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Research on Maintenance Strategies for Different Transmission Sections to Improve the Consumption Rate Based on a Renewable Energy Production Simulation

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Abstract: Renewable energy consumption is one of the most important factors in meeting the goal of "30 and 60" in China. However, the maintenance of the transmission section affects the amount of generation transfer, further affecting the consumption of renewable energy. Hence, in this study, a time-series renewable energy production simulation (REPS) is proposed in order to accurately predict the power generation in a simulated situation. According to the results of the REPS, the sensitivity of the different sections' maintenance can be calculated and determined. The appropriate maintenance strategies can be selected for different situations by comparing the consumption rate; as an example, we conducted a case study. The results show that the quota in the transmission section has higher sensitivity; a larger quota indicates a greater sensitivity to the consumption rate. The results also show that a larger quota is more suitable for maintenance in February or November, since the consumption rate is higher regardless of if it is in a single-transmission-section maintenance strategy or in a two-section simultaneous maintenance strategy.

Keywords: renewable energy; consumption rate; transmission line maintenance; time series; renewable energy production simulation

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1. Introduction

At present, China is building a new power system with a high level of renewable energy; hence, it faces the significant challenge of enhancing renewable energy consumption. The study in [1] presented an overview of China's renewable energy development status and analyzed the mechanism of accommodation of renewable energy and the key factors for the country's curtailment of renewable energy. In the studies in [2,3]—based on experiences in advanced electricity markets in Europe and the United States—the consumption capacities of systems could be greatly improved by power delivery transactions and contract-transfer transactions between renewable energy and traditional power plants. With the deepening complexity of the power grid, as well as the complexity of its infrastructure and technical reform, the transmission lines require repair every year [4]. Therefore, the influences of maintenance on the rate of consumption of renewable energy should be paid more attention, especially in the new power system.

Some previous studies analyzed the maintenance of a traditional transmission line [5–9]. The study in [10] investigated the maintenance of a local power grid. The study in [11] proposed a new decision algorithm for solving the scale and configuration of a distributed power supply in a distribution network system. The study in [12] optimized the expansion costs of a transmission system, network loss, old line replacement, maintenance costs, and so on. According to actual production engineering, an empirical formula has been summarized, but this formula is often only applicable to local production, and it lacks a mathematical and physical basis. The study in [13] proposed a reliability-centered maintenance priority index and proved that it is more cost-effective than the traditional strategy. The study in [14] focused on the co-optimization of maintenance scheduling and production cost minimization. The study in [15] used the weighting–scoring method and the analytical hierarchy process to obtain the transmission line maintenance index. However, these studies of maintenance all focused on the traditional energy mode. In terms of development, few studies have addressed the influence of the maintenance strategy on renewable energy consumption. In order to understand this influence, an accurate predication of renewable energy generation is necessary. Thus, numerical simulation is a scientific way to reflect the effects on the transmission line.

There are three main numerical simulation methods: the typical daily analysis method, the random production simulation method, and the time-series production simulation method [16]. The typical daily analysis method is an analysis of extreme cases, and the calculation results are conservative [17–20]; the random production simulation algorithm removes time constraints and converts a load curve into a continuous curve [21–24]; a time-series production simulation converts the renewable energy output and load into a time series and analyzes its changing trends over time [25–28]. Zhu et al. used a time-series production simulation model to select the power-flow constraints of critical sections of time in order to assess the annual consumption level of new energy in the system [29]. Peng et al. used a time-series production simulation method to establish an optimal consumption model for renewable power sources in inter-provincial power grids and solved for the maximum renewable energy consumption [30]. This paper also used a comparison with the typical daily analysis method to prove the superiority of their method. Ma et al. constructed a multi-point layout-planning model for a multi-energy power supply based on a time-series production simulation. An analysis of the simulation of the actual power system showed that this method was able to accurately and effectively determine the power quota line and provide a reference for power grid construction [31].

Overall, in this paper, a time-series renewable energy production simulation (REPS) was developed and used to analyze the sensitivity of the different sections' maintenance. The maintenance strategies for a sole transmission section or two transmission sections at the same time can be decided by comparing their consumption rates. Finally, a case study was carried out to prove the efficiency of the method and provide a reference for practical projects.

2. Time-Series Production Simulation

In this paper, a time-series RESP was used to simulate a real situation and determine the maintenance strategy for the transmission sections. In comparison with the traditional method, RESP is much closer to the reality of the grid; for example, an interval of 15 min was used for the real situation. RESP pays more attention to real structures and connections within the grid. The framework of this method is established in Figure 1. First, the actual power grid was simplified through aggregation equivalence in order to adapt to the practicality of the simulation (Section 2.1); then, the optimization model was constructed by maximizing the output of renewable energy power generation (Section 2.2). Following this, a quick and useful solver (CPLEX equation solver) was used to calculate a mixed-integer linear program (Section 2.3).

2.1. Renewable Energy Consumption Model

2.1.1. Power Grid Model

The time-series production simulation of renewable energy is based on the grid aggregation model. The grid aggregation model is based on the purpose and requirements of the calculation and analysis, and the aggregation is equivalent in order to make it more adaptable to the practical requirements of the simulation [32]. The complex actual power grid is simplified into one or more aggregated power grids. The aggregation of the power system can not only better reflect the efficiency of power grid energy transmission, but can also provide a better solution for the decentralized layout and centralized scheduling of the power grid.

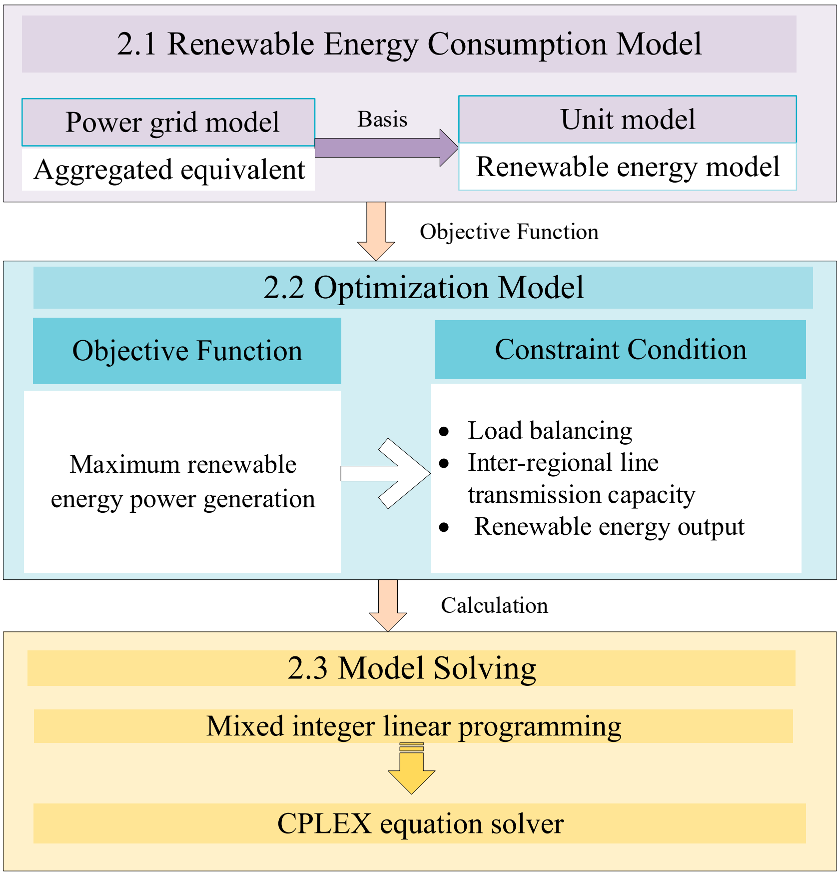

Figure 1. Schematic diagram for time-series production simulation.

2.1.2. Unit Model

In the time-series production simulation, the renewable energy output is regarded as a time-varying sequence, and the characteristics of the renewable energy output of the guaranteed sequence are consistent with the actual characteristics.

2.2. Optimization Model

The time-series production simulation method is based on the consumption capacity of renewable energy.

2.2.1. Objective Function

The aim of the objective function is to maximize the power of renewable energy in a scheduling cycle.

$$\max \sum_{t=1}^{T} \sum_{n=1}^{N} (P_w(t,n) + P_{pv}(t,n)) \tag{1}$$

In the formula, N is the total number of aggregated power grids contained in the system, n is an aggregated power grid, T denotes the duration of the scheduling cycle, t is the simulation time step, $P_w(t,n)$ is the wind power output of aggregated grid n in period t, and $P_{pv}(t,n)$ is the photovoltaic power output of aggregated grid n in period t.

The renewable energy output equation is established based on the load balance constraint, line transmission constraint, and renewable energy output constraint [33].

2.2.2. Constraints

(1) Regional Load Balance Constraint

$$\sum_{j=1}^{J} P_j(t,n) \cdot S_j(t,n) + P_w(t,n) + P_{pv}(t,n) + L_i(t) = P_l(t,n) \tag{2}$$

In the formula, $\sum_{j=1}^{J} P_j(t,n) \cdot S_j(t,n)$ is the sum of the total power of all conventional units in period t of the aggregated grid n, and $L_i(t)$ is the transmission power of the transmission line i in period t.

(2) Inter-Regional Line Transmission Capacity Constraint

$$-L_{i,\max} \le L_i(t) \le L_{i,\max} \tag{3}$$

where $L_{i,\max}$ and $-L_{i,\max}$ are the upper and lower quotas of the transmission capacity of the transmission line i, respectively. The current reference direction is as follows: The inflow area is in the positive direction, and the outflow area is in the negative direction. So, L_i can take positive and negative values, and positive and negative values represent the direction of power transmission.

(3) Renewable Energy Output Constraints

$$0 \le P_w(t,n) \le P_w^*(t,n) \tag{4}$$

$$0 \le P_{pv}(t,n) \le P_{pv}^*(t,n) \tag{5}$$

In the formula, $P_w^*(t,n)$ refers to the wind power time-series output when the installed capacity is constant at time t, and $P_{pv}^*(t,n)$ refers to the photovoltaic time-series output when the installed capacity is constant at time t.

2.3. Model-Solving Method

The mathematical essence of the renewable energy time-series production simulation model is mixed-integer linear programming.

$$\begin{array}{ll} \min f(x) & \\ s.t. g_i(x) \ge 0 & (i = 1,2,\cdots m) \\ h_j(x) = 0 & (j = 1,2,\cdots n) \end{array} \tag{6}$$

where x is the set of variables to be optimized, $f(x)$ is the optimization objective function, $g_i(x) \ge 0$ is the set of inequality constraints, and $h_j(x) = 0$ is the set of equality constraints.

The CPLEX solver can be used to solve complex mixed-integer linear programming problems while ensuring optimal solution accuracy and robustness.

3. Case Study

An area in the northwest of China with abundant renewable energy resources was selected as a case study for this paper. This area contains an abundance of renewable energy that can be transferred to other locations by using transmission sections. Hence, the maintenance strategy for the transmission sections has a profound influence on the accommodation of renewable energy.

3.1. Initial Conditions

There were five renewable energy transmission sections in the chosen northwest region in 2019—section A, section B, section C, section D, and section E—and their topological configuration is shown in Figure 2. The section quota refers to the power of transmission of electricity between two regions in 15 min. The section quota between the main network and section A was 1450 MW; the quota between the main network and section B was 1300 MW;

the quota between the main network and section C was 780 MW; the quota between the main network and section D was 750 MW; the quota between the main network and section E was 1400 MW. Three maintenance scenarios were set from the perspectives of planning and operation based on the actual operation of the region in 2019.

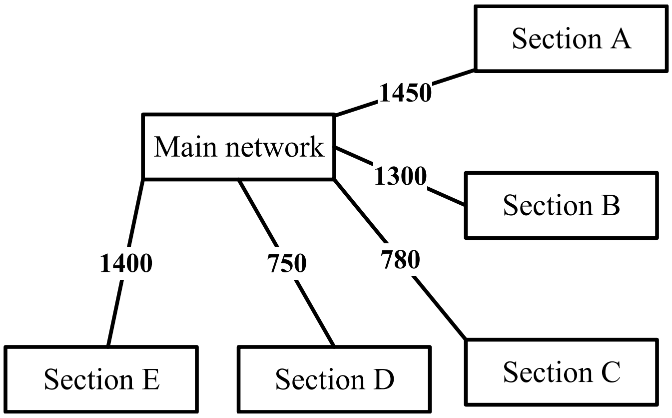

Figure 2. Model of the power grid topology and the renewable energy transmission section quota.

The conditions for the REPS are the key elements. Table 1 presents the real conditions of the renewable energy consumption capacity, and Table 2 shows the initial consumption rates of the renewable energy in the main grids and transmission sections.

Table 1. Real conditions of the renewable energy consumption capacity.

Serial Number	Condition	Calculation Principle
1	Renewable energy resource hours	Actual hours of renewable energy resources used in a quarter
2	Renewable energy output sequence	Restoring a renewable energy sequence using a quarter's renewable energy actual output and power quota record
3	Contact line principle	Actual contact line data for a quarter

Table 2. Initial renewable energy consumption rates of the sections and main network.

Section	Consumption Rate (%)
Section A	97.30
Section B	94.88
Section C	90.30
Section D	98.33
Section E	99.90

3.2. Sensitivity for Section Maintenance

This section analyzes the influences of maintenance factors on renewable energy consumption from a planning perspective. We changed the annual section quota of each section, obtained the corresponding data, fit the function of the section capacity and renewable energy consumption rate, and compared the impacts of the maintenance of the five sections on the accommodation of renewable energy. The maintenance time for zones with a significant impact on renewable energy consumption rates should be as short as possible, and the maintenance should be arranged when the renewable energy generation is lower.

The functional relationships between the section quota reductions and renewable energy consumption rate are as follows:

$$\text{Section } A: y = -0.053x^2 + 0.2915x + 97.173 \quad R^2 = 0.9876$$

$$\text{Section } B : y = -0.0673x^2 + 0.2964x + 97.305 \quad R^2 = 0.9976$$

$$\text{Section } C : y = -0.0517x^2 + 0.0548x + 97.327 \quad R^2 = 0.994$$

$$\text{Section } D : y = -1E - 05x^2 + 0.0024x + 97.338 \quad R^2 = 0.9899$$

$$\text{Section } E : y = -0.009x^2 + 0.0886x + 97.342 \quad R^2 = 0.481$$

The results in Figure 3 show that the renewable energy consumption rate of the whole network section decreased with the decrease in the section quota. The reduction in the section quota of section A ranged from 1000 to 100 MW, and the consumption rate ranged from 97.56% to 94.63%. The reduction in the section quota of section B ranged from 1000 to 100 MW, and the consumption rate ranged from 97.63% to 93.52%. The reduction in the section quota of section C ranged from 660 to 120 MW, and the consumption rate ranged from 97.22% to 91.43%. The reduction in the section quota of section D ranged from 500 to 100 MW, and the consumption rate ranged from 97.49% to 95.48%. The reduction in the section quota of section E ranged from 1000 to 100 MW, and the consumption rate ranged from 97.48% to 97.33%.

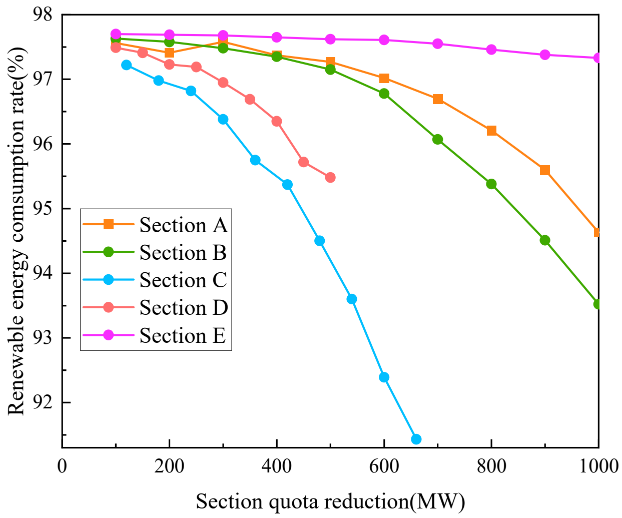

Figure 3. Sensitivity analysis of maintenance factors based on the renewable energy consumption rate.

The maintenance of section C had the greatest impact on the renewable energy consumption of the whole network, while the maintenance of section E had the least impact. Section E should be chosen to overhaul the network, and section C showed the fastest rate of decline regarding the renewable energy consumption rate. Thus, as the section quota decreased, it must be chosen for maintenance carefully.

3.3. Strategy for Single-Section Maintenance

The analysis of the influences of maintenance factors on renewable energy consumption from the perspective of operation was as follows. In this section, we considered the impacts of the maintenance of a single transmission section in different months on renewable energy accommodation. According to the published literature and field research, transmission section maintenance is set to be carried out once a year, and its duration is 1 month. First, when the maintenance of a section was considered, the section quota became 0. The above consumption model was used to calculate the rate of consumption of renewable energy. The power and electricity were found to be unbalanced when the transmission section quota was 0, so the transmission section quota was set to the minimum value under the condition of power and electricity balance. The minimum value of each transmission section under the condition of ensuring power balance during maintenance is shown in Table 3.

Table 3. Transmission section quotas during maintenance in twelve months (MW).

Month	Section A	Section B	Section C	Section D	Section E
January	200	100	100	100	300
February	100	100	100	100	200
March	200	100	100	100	300
April	100	100	100	100	200
May	100	100	100	100	300
June	200	100	100	100	300
July	100	100	100	100	300
August	100	100	100	100	200
September	100	100	100	100	300
October	100	100	100	200	300
November	200	100	100	100	300
December	200	100	100	100	200

The renewable energy consumption rate could be calculated when the five sections were overhauled in different months. The renewable energy consumption rate in the whole network was calculated. For section A, the decrease in the value of renewable energy consumption ranged from 0.98 to 0.31; for section B, this was 0.85 to 0.45; for section C, this was 0.75 to 0.33; for section D, this was 0.53 to 0.21; for section E, this was 0.24 to 0.00.

The degrees of influence of transmission section maintenance on the consumption rate of renewable energy in the whole network were ranked from large to small as follows: section A, section B, section C, section D, and section E. The average decreases in the renewable energy consumption rate of the whole network under the maintenance of the transmission section over 12 months were 0.64%, 0.6%, 0.54%, 0.36%, and 0.05%, respectively, as shown in Table 4 and Figure 4.

Table 4. Decrease in the value of the renewable energy consumption rate in the whole network and in each section (%).

Ranking of Impact	Whole Network (Average Decrease in Rate)
1	Section A (0.64)
2	Section B (0.60)
3	Section C (0.54)
4	Section D (0.56)
5	Section E (0.55)

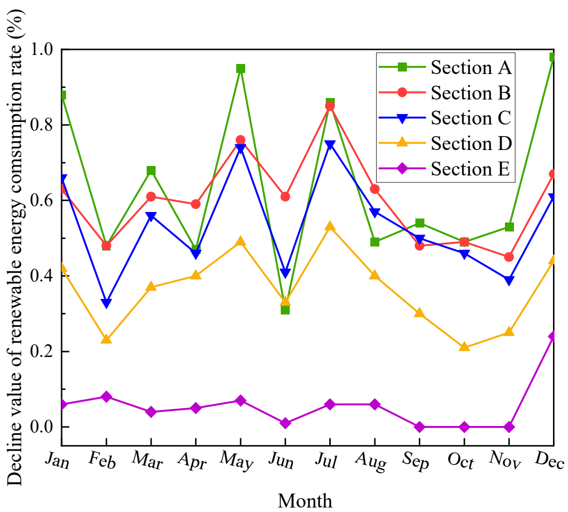

Figure 4. Decrease in the value of the renewable energy consumption rate in the whole grid.

3.4. Strategy for Two Sections' Simultaneous Maintenance

In the actual maintenance process, in order to increase the maintenance efficiency, it is unnecessary to carry out single-section maintenance each time. It is possible to carry out the maintenance of multiple sections at the same time, but the impact of the simultaneous maintenance of more than two sections on the regional power grid is too large. We considered the impact of a typical scenario in which two transmission sections were simultaneously overhauled on the renewable energy consumption of the entire network. Under the condition of power balance, the double-section transmission section quota was set to the minimum value. We calculated the decline in the consumption rate of renewable energy when the two sections were simultaneously under maintenance for a month. The results are shown in Figure 5.

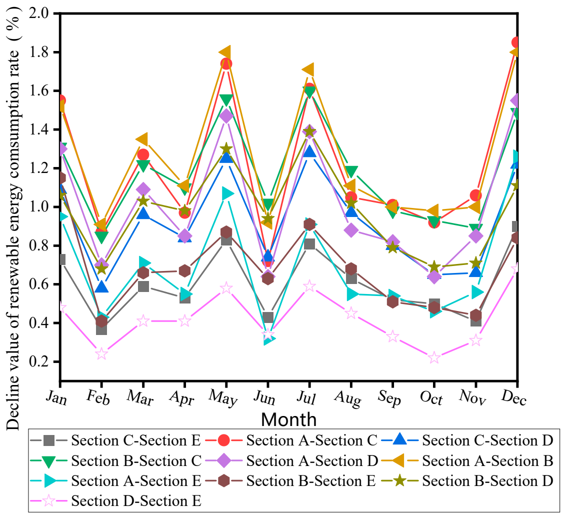

Figure 5. Decrease in the value of the renewable energy consumption rate with the simultaneous maintenance of two transmission sections.

For sections A and B, the decrease in the value of the renewable energy consumption rate ranged from 1.8 to 0.91. For sections A and C, the decrease ranged from 1.85 to 0.72. For sections A and D, the decrease was from 1.55 to 0.64, while for sections A and E, it was 1.26 to 0.32; for sections B and C, it was 1.56 to 0.85; for sections B and D, it was 1.39 to 0.68; for sections B and E, it was 1.15 to 0.41; for sections C and D, it was 1.28 to 0.58; for sections C and E, it was 0.90 to 0.37; for sections D and E, it was 0.68 to 0.22.

By analyzing the above three section maintenance methods, we concluded that the rate of consumption of renewable energy decreased with the increase in the section quota. In the case of reducing the transmission quota to the lowest value according to the power balance rule, the rate of consumption of renewable energy decreased less in summer and autumn, which are more suitable for maintenance. Considering the impacts of the three maintenance strategies on the renewable energy consumption rate, priority should be given to monthly reductions in the transmission quotas for a single section's maintenance.

4. Discussion

4.1. Results

The decreases in the renewable energy consumption rate for sections A, B, and E were significantly slower than those of sections C and D. The quota for sections A, B, and E was larger than that for sections C and D. The sequence of the sensitivity was as follows: Section C > Section D > Section B > Section A > Section E, implying that section E was most suitable for maintenance, with the average rate of consumption of renewable energy being 97.48%.

By analyzing the changes in the renewable energy consumption rates of five transmission sections in each month, the most suitable months for maintenance were found, as shown in Table 5. For the renewable energy consumption of the whole network, section A was most suitable for maintenance in June, section B in November, section C in February, section D in October, and section E in November. Overall, most sections were suitable for maintenance in February and November. Section E was most suitable for maintenance because the value of renewable energy saw no changes.

Table 5. Months suitable for maintenance in each section.

Section	Months Suitable for Maintenance
A	June, April, February
B	November, September, February
C	October, February, November
D	October, February, November
E	October, November, September

The results show that the renewable energy consumption rates of sections D and E were the smallest; the rates decreased by 0.2% to 0.6%. The renewable energy consumption rates with the maintenance of sections A and C or A and B decreased the most, from 0.9% to 1.8%, so the simultaneous overhaul of these sections should be avoided. The transmission sections that were suitable for simultaneous maintenance were sections D and E, C and E, A and E, and B and E. The months that were most suitable for maintenance were February, April, October, and November. The results are shown in Table 6.

Table 6. Sections and months that are suitable for simultaneous overhaul.

Section	Months Suitable for Maintenance
A and B	February, June, October
A and C	February, June, October
A and D	February, June, November
A and E	June, September, October
B and C	February, October, November
B and D	February, October, November
B and E	February, October, November
C and D	February, October, November
C and E	February, June, November
D and E	February, June, October

Through a comparison with the findings in the literature [34,35], the obtained result was found to improve the rate of consumption of renewable energy.

4.2. Implications

RESP is a useful method for predicting the rate of consumption of renewable energy. In actual maintenance projects, RESPs should be used to decide on the maintenance strategy for the transmission sections. It should also be pointed out that economic factors are of great importance, but these were not considered in the current work. The maintenance costs of different sections are quite different in different months. In future work, a more comprehensive model that includes economic factors should be taken into account in order to develop a more reliable strategy.

5. Conclusions

In this study, a time-series REPS was proposed to accurately predict the power generation in a real situation. In a case study, according to the results of the REPS, the maintenance sensitivity of the different sections was calculated and determined. Appropriate maintenance strategies were selected for different situations by comparing the consumption rates. The corresponding results are as follows:

(1) The time-series REPS method could accurately predict the rate of consumption of renewable energy.
(2) Section E had the lowest sensitivity and was most suitable for maintenance, as the average consumption rate was 97.48%
(3) As for monthly maintenance, section E should be given priority because the consumption rate only decreased by 0.32%. Sections D and E were the most suitable sections for simultaneous maintenance, with an average decline of 0.42% in the renewable energy consumption rate. Maintenance should be arranged in February or November in order to achieve a better consumption rate for all sections.

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