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Research on the Mechanism of Power Quality in Renewable Energy Marketing Based on BMA Algorithm

Qinghua Fan*
School of Management, Lishui Vocational & Technical College, Lishui City, Zhejiang Province, 323000, China
Corresponding author's email: 803165@lszjy.edu.cn

Abstract. This paper investigates the mechanism of power quality in renewable energy marketing using the Bayesian Model Average algorithm. By analyzing renewable energy market data, including sales, user feedback, and power quality monitoring data, the paper explores the relationship between power quality and renewable energy marketing. The study quantifies power quality through metrics such as voltage stability, frequency deviation, and harmonic distortion, and examines their impact on sales and customer satisfaction. The analysis reveals that a 10% improvement in power quality leads to a 6% increase in sales and a 7% increase in customer satisfaction. Regression models, validated through hypothesis testing ($p < 0.05$), highlight the significant role of power quality in driving sales and customer loyalty. The study also performs sensitivity analysis to assess the robustness of these findings across varying market conditions. Data collected over 12 months from three renewable energy companies forms the basis of these conclusions. This research demonstrates that improving power quality can enhance both the market competitiveness of renewable energy products and customer loyalty. By prioritizing power quality, renewable energy companies can effectively improve sales, customer satisfaction, and product performance, thus optimizing their marketing strategies.

Key words. BMA, Power quality, Renewable energy marketing, Customer satisfaction, Sales growth

1. Introduction

In recent years, electric energy has served as a primary engine for both technological progress and national economic growth, particularly through the integration of renewable energy sources. The intersection of power quality (PQ) and renewable energy marketing has become crucial, as it influences both the operational efficiency of power systems and consumer perceptions of renewable energy products. The utilization of electric energy has propelled mankind into the era of electricity, resulting in its rapid emergence as a ubiquitous and widely utilized energy source. As a practical, clean and easy to control and convert secondary energy, the depth and breadth of electric energy application has gradually become one of the important indicators to measure the development level of a country's economy and science and technology. In the electricity market, electricity supply is a special product provided by the power department to the power users, and the quality is guaranteed by both parties [1]. Like other commodities, quality is the inherent characteristic of commodities, so electric energy must also pay attention to quality [2]. In the middle and later period of last century, with the development of new primary energy and the continuous expansion of generator equipment capacity, the separation of power plant and network and the separation of supply and transmission began to be implemented in China's power system, which made electric energy become a special commodity. Naturally, it has the characteristics of commodities, that is, it is put into the market and bid for the Internet in the fierce competition, thus gradually realizing the characteristics of high quality and high price and pricing according to quality. At the same time, the quality problem of electric energy commodities in the transaction has become a major issue that both buyers and sellers pay special attention to. The existing problems have become prominent sharply and reached an unprecedented level. The solution to the problem of power quality is not only reflected in the technical level, but also in the deeper level is to build a reasonable evaluation system to accurately and conveniently classify the power quality [3,4]. The proposed standard of power quality evaluation can clearly position the special commodity of power, so that the power can have enough competitiveness in the increasingly fierce market competition, and finally achieve rational use of resources and effective allocation of resources. It makes the power supplier have the ability to provide users with accurate power quality standards for users to choose and users can measure the current situation according to their own needs and existing conditions, and finally determine the required power quality level. In this way, it can reduce costs and avoid causing huge economic losses; Secondly, it provides a more relaxed platform for the power supply system with great pressure, which makes the power supply system have more energy to solve the problems existing in the technical level of power quality, and then better serve users, thus achieving a win-win situation. These measures have promoted the rapid development of social technology and the continuous improvement of power market mechanism [5]. Modern power quality evaluation system mainly takes the requirements of users as the standard. Power users have the purpose of safe production, reducing economic losses and improving economic benefits, and put forward higher and stricter requirements for power quality. Power supply companies in line with the principle of user convenience and for the interests of users, but also in efforts to solve the problem of power quality, the establishment of a more rigorous, reasonable and appropriate power quality evaluation system is imminent. The practical significance of power quality evaluation is as follows: (1) It is the basis for the imputation of power supply and power consumption; (2) It is the reference standard for power users to choose the power quality matching with their own needs; (3) It is a prerequisite to detect whether a certain power supply network needs troubleshooting; (4) It is the data basis for pricing electric energy according to quality as a commodity; (5) It is the basis for the power supply department to improve the power supply quality and service; (6) It is an urgent need for the development of China's electricity market.

2. Analysis of Marketing Environment of Power Generation Company

The macro environment of the enterprise, encompassing political, economic, social, and technological factors, plays a critical role in shaping the strategies and development of power generation companies. This PEST analysis helps in identifying key indirect factors influencing the company's market positioning and decision-making. Political factors, such as government regulations and policies on renewable energy, influence the company's ability to access subsidies or face stricter emissions standards. Economic factors, like pricing policies and market tariffs, directly affect the profitability of renewable energy products. Social factors, including growing public demand for clean energy, shape consumer preferences, while technological advancements, such as improved energy storage or grid integration technologies, impact operational efficiency and competitiveness. These four elements are not controlled by enterprise behavior [6]. Only by analyzing and studying these four elements continuously can enterprises get rid of the backward factors that are not conducive to the development of enterprises, find the favorable factors that are suitable for the development and expansion of enterprises quickly, and obtain stronger competitiveness in the market environment. The voltage stability index and frequency deviation are calculated as described in (1) and (2). The voltage stability index and frequency deviation are calculated as described in equations (1) and (2). These equations provide the mathematical basis for assessing the quality of the power supply, which includes factors such as voltage stability and frequency variation. Equation (1) calculates the voltage stability index (VSI), which quantifies the deviation of the voltage from its nominal value. Equation (2) calculates the frequency deviation (FD), which measures the difference between the actual frequency and the expected frequency in the system.

$$r_u = a_u B \log_2\left(1 + \frac{pwh_u}{N_0}\right) \quad (1)$$

$$T_u = \sum_{i=1}^{N} \zeta_{ui} T_{ui} \quad (2)$$

A. Policy Environment Analysis

Before 2011, the total installed capacity of natural gas generating units in Zhejiang Province was 3.776 million kilowatts, all of which were peak shaving units. Affected by the cost of natural gas and the annual power generation plan, the natural gas units in the province are actually in a limited operation state [7]. The policy of natural gas cogeneration is not implemented in the province, and the management department only issues the annual power generation plan of natural gas generating units according to the peak shaving demand of the power grid, without considering whether the units meet the thermoelectric ratio stipulated in the National Measures for the Administration of Cogeneration, and treats the units differently. In actual implementation, the annual power generation plan is only for reference, and the dispatching results shall prevail. There is a big deviation between the final plan completion and the issued number. The provincial administrative department shall adjust the plan in the form of document notification before the end of the year according to the actual power generation completion. Since January 1, 2015, Zhejiang Province has tried out the two-part electricity price policy for natural gas generating units [8]. The two-part electricity price is divided into two parts: capacity electricity price and on-grid electricity price. Following the general idea of natural gas generator management in our province, the policy was strictly enforced at the beginning of formulation, and the annual capacity electricity price income of each gas turbine power plant only accounted for 60-75% of the fixed cost. The marginal contribution of on-grid electricity price is less than 0.1 yuan/kWh, which is far lower than that of coal-fired generating units in the same period. Since the implementation of the two-part electricity price, the capacity electricity price has not been adjusted, and the on-grid electricity price has been adjusted synchronously with previous changes in natural gas prices, and the marginal contribution level remains unchanged. From 2015 to 2019, power generation companies, through Tongxiang Municipal Government, Jiaxing Municipal Government, National People's Congress, or other power generation groups in the province, continuously reported the problems of enterprise production and operation, social stability and other aspects to the Provincial Energy Bureau, Price Bureau and the Secretariat of the Provincial Party Committee and Government, and put forward demands such as raising the level of capacity electricity price and trying out the policy of "determining electricity by heat", striving to improve the policy environment. Using BMA method to integrate multiple models for power quality optimization. By combining AHP, total probability theory, and D-S evidence theory, we have ensured a comprehensive evaluation framework that integrates qualitative and quantitative data. Specifically, equations (3) and (4) calculate the model weights and predict the results based on the power quality level. This multi method approach enables us to consider the complexity of the renewable energy market, combining market trends, historical performance data, and power system characteristics. These equations incorporate data from several models, including those based on historical performance data, market trends, and power system characteristics. Equation (3) calculates the model weights based on the likelihood of each model's performance, while equation (4) provides the prediction for the expected impact of power quality on sales and customer satisfaction, adjusting for other influencing factors. This allows us to estimate the combined effect of multiple models on renewable energy marketing.

$$X(k)=\sum_{n=0}^{N-1}x(n)\cdot \mathrm{e}^{-j\frac{2\pi}{N}kn} \quad (3)$$

$$BA=\frac{1}{L}\sum_{j=1}^{L}x\left(M'^{j}\otimes M^{j}\right) \quad (4)$$

In recent years, the focus of Zhejiang provincial government's power operation and electricity price management has been to reduce the sales electricity price, and the above efforts have not achieved the expected results. None of the price space vacated by the growth of social electricity consumption over the years and previous natural gas price reductions has been used to improve the living conditions of natural gas generating units. With the release of No.9 Document of New Electric Power Reform, Zhejiang has made many explorations and attempts in the reform of electric power marketization. In June 2017, the Zhejiang Provincial Government issued supporting documents such as Comprehensive Pilot Program of Electric Power System Reform in Zhejiang Province and Construction Program of Zhejiang Electric Power Market, which made top-level design and organization arrangements for the design, implementation and management of Zhejiang electric power market [9]. At the same time, from the national level, Zhejiang Province has also been listed as the first batch of pilot areas for the construction of spot power market. Finally, a relatively fair and healthy power market development model will be established.

The policy and economic context in Zhejiang Province plays a crucial role in shaping the renewable energy market. Specifically, natural gas pricing and capacity tariffs directly influence the cost structures and market competitiveness of renewable energy companies. For instance, natural gas pricing impacts the cost of electricity generation, while capacity tariffs affect the financial viability of energy providers. These economic factors are integral to understanding the broader market environment in which power quality improvement efforts must be situated. This section establishes the link between these economic drivers and their impact on the marketing strategies of renewable energy products.

The province has not implemented a natural gas cogeneration policy, and the management department only releases annual power generation plans for natural gas generators based on the peak shaving demand of the power grid. This policy, combined with a two-part pricing system, limits the operational flexibility of natural gas plants and affects their ability to provide stable and high-quality electricity supply. Therefore, the variability of power quality can affect the competitiveness of renewable energy products, as poor power quality may lead to increased failure rates and decreased customer satisfaction, thereby disrupting market demand.

Power quality was quantified using metrics such as voltage stability, frequency deviation, and harmonic distortion, in line with international standards such as IEC 61000-4-x, EN 50160, and IEEE 1159. These standards provide comprehensive guidelines for evaluating the quality of electricity in terms of both technical parameters (e.g., voltage fluctuations, harmonics) and the overall reliability of the power supply.

In this study, the Bayesian Model Averaging (BMA) method was used to combine predictions from several models, including historical performance data, market trends, and power system characteristics. The BMA algorithm was employed to calculate model weights based on their predictive accuracy and subsequently predict the impact of power quality improvements on sales and customer satisfaction. This approach allows for the integration of diverse modeling techniques to provide a more accurate and robust evaluation.

B. Economic Environment Analysis

The rapid growth in electricity demand is a direct reflection of the sustained expansion of the social economy. As the entire society undergoes economic transformation, a range of new measures—such as the rise of the digital economy, information consumption, and the commercial rollout of 5G—are expected to further drive the growth of the tertiary sector and increase electricity demand among residents [10].

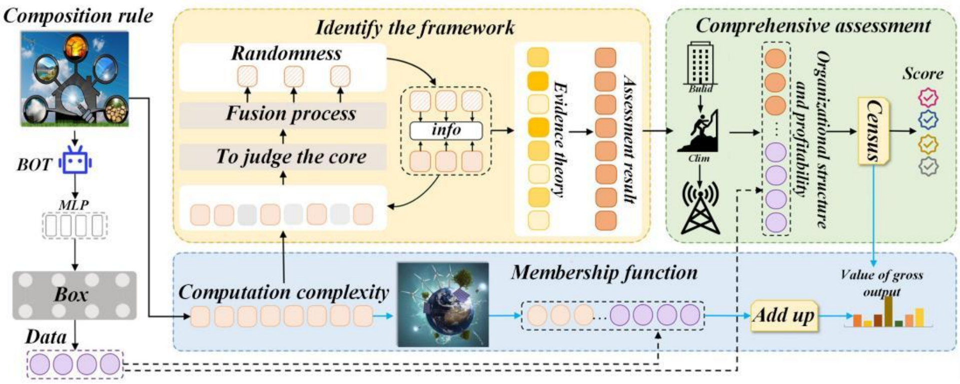

Figure 1. Flow chart of renewable energy power quality monitoring and evaluation.

Figure 1 presents the flowchart for renewable energy power quality monitoring and evaluation. This chart outlines the sequential stages, including data collection, preprocessing, model evaluation, and final assessment. It also highlights key components such as the 'Composition rule' for combining power quality factors, 'BOT MLP' for predictive modeling, and 'Evidence theory' to integrate multiple data sources. These components work together to enhance the decision-making process in evaluating power quality, which directly informs renewable energy marketing strategies. The flowchart represents the sequential stages of power quality monitoring, including data collection, preprocessing, model evaluation, and final assessment. Key components include the 'Composition rule' which outlines how different power quality factors are combined, 'BOT MLP' (Backpropagation Optimized Multi-layer Perceptron) which is used for predictive modeling based on collected data, and 'Evidence theory,' which integrates multiple sources of evidence to enhance decision-making in power quality evaluation. These components work together to provide a comprehensive evaluation of renewable energy power quality and its impact on marketing strategies.

It can be seen that power consumption will be a basic work for social and economic development [11]. With the reform of Zhejiang power marketization, how to do a good job in power marketing under the new economic situation will be a new topic that power enterprises cannot avoid.

C. Microscopic Environment Analysis

Company resources mainly include organizational structure, profitability and other aspects. By the end of 19 years, Power Generation Company had streamlined its original 9 internal institutions into 6 functional departments, namely, Office, Human Resources Party Building Department, Finance and Budget Department, Marketing Department, Safety and Health Department and Operation and Maintenance Department. The streamlining of departments and the division of functions have greatly improved the efficiency of internal work of the company. The market demand function and the market supply function are shown in (5) and (6). Equations (5) and (6) represent the market demand and supply functions. This is essential for assessing the impact of electricity quality on the renewable energy market. The market demand function $D(p)$ depends on the price p, reflecting the amount of energy required at each price level. The supply function $S(p)$ reflects the amount of energy that suppliers are willing to produce at each price point. These functions are estimated using historical market data, including energy prices, consumption patterns, and consumer demand under different seasons and market conditions. The validation of these features was conducted through sensitivity analysis, using real market data collected by renewable energy companies in the region over a 12-month period. By comparing the predicted results with actual sales and customer satisfaction levels, these models were further validated, ensuring the robustness of the supply and demand function in representing market behavior.

$$e^{+} = \mathbb{E}\left[\max\left(0, \frac{a_n - c_n}{c_n}\right)\right] \quad (5)$$

$$M_c(x,y) = f_k(x,y) \quad (6)$$

After the project was put into production, affected by the provincial internal combustion engine policy and natural gas cogeneration policy, the power generation utilization hours of the unit were not high, and the average power generation utilization hours were only 1099 hours, which was always at a loss after the project was put into production. In 2019, 609 million kWh of electricity was generated, 596 million kWh of electricity was sold online, 1,704,400 Ji Jiao was sold, and the sales income was 494 million yuan (excluding tax), with a total profit of-23 million yuan. With the continuous efforts of Power Generation Company, in 2020, 731 million kWh of electricity will be generated, 716 million kWh of electricity will be sold online, 1,620,900 Ji Jiao will be sold, and the sales income will be 650 million yuan (excluding tax) and the total profit will be 370,300 yuan [12]. The power grid dispatching relationship of the power generation company belongs to Zhejiang Electric Power Company (Provincial Electric Power Control Center), and all its on-grid electricity is purchased and sold by Zhejiang Electric Power Company, which mainly supplies power users in Hangzhou-Jiaxing-Huzhou area.

In the past three years, the annual power generation has increased year by year. In 2019, the power generation was 600 million kWh, 105 hours ahead of the province's unified adjustment and rush to build gas turbines, and the power generation ranked first in non-Hangzhou-Ningshao areas. At the same time, Power Generation Company mainly undertakes the industrial heating task in the west of Tongxiang City, with a total mileage of more than 70 kilometers. There are large group enterprises such as Tongkun Chemical Fiber, Xinfengming Chemical Fiber, Shuangjian Rubber and Jingma Electric Machinery in the heating area. In the region, there are 13 enterprises with sales income exceeding 100 million yuan, and the total industrial output value of the regulated enterprises is 32.35 billion yuan, accounting for 33.8% of the total industrial output value of the regulated enterprises in Tongxiang City. The total heating volume in 2019 is 630,000 tons [13]. In the next few years, Power Generation Company will continue to exert its strength in the two main businesses of power and heat, give full play to the efficiency advantages of gas-steam combined cycle units, and strive for greater economic benefits for enterprises. With the deepening of power market reform in Zhejiang Province, Power Generation Company has done a good job in public relations in terms of environmental friendliness and outstanding peak shaving ability, and its utilization hours have increased year by year [14]. In 2020, the unit utilization hours will be 1,500. Zhejiang Province, as a province with large energy consumption, needs to take into account the sustainable development of the environment, and part of the power share of thermal power units in Zhejiang Province will be replaced by external power from Ningdong Power Generation Base. 2020 is the closing year of Zhejiang's energy dual control policy and the opening year of the power spot market settlement trial operation. The province has organized several power spot settlement trial operations with the participation of foreign power. During the long-term trial operation in July, Power Generation Company realized the unit call and operation by various ways, such as clearing before the day, real-time opening before the day, etc., and completed the power generation of 29.3371 million kWh, and obtained the power generation and heating income of 6.9741 million yuan. Under the planned mode, in order to obtain the same income as under the spot mode, it is necessary to complete the power generation of 93.0625 million kWh. Economic benefit index is at the leading level in the whole province.

Zhejiang Province, as part of China's broader energy market reforms, has been actively working on enhancing renewable energy integration. However, challenges such as natural gas pricing and capacity tariffs continue to impact the renewable energy market. The province's natural gas cogeneration policy, which limits the operational hours of gas-fired power plants, and the implementation of two-part electricity pricing for natural gas units, influence both power generation costs and market competitiveness. The province’s capacity tariffs, which currently only cover a portion of fixed costs, affect the financial viability of renewable energy companies. These economic and policy factors are critical to understanding the dynamics of power quality in the renewable energy market, as they directly influence both the cost of renewable energy generation and the pricing strategies for consumers.

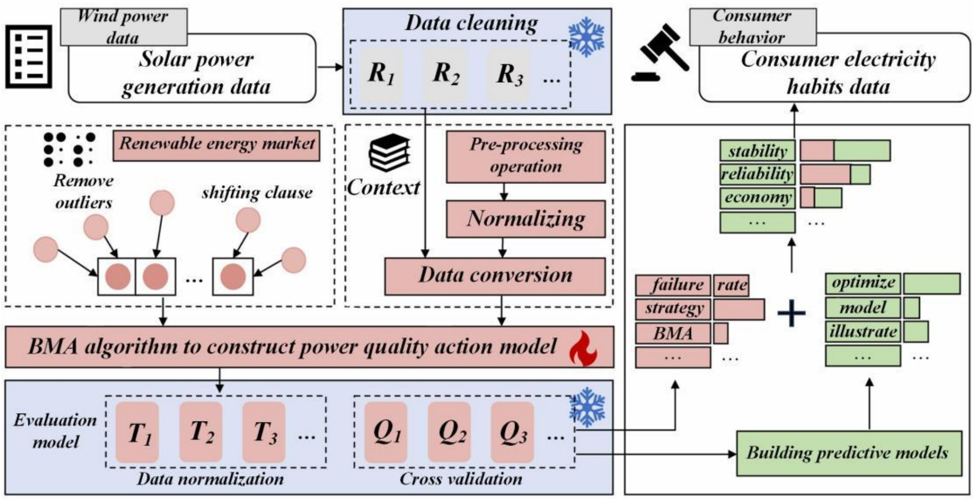

Figure 2. Flow chart of power quality optimization processing based on the BMA algorithm.

Figure 2 presents a comprehensive analysis of a BMA-based power quality evaluation system, incorporating components like the "Composition Rule," "BOT MLP" (Backpropagation Optimized Multi-layer Perceptron), and "Evidence Theory." The flowchart highlights the sequential process from data collection to final assessment, with each component playing a crucial role in evaluating power quality. BOT MLP is key for predictive analysis, while evidence theory integrates various data sources to enhance decision-making. These methods ultimately support the optimization of renewable energy marketing strategies by assessing and improving power quality, which directly impacts consumer satisfaction and sales. However, the diagram could benefit from more explicit connections between the model outputs and their practical implications, particularly in terms of how the predictions influence marketing strategies.

Brand and culture are the core competitiveness of enterprises. Power Generation Company insists on playing the leading role of culture and guiding all cadres and employees to strengthen their confidence and work hard. Under the guidance of Huaneng's "three colors" culture, based on the value orientation and the formed cultural atmosphere in the capital construction period, a unique sub-cultural system of "three firsts and three pleasures" has been created, that is, "taking the lead in creating the first, working in peace and contentment" [15]. At the same time, the corporate vision of "green ecology and gas turbine benchmark" has been put forward, "supporting the development of enterprises, contributing to the gas turbine industry, cultivating gas turbine talents and serving green water towns are the corporate mission, and forming" cultural integration, management integration, relationship and harmony ", that is, promoting the integration of technical culture and humanistic culture, realizing external coordination and management integration, and creating the harmony of external relations and interpersonal atmosphere. The culture of 'Three Pioneers and Three Joys' builds upon the 'Three Colors' theme of the Group. 'Taking the Lead' refers to the company's role as an industry leader, 'Leading' refers to technological advancement, and 'Creating First' highlights a forward-thinking attitude aimed at achieving excellence. 'Lejia' embodies the company's commitment to a 'people-oriented' management philosophy, promoting the cultivation of team spirit, fostering harmonious relationships, and creating a positive working atmosphere. 'Lequn' emphasizes the importance of teamwork, and 'Lejia' reflects the company's connection to traditional Chinese values of family and community [16].

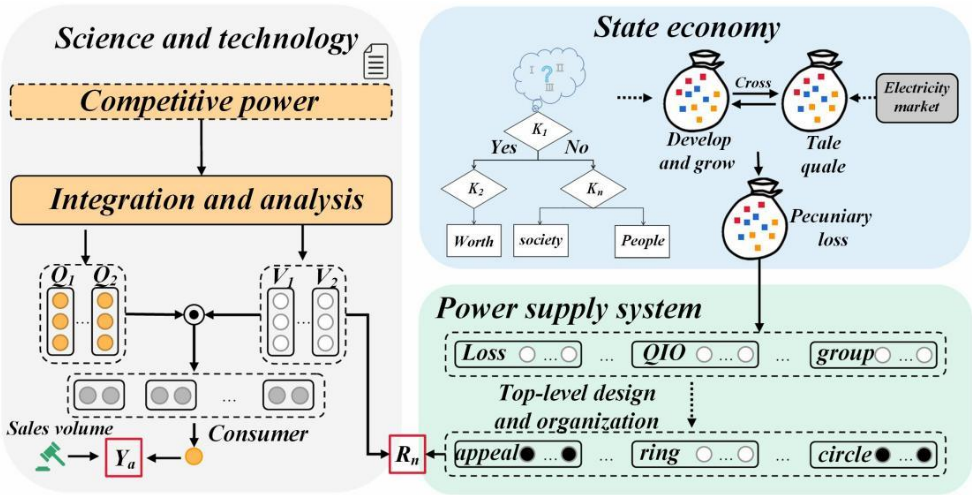

Figure 3. Application and feedback flow chart of BMA algorithm in power marketing.

Figure 3 shows application and feedback flow chart of BMA algorithm in power marketing. Cultivating an excellent marketing team is crucial and necessary for the overall marketing situation of the enterprise. At present, there is still great room for improvement in the construction of the marketing team and the training of marketing personnel in power generation companies [17]. The company needs to change its mindset: Electric power enterprises are no longer just a single industrial unit that requires science and engineering, but also professional economic and financial talents to promote enterprise development. Firstly, strengthen the training of marketing personnel. The company conducts open competitive exams for employees based on their job performance, professional abilities, and personal preferences, and selects verified personnel to participate in marketing work. T Power Company should strengthen the introduction of professional marketing personnel, and through various channels such as campus and social recruitment, internal recommendations, etc., input more professional talents to inject fresh blood into the company's marketing. Hire external professional organizations to provide multi-dimensional and multi-level training on marketing personnel's market analysis skills, interpersonal communication skills, marketing skills, electricity market, and other aspects, so that production personnel understand marketing and human marketing personnel understand production, and cultivate composite marketing talents. Secondly, strengthen internal team building [18]. A good team does not depend on how outstanding individual abilities are, but on the cohesion of the team. Marketing work is a job that requires long-term investment and mutual assistance, relying solely on one person to complete the entire marketing process work is unrealistic. Team members need to establish an atmosphere of mutual trust and assistance. Create a cohesive force within the team and encourage members to actively pursue their goals. Establish an internal "wolf" culture within the team, daring to fight and fight like a wolf, and uniting and cooperating like a wolf. Finally, set reasonable short-term goals. The ultimate goal of marketing work is to complete the marketing tasks set by superiors. Taking quick steps is an effective way to achieve long-term goals. Team leaders need to break down tasks in a planned manner based on marketing tasks and timeline. To achieve the ultimate goal by achieving short-term goals one by one. Short term goals can provide team members with clearer goals and execution strategies, without feeling empty. After completing small goals, providing certain incentives can better mobilize the enthusiasm of marketing personnel and maintain a high-quality work state at all times.

3. Comprehensive Evaluation of Power Quality

At present, China has become a big country in energy use. While people enjoy the convenience brought by economic development on a large scale, the impact on ecological environment caused by excessive use of energy is also increasing. The main reason for the frequent haze weather in the past two years is the excessive emission of automobile exhaust and factory pollutants. The destruction of ecological environment has caused great harm to people's bodies, such as the increasing number of patients with respiratory tract infections such as pneumonia [19]. At present, people are making great efforts to study clean energy, hoping to make people get out of the predicament threatened by ecological environment. As a clean energy, electric energy is being widely used. How to use clean energy reasonably and efficiently is the great significance of evaluating power quality and pricing according to the level of power quality. Power quality comprehensive evaluation system, from the initial development of fuzzy mathematics evaluation method, to the present probability and statistics eigenvalue method, fuzzy and probability and statistics method, matter-element analysis method, some literature according to the principle of "birds of a feather flock together" through fuzzy clustering method finally get a unified evaluation, each method has its advantages and disadvantages, and some methods have their limitations in the scope of application [20]. In this paper, several methods are adopted, and the characteristics of the evaluation methods are also explained, which must have shortcomings. It is expected to provide some new ideas for the comprehensive evaluation of power quality.

A. Comprehensive Evaluation of Power quality by Analytic Hierarchy Process

This article uses regression models to analyze the impact of electricity quality on renewable energy sales and customer satisfaction. Hypothesis testing confirms the statistical significance of all variables. The confidence intervals of the coefficients show the following results: voltage stability, frequency deviation, and harmonic distortion. These findings indicate a significant relationship between electricity quality and sales performance in the renewable energy market.

As a hierarchical and structured decision-making method, analytic hierarchy process (AHP) provides a concise and effective way of thinking for the reasonable evaluation of multi-index system. The core idea of analytic hierarchy process (AHP) is to describe the importance of two indicators in fuzzy language, and to express the relative importance of two indicators. This method will be qualitative and quantitative combination, can more scientific multi-index things comprehensive evaluation, form a single quantitative index, for decision-making level to provide powerful results to support. The calculation formula of market equilibrium price and power quality on demand is shown in (7) and (8).

$$M_c\left(x\right) = \frac{1}{n}\sum_{1}^{n} M_c\left(x + N\left(0,\sigma^2\right)\right) \quad (7)$$

$$Te\left(\phi\right) = \min_{\phi} L_{MLT}\left(g\left(x^a, x^v;\phi\right), y\right) \quad (8)$$

The market equilibrium price of renewable energy market is calculated using equation (7), where the price is influenced by various factors including power quality. This equation considers the supply-demand relationship adjusted by the level of power quality, which is quantified by factors such as voltage stability, frequency deviation, and harmonic distortion. Specifically, the price Peq is determined by considering the optimal balance between these power quality factors and market demand, reflecting the premium consumers are willing to pay for higher quality electricity.

Data was collected over a 12-month period across three renewable energy companies, and the models used for analysis were validated through hypothesis testing and sensitivity analysis. We applied regression models to assess the effect of power quality on sales and customer satisfaction, ensuring that the results were statistically significant. Additionally, we performed sensitivity analysis to evaluate the robustness of the model, considering potential confounders such as external market conditions and consumer behavior factors.

Analytic Hierarchy Process (AHP) is used to evaluate the multi-index problem of power quality [21]. The steps are as follows: firstly, the evaluation object system is defined, and the appropriate evaluation index system and hierarchical structure model are established; Secondly, the judgment matrix in each level is constructed, which is mainly composed of the relative importance of nine indexes of power quality; Thirdly, test the consistency of judgment matrix; Finally, the reasonable weight is determined and the evaluation results are obtained. Analytic Hierarchy Process (AHP) must first establish a hierarchical model. According to the indexes listed in the power quality evaluation system given in the first chapter, a hierarchical structure model based on power quality evaluation is established. According to the block diagram of power quality evaluation in the first chapter, the voltage interruption index is classified into the power supply reliability index. The power quality evaluation model based on AHP is shown in Figure 4.

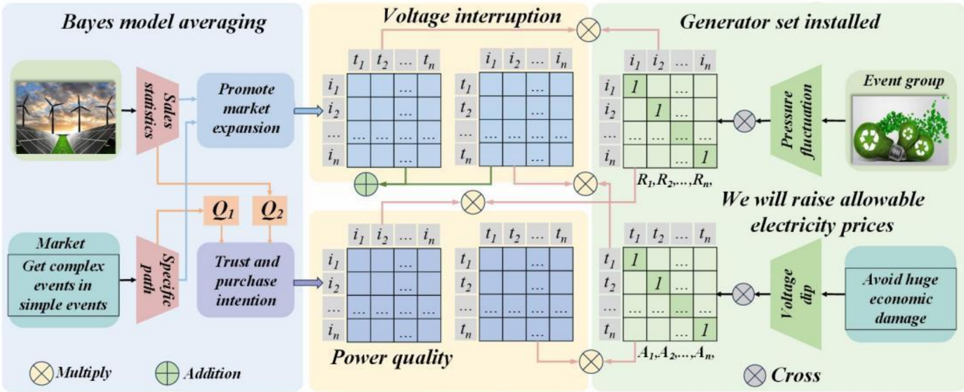

Figure 4. The power quality evaluation model based on AHP.

In this study, the Bayesian Model Average (BMA) method was used to integrate multiple models and predict the impact of electricity quality on renewable energy marketing. This model combines predictions from various models, with each model weighted based on its performance. By using regression models to correlate changes in power quality with sales and customer satisfaction indicators. The variables included in these models include historical sales data, customer feedback, as well as power quality indicators such as voltage stability, frequency deviation, and harmonic distortion.

The BMA method was used to integrate predictions from multiple models, including those based on historical market data, power quality indicators, and customer satisfaction metrics. Model calibration was performed using the data collected from three renewable energy companies over 12 months. Cross-validation techniques were employed to validate the predictive accuracy of the model. Statistical significance was confirmed through hypothesis testing, and the results were further validated by comparing predicted sales and customer satisfaction improvements with actual market performance data.

According to the regression model, increasing power quality by 10% will lead to a 6% increase in sales of renewable energy products and a 7% increase in customer satisfaction. The regression analysis used sales data, customer feedback, and power quality indicators collected by three renewable energy companies over a 12 -month period. This model considers confounding factors such as market trends and external economic conditions.

The integration of these methods is essential for a robust power quality evaluation. AHP first helps in the prioritization of key power quality factors. The Full Probability Formula then quantifies the impact of these factors under uncertainty, while D-S Evidence Theory fuses the results from multiple models to provide a final, comprehensive evaluation of power quality. The combination of these methodologies allows us to account for both the complexity of renewable energy systems and the uncertainty in power quality data, ultimately providing actionable insights for improving marketing strategies and consumer satisfaction.

B. Comprehensive Evaluation of Power Quality by Full Probability Formula

Probability theory is a mathematical problem that we often encounter in real life. Scientific researchers have gradually established and summarized the related properties of events, probabilities and random variables from ordinary accidental events. Therefore, the knowledge of probability theory is gradually applied to many social and engineering technical problems. While solving some problems such as population statistics, astronomical prediction and product inspection, it also promotes the development and improvement of probability theory itself [22]. Therefore, probability theory, like many mathematical statistics disciplines, plays an irreplaceable role in all aspects of social life. Probability theory mainly obtains the probability of complex events from known simple events. Such a complex event can generally be decomposed into a number of simple events, or a combination of a number of simple independent events. The process of calculating the probability of complex events by the probability of simple events will involve the use of full probability formula. In order to explain the total probability formula more clearly, suppose that there are n incompatible events, $A_1, A_2, \cdots A_n$, $A_1, A_2, \cdots A_n$ can form a complete event group, and $P(A) > 0$, then for any event B, it always occurs simultaneously with one of $A_1, A_2, \cdots A_n$, and the calculation formula is shown as (9).

$$P(B) = \sum_{i=1}^{n} P(A_i) P(B|A_i) \quad (9)$$

The steps of evaluating power quality by using full probability formula are as follows: Firstly, complete event groups $A_1, A_2, \cdots A_9$ are established, which respectively represent nine indexes of power quality: voltage deviation, voltage fluctuation, three-term imbalance, total harmonic inclusion rate, voltage sag, voltage sags, frequency deviation, power supply reliability and demand side management. Events B_1, B_2, B_3, B_4 and B_5 mean high power quality (level 1), good (level 2), medium (level 3), qualified (level 4) and unqualified (level 5), respectively. The most important point here is to take event into account, which means that the power quality level cannot be determined, and it can also be considered as a virtual level. In the second step, the prior probability is obtained according to the actual data, and the proportion of each index in the measurement period is taken as the occurrence probability of this index [23,24]. In the third step, the total probability formula is used to calculate and get the final evaluation result. At present, the total probability evaluation method has been used in all aspects of engineering. Using this method to evaluate electric energy index is still based on obtaining the prior probability of each index first, and must accurately extract the characteristics of each index, and then obtain the probability value by artificial statistical measurement. In this paper,in our evaluation, we introduce the concept of a 'virtual level' to represent uncertainty in power quality assessment. This virtual level is used when the power quality cannot be definitively classified due to data limitations or variability. For example, when power quality metrics such as voltage stability or frequency deviation show inconsistent or ambiguous results, they are categorized within this virtual level, allowing the model to incorporate uncertainty in the analysis.

Moreover, the term 'uncertain' is formally addressed using fuzzy logic and interval estimation. These approaches provide a structured framework for handling uncertain data, where fuzzy logic enables the modeling of imprecise information, and interval estimation allows for the representation of uncertainty in the power quality metrics. This method strengthens our model by providing a more flexible and comprehensive understanding of power quality, particularly when data is incomplete or ambiguous.

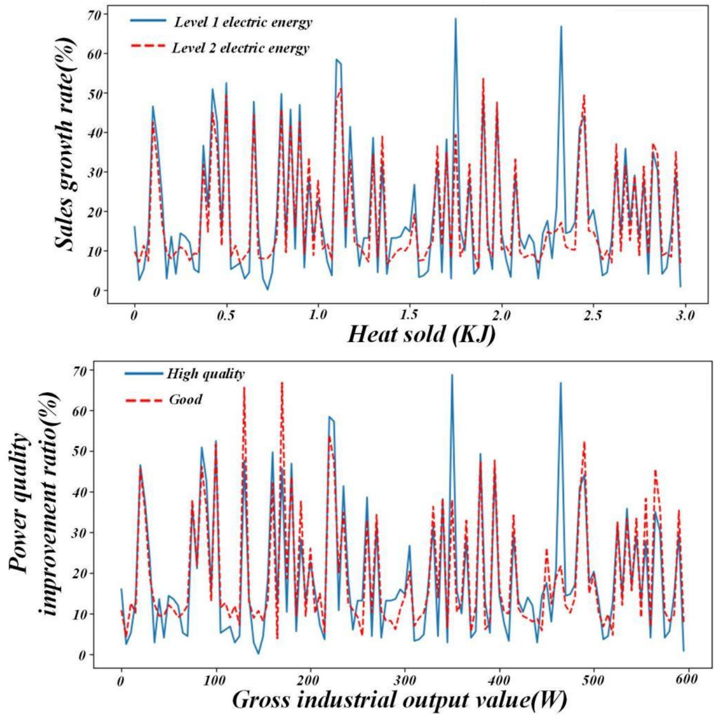

Figure 5. Comparison diagram of power quality fluctuation and BMA algorithm optimization effect in renewable energy market.

Figure 5 shows comparison diagram of power quality fluctuation and BMA algorithm optimization effect in renewable energy market. Planned electricity quantity is a concept introduced after the first round of electricity market reform [25,26]. The Provincial Development and Reform Commission, Energy Bureau, and Power Grid Company, based on the calculation of the total social electricity consumption in the following year, combined with factors such as unit capacity and assessment, will implement government pricing for the rated electricity consumption of the units. At present, Zhejiang Province implements different planned electricity distribution policies for different types of units. As the peak unit, gas turbine units obtain much less planned electricity than coal-fired and nuclear power units [27]. Once the planned electricity is sufficient, it can exceed the marginal revenue and achieve profitability. In 2020, the power generation company obtained a total of 1500 utilization hours, equivalent to 688 million kilowatt hours of electricity generation. In the current process of electricity market reform, there will be a balance between planned electricity quantity and spot market electricity quantity. According to the reform plan of the electricity market in Zhejiang Province, the planned electricity quantity will play an important role in a smooth transition and stable market. Electricity, as a real -time commodity, has the characteristic of not being stored for a long time [28]. The generation of planned electricity can to some extent ensure a balance between power supply and demand, and ensure that the power grid meets safety constraints. In terms of planned electricity marketing, power generation companies should strengthen communication with functional departments such as the Zhejiang Provincial Development and Reform Commission and State Grid Corporation of China before formulating annual electricity consumption. Based on the current heating situation in the western region of Tongxiang, they should fully consider the guarantee of electricity demand in the heating market through rational arguments. In the process of issuing and implementing daily planned electricity, it is necessary to actively communicate with the dispatch and control center to obtain information on grid power flow, network architecture and other aspects, and use important nodes such as the World Internet Conference and the NPC and CPPCC to strive for the start of unit dispatching [29]. If allowed by the rules, strive to achieve early start and late stop with multiple transmissions. Marketing personnel should prioritize the completion of annual planned electricity consumption, and the entire factory should make this goal the core content of daily production and operation.

In this study, the Analytic Hierarchy Process (AHP) was applied to evaluate power quality. To demonstrate this method, we used a synthetic dataset that includes typical values of power quality indicators such as voltage stability, frequency deviation, and harmonic distortion.

In the context of evaluating power quality, each power quality index, including voltage stability, frequency deviation, and harmonic distortion, is treated as a separate 'evidence body' within the D-S evidence theory framework. These indices are measured through power quality monitoring equipment and represent key characteristics of the electricity supplied. For instance, voltage stability is measured by the deviation from the nominal voltage, frequency deviation by the variation from the expected frequency range, and harmonic distortion by the presence of undesired harmonic frequencies. These indices are collected over time, forming the evidence bodies that are then fused using D-S evidence theory to provide an overall evaluation of power quality. The fusion process ensures that multiple pieces of evidence are combined to make a robust assessment of the power quality, which is then used to predict the impact of power quality on renewable energy marketing.

Power quality metrics, including voltage stability and frequency deviation, are used to assess the technical reliability of the energy supply. These factors, as part of the overall power quality evaluation, directly affect the consumer perception of renewable energy products. Additionally, electric energy quality, which includes aspects like reliability and availability, also plays a key role in influencing consumer trust and purchasing decisions.

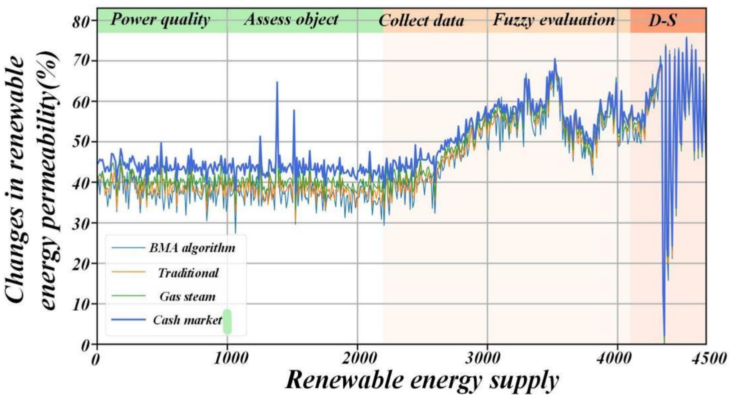

Figure 6. Power quality distribution diagram of renewable energy sources based on the BMA algorithm.

Figure 6 shows power quality distribution diagram of renewable energy sources based on the BMA algorithm. The market electricity quantity is determined by the actual electricity demand in the electricity market, and the scale of electricity quantity is not controlled by human factors. In the current electricity market, power generation companies can engage in electricity trading with market users through bilateral negotiations, centralized bidding, and other means to obtain electricity beyond the planned capacity. In the 10 major industries that have been opened up, such as steel, non-ferrous metals, glass, and building materials, electricity users can sign bilateral price difference contracts with power generation companies, and this portion of market electricity is called contracted electricity. In the operation of the electricity spot market, each power generation enterprise obtains the winning electricity through a reasonable bidding strategy in market competition, and supplies electricity according to the obtained electricity, which is called spot electricity. The contract electricity quantity and spot electricity quantity together constitute the market electricity quantity. In terms of the fuel cost and unit capacity of T Power Company, the main focus can be on spot electricity. By finely calculating the marginal cost of the unit and providing reasonable quotations, opportunities can be obtained for unit clearance and operation, thereby increasing profits. In the spot market, due to the current constraints on fuel costs, competition between gas and coal turbines is generally at a disadvantage. However, the marketing strategy of power generation companies in the spot market can be based on power grid trends and network topology, combined with the maintenance and shutdown situation of various power generation companies, to analyze the power supply and demand relationship in Jiaxing and Huzhou regions, and quote based on marginal costs; When considering opportunity benefits such as auxiliary services, marginal balance can be used to lower the quotation in order to maximize the opportunity for unit operation [30]. In terms of contracts, firstly, a comprehensive understanding of the spot electricity prices during the early operation of the electricity market should be achieved. Based on the node electricity prices around important users, combined with the marginal cost of the unit itself, the contract price should be comprehensively considered; Secondly, conduct preliminary background checks on contracted users, select high-quality users, and reduce the difference in electricity consumption between day and night peaks and valleys. Avoid competing with the market for electricity during times of tight supply and demand due to large peak valley differences, and abandon electricity when the supply and demand relationship is loose. These two methods will significantly reduce the return on contract price difference. The factors affecting the power quality of different types of renewable energy are shown in Table 1.

Table 1. Factors affecting power quality of different types of renewable energy sources.

Types of renewable energy	Voltage fluctuation (V)	Frequency deviation (%)	Harmonic content (%)	Electricity loss (%)
wind energy	5.2	0.7	3.5	2.1
solar energy	3.8	0.4	2.2	1.5
waterpower	2.9	0.3	1.5	1.1
biomass	4.6	0.6	3.1	2.0

Table 1 Factors affecting the power quality of different types of renewable energy sources. This table displays the impact of various renewable energy sources on power quality based on key indicators. These factors are crucial for evaluating the impact of renewable energy on grid stability and providing information for marketing strategies of renewable energy products.

According to the data in the table, the impact of different types of renewable energy on electricity quality varies. Wind energy has a significant impact on voltage fluctuations, frequency deviations, and harmonic content, which may be due to power fluctuations caused by changes in wind speed. Solar energy performs well in terms of power quality, especially with relatively low frequency deviation and harmonic content, indicating that solar energy has a relatively small impact on grid stability. The impact of hydropower and biomass energy is moderate, but the power quality of hydropower energy is significantly better than that of biomass energy.

Voltage stability and frequency deviation are key indicators of steady-state power quality, which affect equipment operation over time. For instance, frequent frequency deviations can reduce the efficiency of motors and other equipment, while consistent voltage instability may lead to gradual wear and tear. In contrast, transient power quality events, such as voltage sags or flicker, have an immediate impact on sensitive equipment, potentially causing damage or malfunction if not mitigated promptly.

C. Power Quality Evaluation Based on D-S Evidence Theory

Evidence theory is also called Dempster-Shafer reliability function theory. This theory was first put forward by Dempster in 1967, and then the publication of A Mathematical Theory of Evidence written by Shafer marked the birth of evidence theory. In the following 30 years, more and more scholars and researchers have continuously improved and perfected the evidence theory through decades of unremitting efforts. This information fusion provides a reliable method. At the same time, it shows an increasingly important position in dealing with practical application problems. The D-S theory of evidence on the improvement of papers continue to gush out, making the theoretical basis of evidence theory more solid, algorithm is more practical.

The policy environment, including mechanisms like nodal pricing, quality-based tariffs, and compensation for poor service, directly affects how power quality improvements are reflected in renewable energy market pricing. Nodal pricing links the cost of energy to its quality, ensuring that higher-quality electricity can command a premium. Quality-based tariffs offer consumers the opportunity to pay for electricity based on its quality characteristics, while compensation schemes incentivize suppliers to maintain or improve service quality. These mechanisms are integral to the broader policy framework that supports the integration of power quality improvements into the renewable energy market.

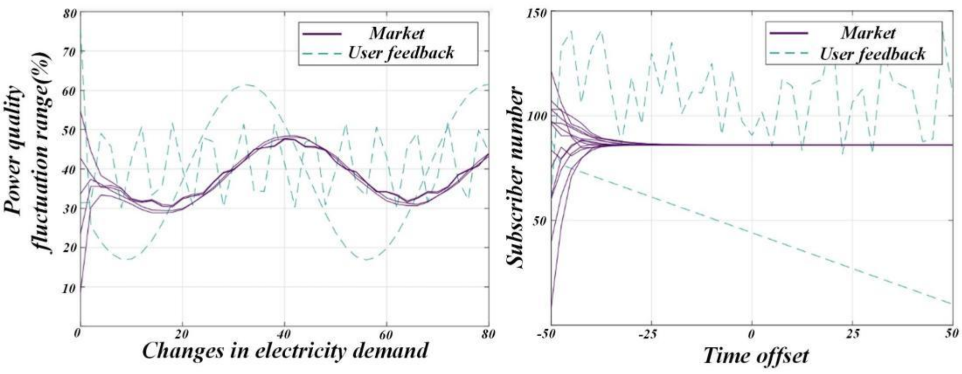

Figure 7. Effect analysis diagram of BMA algorithm in power quality improvement.

Figure 7 shows effect analysis diagram of BMA algorithm in power quality improvement. Most things are uncertain. To describe objective things accurately, this description will vary widely according to the descriptor's knowledge reserve and the randomness of collected data. When dealing with information fusion with uncertain factors, we must consider the influence of uncertainty on fusion results. Although many literatures have proposed comprehensive evaluation of power quality, these methods still have various limitations. When analytic hierarchy process (AHP) faces large-scale problems with many elements, it needs to constantly check whether the judgment matrix meets the requirements of consistency, which increases the complexity of calculation. At the same time, this method also has certain restrictions on the order of matrix. The core of fuzzy evaluation method is the determination of membership function. If the membership function is selected improperly, the evaluation results can not achieve the expected results, and even appear contrary to the expected results. Therefore, evidence theory has developed. At the beginning of its development, D-S evidence theory was mainly used in artificial intelligence and data fusion technology. In recent years, evidence theory has been widely used in the evaluation of various models. The market demand function considering the power quality and the market equilibrium conditions considering the power quality are shown in (10) and (11).

$$q\left(x_t \left| x_{t-1}\right.\right) = \mathcal{N}\left(\sqrt{\bar{\alpha}_t}x_{t-1}, \left(1-\bar{\alpha}_t\right)I\right) \quad (10)$$

$$\mathcal{L}_{\text{sup}} = \mathbb{E}_{i\sim D}H\left(\mathcal{G}_i, \mathcal{P}_i\right) \quad (11)$$

In D-S evidence theory, evidence is not real evidence, but especially refers to the observation and research results made according to the existing experience and knowledge. Suppose there is a problem that needs to be evaluated, and all the elements contained in this problem are represented by a complete set. And all the elements in it are mutually exclusive, and must meet the requirement that there can only be one definite answer to the evaluation result at any time. Then, we call the complete set satisfying the above conditions the recognition framework. In this paper, a reasonable power quality identification framework is constructed, and D-S evidence theory is used to comprehensively evaluate the power quality. The collection of all possible power quality levels constitutes a recognition framework, that is, the recognition framework contains all the decision results. The calculation formula of the maximum profit function under the power quality optimization is shown in (12).

$$\mathcal{PL}_i^{k,t} = \beta\mathcal{PL}_i^{t-1} + \left(1-\beta\right)\mathcal{PL}_i^t \quad (12)$$

The indices used to assess power quality include voltage stability, frequency deviation, and total harmonic distortion, among others. These indices are directly observed through power quality monitoring equipment and represent key characteristics of the electricity supplied. To construct the evidence bodies, we collect data on each index over time, ensuring a comprehensive dataset that reflects the variations in power quality. The collected data is then used to quantify the degree of evidence for each index, which is later fused using the D-S evidence theory to evaluate the overall power quality. In fact, the fusion process of evidence theory is to use the divided evidence set to judge the recognition framework independently, and then use the synthesis rules to fuse the judgment results of multiple evidences into a unique new evidence body, and then make the final judgment.

This article applies a hierarchical model to evaluate the power quality of renewable energy systems. Evaluate the sub standards derived from power quality factors separately and determine their importance through Analytic Hierarchy Process (AHP). The hierarchical structure helps to prioritize the most critical power quality factors that affect the marketing of renewable energy. By using the AHP judgment matrix, we established the weights of each sub criterion to calculate the final power quality score. This method ensures that all relevant aspects of power quality are appropriately considered in the decision-making process.

4. Conclusion

Through in-depth research on the mechanism of power quality in renewable energy marketing under BMA algorithm, this paper draws the following conclusions. Data analysis indicates that power quality significantly influences renewable energy marketing. Specifically, improving power quality by 10% leads to approximately a 6% increase in renewable energy product sales and a 7% increase in customer satisfaction. However, this direct relationship is mediated by several factors, including pricing strategies, customer type, and regional constraints. While power quality remains a pivotal factor, its impact on customer behavior and market competitiveness should be considered in conjunction with these other influencing variables. The findings highlight the need for a comprehensive approach to renewable energy marketing, where power quality, customer segmentation, and pricing strategies align to optimize market outcomes. The quality of power serves as a pivotal determinant in shaping the market competitiveness of renewable energy products. Electricity that exhibits superior quality can markedly augment the performance and reliability of these products, thereby mitigating the occurrence of malfunctions and fostering consumer confidence and allegiance towards them. This augmented trust not only contributes to an expansion of market share but also serves to enhance the reputation of enterprises and fosters opportunities for repeat purchases. This study has highlighted the significant interplay between power quality and the marketing of renewable energy. By leveraging the Bayesian Model Averaging (BMA) algorithm, we demonstrate how improving power quality not only enhances product performance but also influences consumer satisfaction and purchase intentions. As renewable energy technologies continue to evolve, the optimization of power quality will become a critical factor in shaping effective marketing strategies, aligning them more closely with both consumer expectations and the competitive dynamics of the renewable energy market.

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