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Research on Quantitative Evaluation Methods of New Energy Accommodation Factors under Synergistic Scenes

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Abstract: In light of the recent announcement of the primary construction objectives of the modern energy system during the "14th Five-Year Plan", the renewable energy industry has experienced rapid growth. The accurate assessment of the effects of renewable energy accommodation driven by various factors under the synergistic influence of "Source-Grid-Load-Storage" is vital for guiding the scientific planning and rational arrangement of the future energy system. For this purpose, this paper comprehensively considers boundary conditions such as power demand, load characteristics, cross-regional transmission characteristics, renewable energy resources and output characteristics, as well as energy storage characteristics. Based on the principle of simulation of time series production, this paper establishes a model for evaluating renewable energy accommodation and introduces a continuous optimization solution method. Taking the renewable energy accommodation of the power grid in a Chinese region as a case, this paper constructs 16 representative scenes that satisfy the development plans of various factors in the region. In conjunction with the simulation results of these 16 scenes, this paper uses the Shapley value method to determine the increased accommodation capacity of renewable energy promoted by multiple factors under the synergistic effect. The analysis results show that the Shapley value method examines the entire development process from the current situation to the synergistic scenes. By comprehensively weighing all development scenes regarding the increased accommodation capacity of various factors, this paper quantifies the effects of each factor under the synergistic scenes.

Keywords: renewable energy; synergistic accommodation; simulation of time series production; quantitative evaluation; power grid planning

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Citation: He, G.; Zhang, X.; Cui, K.; Wang, X.; Zhang, H.; Wang, Z. Research on Quantitative Evaluation Methods of New Energy Accommodation Factors under Synergistic Scenes. *Processes* **2023**, *11*, 2896. https://doi.org/10.3390/pr11102896

Received: 2 September 2023
Revised: 23 September 2023
Accepted: 28 September 2023
Published: 30 September 2023

1. Introduction

The "14th Five-Year Plan" specifies the principal construction objectives of the contemporary energy system. To further advance energy conservation and carbon reduction in key areas, expedite the green transformation of the manufacturing industry, and foster the establishment of green and patterns of low-carbon production, the renewable energy sector has experienced rapid growth. Over the past few years, the power generation efficiency of renewable energy has gradually improved as the industry of power generation using renewable energy has undergone rapid development [1]. At present, the total amount of power generation using renewable energy has reached a considerable scale. However, it is worth noting that the issue of power curtailment in renewable energy poses a serious threat to the progress and development of the power system [2,3]. Therefore, emphasizing and enhancing the efficiency of integration of renewable energy into the grid and reducing power wastage constitute crucial measures for the power department to achieve progress and development in the current context [4]. Integrating and coordinating various technological measures for accommodating renewable energy is of great significance in addressing the issue of power curtailment resulting from inadequate accommodation of renewable energy. In line with the guidance on enhancing the regulation capacity of the power system, the

National Energy Administration has formulated relevant measures from multiple perspectives, including the load, power supply, and grid, and put forth constructive policies and proposals [5]. Thus, in order to maximize the utilization of accommodation resources, it holds immense social value and significance to coordinate accommodation measures from the dimensions of "power supply-power grid-load-energy storage" to tackle the problem of power wastage in renewable energy.

From the perspective of power supply, the flexible adjustment of various types of generator sets is beneficial for improving and promoting the accommodation of renewable energy. Power plants have the capability to flexibly integrate more wind and solar energy, thereby avoiding the waste of renewable energy and achieving more efficient energy systems [6]. Improving the deep peak shaving capacity of conventional thermal power units and conducting flexible transformations of thermal power units are considered effective strategies to support the development of new energy [7]. Kubik identified potential and favorable factory renovation strategies for current coal power plants and appraised the procedures that could be taken to respond to power abandonment and ramping challenges caused by variable renewables by improving current thermal plant flexibility [8]. Kopisk confirmed how the increased share of renewable energy affects the value of power plant flexibility [9]. The flexible transformation of Chinese thermal power plants is a crucial way to increase renewable energy consumption. However, thermal power plants in China were built in different eras, and achieving the ideal solution for the energy supply in China through overall uniform flexible transformation is difficult [10], requiring the district to develop a flexible transformation plan of "One Unit One Policy" based on the actual situation of the company [11]. From the perspective of the load, stimulating power load growth and increasing the demand response resource schedule capability are considered effective measures to promote the accommodation of renewable energy. Some researchers alleviate renewable energy accommodation issues by increasing the type and size of loads in the power grid, including increasing the air conditioning load to effectively accommodate photovoltaic power generation [12] and applying electric vehicles to increase the grid load and improve the capacity of renewable energy [13,14]. Van der Kam and van Sark constructed a self-consuming model for studying intelligent charging of electric vehicles and grid technology, increasing photovoltaic power, exploring large-scale deployment and promotion of electric vehicles, as well as alternative solutions for integrating photovoltaic power into the grid [15]. Jiang Yuewen constructed a nonlinear optimization model for the P2G device-integrated microgrid of power, heat, and gas, with the goals of the minimum operating cost, minimum wind abandonment rate, and minimum comprehensive cost, and applied power to natural gas to increase the capacity of wind power [16] (and increase the adaptation of wind power through the application of power to natural gas [16]). Based on relevant testing, the cuckoo search optimization (CSO) algorithm, and the extreme learning machine (ELM) method, Wu Jing et al. constructed a prediction model to predict and analyze the development potential of power substitution [17]. From the perspective of the power grid, Bu Yinhe proposed applying power transmission across regions to improve the accommodation capacity, focusing on increased exchange power for interprovincial tie lines and an increased interprovincial power transmission capacity [18]. Combining case studies, Nysander et al. found that the most important measure to reduce wind abandonment was to increase the transmission capacity [19]. Based on the model for series production simulation, Li Guodong proposed a new model for the capacity for accommodating renewable energy that considers the utilization level of interprovincial interconnection lines. The analysis results of the instance show that effective utilization of the transmission capacity of interprovincial interconnection lines can significantly improve the accommodation capacity of renewable energy [20]. Based on the complementarity of the capacity for accepting renewable energy in different regions, Gao Che et al. established an evaluation model for renewable energy accommodation that analyzes the interregional energy export and the interconnected energy accommodation of the sending and receiving ends [21]. From the perspective of energy storage, reasonable allocation of energy storage power stations can promote the accommodation of renewable energy. Connolly analyzed the role of pumped storage in integrating wind energy in Ireland under different capacities, operational strategies, costs, and alternative solutions [22]. The authors of [23] studied the benefits of PHES for the energy system in Britain and concluded that energy storage is capable of reducing system costs, wind abandonment, and the energy required for traditional power generation. The authors of [24] established a correlation model for analyzing energy storage capacity and renewable energy consumption. Through model analysis, the impact of different schemes for energy storage configuration on the system's capacity for accommodating renewable energy was explored and analyzed. Denholm emphasized that energy storage configurations are crucial for achieving high penetration rates of wind and solar energy. A large portion of wind and solar energy may be limited if energy storage is not properly configured [25].

In their study, Liu Mengchen et al. engaged in a discussion concerning the comprehensive configuration effect of the multifaceted impact of the "power supply-power grid-load-energy storage" factors on the advancement of new energy accommodation [26]. Malik et al. explored five distinct configurations of hybrid energy systems and identified the best configuration through algorithmic analyses [27]. Similarly, Mishra's group devised a model of a grid-connected hybrid system grounded in renewable energy sources and identified the optimal set-up by utilizing the DHS algorithm [28]. Meanwhile, Xie Guohui et al. delved into the accommodation effect of individual factors and devised an evaluation model to assess the contribution of each factor in promoting accommodation [29,30]. However, the authors of [29,30] failed to consider the entire progression from a single factor to the synergistic effect of multiple factors, thus rendering the calculation results incomplete. To address this limitation, this study takes into account boundary conditions such as power demand, load characteristics, cross-regional transmission characteristics, renewable energy resource and output characteristics, and energy storage characteristics. By applying the principle of timing production simulation, an evaluation model for renewable energy accommodation is established, and a continuous optimization algorithm is proposed to quantify the accommodation effect of renewable energy in synergistic scenarios. Additionally, the Shapley value decomposition method is employed to determine the increased accommodation of renewable energy brought about by each factor under the synergistic effect of multiple factors. The application of the Shapley value method is illustrated in Figure 1. The analysis results demonstrate that the Shapley value analyzes the entire developmental process from the current state to synergistic scenarios. Through a comprehensive weighting of all developmental scenarios on the increased accommodation capacity of various factors, the augmented accommodation capacity of renewable energy and the quantification of factors' accommodation results under the synergistic scene can be determined.

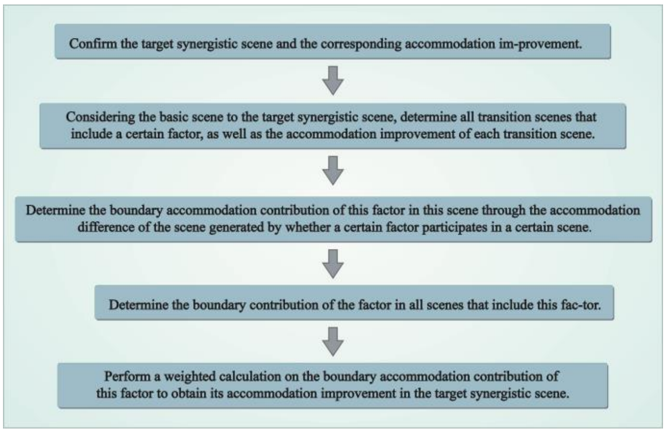


Figure 1. The approach to applying the Shapley value method.

The methods and contributions of this paper are summarized as follows:

- Construction of an evaluation model for renewable energy accommodation based on timing production simulation, along with the proposal of a continuous optimization algorithm to enhance model efficiency and accuracy, thereby proficiently quantifying the accommodation effect of renewable energy in synergistic scenarios.
- Proposal of an evaluation method for quantifying the accommodation effect of various factors in synergistic scenarios and utilization of the Shapley value to decompose the effect of each factor in promoting renewable energy accommodation in each synergistic scenario by quantifying the accommodation effect in the synergistic scenario based on the timing production model.

2. Theoretical Analysis of New Energy Accommodation

2.1. Theory of Renewable Energy Accommodation Space

The accommodation of renewable energy primarily pertains to field load accommodation, system peak shaving and valley filling, as well as AC/DC external transmission and accommodation. This accommodation is influenced by factors such as the power demand, system regulation capability, trading mechanism, network structure, and power price policy. Figure 2 presents a schematic diagram illustrating the accommodation of renewable energy. As depicted in Figure 2, the integration between the load and output curve and the minimum output of conventional units represents the maximum space available for accommodating renewable energy. Therefore, to maintain power balance, the maximum accommodation value of renewable energy at any given time equals the load at that time plus the output power minus the minimum output of the unit. To ensure the stable operation of the system, any excess renewable energy beyond the accommodation space will be cut off due to the system's inability to consume it, resulting in wind and light abandonment.

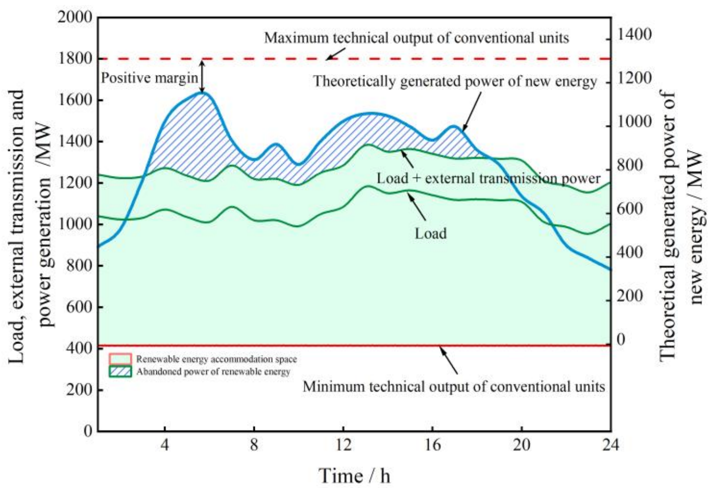


Figure 2. Schematic diagram of renewable energy accommodation.

2.2. Accommodation Factors and Improvement Measures of Renewable Energy

In recent years, the rapid advancement of the wind and solar power industries, as well as the photovoltaic sector, coupled with the publication of renewable energy policies by the government has led to an escalating concern in society regarding the issue of new energy abandonment. This predicament arises due to the sluggish progress in grid transformation, surplus installed capacity, and inadequate peak shaving capabilities. ① The growth rate of the power load remains relatively sluggish, while the development of new energy sources progresses at a rapid pace. Therefore, the newly added power market and demand fail to keep up with the swift expansion of power sources, thereby exacerbating the challenges associated with system peak shaving. ② Regional and economic disparities further compound the issue, impeding wind and photovoltaic accommodation due to limitations in distribution network structures, delayed construction of cross-provincial and power transmission across regions channels, and sluggish grid and transmission channel development. ③ These bottlenecks give rise to a series of challenges, including significant peak-valley disparities in the power grid, changes in power accommodation structures, contradictions in power supply structures, and the reverse peak shaving of wind and photovoltaic renewable energy sources, all of which pose a grave threat to the system's peak shaving capabilities. ④ Moreover, the system backup level is inadequate, necessitating sufficient backup usage to ensure the stable operation of regional power grids. However, regions abundant in renewable energy impose higher demands for system backup space.

The achievement of large-scale grid connection and accommodation of renewable energy involves two primary aspects: enhancing the flexible operation of the power system and changing the spatial constraints of renewable energy consumption. First, enhancement of the flexible operation of a power system entails transforming the power supply structure of conventional units, primarily reliant on coal, power, and gas, as well as the implementation of pumped storage technology. Secondly, the changes to the spatial constraints of renewable energy accommodation involve improving local load levels and expanding the capacity of external transmission lines. By integrating multiple accommodation resources from sources, networks, loads, and storage, synergistic accommodation schemes can be devised, effectively bolstering the capacity for renewable energy accommodation and mitigating wind and solar waste.

3. Evaluation Model of Renewable Energy Accommodation

3.1. Simulation of the Time Series Production Method

To accomplish this, the establishment of a technology for simulating timed production in power systems is necessary. This technology facilitates the operation simulation model of each link, the random operation simulation model of new energy, and the mathematical model of various conventional unit operation modes. In accordance with the power planning scheme, timing production simulation technology can simulate the year-round operation of the system under the given system operation mode. Moreover, the timing production simulation is based on an hourly or shorter time resolution, treating the system load, generator unit operating statuses, and renewable energy output as time series that evolve over time. The changes in these time series should align with the variations in renewable energy resources and system loads in the corresponding regions. This paper utilizes historical time series data from a power grid of a Chinese region as the data basis for the renewable energy time series and load series, as depicted in Figure 3.

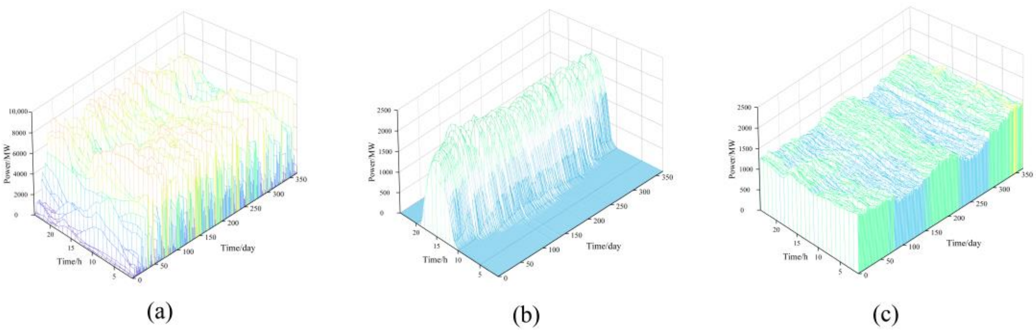


Figure 3. Historical time series data from a power grid of a Chinese region. (**a**) Annual wind power output curve from a power grid of a Chinese region. (**b**) Annual photovoltaic power output curve from a power grid of a Chinese region. (**c**) Annual load power accommodation curve from a power grid of a Chinese region.

3.2. Objective Function

This paper takes the maximized accommodation of renewable energy as an optimization goal, as shown in Equation (1):

$$f = \max[\sum_{i=1}^{Nw}\sum_{t=1}^{T} P_{w,i}(t) + \sum_{i=1}^{Nv}\sum_{t=1}^{T} P_{v,i}(t)] \tag{1}$$

where $P_{v,i}(t)$ represents the output of the photovoltaic power plant I at time t; N_v represents the number of photovoltaic power stations; $P_{w,i}(t)$ represents the output of wind power plant i at time t; and N_w represents the number of wind plants.

3.3. Constraints

3.3.1. Power Balance Constraints

$$\begin{aligned} &\sum_{n=1}^{N} P_{g,n}(t) + \sum_{i=1}^{Nw} P_{w,i}(t) + \sum_{i=1}^{Nv} P_{v,i}(t) + P_h(t) \\ &+P_{stdch}(t) = P_l(t) + P_s(t) + P_{stch}(t) \end{aligned} \tag{2}$$

Here, $P_{g,n}(t)$ represents the output of the thermal motor group n at time t; N represents the number of thermal power units; $P_{stdch}(t)$ represents the discharge power of the energy storage station at time t; $P_{stch}(t)$ represents the discharge power of the energy storage station at time t; $P_h(t)$ represents the output of the hydroelectric unit at time t; $P_l(t)$ represents the transmission power of the high-voltage transmission line at time t; and $P_s(t)$ represents the load power at time t.

3.3.2. Thermal Power Unit Output Constraints

The thermal power unit output constraints are expressed by

$$P_{g\min,n} \le P_{g,n}(t) \le P_{g\max,n} \tag{3}$$

The climbing constraints for thermal power units are expressed by

$$\begin{cases} P_{g,n}(t+1) - P_{g,n}(t) \le P_{gcu,n} \\ P_{g,n}(t) - P_{g,n}(t+1) \le P_{gcd,n} \end{cases} \tag{4}$$

where $P_{gcu,n}$ represents the constraint of increasing the output of the thermal motor group n; $P_{gcd,n}$ represents the constraint of reducing the output of the thermal motor group n; $P_{g\max,n}$ represents the maximum output of the thermal power unit; and $P_{g\min,n}$ represents the minimum output of the thermal power unit.

3.3.3. Output Constraints of Energy Storage Power Plants

The energy storage output constraint is expressed as follows:

$$\begin{cases} P_{stch\min} \le P_{stch}(t) \le P_{stch\max} \\ P_{stdch\min} \le P_{stdch}(t) \le P_{stdch\max} \end{cases} \tag{5}$$

The energy storage capacity constraints are expressed by

$$\begin{cases} C_{st}\lambda_{\min} \le E_{ess}(t) \le C_{st}\lambda_{\max} \\ E_{ess}(t+1) = E_{ess}(t) + \varphi_{sc}P_{stch}(t) \quad - \varphi_{sd}P_{stdch}(t) \\ E_{ess}(0) = E_{ess}(T) \end{cases} \tag{6}$$

where $P_{stch\min}$ represents the minimum power of energy storage charging; $P_{stch\max}$ represents the maximum power of energy storage charging; $P_{stdch\min}$ represents the minimum power of energy storage discharge; $P_{stdch\max}$ represents the maximum power of energy storage discharge; $P_{stch\min}$ represents the minimum power of energy storage discharge;

C_{st} represents the total energy storage capacity; $\lambda_{\min}$ represents the minimum state of charge for energy storage; $\lambda_{\max}$ represents the maximum state of charge for energy storage; $E_{ess}(t)$ represents the energy storage capacity at time t; φ_{sc} represents the charging efficiency; and φ_{sd} represents the discharge efficiency.

3.3.4. Output Constraints of Hydroelectric Units

$$P_{h\min} \leq P_h(t) \leq P_{h\max} \tag{7}$$

Here, $P_{h\min}$ represents the minimum output of the hydroelectric unit, and $P_{h\max}$ represents the maximum output of the hydroelectric unit.

3.3.5. Rotation Backup Constraint

$$\begin{cases} (1+\beta_{wv})\left(\sum\limits_{i=1}^{Nw} P_{w,i}(t) + \sum\limits_{i=1}^{Nv} P_{v,i}(t)\right) \leq \sum\limits_{n=1}^{N} P_{g,nsr} + P_{hsr} \\ (1+\beta_{sl})(P_s(t) + P_l(t)) \leq \sum\limits_{n=1}^{N} P_{g,nsr} + P_{hsr} \end{cases} \tag{8}$$

Here, β_{wv} represents the proportion of renewable energy rotating reserve; β_{sl} represents the proportion of load rotation reserve; $P_{g,nsr}$ represents the rotating spare capacity provided by the thermal motor group n; and P_{hsr} represents the rotating reserve capacity provided by the hydroelectric unit.

3.3.6. Output Constraints of External Transmission Lines

$$P_{l\min} \leq P_l(t) \leq P_{l\max} \tag{9}$$

Here, $P_{h\min}$ represents the minimum power of the high-voltage transmission line, and $P_{h\max}$ represents the maximum power of the high-voltage transmission line.

3.3.7. Renewable Energy Output Constraints

$$\begin{cases} P_{w,i\min} \leq P_{w,i}(t) \leq P_{w,i\max} \\ P_{v,i\min} \leq P_{v,i}(t) \leq P_{v,i\max} \end{cases} \tag{10}$$

Here, $P_{w,i\min}$ represents the minimum output of wind farm i; $P_{w,i\max}$ represents the maximum output of wind farm i; $P_{v,i\min}$ represents the minimum output of photovoltaic power station i; and $P_{v,i\max}$ represents the maximum output of the photovoltaic power plant i.

3.4. Calculation Method

A simulation of the time series production model was constructed using YALMIP in the MATLAB platform. In typical MATLAB solving, variables with the same definition overwrite the original variables. However, during the YALMIP calculation solution, the original variables are not overwritten, and new variables are continuously created, resulting in variable accumulation. Conducting simulation calculations throughout the year directly would lead to an excessive number of variables, causing the required time to exceed a reasonable range. To address this issue, this study proposes a continuous optimization algorithm for solving time series models. This algorithm continuously increases the time series length to maintain stable system operation until reasonable time expectations are met. Additionally, this study determines the time series step size and converts the entire year's time series simulation calculation into a continuous solution for each time series step size. By utilizing the superposition optimization of continuous time series steps, the overall optimization results are obtained.

First, this study set the expected calculation time and continuously increased the timing length. When the required calculation time equaled the expected calculation time, the timing step M was determined, resulting in an ordering of N = T/M. This division allowed the entire year's time period to be divided into N segments of consecutive sub-time sequences:

$$\begin{bmatrix} h_1 \\ h_2 \\ h_3 \\ \vdots \\ h_N \end{bmatrix} = \begin{bmatrix} 1 & 2 & \cdots & M \\ M+1 & M+2 & \cdots & 2M \\ 2M+1 & 2M+2 & \cdots & 3M \\ \vdots & & & \\ (N-1)M+1 & (N-1)M+2 & \cdots & NM \end{bmatrix} \quad (11)$$

Each segment had a step size of M. The sub-time sequence was then simulated and calculated, and the results of the current time sequence were transmitted to the next period to serve as the initial conditions for the subsequent time sequence. By continuously transmitting the simulation results of the N sub-time series, the simulation results for the entire year could be obtained.

4. Quantitative Evaluation of Accommodation Factors in Synergistic Scenes

4.1. Synergistic Scene Configuration and Accommodation Calculation

The specific steps of the synergistic scene configuration method and accommodation calculation method are shown in Figure 4 with the steps following it.

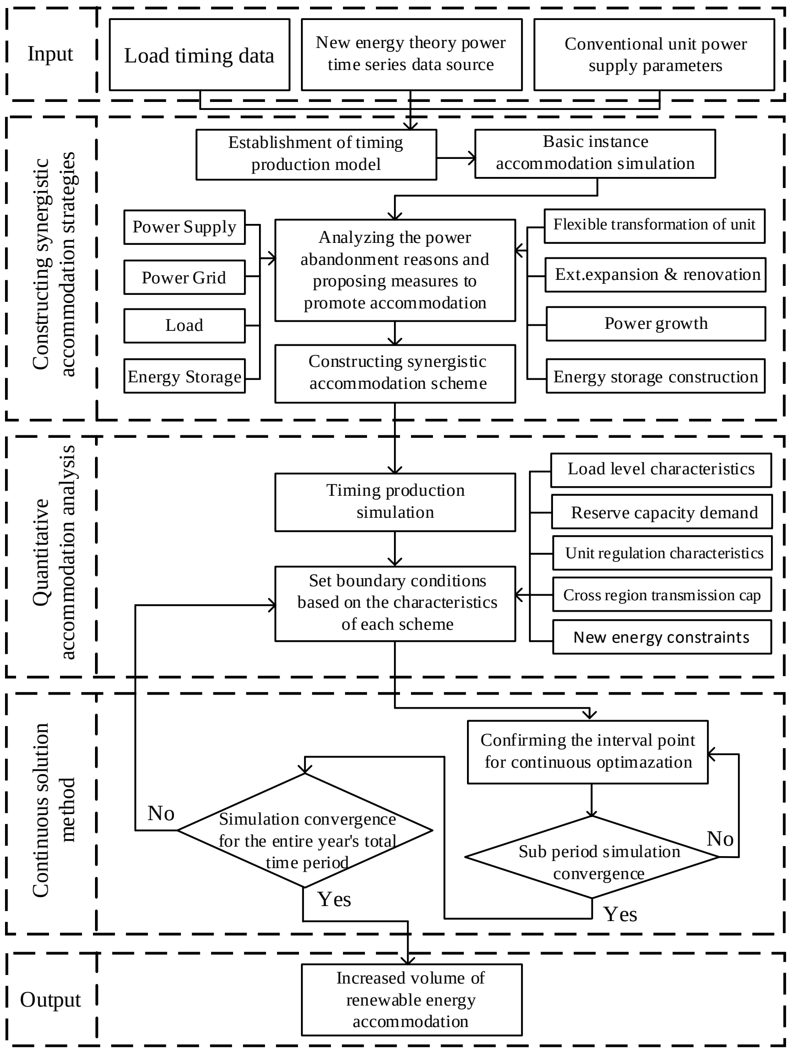


Figure 4. Synergistic scene configuration and flowchart for calculating accommodation capacity.

First, this paper prepared basic data and incorporated data from the time series load, wind power, photovoltaic theoretical output data, and conventional unit output data into the accommodation model. The study conducted a simulation of new energy accommodation in regional power grid basic cases, analyzed the accommodation status of the region, and constructed a synergistic scene of the interaction of various factors within the "power supply-power grid-load-energy storage" framework. Subsequently, based on the specific requirements in each scene, the study further adjusted conditions such as the unit regulation constraints, reserved capacity constraints, renewable energy output constraints, and cross-regional transmission constraints and constructed their corresponding boundary constraints. Finally, the continuous solution method was applied to perform a time series simulation of the model, and the overall accommodation under the scene was obtained.

4.2. Quantitative Evaluation Methods for Accommodation Factors in Synergistic Scenes

It is extensively understood that the total accommodation improvement under the influence of multiple factors is generally not equal to the direct superposition of the accommodation improvement when each factor acts alone. In a synergistic scene, the amount of accommodation improvement brought about by a certain factor differs from the amount of accommodation improvement brought about by that factor alone. If the increase in accommodation caused by a factor acting alone is directly taken as the increase in accommodation caused by that factor in a synergistic scene, errors may arise. Therefore, this study introduces the Shapley value method and the proportion method.

4.2.1. Proportion Method

The proportion method employs a proportion factor [31] to modulate the incremental accommodation of individual elements in isolation. This ensures that the combined adjusted incremental accommodation of all factors matches the cumulative incremental accommodation in the combined setting:

$$\alpha = V(W) / \sum_{i=1}^{N} L_{i,sep} \tag{12}$$

$$Li = \alpha \cdot L_{i,sep} \tag{13}$$

$$V(W) = \sum_{i=1}^{N} Li \tag{14}$$

where $V(W)$ represents the overall accommodation improvement in a synergistic scene; $L_{i,sep}$ represents the accommodation improvement contributed by factor i when acting independently; and Li represents the accommodation improvement brought about by the factor i in the synergistic scene.

The proportion method modifies the incremental accommodation of each factor with a proportion factor to deduce each factor's contribution in the combined context. This technique mirrors the linear decomposition of the total incremental accommodation in the combined setting, factoring in the relative accommodation contributions of different elements [29]. The governing equation is

$$Li = \alpha \cdot L_{i,sep} = V(W) \cdot (L_{i,spe} / \sum_{i=1}^{N} L_{i,sep}) \tag{15}$$

$$R_i = L_{i,spe} / \sum_{i=1}^{N} L_{i,sep} \tag{16}$$

where R_i represents the ratio of factor i's contribution to accommodation.

4.2.2. Shapley Value Method

The Shapley value refers to a means to determine the individual contributions made by each participant in a synergistic effort, thereby facilitating the equitable distribution of benefits among them. By employing the Shapley value method, one can effectively dissect the overall improvement in accommodation achieved within synergistic settings, thereby determining the specific contributions made by various factors. In the process of computation, this paper sequentially evaluates the benefits yielded by each potential scenario involving a particular factor, subsequently assigning them weighted averages in proportion to obtain a comprehensive income. The Shapley value method, taking into account the combined impact of multiple factors on the overall outcome, enables the disentanglement of each factor's contribution to the overall enhancement of accommodation during synergistic efforts. Therefore, this method has been widely adopted as a means of quantifying the accommodation improvement resulting from diverse factors in the context of synergistic effects, as represented by the following formula:

$$M_i = V(S) - V(S \backslash \{i\}) \tag{17}$$

where M_i represents the marginal benefit of the i^{th} factor; $V(S)$ denotes the total revenue including factor i; and $V(S \backslash \{i\})$ indicates the benefit after excluding factor i under scene $V(S)$:

$$W|S| = \frac{(n - |S|)!(|S| - 1)!}{n!} \tag{18}$$

where $W|S|$ represents the weighting factor; $|S|$ denotes the number of factors in set S; and n indicates the total number of factors:

$$K_i(V) = \sum_{s \in Ri} W|S| \cdot [V(S) - V(S \backslash \{i\})] \tag{19}$$

where $K_i(V)$ represents the Shapley value of the ith factor in the synergistic allocation and Ri denotes all subsets including i.

The application of the Shapley value method facilitates the decomposition and calculation of the total accommodation improvement within a synergistic scene, with the Shapley values corresponding to each factor representing the accommodation improvement attributable to said factor within said scene. Two methods of calculating the increase in renewable energy accommodation resulting from various factors within the synergistic scene are illustrated in Figure 5.

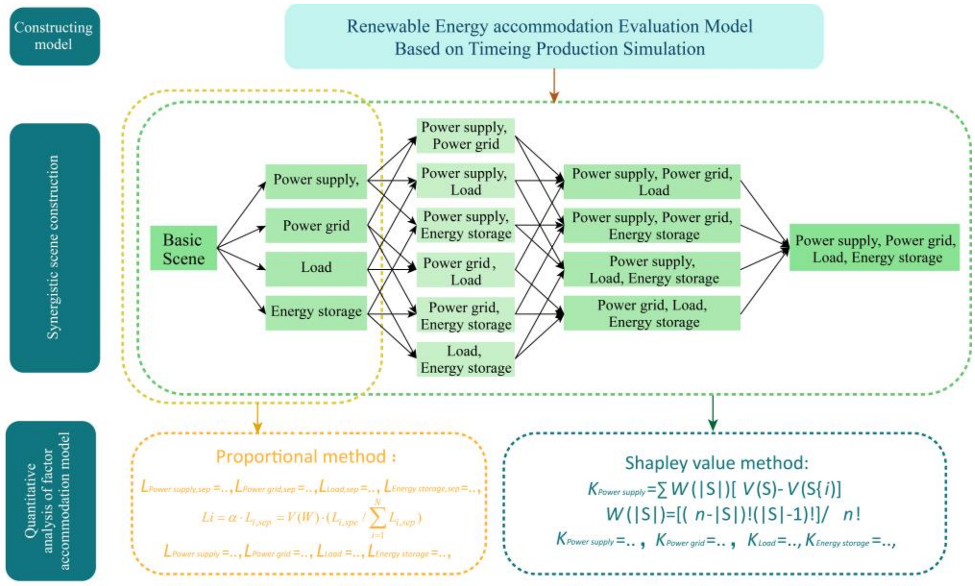


Figure 5. Flowchart for effect quantification of various factors for promoting the accommodation of renewable energy in synergistic scenes.

5. Example Analysis

5.1. Basic Instance

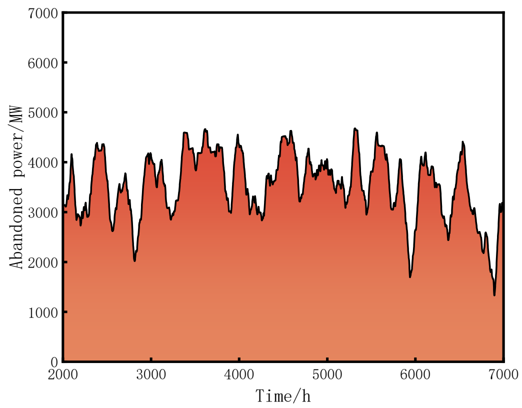
To illustrate the numerical analysis, this paper selected the accommodation situation of a power grid in a Chinese region. In the production calculations for the time series of the baseline scene, both the load data and the time series data for renewable energy drew from the grid's actual operation data from 2022. This is depicted in Figure 3 with a resolution of 1 h. This region has an installed capacity of 3240 MW for the total thermal power unit and an output limit of the conventional thermal power unit ranging from 25% to 100%. The maximum and minimum power capacities of the units used in this case, along with other pertinent boundary conditions, are presented in Tables 1 and 2. The annual accommodation of renewable energy in this region amounts to 29.423 billion kWh, with an annual surplus of 2.14 billion kWh. Notably, the months of April and October exhibited an abundance of scenic resources. However, the abandonment of wind and solar energy during this period was also relatively pronounced, accounting for 75% of the total surplus. By employing the timing production simulation method, the annual accommodation situation and the proportion of wasted power per month were obtained, as depicted in Figure 6.

Table 1. Boundary conditions for renewable energy penetration calculation.

Boundary Conditions	Calculation Conditions:
Wind and photovoltaic power output	Actual outputs for wind and photovoltaic power in 2022, as shown in Figure 3a,b.
Load	Time series load curve for 2022 as per actual data, as shown in Figure 3c.
System reserve capacity	Set to 5% of the daily maximum load.
Load-to-renewable energy reserve coefficient	Load rotation reserve coefficient was set to 0.08, and renewable energy fluctuation rotation reserve coefficient was set to 0.06.
Maximum and minimum output power of units	Based on the actual minimum operating mode of units, specific data are provided in Table 2.
External power output limit	The maximum and minimum values of external power output serve as the grid's external power planning limits.
Renewable energy output limit	The maximum and minimum values of wind and photovoltaic power output serve as the limits for renewable energy output.

Table 2. Configuration information for standard equipment.

Power Type	Thermal Power Unit 1	Thermal Power Unit 2	Thermal Power Unit 3	Hydro Power Unit 1
Quantity or Number	2	5	1	2
Single Unit Capacity (MW)	600	350	300	100
Maximum Output Power (%)	100%	100%	100%	100%
Minimum Output Power (%)	25%	25%	25%	25%
Ramp Rate (MW/min)	18	10.5	9	3



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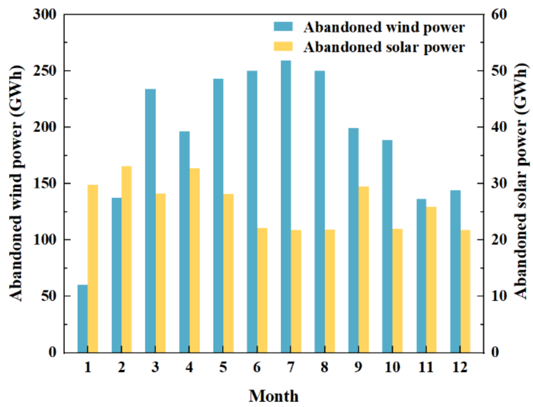

(**b**)

Figure 6. Timing production simulates the annual accommodation of renewable energy. (**a**) Annual accommodation of new energy. (**b**) Monthly proportion of abandonment of wind and photovoltaic power.

5.2. Construction and Accommodation Calculation of Synergistic Scenes

By integrating the analysis of fundamental accommodation cases with the optimal utilization of accommodation resources, this paper proposes four primary factors, namely "power supply", "power grid", "load", and "energy storage", as key drivers for promoting renewable energy consumption. Each factor is tailored to the specific circumstances and development plans.

Power supply: This paper implements a flexibility enhancement project for thermal power units, entailing a reduction in the minimum output of said units and an expansion of their peak shaving capacity. The maximum deep regulation capacity of the currently operational thermal power units stands at 75%, with projections indicating an anticipated increase to 80% by 2023. The rational development plan for this factor involves setting the minimum technical output reduction of thermal power units at 5%.

Power grid: The restricted congestion of transmission lines is identified as one of the primary causes for power abandonment within the power grid. To address this issue, the external transmission lines will undergo expansion and renovation, aiming to optimize the network structure and enhance the transportation capacity of key sections. Statistical data revealed an 8.58% year-on-year increase in the outbound power supply of the power grid within this region in 2022. Therefore, an 8% increase in the external transmission capacity is deemed a reasonable course of action.

Load: The country will expedite the construction of power substitution projects while fostering the development of diverse flexible power loads. This approach aims to bolster the overall load volume through power substitution and the utilization of flexible loads. Notably, the electricity consumption of all sectors in this region experienced 12.1% of year-on-year growth in 2022. Therefore, a 12% increase in the local power load is considered a reasonable proposition. In addition, the integration of renewable energy and power substitution technology will be employed to facilitate sustainable development on the consumer side and promote the accommodation of renewable energy within the region.

Energy storage: Uncertainties persist regarding the production of the pumped storage power station in this region as the "14th Five-Year Plan" draws to a close. Based on the energy storage construction progress in the northern region, the energy storage capacity is defined as 0.5 million kW. Additionally, by leveraging the rapid ascent and swift, adaptable adjustment characteristics of energy storage stations, surplus energy generated from renewable sources can be effectively redirected to peak load periods, thereby optimizing the utilization rate of renewable energy.

Drawing upon the aforementioned four factors that facilitate the integration of renewable energy, a total of 16 representative scenarios can be constructed to align with the development plans of various factors within the region. These 16 scenarios involve all possible synergistic combinations, including 4 factor collaboration, 3 factor collaboration, and 2 factor collaboration. Moreover, transitional scenes from basic scenarios to any synergistic scenario are also incorporated. By considering the boundary constraints of each scenario, the model for accommodating timed production simulation can accurately calculate the amount of renewable energy waste and the corresponding increase in renewable energy accommodation for each scenario. Refer to Table 3 for specific data.

Table 3. Scene configuration and accommodation calculation results.

Scene No.	Number of Synergistic Factors	Synergistic Factors				Accommodation Results	
		Unit Flexible Transformation (%)	Line Expansion and Renovation (%)	Load Increase (%)	Energy Storage Capacity/ 10,000 kW	New Energy Abandonment (GWh)	Consumption of New Increment (GWh)
1	0	0	0	0	0	2140	0
2	1	5	0	0	0	1822	318
3	1	0	8	0	0	1588	552
4	1	0	0	12	0	1918	222
5	1	0	0	0	50	1988	152
6	2	5	8	0	0	1402	738
7	2	5	0	12	0	1664	476
8	2	5	0	0	50	1705	435
9	2	0	8	12	0	1470	670
10	2	0	8	0	50	1502	638
11	2	0	0	12	50	1788	352
12	3	5	8	12	0	1346	794
13	3	5	8	0	50	1363	777
14	3	5	0	12	50	1587	553
15	3	0	8	12	50	1421	719
16	4	5	8	12	50	1335	805

5.3. Calculation of the Accommodation and Improvement of Factors

5.3.1. Scenes of Four-Factor Synergistic Action

In Scene 16, there exist a total of four synergistic factors, namely the flexible transformation of thermal power units, the expansion of transmission lines, the increase in load, and the construction of energy storage facilities. Within the basic scene, the cumulative amount of wasted renewable energy stands at 2140 GWh. However, after the synergistic effect of the aforementioned four factors, the abandoned renewable energy decreased to 1335 GWh, while the newly accommodated energy amounted to 805 GWh. Figure 7 provides a comparative analysis of the power abandonment situation between the basic scene and Scene 16. The calculation of accommodation improvement resulting from various factors in Scene 16 was conducted.

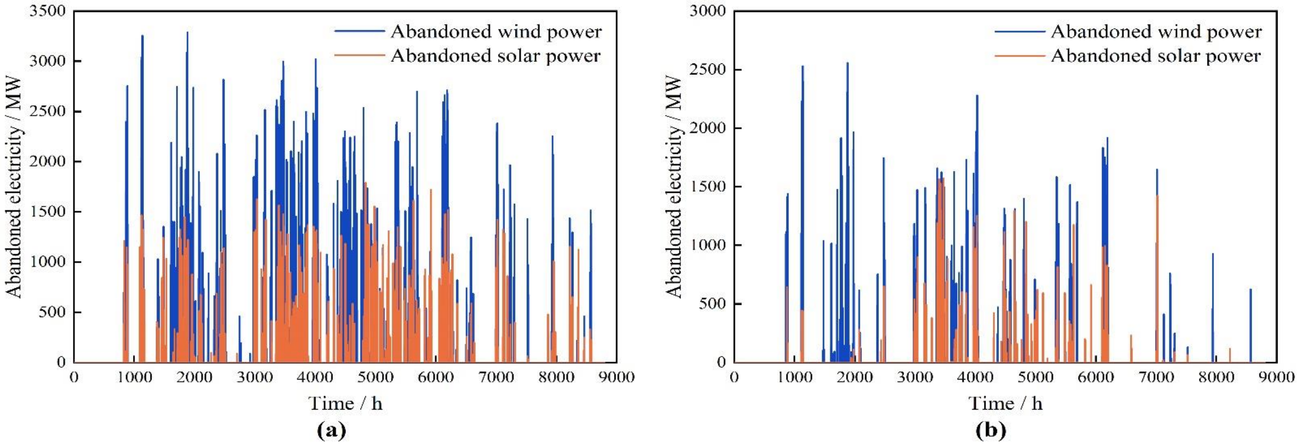

Figure 7. Annual power abandonment situation. (**a**) Basic scene power abandonment situation. (**b**) Scene 16 power abandonment situation.

Proportion method: In Scene 16, four distinct factors come into play. When these factors operate individually, they correspond to Scenes 2, 3, 4, and 5. The total accommodation values for these individual scenes are 318 GWh, 552 GWh, 222 GWh, and 152 GWh, respectively. We define R1 as the accommodation contribution ratio due to the flexibility retrofit of thermal power units, R2 as the external transmission line expansion, R3 as the load increase, and R4 as the energy storage station construction. The accommodation values when these factors operate in tandem in the synergistic scene are labeled L1, L2, L3, and L4, respectively. By employing Equation (16), the values deduced were R1 = 0.2556, R2 = 0.4437, R3 = 0.1784, and R4 = 0.1221. The total accommodation for Scene 16 totaled 805 GWh. By applying Equation (15), we found L1 = 205.8 GWh, L2 = 357.2 GWh, L3 = 143.6 GWh, and L4 = 98.3 GWh.

Shapley value method: Taking the increase in accommodation brought about by the flexibility transformation of the thermal motor unit as an example, there are four factors that operate in conjunction, with a corresponding value of n equal to four. Among all the scenes, a total of 8 scenes including the renovation factors of thermal power units could be identified, namely Scene 2, Scene 6, Scene 7, Scene 8, Scene 12, Scene 13, Scene 14, and Scene 16. The respective total accommodation improvement amounts for these scenes were 318 GWh, 738 GWh, 476 GWh, 435 GWh, 794 GWh, 777 GWh, 553 GWh, and 805 GWh. In the aforementioned scenes, after removing the factors associated with the renovation of thermal power units, the corresponding scenes were Scene 1, Scene 3, Scene 4, Scene 5, Scene 9, Scene 10, Scene 11, and Scene 15, respectively. The total accommodation improvement for the corresponding scenes was 0 GWh, 552 GWh, 222 GWh, 152 GWh, 670 GWh, 638 GWh, 352 GWh, and 719 GWh. The two sets of scenes were then matched and subtracted from one another, yielding the marginal accommodation increase Mi for each scene in which the thermal power unit renovation factors were involved. The first set of scenes comprised Scenes 2, 6, 7, 8, 12, 13, 14, and 16, with corresponding $|S|$ values of 1, 2, 2, 2, 3, 3, 3, and 4, respectively. By employing Equation (18), the W (|S|) values for the corresponding scenes could be calculated, resulting in 1/4, 1/12, 1/12, 1/12, 1/12, 1/12, and 1/4, respectively. In this context, the Shapley value for the flexibility modification factor of the thermal power unit is denoted as K1 (V), the Shapley value for the expansion factor of the external transmission line is denoted as K2 (V), the Shapley value for the electric energy replacement factor is denoted as K3 (V), and the Shapley value for the construction factor of the energy storage power station is denoted as K4 (V). The marginal accommodation improvement amount Mi for each scene involved in the thermal power unit modification factor was multiplied by the corresponding weighting factor W (|S|) and subsequently added in sequence. This process allowed us to obtain a K1 (V) value of 200 GWh. The specific data pertaining to the calculation process are presented in Table 4. The same methodology could be applied to derive K2 (V) = 399.4 GWh, K3 (V) = 123.4 GWh, and K4 (V) = 82.2 GWh.

Table 4. Calculation of process parameters.

Unit Flexible Transformation								
Calculation Formula	**Scene 2**	**Scene 6**	**Scene 7**	**Scene 8**	**Scene 12**	**Scene 13**	**Scene 14**	**Scene 16**
$V(S)$	318	738	476	435	794	777	553	805
$V(S) - V(S\backslash\{i\})$	318–0	738–552	476–222	435–152	794–670	777–638	553–352	805–719
$\lvert S \rvert$, $W(\lvert S \rvert)$	1, 1/4	2, 1/12	2, 1/12	2, 1/12	3, 1/12	3, 1/12	3, 1/12	4, 1/4
$W(\lvert S \rvert) \cdot V(S) - V(S\backslash\{i\})$	79.5	15.5	21.2	23.6	10.3	11.6	16.7	21.5
Line expansion and renovation								
Calculation formula	Scene 3	Scene 6	Scene 9	Scene 10	Scene 12	Scene 13	Scene 15	Scene 16
$V(S)$	552	738	670	638	794	777	719	805
$V(S) - V(S\backslash\{i\})$	552–0	738–318	670–222	638–152	794–476	777–435	719–352	805–553
$\lvert S \rvert$, $W(\lvert S \rvert)$	1, 1/4	2, 1/12	2, 1/12	2, 1/12	3, 1/12	3, 1/12	3, 1/12	4, 1/4
$W(\lvert S \rvert) \cdot V(S) - V(S\backslash\{i\})$	138	35	37.3	40.5	26.5	28.5	30.6	63
Load increase								
Calculation formula	Scene 4	Scene 7	Scene 9	Scene 11	Scene 12	Scene 14	Scene 15	Scene 16
$V(S)$	222	476	670	352	794	553	719	805
$V(S) - V(S\backslash\{i\})$	222–0	476–318	670–552	352–152	794–738	553–435	719–638	805–777
$\lvert S \rvert$, $W(\lvert S \rvert)$	1, 1/4	2, 1/12	2, 1/12	2, 1/12	3, 1/12	3, 1/12	3, 1/12	4, 1/4
$W(\lvert S \rvert) \cdot V(S) - V(S\backslash\{i\})$	55.5	13.2	9.8	16.7	4.7	9.8	6.7	7
Energy storage construction								
Calculation formula	Scene 5	Scene 8	Scene 10	Scene 11	Scene 13	Scene 14	Scene 15	Scene 16
$V(S)$	152	435	638	352	777	553	719	805
$V(S) - V(S\backslash\{i\})$	152–0	435–318	638–552	352–222	777–738	553–476	719–670	805–794
$\lvert S \rvert$, $W(\lvert S \rvert)$	1, 1/4	2, 1/12	2, 1/12	2, 1/12	3, 1/12	3, 1/12	3, 1/12	4, 1/4
$W(\lvert S \rvert) \cdot V(S) - V(S\backslash\{i\})$	38	9.7	7.2	10.8	3.2	6.4	4.1	2.8

5.3.2. Scenes of Three-Factor Synergy

In Scene 15, 3 synergistic factors contributed to the overall outcome, namely the expansion of transmission lines, load increase, and energy storage construction. The combined effect of these factors resulted in an abandoned power of renewable energy amounting to 1421 GWh, with a corresponding new accommodation of 719 GWh. Figure 8 illustrates the comparison of abandoned power between the basic scene and Scene 15. This study proceeds to assess the accommodation improvement attributed to various factors in Scene 15.

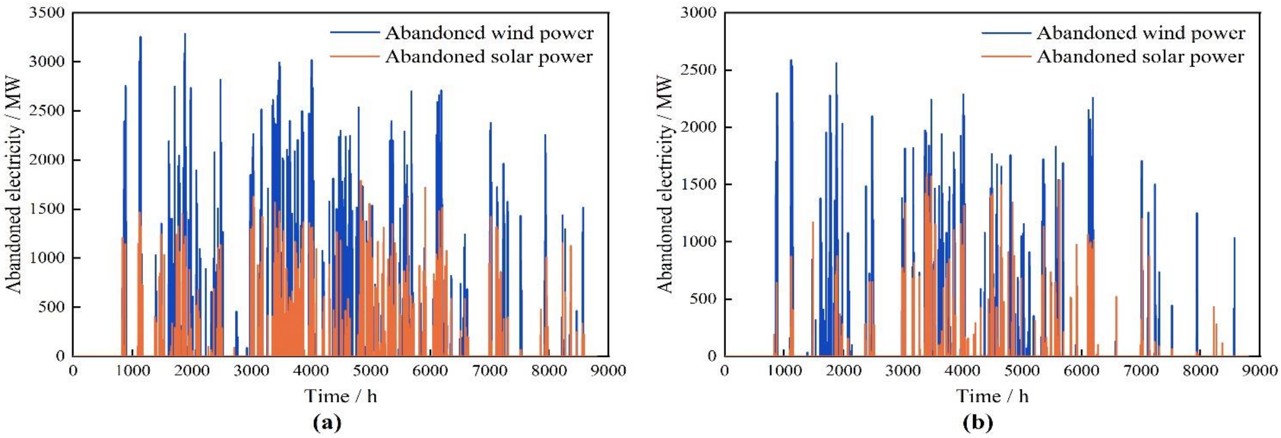

Figure 8. Annual power abandonment situation. (**a**) Basic scene power abandonment situation. (**b**) Scene 15 power abandonment situation.

Proportion method: In Scene 15, 3 distinct factors come into play. These factors operate individually in Scenes 2, 4, and 5, resulting in total incremental accommodation of 552 GWh, 222 GWh, and 152 GWh, respectively. Let R_1 represent the accommodation contribution ratio attributed to the flexibility retrofit for thermal power units. Let R_2 denote the ratio for the load increase factor and R_3 the construction factor for the energy storage station. In the combined scene, the accommodation values corresponding to these factors are labeled L1, L2, and L3. By employing Equation (16), we deduce that R_1 = 0.5961, R_2 = 0.2397, and R_3 = 0.1641. The aggregate incremental accommodation for Scene 15 amounted to 719 GWh. Utilizing Equation (15), we determined that L1 = 428.6 GWh, L2 = 172 GWh, and L3 = 118 GWh.

Shapley value method: For instance, the expansion of external transmission lines led to an accommodation improvement, where the interaction of three factors yielded a corresponding n value of three. Among all the scenes, 4 scenes incorporated the expansion factor of the transmission line, namely Scene 3, Scene 9, Scene 10, and Scene 15. The total accommodation improvement values for these scenes were 552 GWh, 670 GWh, 638 GWh, and 719 GWh, respectively. Upon removing the expansion factor of the transmission line from the aforementioned scenes, the corresponding scenes were Scene 1, Scene 4, Scene 4, and Scene 11, with a total accommodation improvement of 0 GWh, 222 GWh, 152 GWh, and 352 GWh, respectively. By subtracting the two sets of scenes from each other, the marginal accommodation improvement Mi under each scene involving the expansion factor of the transmission line could be determined. The corresponding |S| values for scenes 3, 9, 10, and 15 were 1, 2, 2, and 3, respectively. Utilizing Equation (18), the W (|S|) values for the corresponding scenes could be calculated to be 1/3, 1/6, 1/6, and 1/3, respectively. The Shapley value for the expansion factor of the external transmission line is denoted as K1 (V), the Shapley value for the load increase factor is denoted as K2 (V), and the Shapley value for the construction factor related to energy storage is denoted as K3 (V). Multiplying the marginal accommodation improvement amount Mi of each scene involving the expansion factor of the external transmission line by the corresponding weighting factor W (|S|) and subsequently summing them in sequence yielded K1 (V) being 462 GWh. Table 5 presents the specific data for the calculation process. The same methodology could be applied to obtain K2 (V) = 154 GWh and K3 (V) = 103 GWh.

Table 5. Calculation of process parameters.

Line Expansion and Renovation				
Calculation Formula	**Scene 3**	**Scene 9**	**Scene 10**	**Scene 15**
$V(S)$	552	670	638	719
$V(S) - V(S\backslash\{i\})$	552–0	670–222	638–152	719–352
$\lvert S \rvert, \mathrm{W}(\lvert S \rvert)$	1, 1\3	2, 1\6	2, 1\6	1, 1\3
$\mathrm{W}(\lvert S \rvert) \cdot V(S) - V(S\backslash\{i\})$	184	74.7	81	122.3
Load increase				
Calculation formula	Scene 4	Scene 9	Scene 11	Scene 15
$V(S)$	222	670	352	719
$V(S) - V(S\backslash\{i\})$	222–0	670–552	352–152	719–638
$\lvert S \rvert, \mathrm{W}(\lvert S \rvert)$	1, 1\3	2, 1\6	2, 1\6	3, 1\3
$\mathrm{W}(\lvert S \rvert) \cdot V(S) - V(S\backslash\{i\})$	74	19.7	33.3	27
Energy storage construction				
Calculation formula	Scene 5	Scene 10	Scene 11	Scene 15
$V(S)$	152	638	352	719
$V(S) - V(S\backslash\{i\})$	152–0	638–552	352–222	719–670
$\lvert S \rvert, \mathrm{W}(\lvert S \rvert)$	1, 1\3	2, 1\6	2, 1\6	3, 1\3
$\mathrm{W}(\lvert S \rvert) \cdot V(S) - V(S\backslash\{i\})$	50.7	14.3	21.7	16.3

5.3.3. Scenes of Two-Factor Synergy

Taking Scene 11 as an example, two synergistic factors, namely load increase and energy storage construction, were observed. Following the confluence of these two factors, the discarded power of renewable energy amounted to 1788 GWh, while the newly accommodated power reached 352 GWh. The comparison of power wastage between the basic scene and Scene 11 is visually depicted in Figure 9. This study undertook a calculation of the accommodation enhancement resulting from various factors in Scene 11.

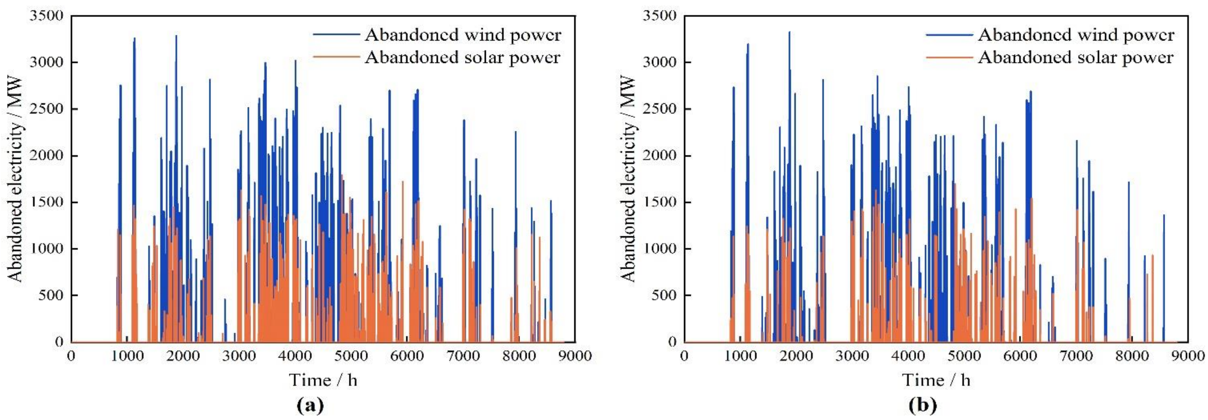

Figure 9. Annual power abandonment situation. (**a**) Situation of power abandonment in the basic scene. (**b**) Situation of power abandonment in Scene 11.

Proportion method: For instance, in Scene 11, two factors exhibited synergistic effects. When these factors functioned separately, they corresponded to Scenes 4 and 5, leading to a total incremental accommodation of 222 GWh and 152 GWh, respectively. Let R_1 represent the accommodation contribution ratio of the load increase factor and R_2 represent the construction factor for the energy storage station. The corresponding incremental accommodation in the synergistic scene for these factors is L1 and L2, respectively. Using Equation (16), we found $R_1 = 0.5935$ and $R_2 = 0.4064$. The total incremental accommodation in Scene 11 was 352 GWh through Equation (15).

Shapley value method: For instance, when considering the accommodation increase caused by load increase factors, two factors were found to operate in unison, yielding a corresponding n value of two. Across all scenes, a total of 2 scenes including load increase factors were identified, namely Scene 4 and Scene 11, which corresponded to an overall accommodation increase of 222 GWh and 352 GWh, respectively. In the aforementioned scenes, upon the removal of the load increase factor, the corresponding scenes were Scene 1 and Scene 5, leading to a total accommodation increase of 0 GWh and 152 GWh, respectively. The two sets of scenes were paired and subtracted from each other, thereby yielding the marginal accommodation increase M_i under each scene where the load increase factor was involved. The corresponding ∣S∣ values in Scene 4 and Scene 11 of the first set of scenes were 1 and 2, respectively. By employing Equation (18), the W (∣S∣) values for the corresponding scenes could be calculated, resulting in 1/2 and 1/2, respectively. Assuming the Shapley value of the load increase factor is denoted as K1 (V), and the Shapley value of the construction factor for the energy storage station is denoted as K2 (V), the marginal accommodation increased by M_i in each scene, where the load increase factor present was multiplied by the corresponding weighting factor W (∣S∣) and subsequently summed in sequence to obtain K1 (V) being 211 GWh. The specific data pertaining to the calculation process are presented in Table 6. By employing the same methodology, K2 (V) = 141 GWh could be derived.

Table 6. Calculation of process parameters.

Load Increase			Energy Storage Construction		
Calculation Formula	**Scene 4**	**Scene 11**	**Calculation Formula**	**Scene 5**	**Scene 11**
$V(S)$	222	352	$V(S)$	152	352
$V(S) - V(S\backslash\{i\})$	222–0	352–152	$V(S) - V(S\backslash\{i\})$	152–0	352–222
∣S∣, W(∣S∣)	1, 1\2	2, 1\2	∣S∣, W(∣S∣)	1, 1\2	2, 1\2
W(∣S∣)·$V(S) - V(S\backslash\{i\})$	111	100	W(∣S∣)·$V(S) - V(S\backslash\{i\})$	76	65

5.3.4. Analysis of the Effects of Factors in the Overall Synergistic Interaction Scene Accommodation

The calculation results of the accommodation improvement for each factor in all synergistic scenes that met the development plan are shown in Figure 10.

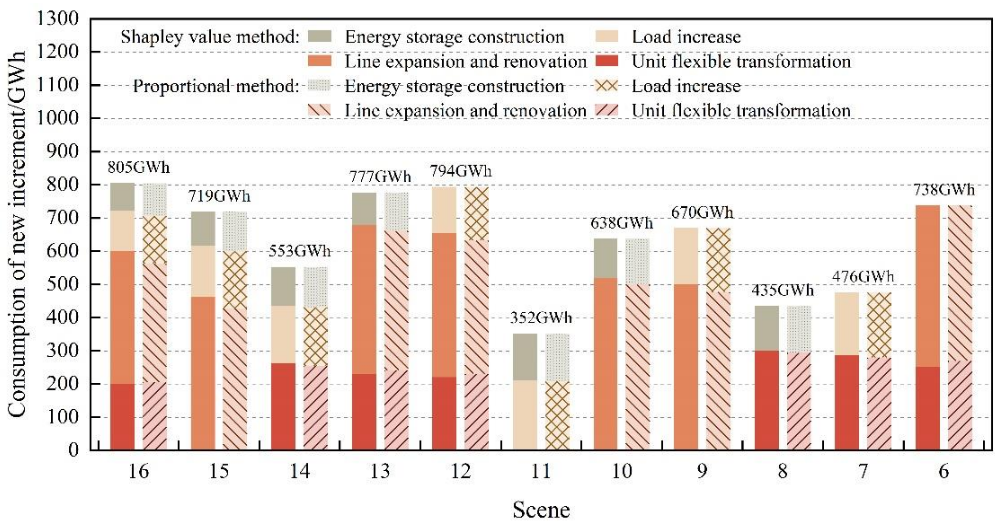

Figure 10. Simulation results of each scene accommodation.

Scene 16 presents the synergistic effect of 4 factors, while Scenes 12–15 demonstrate the synergistic effect of 3 factors, and Scenes 6–11 exhibit the synergistic effect of 2 factors. The total accommodation increase in Scene 16 amounted to 805 GWh. The Shapley value approach breaks down the incremental accommodation resulting from the synergistic scene into four factors: flexible retrofitting of thermal power units, expansion of external transmission lines, load growth, and construction of energy storage. These factors contributed 200 GWh, 399.4 GWh, 123.4 GWh, and 82.2 GWh, respectively. On the other hand, the proportion method attributed the incremental accommodation to these same factors being 205.8 GWh, 357.2 GWh, 143.6 GWh, and 98.3 GWh respectively. For other synergistic situations, the incremental accommodation for each factor, as determined by both methods, is depicted in Figure 10. The proportion method allocates the total incremental accommodation in the synergistic scene linearly based on the accommodation contribution ratios of each factor in isolation. This approach offers a general quantitative assessment of each factor's accommodation impact in the synergistic scene. However, because the proportion method only evaluates the final synergistic scene's accommodation impacts based on the effects of each factor in isolation, the insights derived are somewhat limited. Conversely, the Shapley value approach assesses the entire progression from the present state to the synergistic scene. By considering all developmental situations, it fully measured the incremental accommodation attributed to each factor, yielding the accommodation of incremental renewable energy for each factor in the synergistic scene. Thus, the Shapley value method provides a more thorough and unbiased evaluation of the incremental accommodation from each factor in the synergistic scene than the proportion method.

Premised on the decomposition and accommodation results of the Shapley values in 16 scenes, it is evident that, under the influence of four factors, the priority of accommodation improvement is as follows: expansion of external transmission lines, flexibility transformation of thermal power units, replacement of load energy, and construction of energy storage power plants. Upon analyzing the accommodation improvement caused by the synergistic effects of two or three factors in other scenes, the results demonstrate that the priority of accommodation improvement remains unchanged. Based on the aforementioned findings, the calculation results of the accommodation improvement of various factors in the synergistic scene indicate that the expansion of transmission lines and the flexibility transformation of thermal power units contribute the most to the accommodation of the power grid. This implies that the external transmission of renewable energy and the peak shaving capacity of the power grid in this region are the primary factors promoting the accommodation of renewable energy. When formulating subsequent accommodation configurations, emphasis can be placed on these two aspects. It is important to note that the power grid of this region possesses a large installed capacity and a small load, and it is expected that the increased accommodation volume will significantly increase if measures to replace load electric energy intensify.

6. Conclusions

It is acknowledged that the accommodation of new energy constitutes a systematic project. Comprehensive optimization of the various development stages of the power system's power supply, power grid, and load is advantageous for resolving accommodation conflicts. Exploring the effects of various factors that promote the accommodation of renewable energy under the synergistic effect of "power supply-power grid-load-energy storage" provides guidance for the scientific planning and rational layout of the future energy system. This research introduced a novel energy accommodation evaluation model grounded on time series production simulation principles. Taking the renewable energy accommodation in a particular zone of China's power grid as an example, this study formulated 16 representative scenes aligning with the region's developmental blueprint. In addition, it numerically broke down the accommodation impacts of distinct elements within these combined scenes using the Shapley value approach. Through the case study, this study drew the following conclusion:

(1) Through the Shapley value approach, the collective marginal accommodation advantages of an element across all conceivable scenes can be aggregated. This captures the accommodation of incremental renewable energy attributable to each element in the

combined scene, offering a holistic quantitative appraisal of the accommodation influences of each element.

(2) The case study analysis suggests that, when considering a combination of factors, the sequence for advancing renewable energy accommodation is as follows: expanding external transmission lines, retrofitting thermal power units for flexibility, increasing the load, and constructing energy storage. This sequence underscores the grid capacity to transfer renewable energy and offer peak load assistance as pivotal elements in fostering renewable energy accommodation in the area. These simulation results can offer a foundational framework for prospective planning of renewable energy accommodation for this grid.

Author Contributions: Conceptualization, G.H. and X.Z.; methodology, G.H and X.Z.; software, G.H. and X.W.; validation, G.H. and H.Z.; formal analysis, G.H.; investigation, G.H., K.C. and Z.W.; resources, G.H.; data curation, G.H.; writing—original draft preparation, G.H.; writing—review and editing, G.H.; supervision, X.Z.; literature research, G.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (51667018) and Natural Science Foundation of Xinjiang Uygur Autonomous Region (2021D01C044).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

$P_{v,i}(t)$	Output of photovoltaic power station i at time t
N_v	Number of photovoltaic power stations
$P_{w,i}(t)$	Output of wind power station i at time t
N_w	Number of wind power fields
$P_{g,n}(t)$	Output of thermal power unit n at time t
N	Number of thermal power units
$P_{stdch}(t)$	Discharge power of energy storage station at time t
$P_{stch}(t)$	Discharge power of energy storage station at time t
$P_h(t)$	Output of hydropower unit at time t
$P_l(t)$	Transmission power of high-voltage transmission line at time t
$P_s(t)$	Load power at time t
$P_{gcu,n}$	Upper output constraint of thermal power unit n
$P_{gcd,n}$	Lower output constraint of thermal power unit n
$P_{g\max,n}$	Maximum output of thermal power unit
$P_{g\min,n}$	Minimum output of thermal power unit
$P_{stch\min}$	Minimum charging power of energy storage
$P_{stch\max}$	Maximum charging power of energy storage
$P_{stdch\min}$	Minimum discharge power of energy storage
$P_{stdch\max}$	Maximum discharge power of energy storage
C_{st}	Total capacity of energy storage
$\lambda_{\min}$	Minimum state of charge of energy storage
$\lambda_{\max}$	Maximum state of charge of energy storage
$E_{ess}(t)$	Energy storage capacity at time t
φ_{sc}	Charging efficiency
φ_{sd}	Discharge efficiency
$P_{h\min}$	Minimum output of hydropower unit
$P_{h\max}$	Maximum output of hydropower unit
β_{wv}	Proportion of renewable energy spinning reserve
β_{sl}	Proportion of load spinning reserve

$P_{g,nsr}$	Spinning reserve capacity provided by thermal power unit n
P_{hsr}	Spinning reserve capacity provided by hydropower unit
$P_{h\min}$	Minimum power of high-voltage transmission line
$P_{h\max}$	Maximum power of high-voltage transmission line
$P_{w,i\min}$	Minimum output of wind power field i
$P_{w,i\max}$	Maximum output of wind power field i
$P_{v,i\min}$	Minimum output of photovoltaic power station i
$P_{v,i\max}$	Maximum output of photovoltaic power station i
$V(W)$	Total increase in absorption in synergistic scene
$L_{i,sep}$	Absorption increase brought by factor i when acting alone
Li	Absorption increase brought by the ith factor in synergistic scene
α	Proportional factor
R_i	Contribution ratio of factor i to absorption
M_i	Marginal benefit of the i-th factor
$V(S)$	Total benefit including factor i
$V(S\backslash\{i\})$	Benefit excluding factor i in scene
$W\|S\|$	Weighting factor
$\|S\|$	Number of factors in set S
n	Total number of factors
$K_i(V)$	Shapley value of the ith factor in synergistic allocation
Ri	All subsets including i

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