy and other energy sources is mainly solar–biomass energy MECS. Ankit et al. established a solar–biogas hybrid renewable energy system suitable for rural areas in India and used a particle swarm optimization algorithm to optimize the system capacity. The research results showed that the built system was more economical than similar systems [21]. Heydari et al. regarded the BPG system as a backup system for off-grid photovoltaic power plants in view of its reliability, and optimized the area of the photovoltaic system and the size of the generator set in the proposed hybrid system. The research results showed that the solar–biomass energy hybrid power generation system is better than a single power generation system [22]. In the current literature, the operation mode of the MECS is mainly divided into two types: the grid-connected type [23] and the off-grid type [24]. However, the grid-connected type mainly adopts the operation mode of selling the residual electricity to the grid, which could have an impact on the security of grid operation, and also cause wind and solar abandonment. Moreover, the off-grid type needs to be equipped with a large-capacity energy storage device, and the investment cost is high.

The optimal operation of the MECS is mainly based on different optimization objectives and constraint conditions to distribute the load of the units. The optimization objectives include economic, environmental, and other indicators. Among them, the eco-

nomic indicators are adopted the most, mainly considering the maximum comprehensive income and the minimum comprehensive cost of the system. At present, heuristic algorithms are mostly used to solve such optimization problems, such as particle swarm optimization [25], firefly algorithm [26], genetic algorithm [27,28], etc. Yu et al. used existing hydropower stations as power generation and energy storage components, and then introduced wind and solar hybrid power generation, established a complementary micro-grid optimization operation model, and used particle swarm optimization to optimize the system with the goal of maximizing daily income [29]. Yang et al. configured pumped storage power stations in the wind–solar hybrid power generation system to form a wind–solar–pumped–storage joint operation system. With the goal of maximizing system economic returns, an improved particle swarm algorithm was used to solve the optimization model of system capacity configuration. The results showed that pumped storage power plants can improve the utilization efficiency of wind and solar energy, and can increase the economic benefits of wind and solar power generation systems [30].

The main purpose of this article is to propose a wind–solar–biomass–storage MECS suitable for rural areas, which can not only solve the problem of environmental pollution such as straw burning in place in rural areas but also meet the growing power demand in rural areas. In addition, to maximize the daily operating benefit of the system, the optimization operation model of the MECS is established by fully considering the generation characteristics and operation constraints of various energy sources. The multi-population genetic algorithm (MPGA) is introduced to solve the simulation case, and the optimal operation mode of the system under four typical weather scenarios is obtained, which further verifies the effectiveness and realizability of the MECS. Finally, the research results of this paper will be of great significance to solve the energy shortage and ecological problems in rural areas of developing countries. This will help drive policymakers to actively develop renewable energy in rural areas and realize sustainable economic and power development.

In summary, the main contributions of this paper are summarized as follows.

- Propose a new type of wind–solar–biomass–storage MECS suitable for rural areas. The system can not only effectively promote the rural energy transition but also has great significance for achieving carbon neutrality in the energy system.
- Adopt a more practical grid-connected non-sales operation mode. That is, renewable power generation is all absorbed locally, and the insufficient part is supplemented by power purchase from the power grid. This operation mode can effectively reduce wind and solar abandonment and can reduce the impact of system grid connection on the grid.
- Establish a system economic operation optimization model and use an improved genetic algorithm to realize the simulation. This method overcomes the shortcomings of the standard genetic algorithm (SGA) which is easy to converge prematurely. In addition, the simulation results are compared with the SGA to verify the effectiveness of the MPGA.

2. System Description

Limited by natural conditions, wind power and photovoltaic power generation have random properties, which have a certain impact on the stability and safety of the energy supply [31]. The MECS studied in this paper adds energy storage equipment and operates in a way of connecting to the grid without selling electricity. The power generated by wind, solar, and biomass energy can be consumed locally, and the shortfall is supplemented by purchasing electricity from the grid.

2.1. System Structure

The wind–solar–biomass–storage MECS is mainly composed of wind power generation (WPG), photovoltaic power generation (PVG), biogas power generation (BPG), energy storage system (ESS), control system, and load [32]. The system structure is shown in Figure 1.

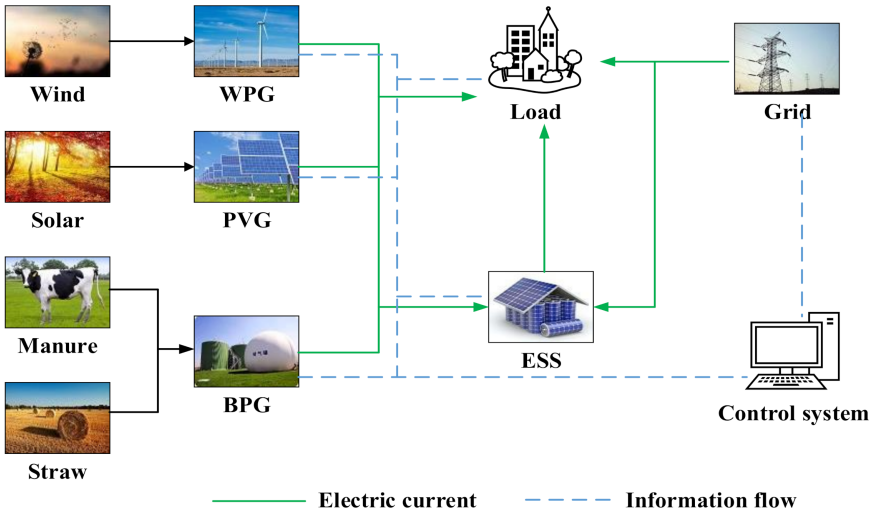


Figure 1. The basic structure of the wind–solar–biomass–storage multi-energy complementary system (MECS).

2.2. Principle of System Operation

In the wind–solar–biomass–storage MECS, the output of the power supply is mainly composed of WPG, PVG, BPG, and ESS discharge. WPG and PVG output are greatly affected by the climate, so they are uncontrollable units. BPG is relatively stable and can be flexibly dispatched as a controllable unit [33]. In the grid-connected non-sales operation mode, the ESS is a significant component of ensuring the safe operation of the system, which can play a role in balancing the time difference between the power supply and demand [34]. The charging and discharging state of the ESS is generally determined by the electricity price, system load level, and the state of charge of the ESS itself, so it is also a controllable unit.

The working principle of the system is that WPG and PVG provide power first. If there is still surplus after the WPG and PVG meet the load demand, the remaining power generation is used for charging the ESS; if the WPG and PVG cannot meet the load demand, it can choose BPG and ESS to fill the gap; and when the system power generation and the stored electricity cannot meet the load demand, the power supply can be guaranteed by purchasing electricity from the power grid. The system can also take advantage of the grid's peak-to-valley price difference, purchase electricity during low electricity price periods to charge the ESS, and discharge the ESS to provide electrical energy to the load during peak electricity price periods, so as to reduce system power purchase costs. The monitoring and management center is responsible for the coordinated control of the entire system through the controller. It manages the operation state of each generation power in real-time to ensure the stable operation of the system and coordinate the load demand of all parties [35].

The system not only meets the electricity demand in rural areas but also makes full use of renewable energy. In addition, it can also improve the environment, reduce dependence on the power grid, and achieve coordinated development of energy, environment, and economy.

3. Methodology Description

3.1. Optimal Operation Model of the System

3.1.1. System Operation Objective

On the ground of the forecast results of load and wind, photovoltaic power output in the next 24 h, the objective of the optimal operation of the MECS is to maximize the daily economic benefit by optimizing the output plan of controllable units in each period under the basic premise of ensuring the safe and stable operation of the system, which including BPG, ESS charge and discharge power and power purchase. Among them, the

revenue includes the system to load end electricity sale revenue and state subsidy revenue. The expenditure includes system operation and maintenance costs, generation costs, and purchase costs [36]. Since WPG and PVG use natural wind and solar energy, the marginal cost of power generation is extremely low. The raw materials of BPG are agricultural and forestry wastes and livestock manure, and their collection costs are also low. Therefore, this article ignores the power generation cost of WPG, PVG, and BPG

Above all, the economic benefit F of the system running for one day can be expressed as

$$\max F = \sum_{t=1}^{24} \left(\gamma_t P_{load}(t) + \sum_{i=1}^{3} k_i P_i(t) - \beta |P_{ES}(t)| - \alpha_t P_G(t) \right) - \sum_{i=1}^{4} C_i, \quad (1)$$

where γ_t is the electricity price that the system sells to the load terminal during t period; $P_{load}(t)$ is the power load of the system during the period t; α_t is the electricity price purchased from the grid during t period; $P_G(t)$ is the electricity purchased from the grid during t period; β shows the unit charge and discharge cost coefficient of the ESS; $P_{ES}(t)$ is the charge and discharge power of energy storage in t period, the value is negative for charge and positive for discharge; k_i denotes subsidized electricity prices for wind (photovoltaic, biogas) power generation; $P_i(t)$ is the generation power of the power generation system i during the t period; C_i represents the daily operation and maintenance cost of power generation system i; among them, i = 1,2,3,4 indicates WPG, PVG, BPG, and ESS, respectively.

3.1.2. System Constraints

(1) Load supply and demand balance constraint

In order to ensure the safety of the system and the service life of the equipment, the balance of supply and demand is regarded as a strong constraint [37]. According to the power balance constraint, the following formula can be obtained:

$$P_{PV}(t) + P_{wind}(t) + P_{BIG}(t) + P_G(t) + P_{ES}(t) = P_{load}(t), \quad (2)$$

where $P_{PV}(t)$ is the output power of PVG during the t period; $P_{wind}(t)$ is the output power of WPG during the t period; $P_{BIG}(t)$ is the output power of BPG during the t period.

(2) Units output constraint

In order to ensure the safety and stability of system operation, each power generation system (including ESS) has strict upper and lower limits [38]. This paper does not consider the upper and lower limits of the circulating power of the tie line.

$$P_i^{\min} \le P_i(t) \le P_i^{\max}, \quad (3)$$

where $P_i(t)$ is the generation power of the power generation system i during the t period, among them, i = 1,2,3,4 indicates WPG, PVG, BPG, and ESS respectively, and the superscripts max and min, respectively, represent the maximum and minimum output power of each power generation system.

(3) Daily biogas power generation constraint

Livestock farms in rural areas produce large amounts of livestock manure every day, failure to treat them in time will cause certain pollution to the soil, water bodies, and air environment, and will also lead to the spread of pathogenic bacteria, posing a threat to the health of livestock and humans [39]. BPG can realize the effective utilization of agricultural and forestry wastes and livestock manure in rural areas, which has good environmental and social benefits. In order to timely absorb the daily livestock manure, make rational use of agricultural and forestry waste resources in rural areas, and reduce environmental

pollution, considering the scale of these resources, the total daily power generation of the BPG system is set as a fixed value in the system operation.

$$\sum_{t=1}^{T} P_{BIG}(t) = M, \tag{4}$$

where M is a constant, which is determined by the installed capacity of biogas.

(4) Energy storage system operation constraint

The shorter the battery life, the more times it needs to be replaced, and the cost will increase accordingly. Certain restrictions on the charge and discharge of the battery can effectively extend the battery life. The depth of charge and discharge of a battery is a key factor affecting its life. The limit of the depth of charge and discharge is determined by its state of charge (SOC). The state of charge must satisfy the following formula [40]:

$$SOC(\mathrm{t}) = \begin{cases} (1-\omega)SOC(t-1) - \frac{\eta_c P_{ES}(t)\Delta(t)}{E_{st}} & P_{ES}(t) \le 0 \\ (1-\omega)SOC(t-1) - \frac{P_{ES}(t)\Delta(t)}{\eta_d E_{st}} & P_{ES}(t) > 0 \end{cases}, \tag{5}$$

$$SOC_{\min} \le SOC(t) \le SOC_{\max}, \tag{6}$$

where *SOC(t)* indicates the SOC of the battery in t period; *SOC(t + 1)* indicates the SOC of the battery during $t + 1$ period; ω is the self-discharge coefficient of the battery; E_{st} shows the rated capacity of the battery; Δt is the time interval between t period and $t + 1$ period; η_c is the battery charge efficiency; η_d is the battery discharge efficiency. When $SOC(t) = SOC_{max}$, the battery energy storage controller stops the battery from charging, whereas when $SOC(t) = SOC_{min}$, the battery will stop discharging.

3.2. Solution Algorithm

3.2.1. Principle of MPGA

Drawing lessons from the evolutionary laws of the biological world (survival of the fittest and extinction of the unfitness), genetic algorithm, as a global optimization probability search algorithm, has been widely used in machine learning, pattern recognition, and other fields [41]. However, with the extensive application and in-depth research of genetic algorithm, its problems and shortcomings are gradually exposed, and the most typical problem is premature convergence [42]. In view of the premature convergence of the Standard Genetic Algorithm (SGA), that is, the problem that all individuals in the population tend to the same state and stop changing, the Multiple Population Genetic Algorithm (MPGA) is proposed [43]. On the basis of SGA, MPGA adopts the idea of the parallel evolution of multiple groups. The specific innovative ideas are as follows:

- Multiple populations with different control parameters are introduced to optimize the search at the same time to achieve different search purposes;
- The migration operator is used to connect each population and realize the co-evolution of multiple populations;
- The optimal individuals of various group evolutionary generations are preserved by the artificial selection operator and are used as the basis for judging the convergence of the algorithm.

MPGA takes into account both the global search and the local search of the algorithm. The sensitivity of the calculation results to genetic control parameters is greatly reduced, and the convergence speed is fast. It has a significant effect on overcoming immature convergence and is suitable for the optimization of complex problems [43]. The limitation of MPGA is that the increase of several populations will increase the complexity of the algorithm; moreover, there are more parameters to be set, and the difference of the parameters will have a huge impact on the model. At present, the specific setting of parameters is obtained from experience, and there is no specific reference method, which increases the difficulty of parameter setting [41].

3.2.2. MPGA Implementation Process

The steps and parameter settings of the MPGA implementation process are as follows [44].

Step 1: Population initialization. By setting the population number, the number of individuals in the initial population, and the length of individuals, the initial population $P(t)$ is randomly generated according to the setting. Meanwhile, on the basis of the information exchange model, the initial population is divided into various populations: $P(t) = \{P_1(t), P_2(t), \ldots, P_n(t)\}$. Then calculate the fitness of each individual according to the fitness function [42].

Step 2: Determination of control parameters. Different control parameters are used to ensure the differential evolution of various populations. The main control parameters are crossover probability P_c and mutation probability P_m. Their value determines the balance of the algorithm's global search and local search capabilities, which can be calculated as follows [42].

$$\begin{cases} P_c = P_{co} + c \cdot f_{rand}(G, 1) \\ P_m = P_{mo} + m \cdot f_{rand}(G, 1) \end{cases}, \quad (7)$$

where P_{co}, P_{mo} are the initial crossover probability and mutation probability respectively; G is the population number; c, m are the interval length of crossover and mutation operations; f_{rand} is a function to generate random numbers. After sufficient research, P_c is generally randomly generated within the interval of [0.7, 0.9], and P_m is randomly generated within the interval of [0.001, 0.05].

Step 3: Immigration operator and manual selection operator. Setting up the migration operator is to replace the worst individual in the target population with the best individual in the source population to achieve the goal of co-evolution of multiple groups [45]. The function of the manual selection operator is to select the best individuals in various populations and put them into the elite population for preservation, so as to ensure that the best individuals produced by various populations are not destroyed or lost.

Step 4: Convergence conditions. The MPGA determines algorithm termination based on the elite population. The criterion for the termination of the algorithm in this paper is the minimum preserving algebra of the best individual in the elite population, that is when the retention algebra of the best individual exceeds the set value, the algorithm is judged to converge. This criterion makes full use of the knowledge accumulation of genetic algorithm in the evolution process, which is more reasonable than the maximum genetic algebra criterion and improves the convergence efficiency. The MPGA flowchart is shown in Figure 2 [43].

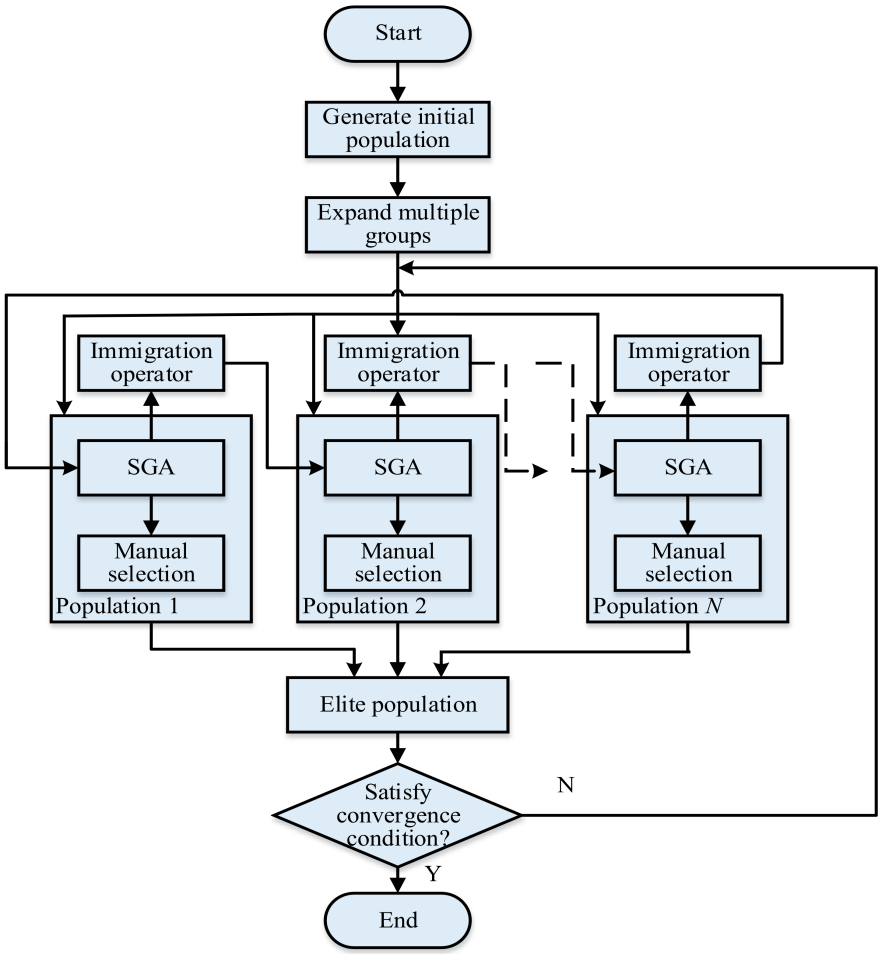


Figure 2. The flow chart of multi-population genetic algorithm (MPGA).

4. Case Analysis

4.1. Data Description

In the case of this paper, the rated power of the WPG system in the MECS is 80 kW. The solar cells are composed of 200 photovoltaic modules of 200 W, which are connected in series by 25 modules in each group to form 8 photovoltaic arrays with a total peak power of 40 kW [46]. BPG system rated 20 kW. The energy storage device uses a lead-acid battery with a rated power of 10 kW and a rated capacity of 100 kWh. Considering the battery loss caused by overcharge and over-discharge of the battery, this paper takes the SOC working range of ESS as 10–90% [47], that is, its capacity range is limited to 10–90 kWh. The initial SOC value is set to 0.1 [48]. The charge and discharge efficiency is 95%, and the self-discharge coefficient is 1% [49]. In this paper, it is assumed that the sum of daily power generation of the biogas generator unit is a fixed value, and the total daily power generation is calculated by the continuous operation of the unit for 24 h at 70% rated power. Other basic parameters of each generator set are shown in Table 1. Data are obtained from [48,49].

The data in Table 2 are the forecast values of load demand, wind and photovoltaic power output, and electricity price within the next 24 h. The data comes from the experimental simulation in [46]. According to China's current electricity price policy, the region where it is located implements the three-level time-of-use power price of six periods. Among them, peak hours are 10:00–15:00, 18:00–21:00, normal hours are 07:00–10:00, 15:00–18:00, 21:00–23:00, and valley hours are 00:00–07:00, 23:00–24:00 [50]. Since the output of wind power and photovoltaic power is affected by wind speed and light intensity respectively, there is great uncertainty. In order to reflect the optimization results under

various weather conditions, this paper considers the different output prediction values of wind power and photovoltaic power under the typical weather conditions of light wind, strong wind, cloudy and sunny days [46]. The optimized output schemes of each unit in the four scenarios, including light wind and sunny days, light wind and cloudy days, strong wind and sunny days, and strong wind and cloudy days, are discussed here. In this way, the optimization results with large and small output changes can be comprehensively analyzed.

Table 1. Parameters in wind–solar–biomass–storage MECS [48,49].

Types	Power (kW)		Cost Coefficient Per Unit Generation (¥/kWh)	Subsidy Electricity Price (¥kWh)	Average Daily Operation and Maintenance Cost (¥)
	Lower Limit	Upper Limit			
WPG	0	80	0.00	0.05	8.74
PVG	0	40	0.00	0.10	10.98
BIG	0	20	0.00	0.25	5.06
ESS	−10	10	0.10	0.00	1.34

Table 2. Electricity price and load demand, wind, and photovoltaic power (PV) power output forecast data hourly [46].

Time (h)	Load (kW)	Wind Power Output (kW)		PV Power Output (kW)		Electricity Sales Price [¥/kWh]	Electricity Purchase Price [¥/kWh]
		Strong Wind	Light Wind	Sunny Day	Cloudy Day		
1	67.6	69	60	0	0	0.46	0.41
2	65	70	52	0	0	0.46	0.41
3	65	69	48	0	0	0.46	0.41
4	66.3	65	44	0	0	0.46	0.41
5	72.8	61	40	2	0	0.46	0.41
6	81.9	65.8	45.6	6	2	0.46	0.41
7	91	69	48	10	4	0.46	0.41
8	97.5	63	52.8	20	10	0.87	0.82
9	98.8	58	40	30	16	0.87	0.82
10	104	60.6	46.4	32	20	0.87	0.82
11	101.4	62	48	34	20	1.29	1.04
12	96.2	54	48	40	24	1.29	1.04
13	93.6	57	45.6	40	24	1.29	1.04
14	93.6	49	40	40	20	1.29	1.04
15	98.8	53	48.8	36	16	1.29	1.04
16	104	50	46.4	30	16	0.87	0.82
17	110.5	65	44	20	12	0.87	0.82
18	114.4	69	52	20	8	0.87	0.82
19	117	65	44.8	10	4	1.29	1.04
20	113.1	69	48	6	2	1.29	1.04
21	101.4	77	57.6	0	0	1.29	1.04
22	92.3	73	52.8	0	0	0.87	0.82
23	84.5	69	60	0	0	0.87	0.82
24	72.8	71	60.8	0	0	0.46	0.41

4.2. Optimization Results

According to the optimization model established above, a multi-population genetic optimization algorithm is written in Matlab language to simulate this example. The relevant algorithm parameters are set as follows: the number of population is 10; the number of population individuals is 40; the crossover probability is randomly generated in the interval [0.7, 0.9]; the mutation probability is randomly generated in the interval [0.001, 0.05] and the optimal individual maintains at least 20 generations [51].

After simulation calculation, the optimization results under four typical weather conditions are shown in Figure 3. In the figure, the bar chart shows the charge-discharge

power of the ESS in 24 periods (positive value for discharge and negative value for charge), and the blue and red lines respectively represent the power output of BPG and power purchased from the large grid in 24 periods. From the diagram, we can also clearly see the comparison of the load demand and the forecast output curve of the wind and solar in different scenarios.

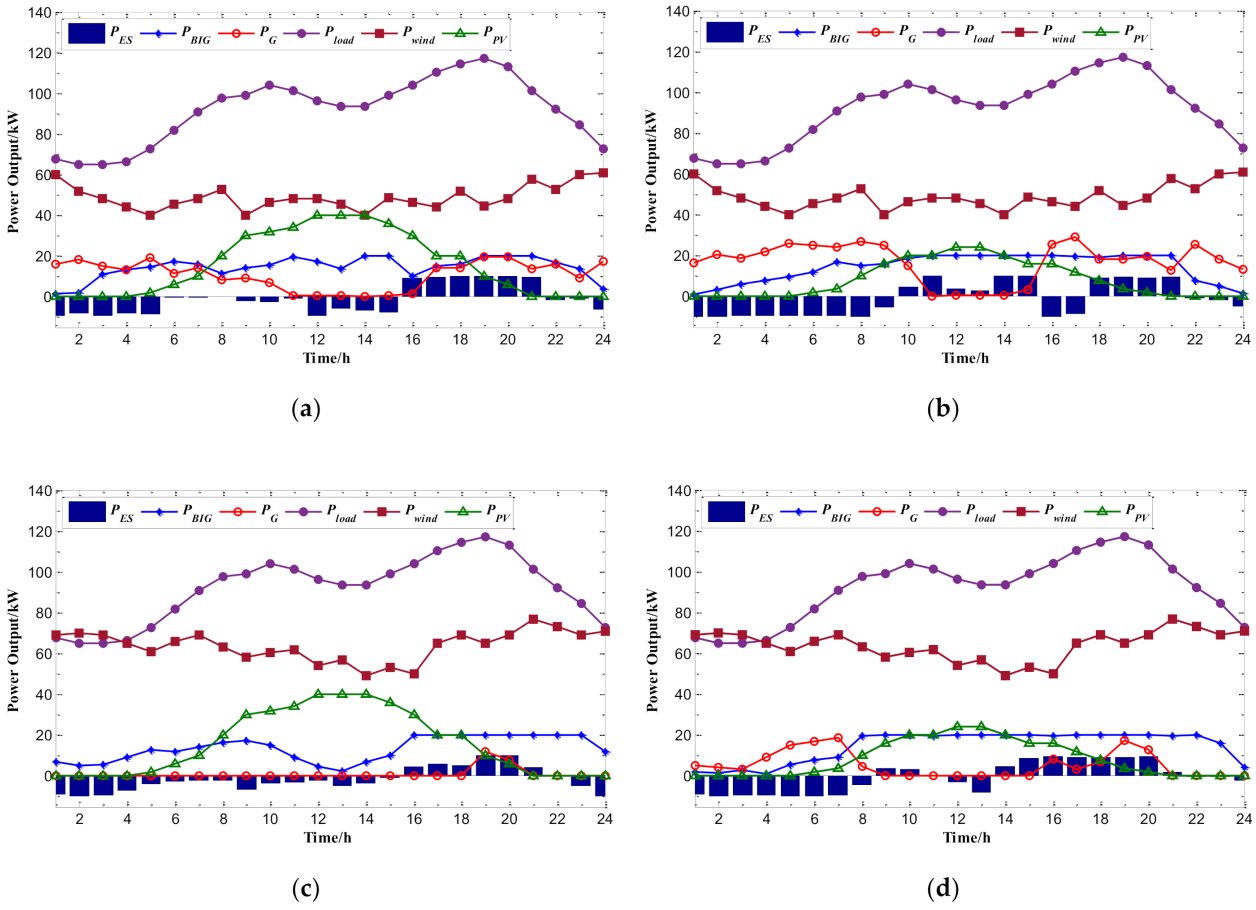


Figure 3. The optimal operation results of MECS under four scenarios. (**a**) Optimization results of the MECS on light wind and sunny days; (**b**) Optimization results of the MECS on light wind and cloudy days; (**c**) Optimization results of the MECS on strong wind and sunny days; (**d**) Optimization results of the MECS on strong wind and cloudy days.

Figure 3a shows the optimization results of the system on light wind and sunny days. In this scenario, the output of wind power is small, and the combined output of wind and solar is less than the load demand. During the period from 0:00 to 10:00, the electricity purchase price is relatively low, and the system gives priority to purchase electricity from the large power grid. The ESS is charged at the maximum power in the first five hours, and basically does not work in the last five hours. Due to the constraint of the total daily power generation, the power generation of the BPG system also shows an upward trend in this period. During the period from 10:00 to 15:00, the electricity purchase price is relatively high, the system does not purchase electricity from the large power grid. The BPG system is basically in a state of full power generation, and its power generation only declines during the period from 12:00 to 14:00 at noon, when the load is reduced and the photovoltaic output is at its maximum, during which the excess power generation is stored by the battery. During the period from 15:00 to 21:00, the power load increases, and the system power output is insufficient to meet the load demand. It is necessary to discharge the battery and purchase electricity from the large power grid to achieve the system power balance. During the period from 21:00 to 24:00, the power load decreases, the battery starts to charge, and the BPG system continues to complete the remaining power for the day.

According to formula (1), the maximum economic benefit of the system in this scenario is 1987.4 yuan per day.

Figure 3b shows the optimization results of the system on light wind and cloudy days. Due to the small installed photovoltaic capacity, there is little difference in photovoltaic output power between sunny and cloudy days, so the system optimization result curve is similar to Figure 3a. However, in Figure 3b, due to the decrease of photovoltaic output, the battery charging times increase during the period from 0:00 to 10:00, and the power purchased from the large power grid also increases accordingly. During the period from 10:00 to 15:00, the purchase price of electricity is relatively high. In order to meet the demand for power supply, the storage battery begins to discharge at higher power, and the system basically does not purchase electricity from the large grid. Due to the low wind and solar combined output in this scenario, the BPG system continues to generate power at rated power from 11:00 to 21:00. During the period from 15:00 to 17:00, the storage battery is charged strategically to reduce the amount of electricity purchased from the large grid during peak electricity prices. In the same way, the maximum economic benefit of the system in this scenario is 1861.6 yuan per day.

Figure 3c shows the optimization results of the system on strong wind and sunny days. In this scenario, due to the high wind speed and light intensity, the combined output of wind–solar–biomass exceeds the load demand, and the system basically does not need to purchase electricity from the large power grid. During the period from 0:00 to 16:00, the storage battery is in a charging state all the time. The power generation of the BPG system gradually rises first, and then rises again after the decline in the peak period of PVG at noon. During the period from 16:00 to 22:00, the load reaches its peak, the photovoltaic output is reduced, and the BPG system is not enough to meet the load demand in the state of full generation. The storage battery starts to discharge and the system purchases electricity from the grid. During the period from 22:00 to 24:00, the load decreases, the storage battery starts to charge, and the power generated by the BPG system decreases. In the same way, the maximum economic benefit of the system in this scenario is 2155.7 yuan per day.

Figure 3d shows the optimization results of the system on strong wind and cloudy days. By the same token, the system optimization result curve is similar to Figure 3c. The difference is that due to the reduced photovoltaic output, the system began to strategically purchase and store electricity from the grid during the period from 0:00 to 7:00, that is, during the double low of electricity prices and load. The power generation of the BPG system during this time period is relatively small. However, due to the restriction on the total amount of power generated, the BPG system will continue to operate at full power during the period from 8:00 to 22:00. During the period from 9:00 to 11:00, the electricity load increases, the battery begins to discharge. Then the photovoltaic output increases from 12:00 to 13:00, and the battery stores the excess power generation of the system. In the same way, the maximum economic benefit of the system in this scenario is 2082.2 yuan per day.

In order to compare the superiority of the improved algorithm MPGA, a standard genetic optimization algorithm under similar parameters is written in Matlab language to re-simulate the above examples, which is according to formula (1)–(6). The SGA parameters are set as follows: the population size is 400; the maximum number of iterations is 50; the crossover probability is 0.9, and the mutation probability is 0.05 [51]. According to the optimization results, the real-time power of each controllable unit is obtained, and then according to formula (1), the maximum economic benefits of the system in different scenarios are calculated. The economic benefits and running time comparison results of using SGA and MPGA optimization are shown in Table 3. The four scenarios in a sequence are light wind and sunny days, light wind and cloudy days, strong wind and sunny days, and strong wind and cloudy days. It can be seen from the table that MPGA is superior to SGA in terms of convergence time and convergence results, especially in terms of convergence speed.

Table 3. Comparison of the operation of standard genetic algorithm (SGA) and MPGA in different scenarios.

Algorithm	Scenario	Economic Benefit (¥)	Operation Time (s)
SGA	Scenario one	1865.6	652.32
	Scenario two	1796.8	586.49
	Scenario three	2063.5	623.58
	Scenario four	1942.6	689.41
MPGA	Scenario one	1987.4	26.01
	Scenario two	1861.6	25.89
	Scenario three	2155.7	24.93
	Scenario four	2082.2	26.75

5. Discussion

Renewable energy can effectively cope with climate change and achieve environmental sustainability, thus attracting more and more attention [52]. Moreover, with the promotion of scientific and technological innovation, the cost of renewable energy power generation continues to decline which has good economic benefits, and it has become the first choice for many countries to pursue a low-carbon economy and achieve long-term sustainable energy [2]. At present, many scholars have studied the renewable energy power generation technology and the application of MECS [12–18]. The technical feasibility of the MECS has been verified from many aspects, but the economic benefits of the MECS have not been fully reflected [46]. However, the economy of the system operation is the key to attract the majority of users and to be popularized in the power system. In addition, there are still few types of research on the MECS suitable for specific areas such as rural areas.

This paper complements the research on MECS, which has an important enlightening effect on solving the sustainable energy problems in rural areas. Moreover, as the fourth largest energy source in the world, biomass energy has not been fully utilized in previous studies [21,22], and the MECS established in this paper has important value for the rational development and utilization of biomass energy. Hu et al. reduced the phenomenon of wind and solar abandonment by adding penalty cost into the optimization objective [4]. In this paper, renewable energy generation can be fully absorbed by adopting the grid-connected non-sales operation mode and adding ESS in the system. Moreover, it effectively avoids the potential safety hazards of large-scale wind and solar grid connection to the power system's consumption of new energy.

The simulation case in this paper is divided into four scenarios for discussion, and the results show that the operation model of the system can be applied to a variety of occasions, and can be flexibly adjusted with the change of weather and load. It can also be seen from the comparative results in Table 3 that the optimization method proposed in this paper can improve the economic benefit of the MECS and make its operation more economical. Compared with the optimization results of the above four scenarios, it can be concluded that the basic operation strategies of BPG, ESS, and power grid purchase strategy are as follows.

- The BPG system can well make up the load demand when the wind and solar power output is insufficient, and undertake certain peak shaving tasks. On a light wind and cloudy day, the output of BPG is relatively uniform; on a light wind and sunny day or a strong wind and cloudy day, the output of BPG is small in the early morning and midnight, and the rest of the time is basically full-load operation; On a strong wind and sunny day, the trend of BPG output curve and load curve is basically consistent.
- The ESS will be charged in the case of excess wind and solar power output, in order to timely absorb the excess renewable energy and ensure the safe and stable operation of the system; it will also be charged during the low electricity price period, and be discharged during the double peak period of electricity price and load, so as to realize the low electricity peak use and increase the economic benefits of system operation.

- The system only purchases electricity from the power grid when the electricity price is low, the power generation and energy storage capacity of the system cannot meet the load demand during the peak period of power consumption, and the reduced energy storage capacity cannot meet the discharge demand during the peak load period and needs to be charged.

6. Conclusions

Based on the perspective of rural areas in developing countries, this paper makes research for the current situation of increasing power demand for rapid rural economic development and serious pollution caused by lacking management in rural areas, aiming to provide specific clues for national policymakers in rural power supply and sustainable realization. In order to achieve this goal, this paper constructs a new type of wind–solar–biomass–storage MECS suitable for rural areas. The system uses renewable energy of wind energy, solar energy, and biomass energy to replace traditional fossil energy, and reduces the environmental pollution caused by energy consumption. It cannot only meet the growing demand for electricity in rural areas but also effectively promote the rural energy transformation. Based on the built system, this paper proposes a more practical grid-connected non-sales operation mode, which can effectively reduce wind and solar abandonment, and can reduce the impact of system grid connection on the grid. In addition, a mathematical model of optimal scheduling with the goal of maximizing daily operating economic benefits is established and an improved genetic algorithm is used to solve the model. Then, through specific examples, the results of economic operation optimization of the MECS under four typical weather conditions are discussed, and the real-time optimal power of the controllable units in the system is solved to achieve the optimal operation target of the system. Through the simulation of four scenarios, the basic operation scheme of the controllable unit is summarized. Finally, the comparison of the SGA confirms the optimization method proposed in this paper has great advantages in convergence time and results.

According to the results, it can be seen that BPG in the MECS can play a good role in peak shaving, which can well replace coal power and natural gas peak shaving units. The ESS plays two roles in the steady-state operation of the MECS. One is the safety role, which makes the system power balance; the other is the economic role, ESS adjusts the charging and discharging power according to the real-time electricity price and load to maximize the economic income. The two functions are mainly determined by the size relationship between wind power, photovoltaic power, and load demand. If the correlation is large, ESS plays a major role in safety; only when the output of wind and photovoltaic power is equal to or slightly less than the load demand, the economic optimization effect of ESS can be reflected. It can be seen that the reasonable allocation of system capacity is of great significance to its economic and safe operation.

In the future, modern optimization technology will be used to determine the reasonable configuration of the MECS capacity, and further improve the economic and safe operation research of the system. Finally, it is hoped that the research work of this paper can provide a useful reference for solving the problem of power supply difficulties and poor power supply quality in rural areas of developing countries and promoting the consumption of new energy and sustainable development in rural areas of developing countries.

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Nomenclature

Abbreviations

BPG	Biogas power generation
ESS	Energy storage system
MECS	Multi-energy complementary system
MPGA	Multi-population genetic algorithm
PVG	Photovoltaic power generation
SGA	Standard genetic algorithm
SOC	State of charge
WPG	Wind power generation
¥	China Yuan

Variables

c	The interval length of crossover operations
C_i	Daily operation and maintenance cost [¥]
E_{st}	The rated capacity of ESS [kWh]
F	Total economic benefit of MECS [¥]
f_{rand}	A function to generate random numbers
G	The population number
i	Index of facilities (WPG, PVG, BPG, ESS)
k_i	Subsidy electricity price of WPG (PVG, BPG) [¥/kWh]
M	Daily output of BPG [kW]
m	The interval length of mutation operations
P ()	The initial population
P_{BIG} ()	Hourly output power of BPG [kW]
P_c	Crossover probability [%]
P_{co}	The initial crossover probability [%]
P_{ES} ()	Hourly output power of ESS [kW]
P_G ()	Hourly electricity purchased from the grid [kW]
P_i ()	Hourly output power of WPG (PVG, BPG) [kW]
P_i^{max}	Upper limit of output power [kW]
P_i^{min}	Lower limit of output power [kW]
P_{load} ()	Hourly power load [kW]
P_m	Mutation probability [%]
P_{mo}	The initial mutation probability [%]
P_{PV} ()	Hourly output power of PVG [kW]
P_{wind} ()	Hourly output power of WPG [kW]
SOC ()	Hourly SOC of ESS
SOC_{max}	Upper limit of SOC
SOC_{min}	Lower limit of SOC
t	Time
Δt	Time interval
α_t	The electricity price purchased from the grid [¥/kWh]
β	Unit charge/discharge cost coefficient of ESS [¥/kWh]
γ_t	The electricity price sold to the load terminal [¥/kWh]
η_c	The battery charge efficiency [%]
η_d	The battery discharge efficiency [%]
ω	The self-discharge coefficient of ESS [%]

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