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Smart Grid Renewable Energy Configuration Decision Model Based on Multi-Objective Optimization

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ABSTRACT

The paper constructs a multi-objective decision-making model in the configuration of renewable energy in the smart grid. This is a management tool for finding the configuration of renewable energy in the smart grid to get the maximum economic benefit and use energy most efficiently while considering environmental protection. This paper uses economic theory fully in the application, mathematical modeling, methods for conducting cost-benefit analysis, and optimization algorithms. The power demand, renewable energy supply, and economic and environmental data between the years 2020 and 2024 in one region are used in testing the performance and optimization of the model using genetic algorithms. The results show that the optimization model has significant effects in reducing costs, improving economic benefits and reducing environmental impacts, and the optimized energy configuration scheme significantly reduces CO2 emissions. More references are given on how a multi-objective optimization model is constructed and proved for its practicality for scientific planning and optimization of renewable energy in a smart grid, with high-level feasibility and application value in practicality.

KEYWORDS

Smart grid; Renewable energy; Multi-objective optimization; Genetic algorithm

1. INTRODUCTION

1.1. Research Background and Importance

As global energy demand continues to rise and environmental awareness increases, the significance of renewable energy in power production is growing. An essential component of today's power systems, the main objective of the smart grid is to achieve effective, dependable, and environmentally friendly energy use. Still, the smart grid encounters significant challenges because of the sporadic and unpredictable characteristics of renewable energy sources like solar and wind power, requiring the establishment of a balance mechanism between energy supply and demand for system stability and economic optimization [1].

Multi-objective optimization method has shown strong advantages in solving resource allocation problems of complex systems. By comprehensively considering the optimization needs of multiple dimensions such as economy, environment and technology, it can provide theoretical support and technical means for the scientific planning and optimization of renewable energy in smart grid. For example, genetic algorithm, as an evolutionary computing method, is widely used in the research of energy optimization configuration of smart grid due to its excellent performance in dealing with nonlinear and multi-objective optimization problems [2][3]. In addition, the construction of smart grid also needs to take into account environmental protection, and effectively reduce greenhouse gas emissions and achieve sustainable development goals by optimizing energy configuration [4]. Therefore, studying the decision-making model of renewable energy configuration of smart grid based on multi-objective optimization is not only of theoretical research value, but also provides important reference for practical engineering applications. This will help improve energy utilization efficiency, reduce operating costs, reduce environmental pollution, and promote the development and popularization of smart grid [5].

1.2. Research Objectives

The main objective of this study is to construct a smart grid renewable energy configuration decision model based on multi-objective optimization. By comprehensively applying economic theory, mathematical modeling, cost-benefit analysis methods and optimization algorithms, the renewable energy configuration in the smart grid is planned and optimized to achieve maximum economic benefits and optimal energy utilization, while taking into account environmental protection. Specifically, this study will use genetic algorithms for optimization, and use the electricity demand, renewable energy supply, economic and environmental data of a certain region from 2020 to 2024 as an example to verify the effectiveness of the model. Ultimately, the research results will demonstrate the high feasibility and value of the model in practical applications.

2. LITERATURE REVIEW

2.1. Smart Grid and Renewable Energy

Innovative grid technology is seen to play a vital role in the integrated use of renewable energy sources and betterment in the efficiency and reliability of power continuously. Since the buzz of renewable sources of energy, the most enhanced possibility has been intelligent grid technology. For example, Noppers et al. (2016) found that users' positive evaluation of the symbolic attributes of smart grid systems (such as identity symbols) significantly increased their willingness to adopt smart grid technology [6]. In addition, the study by Ratner et al. (2021) showed that although Russian consumers generally have low awareness of smart grid technology, most respondents believe that smart grid technology can improve energy efficiency and thus reduce the burden of energy consumption [7]. This finding emphasizes the importance of improving public awareness of smart grid technology, which will help realize the potential socioeconomic and environmental benefits of smart grid projects. Therefore, smart grids have important research value in promoting the application of renewable energy.

2.2. Multi-objective Optimization Method

Multi-objective optimization methods show strong advantages in dealing with resource allocation problems of complex systems. Sohrabi and Tajik (2017) used a multi-objective feature selection method to improve the decision support system for warfarin dose prediction, demonstrating the superiority of multi-objective optimization algorithms in improving model accuracy and performance [8]. In addition, Azriel and Feigin (2014) found in their study of clinical trial design that multi-objective optimization can significantly improve the statistical power of the trial by allocating subjects to different treatment groups and maximizing the statistical power of relevant tests [9]. These studies show that multi-objective optimization methods are not only widely used in the medical field, but also have significant advantages and potential in optimizing renewable energy configuration in smart grids.

2.3. Cost-Benefit Analysis

Cost-Benefit Analysis (CBA) is an important tool for evaluating the economic benefits of environmental improvement measures. Hanley et al. (2003) evaluated the environmental improvement benefits of reducing the low flow problem of the Mimram River in southern England and proposed a distance decay function to solve the problem of evaluating the beneficiary population [10]. In addition, Faccioli et al. (2016) studied the time sensitivity of social preferences in long-term environmental benefits. The results showed that the difference in environmental benefits between individuals during their life cycle and between future generations was not significant, reflecting the importance of sustainability issues [11]. Marinoski et al. (2018) analyzed the environmental benefits of using water-saving equipment and rainwater recycling systems in low-income houses in Brazil and demonstrated the significant effects of these strategies in saving water and reducing sewage discharge [12]. These studies provide theoretical and practical references for cost-benefit analysis of renewable energy configuration in smart grids.

2.4. Policy Environment

For the development of the policy environment, the critical factor that would influence the latter is the construction of renewable and the development of smart grids. The study by Irfan et al. conducted on the adoption of renewable energy by residents in Pakistan identifies reform in the policy structure and transformation in social norms as critical factors for fostering the development of renewable energy [13]. Obrecht et al. (2020) emphasized the importance of integrating social dimensions in the design of energy supply networks, pointing out that public participation and willingness to pay are key to achieving sustainable energy supply [14]. Peng et al. (2018) found through their study of China's high-pollution industries that environmental regulations and environmental strategies have a significant impact on corporate performance, and suggested that the government should coordinate industry to formulate and enforce environmental laws and regulations to promote the development of renewable energy [15]. These studies show that improving the policy environment is crucial to promoting the configuration of renewable energy in smart grids.

3. THEORETICAL BASIS

3.1. Economic Theory

When studying the configuration of renewable energy in smart grids, economic theory provides a basis for understanding and analyzing market behavior and policy effects. The following are several key economic theories:

Supply and Demand Theory: This is what shall shape the lifeline of market economics and, therefore, the price that the market will yield for renewable energy. This shall be brought about by the matching of demand and supply. It is brought about by the supply curve, which reflects the quantity the producers are willing to supply at different price levels. The demand curve records the quantity consumers will be willing to buy at different price levels. Mathematically:

$$Q_d = Q_s \tag{1}$$

Among them, Qd represents the demand, and Qs represents the supply. At the equilibrium point, the supply is equal to the demand, and the market reaches equilibrium.

Cost-Benefit Analysis (CBA): CBA is used to evaluate the economic value of a project, comparing its total costs and total benefits to determine its feasibility. Net present value (NPV) is a commonly used indicator. The NPV formula is as follows:

$$NPV = \sum_{t=0}^{T} \frac{B_t - C_t}{(1+r)^t} \tag{2}$$

Among them, Bt represents the benefit at time t, Ct represents the cost at time t, r is the discount rate, and T is the total time of the project.

Externality: Renewable energy production and consumption are often accompanied by externalities, especially environmental externalities. Externality refers to the costs or bene

fits caused by an economic activity to unrelated third parties, which are not reflected in market transactions.

The relationship between social marginal cost (SMC) and social marginal benefit (SMB) can be expressed as:

$$SMC = PMC + EMC \tag{3}$$

$$SMB = PMB + EMB \tag{4}$$

Among them, $SMC$is the social marginal cost, $PMC$is the private cost, EMC is the external cost, SMB is the social marginal benefit, PMB is the private benefit, and EMB is the external benefit.

3.2. Basics of Mathematical Modeling

In the configuration of renewable energy in smart grids, mathematical modeling is an important tool for system analysis and optimization. The following are several key basics of mathematical modeling:

Linear Programming (LP):

Linear programming is used to optimize a linear objective function subject to linear constraints. The standard linear programming model is in the form of:

$$SMC = PMC + EMC \tag{5}$$

$$SMB = PMB + EMB \tag{6}$$

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$$\text{maximize } Z = c_1x_1 + c_2x_2 + \ldots + c_nx_n \tag{7}$$

$$\text{subject to } a_{11}x_1 + a_{12}x_2 + \ldots + a_{1n}x_n \le b_1 \tag{8}$$

$$a_{21}x_1 + a_{22}x_2 + \ldots + a_{2n}x_n \le b_2 \tag{9}$$

$$a_{m1}x_1 + a_{m2}x_2 + \ldots + a_{mn}x_n \le b_m \tag{10}$$

$$x_1, x_2, \ldots, x_n \ge 0 \tag{11}$$

Multi-objective Optimization The configuration of renewable energy in the Smart Graids should, at most times, optimize the various objectives simultaneously, the benefits in economics and the benefits in environmental protection. The multi-objective optimization model can be expressed as:

$$\text{maximize } f_1(x), f_2(x), \ldots, f_k(x) \tag{12}$$

$$\text{subject to } g_i(x) \leq 0, i = 1, 2, \ldots, m \tag{13}$$

$$h_j(x) = 0, \ j = 1, 2, \ldots, p \tag{14}$$

Among them, $f1(x)$, $f2(x)$, …, $fk(x)$ are the objective functions to be optimized, and $gi(x)$≤0 and h $j(x)$=0 are constraints.

Dynamic Programming (DP): Dynamic programming is used to solve multi-stage decision-making problems, where the decisions made at each stage affect the subsequent stages. The basic dynamic programming formula is the Bellman equation:

$$V(s) = \max_a \left[R(s,a) + \gamma \sum_{s'} P(s' \mid s,a) V(s') \right] \tag{15}$$

Among them, $V(s)$ is the value of state ss, $R\ (s,\ a)$ is the immediate reward of taking action a in state s, γ is the discount factor, and $P\ (s'|s,\ a)$ is the state transition probability.

3.3. Cost-Benefit Analysis Methods

Cost-Benefit Analysis (CBA) is an important method for evaluating the economic and social benefits of a project or policy. The following are several key steps:

$$BCR = \frac{\sum_{t=0}^{T} \frac{B_t}{(1+r)^t}}{\sum_{t=0}^{T} \frac{C_t}{(1+r)^t}} \tag{16}$$

Where $BCR$is the cost-benefit ratio, Bt is the benefit at time t, $Ct$is the cost at time t, r is the discount rate, and T is the total time of the project.

4. OPTIMIZATION ALGORITHM AND MODEL DESIGN

4.1. Introduction to Optimization Algorithm

This paper primarily uses a genetic algorithm whose application lies in configuring renewable energy in smart grids. A genetic algorithm is, by nature, a heuristic search algorithm that uses natural selection and genetic mechanisms for optimization problems. The basic steps include selection, crossover, and mutation. The fitness function is expressed as:

$$F(x) = \sum_{i=1}^{n} w_i f_i(x) \tag{17}$$

Among them, $F(x)$ is the fitness of individual x, $f_i(x)$ is the objective function, and w_i is the weight.

4.2. Renewable Energy Configuration Model

This paper presents an optimization model that maximizes the economic benefits and minimizes the environmental impacts while configuring renewable energy in an intelligent grid. Economic benefit objective function:

$$\text{maximize } Z_1 = \sum_{t=1}^{T} \frac{R_t - C_t}{(1+r)^t} \tag{18}$$

Among them, Rt represents the benefit at time t, Ctrepresents the cost at time t, r is the discount rate, and $T$is the total time of the project.

Environmental impact objective function:

$$\text{minimize } Z_2 = \sum_{t=1}^{T} \frac{E_t}{(1+r)^t} \tag{19}$$

Where Et represents the environmental impact at time t.

Energy balance constraints:

$$\sum_{i=1}^{n} P_i(t) = D(t) \tag{20}$$

Capacity Limit Constraints:

$$0 \le P_i(t) \le P_{i,\max} \tag{21}$$

Among them, $P_{i,\max}$ represents the maximum capacity of the i-th energy source.

4.3. Model Solving Method

This paper uses genetic algorithm to solve the above multi-objective optimization model. It includes population initialization, fitness evaluation, selection, crossover, mutation and iteration process (as shown in Figure 1).

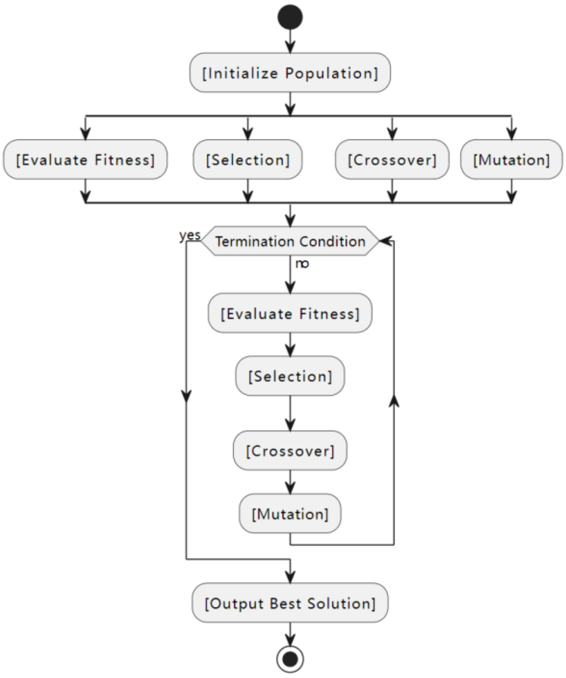

Figure1. Multi-objective optimization model process

5. CASE STUDY

5.1. Case Study Method

This chapter uses a case study method to conduct a detailed analysis of the renewable energy configuration in a region's smart grid. The research method includes data collection, model application, and result analysis. Through the analysis of actual cases, the aforementioned optimization models and algorithms can be verified and improved.

5.2. Analysis of Smart Grids in a Certain Region

Data collection

A region is selected as the research object to collect the region's electricity demand, renewable energy supply, economic data, and environmental data. The data comes from the annual report of the power company in the region (January 2020 to December 2024), including monthly electricity demand and renewable energy supply data, a total of 60 sets of data. Economic and environmental data come from the annual monitoring reports of the government statistics bureau and environmental protection agency, covering annual data for the same time range. Here is the electricity demand and renewable energy supply in the region:

Table 1. Electricity demand and renewable energy supply in the case regions

Year	Electricity Demand (MWh)	Renewable Energy Supply (MWh)
2020	150,000	80,000
2021	155,000	85,000
2022	162,000	88,000
2023	158,000	92,000
2024 (First quarter data)	65,000	15,000

The following are the economic and environmental data of the region (see Table 2):

Table 2. Economic and environmental data of the case regions

Year	Environmental Impact (tons CO2)
2020	50
2021	48
2022	47
2023	45
2024(First quarter data)	12

Table 2 shows the environmental impact data of a region between 2020 and 2024, specifically the annual CO_2 emissions. As time goes by, CO_2 emissions decrease year by year. This trend shows that the gradual optimization of renewable energy configuration has a positive impact on environmental protection.

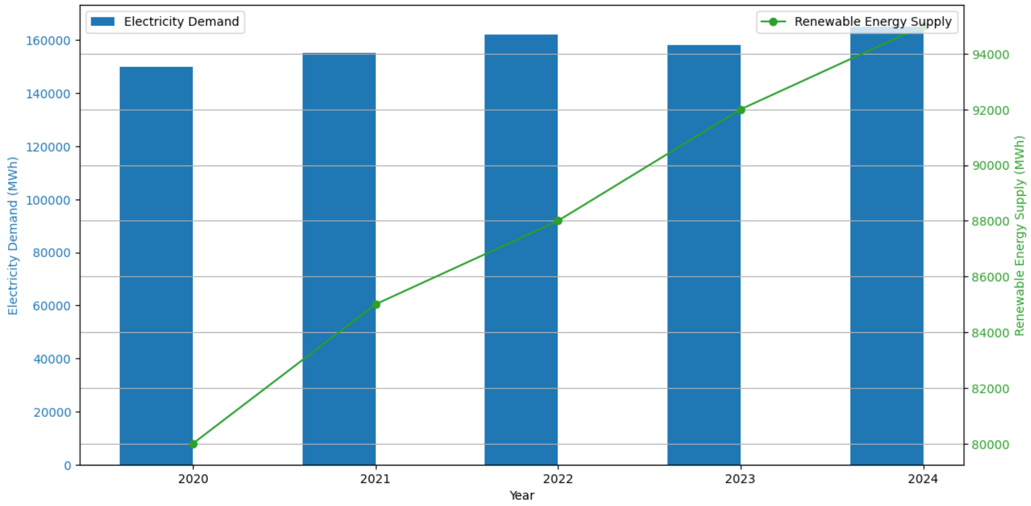

Figure 2. Electricity Demand and Renewable Energy Supply

This is Figure 2, which illustrates a region's electricity demand and renewable energy supply from 2020 to 2024. A bar graph represents the variations from one year to another in the total electricity demand. At the same time, the other is a line graph indicating the measurement of the amount of renewable energy supplied to a region over the years. According to the data read from the figure, electricity demand rose slightly every other year, declining in 2022, which was a rare statistic, but it grew in the next year. However the growth rate is relatively stable, with the supply of renewable power from time to time swelling in line with the report. The growth rate of electricity demand continues to climb, meaning that although it grows from year to year, a gap is acknowledged where further energy allocation is optimized.

5.3. Model Verification and Improvement

Based on the above case data, the optimization model is applied to the renewable energy configuration in the region to verify the effectiveness of the model. Genetic algorithms are used to solve the optimization problem and obtain the optimized energy configuration plan. The following is a comparison table before and after optimization:

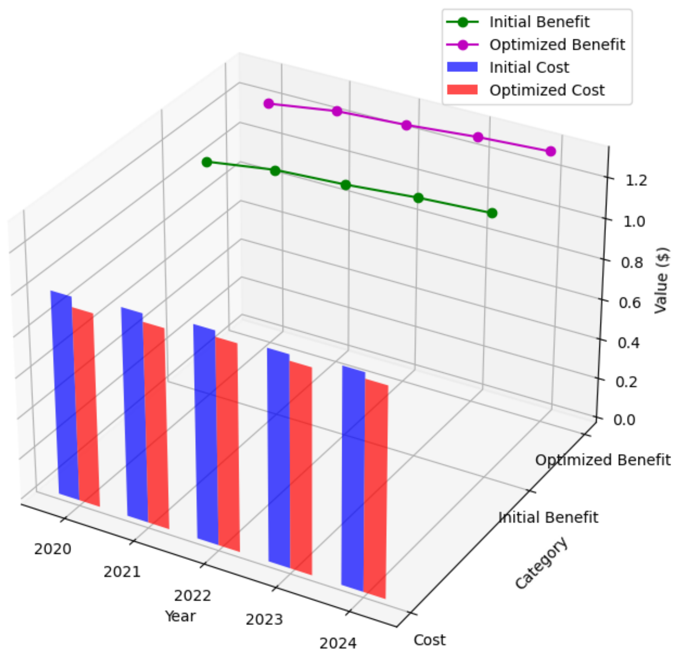

Figure 3. Cost and Benefit Comparison (Initial vs Optimized)

Figure 3. Costs and Benefits: Pre and Post Optimisation 2020-2024. It is a 3D bar chart that shows the annual changes in the initial cost and the optimized cost, while the line chart is represented the yearly changes in the initial benefit and the optimized benefit. If this result is compared to the above-presented consequence, then it is pretty evident that the optimized cost is too little compared to the initial cost, and the optimized benefit is much more significant than the initial benefit. This reflects the fact that the optimization model may very well optimize the cost and increase the benefit to confirm that the developed model is practical in nature.

6. CONCLUSION

6.1. Main Conclusions

This study constructed a decision-making model for renewable energy configuration in smart grids through a multi-objective optimization method, and verified and analyzed the actual data of a certain region. The results show that the use of genetic algorithms for optimization can effectively reduce the cost of energy configuration and improve economic benefits, while significantly reducing environmental impact, as reflected in the year-on-year decline in CO2 emissions. These results verify the effectiveness and practicality of the model and provide an important reference for the scientific planning and optimization of renewable energy in smart grids.

Specifically, through the analysis of electricity demand, renewable energy supply, economic data and environmental data in a certain region from 2020 to 2024, the study found that although the supply of renewable energy has increased year by year, the growth rate of electricity demand has been faster, and there is still a certain gap. The optimization model not only effectively meets the electricity demand by reasonably configuring different types of renewable energy, but also achieves significant results in reducing costs and increasing benefits. In addition, the optimized energy configuration scheme significantly reduces CO2 emissions and demonstrates good environmental benefits. These results show that the optimization model has high feasibility and value in practical applications.

6.2. Research Limitations

Although this study has achieved positive results in optimizing the configuration of renewable energy in smart grids, there are also some limitations. Notably, in 2020-2024 research, it is stated that even though the supply of renewable energy has been increasing year by year, the growth in electricity demand is still growing faster from year to year, and there is still a certain kind of gap. The result of the optimization model is to satisfy electricity demand effectively with a reasonable mix of various renewable energy types, along with good performance towards cost reduction and increment in benefits. The first is considering the actual data of a particular region, mainly in the construction and optimization of the model. The characteristics of the data may not be performed the same for those of the other areas. Therefore, further verification is needed for the applicability and universality of the model. The data sources of this study are included the annual reports of the power companies, governmental statistics, and reports of research institutes. Although these data have certain authority, there are still problems such as incomplete data acquisition or untimely data updates, which may affect the accuracy and reliability of the model.

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