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Determinants of Willingness to Participate in Urban Incentive-Based Energy Demand-Side Response: An Empirical Micro-Data Analysis

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Abstract: Demand-side management provides important opportunities to integrate renewable sources and enhance the flexibility of urban power systems. With the continuous advancement of the smart grid and electricity market reform, the potential for residential consumers to participate in energy demand response is significantly enhanced. However, not enough is known about the public perception of energy demand response, and how sociopsychological and external factors could affect public willingness to participate. This study investigates the public perception of and willingness to participate in urban energy demand response through a questionnaire survey and employs multiple linear regression models to explore the determinants of public willingness to participate. The results suggest that income level, energy-saving attitudes, behaviors, external motivation factors, and energy-saving technologies are the key factors that determine public willingness to participate. Although most respondents are willing to participate, the effects of monetary incentives are more significant than the effect of spiritual inducements, and respondents are more sensitive to compensation than to dynamic electricity prices. The further improvement of residential responsiveness requires continuous infrastructure building by technical support, public energy-saving awareness, and public perception of energy demand response. Policy implications are proposed to achieve a sufficient residential response from an aggressive policy framework and energy-saving behavioral guidance.

Keywords: demand-side management; willingness to participate; determinants; spiritual incentives

1. Introduction

Renewable energy has been increasingly integrated into clean electricity generation, which helps to reduce the dependence on fossil fuel and greenhouse gas emissions. According to the report from REN21, the installed capacity of renewable energy has grown to over 33% of the global total installed capacity, and the installed renewable electricity capacity at the end of 2018 was sufficient to supply approximately 26.2% of global electricity production [1]. The Zero-Carbon China report states that China's total power demand will increase from about 6 trillion kWh in 2016 to about 15 trillion kWh in 2050 in order to achieve a zero-carbon economy, of which nearly 70% of its electricity will come from solar and wind energy [2]. With the increase of renewable sources penetration in electricity generation, the intermittent and limited controllability of renewable energy generation restricts the

security, reliability, and sustainability of the power systems [3,4]. Power systems should be more flexible to maintain economic profitability, and operation safety [5].

Demand-side management (DSM), as an important controllable virtual resource, has the advantages of low marginal cost and short response time, and can effectively overcome the randomness of renewable energy generation and the adverse impacts of power supply and demand mismatch on power system [6,7]. Furthermore, by increasing end-user participation and responsiveness, it has greater flexibility than expanding power generation and distribution capabilities, and affects consumer demand for greater technical and environmental efficiency [8,9]. Therefore, demand response is considered as the most promising option for integrating renewable sources and increasing the flexibility of the power system [10,11]. It is noticeable that the market mechanism significantly affects the development of demand response. Only by giving full play to the role of the market and intelligently managing the demand-side can the potential of demand response be fully realized [12,13]. With the advancement of China's smart grid construction and power marketization reforms, and the continuous improvement of domestic electrification, the ability for residents to participate in demand response is greatly stimulated [14,15].

However, researches on the obstacles and challenges of demand response suggest that how to change residential energy consumption behaviors to achieve sufficient response has become a core part of the successful implementation of demand response management [16,17]. Although the concept of demand response is based on the assumption of rational decision-making by end-use customers, residential energy consumption behavior is often irrational and affected by numerous factors, such as values, daily habits, social norms, and personal preferences [18,19]. The factors of how public perception affects demand response should be investigated to develop efficient demand response strategies [20]. Thus, it is necessary to further analyze public attitudes towards demand response in combination with the factors affecting the residents' energy consumption behavior.

The aims of this research are twofold for sustainable power demand-side regulation. Firstly, public perceptions of energy demand response are measured from different perspectives, including public willingness to participate (WTP) from material and spiritual incentives, public preferences for different participation forms and measures, and public perception of the difficulty of participating in energy demand response. Secondly, combining with economic, social, and psychological drivers of energy consumption behaviors, this research quantitatively analyzes the relationships between major influencing factors and public WTP in energy demand response. This research divides these factors into five categories, including socio-demographic characteristics, energy-saving attitudes, behavior abilities, external motivating factors, and energy-saving technologies. In this way, it is possible to provide a panorama of the public responsiveness to energy demand response, thereby assessing the potential of residential demand response, and to propose a policy framework for the successful implementation of residential demand response.

The rest of this paper is organized as follows. Section 2 provides a review of previous researches on demand-side response. Section 3 outlines the methodology and describes the research framework, the design and collection of the questionnaire, and methodologies in this study. Section 4 introduces the results analysis, and Section 5 gives the discussions for how to make active WTP in power demand response. Finally, conclusions and policy implications for achieving active participation and sufficient response are shown in Section 6.

2. Literature Review

2.1. Concepts and Benefits behind Demand Response

Demand response refers to the concept that “consumers voluntarily provide load reduction based on electricity price changes over time; or incentive payments for inducing customers to reduce electricity consumption when the wholesale market is expensive or the reliability of the power systems is jeopardized” [8,21]. Demand response aims to encourage consumers to provide load reduction

during peak periods to ensure the reliability of power system operations, and it can be roughly divided into two categories: Price-based programs (PBP) and incentive-based programs (IBP). PBP refers to flattening the demand curve by responding to changes in electricity prices over time [8]. The choice of the price includes time of use pricing (TOU), real-time pricing (RTP) and critical peak pricing (CPP), etc. [22]. IBP refers to providing incentive payment for users to participate in slashing power during peak periods. IBP can be further divided into classical IBP and market-based IBP. Classical IBP includes direct load control (DLC), interruptible load (IL), etc. Market-based IBP includes demand-side bidding (DSB), emergency demand response (EDR), capacity market (CM), and ancillary service market solutions [8]. In addition, there are three types of actions that customers can choose in demand response. One is that customers can reduce the load power consumption during peak periods, and do not change load pattern during off-peak periods, such as adjusting the temperature of refrigerators and water heaters [4,21]. Secondly, customers shift load from peak periods to off-peak periods, such as avoiding the use of energy storage equipment, washing machines, and dishwashers during peak periods. Thirdly, the public is able to make access to electricity by distributed power generation, thereby limiting their dependence on the power grid [23].

Potential benefits of demand response involve economic, environmental, and systematic reliability aspects. In terms of economy, demand response can get compensation and save electric bills for participants. For power systems, demand response can reduce the need for reserving capacity and alleviating grid congestion, thus delaying or avoiding the cost of grid reinforcement and investment in capacity reserve [24,25]. And demand response flattens the demand curve, further improving the effective utilization of existing infrastructure and reducing high supply costs during peak periods [26]. The overall operating costs of the distribution grid are reduced through demand response [27]. In addition, demand response can enable customers to respond to price signals and fairly reflect the actual costs of power generation and grids operation [21]. In terms of the environment, demand response can not only reduce power generation and improve energy efficiency [28,29], but also increase the portfolio capacity of a large number of uncontrollable renewables, thereby reducing greenhouse gas emissions and enhancing the environmental sustainability of the power systems [3,10]. In addition, demand response can also help increase consumer awareness of electricity consumption and indirectly affect carbon emissions [19]. In terms of reliability, through careful design on demand response programs, the generation, transmission, and distribution capacity can be cut down in a short time, thereby reducing the risk of network peaks and system crashes and ensuring the reliability of power system operation [26].

2.2. Barriers and Challenges for Demand-Side Management

Although demand response may bring potential benefits, there are still many barriers and challenges to achieving broad participation in demand response. For example, Good et al. divides the barriers to demand response to fundamental and secondary barriers [30]. Fundamental barriers could be classified as economic, social, and technological, whilst the secondary obstacles include anthropogenic institutions, system feedback, market rules, and physical constraints. Oconnell et al. believed that the key challenge of demand response is how to establish reliable control strategies and market frameworks, and one of the greatest challenges for demand response is the lack of experience [20].

The obstacles to demand response involve market, policy, and technology issues [31]. The major challenge is how to improve the end-use customers' support and interest, because the effectiveness of demand response is ultimately limited by end-use customers' response [17,19]. Because end-user customers (especially the household sector) often are not the economically rational decision-maker, it is difficult to predict responses using conventional economic models [20,32]. And for most consumers, electricity is seen as a service rather than a commodity, and the potential electricity bill that may be saved by the demand response may not be their main goal [21]. Apart from the limited rationality of end-users, factors affecting household energy consumption behaviors (such as socio-demographic

characteristics, value, daily habits, and routines, lifestyles, et al.) are also important factors that limit public participation in demand response [19]. The effective implementation of demand response measures requires the productive mixture of mutually supporting elements by the competences, engagement, and devices [33].

2.3. Key Factors Governing Residential Electricity Demand Response

Numerous studies have investigated the factors that influence residential demand response, in order to efficiently understand user perceptions to demand response. The potential of different types of households for demand response programs is explored [9]. Setlhaolo et al. found that households can change electricity consumption based on changes in electricity prices and incentives, but whether participate in demand response ultimately depends on preferences for cost and inconvenience [34]. It is found that the potential of demand response was driven by the buildings and their systems, physical and contractual environments, and the behavior and preferences of occupants [35]. Gyamfi et al. stated that some residential customers, especially the rich, were slow to respond to price signals and did not even respond [36]. Previous researches reveal that although prices or incentives will promote residential responsiveness to a certain extent, costs may not be their main goal, due to the limited rationality of residential behaviors. The successful implementation of demand response requires greater understandings of the energy consumption behavior of residents from broad aspects of economics, socio-demographic, and psychology [37]. Economic aspect research has used prices and customer income as determinants of resident energy consumption, while socio-demographic and psychological studies have shown that energy consumption behaviors are affected by various factors, such as family characteristics, habits, attitudes, values, social norms, ability, etc. [3,38,39]. Horne and Kennedy indicated that the power of social norms could not only directly affect household electricity consumption, but also promote the integration of renewable sources in electricity generation by changing the usage time [40]. The relationship between the user's response and family attitudes towards smart devices through a Belgian demand response trial was investigated [41].

Based on the literature review, this study takes socio-demographic characteristics, energy-saving attitudes, behavior abilities, external motivating factors, and energy-saving technologies as the major influencing factors for public participation in demand response. Socio-demographic characteristics include opportunities and constraints on household energy consumption, such as age, the number of households, income, education level, etc. Energy-saving attitudes include factors that influence motivation for energy-saving behaviors, such as personal norms, energy-saving beliefs, energy-saving responsibilities, and awareness of consequences. Behavior ability reflects the individual's past experience and future obstacles, including factors of behavior knowledge and behavior constraints. External motivating factors mainly refer to incentives, policies, regulations, rewards, compensation, that change energy consumption behavior. Energy-saving technologies refer to advanced technologies that change personal energy consumption behaviors, such as information feedback, intelligent control technologies, etc. [42,43].

3. Materials and Methods

3.1. Research Framework for This Study

This research aims to provide a deeper understanding of public responsiveness to demand response by exploring the relationship between public WTP in energy demand response and influential factors. The key factors affecting public WTP can be summarized into five main categories: Socio-demographic characteristics, energy-saving attitudes, behavior abilities, external motivating factors, and energy-saving technologies. The study attempts to provide more broad insights by measuring public WTP in three different scenarios with respect to two levels of material incentives and spiritual incentives, namely, dynamic electricity price, compensation, and the issue of honorary citizenship certificates.

The framework involves three processes (as illustrated in Figure 1). The first process is to employ the 1–5 Likert scale questionnaire to survey public WTP and the key influencing factors. The second one is to quantitatively analyze the relationship between WTP and its key influencing factors using the quantitative data from the survey. Based on the sample data and quantitative analysis, the third task is to find the deep meaning behind the data and make conclusions and policy implications. In the quantitative analysis process, public willingness to participate is the average of public willingness to participate in the three scenarios. Among the influencing factors, the socio-demographic characteristics, including age, gender, income, and education level, are coded by category, and the remaining influencing factors are the weighted average of the respective measurement items, while the weight value is the magnitude of the correlation between each measurement item and the average willingness of the respondents to participate.

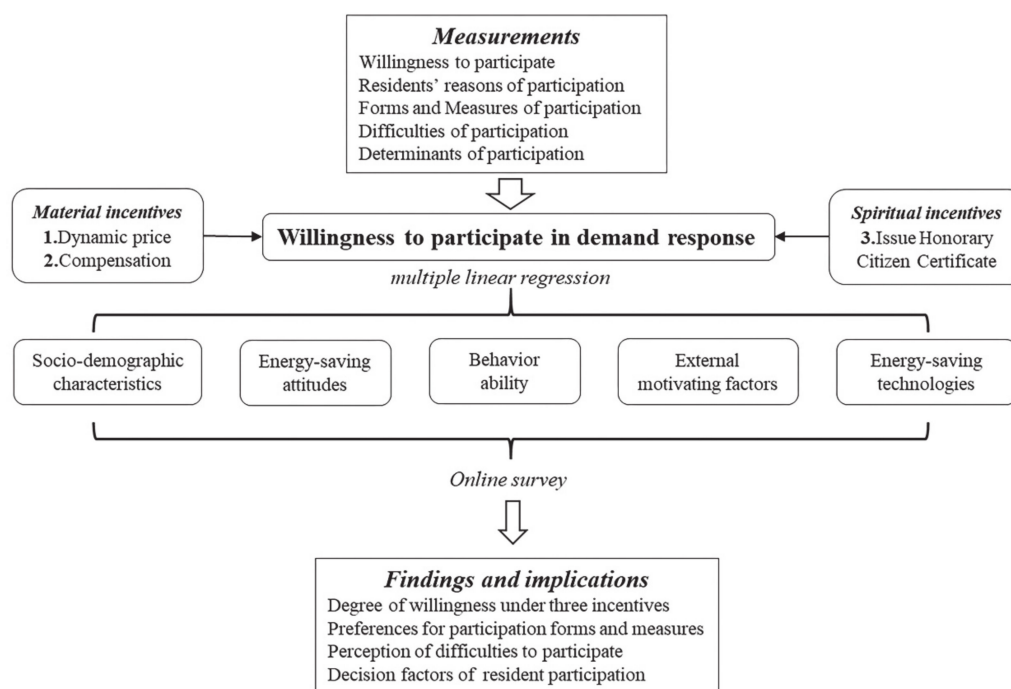


Figure 1. Research framework for willingness to participate in demand response.

3.2. Questionnaire Design and Data Collection

The questionnaire is designed by the following steps. Firstly, based on clear survey objectives, the preliminary design of the questionnaire is completed by reviewing relevant literature. Through the questionnaire inspection and internal discussions, some items, which are not closely related to the research purpose, are deleted, and the content of the questionnaire is refined. Secondly, we conducted internal tests in order to eliminate the errors or ambiguities in the questionnaire. Thereby, the first draft of the questionnaire becomes more concise and easier to understand. Finally, the first draft of the questionnaire is examined through a two-step pre-test. In the first step, the questionnaire is modified based on professional feedback from researchers in the field of social statistics and investigation. In the second step, with a small-scale survey test, the first-round draft of the questionnaire is slightly adjusted based on the suggestions from the focus group discussion. Therefore, the final draft questionnaire for the formal survey is formed and submitted for field survey.

The questionnaire begins with a short introduction that outlines the related knowledge of demand response. The main body of the questionnaire includes four parts. The first part surveyed the demographic characteristics of the respondents, including gender, age, family size, income, and education level. The second section sets the influencing factors of public participation in demand response, including energy-saving attitudes, behavior ability, external motivating factors,

and energy-saving technologies. The items for each influencing factor are measured by 1–5 Likert-type scale, ranging from 1 (strongly disagree) to 5 (strongly agree). Among them, energy-saving attitudes include three items adapted from [44], and behavior ability includes three items, adapted from [38]. Energy-saving technologies set up two items, including information feedback and intelligent control technology, because related research stated that information feedback and smart devices can promote the change of residents' energy consumption behavior [41,42].

Based on the above description, the specific items are shown in Table 1. Combining the types of demand response (PBP and IBP) with the public pursuit of social reputation, the third part of the questionnaire investigates the public WTP in three different situations: Subsidies, dynamic electricity prices, and the issuance of honorary citizenship certificates. The specific items also are illustrated in Table 1. The fourth part of the questionnaire asks the public about the main measures to participate in the demand response, the preference of participation form, and the awareness of participation difficulty.

The target group for this survey is residents over age 18. The survey method uses an online survey method. The online questionnaire was distributed through a professional online questionnaire platform with paid services. A total of 350 questionnaires were recovered. The effective questionnaire was 324, and the qualified rate was 92.6%. The questionnaires that were deleted were mainly due to too short time to work, only the same option selected or contradictory options. When the total sample size is very large, there is no necessary relationship between sample size and the total sample, but it is related to the confidence level and relative error [45]. The formula for calculating the minimum sample size is shown in Equation (1).

$$n = \frac{Z^2 \sigma^2}{d^2} \quad (1)$$

where n is the sample size; Z is a statistic of different confidence levels, σ is the standard deviation, which is generally taken as 0.5; d is the relative error.

When the confidence level is 90%, and the relative error is 5%, the minimum sample size is 269 by calculation. The 324 valid questionnaire samples collected in this survey fully met the confidence and accuracy requirements.

The sample demographic characteristics are shown in Table 2. From the perspective of gender, males account for 51.9%, and females account for 48.1%. Young people aged 35 and below accounts for the majority, while middle-aged and elderly people aged 46 and above account for a relatively small proportion. In terms of family size, three-person families and four-to-five families account for a relatively large proportion, at 43.2% and 40.4%, respectively. From the perspective of income, the proportion of the population below 5000 yuan is 41.7%, and the proportion between 5000 yuan and 10,000 yuan is 38.3%, but the high-income group is relatively small. In terms of education level, more than half of the respondents had a bachelor degree, while the number of respondents with compulsory or less, and master degree and above accounted for a relatively small part at 7% and 8%, respectively.

Table 1. Measurement scales for factors governing behaviors of electricity demand-side response.

Influence Factors	Description	Item
Energy-saving attitude	Reflecting the motivation for energy-saving behavior	• No matter what others do, I have a moral obligation to reduce power consumption.
		• I think my energy-saving actions can help reduce air pollution and alleviate power shortages.
		• I see energy waste and often consciously reduce it.
Behavior ability	Reflecting personal past experience and future obstacles	• I think it is troublesome to save electricity (Reverse scoring).
		• I don't think I know how to save electricity. (Reverse scoring).
		• I don't think I can reduce my electricity use because it will reduce my home comfort. (Reverse scoring).
External motivating factors	Incentives and policy factors that change personal energy consumption behavior	• Providing a discount price for consumers who save electricity, I tend to reduce electricity consumption.
		• Providing subsidies for smart energy-saving appliances, I will be willing to replace non-energy-saving appliances.
		• Providing monetary rewards to consumers who save electricity, I would be more willing to save electricity.
		• The rules and regulations require saving electricity, and I will resolutely implement it.
Energy-saving technology	Advanced technologies that change personal energy consumption behavior	• Using smart meters to monitor and feedback the saved electricity in real-time, I will tend to save electricity.
		• Using a mobile application to achieve remote energy-saving control of electrical equipment, I will tend to save electricity.
Willingness to participate	Public willingness to participate (WTP) in energy demand response	• If the electricity saved during peak periods is subsidized, are you willing to slash electricity consumption during peak hours?
		• If electricity prices rise during peak periods and fall during off-periods, are you willing to slash electricity during peak periods?
		• If an Energy Pioneer Honorary Citizenship Certificate is issued to residents who participate in DSM, are you willing to slash electricity consumption?

Note: Response choices: 1–5 Likert scale (Strongly disagree; Disagree; Neutral; Agree; Strongly agree).

Table 2. Characteristics of the sample.

Item	Category	Number	Percentage (%)
Gender	Male	168	51.9
	Female	156	48.1
Age	18–25	99	30.6
	26–35	114	35.2
	36–45	70	21.6
	46–60	36	11.1
	More than 60	5	1.5
Family size	1	6	1.9
	2	14	4.3
	3	140	43.2
	4–5	131	40.4
	More than 5	33	10.2
Monthly income	Less than 5000 RMB	135	41.7
	5000–10,000 RMB	124	38.3
	10000–15,000 RMB	39	12
	15000–20,000 RMB	21	6.5
	More than 20,000RMB	5	1.5
Education	Compulsory or less	24	7.4
	High school or professional training	85	26.2
	University	189	58.3
	Master's degree or higher	26	8
Total		324	100

3.3. Multiple Factors Modeling for Willingness to Participate in Energy Demand Response

According to the literature review, public willingness to participate in energy demand response is affected by a series of factors, including socio-demographic characteristics, energy-saving attitudes, behavior ability, energy-saving technologies, and external motivating factors. To explore the relationship between the influencing factors and the willingness to participate, a Multiple Linear Regression model is introduced in the study, as shown in Equation (2).

$$Y_j = \alpha + \beta_1 X_j^1 + \beta_2 X_j^2 + \beta_3 X_j^3 + \beta_4 X_j^4 + \beta_5 X_j^5 + \beta_6 X_j^6 + \beta_7 X_j^7 + \beta_8 X_j^8 + \varepsilon \quad (2)$$

In Equation (2), the explained variable Y_j indicates the willingness of respondent j to participate where $j = 1, 2, \dots, 324$. The explanatory variable X_j^k indicates the measurement value of influence factor (gender, age, family size, monthly income, education, energy-saving attitude, behavior ability, external factors) k ($k = 1, 2, \dots, 8$) by respondent j . β_k denotes the regression coefficient of influence factors k . The α and ε denote a constant term and random error term.

Since energy-saving attitudes, behavior ability, external motivating factors, and energy-saving technologies are difficult to observe directly, this study sets several measurement items for each index. To verify the validity and reliability of the four explanatory variable measurement items, the research first performs confirmatory factor analysis and reliability analysis before regression analysis. Pearson correlation coefficients and Cronbach's coefficients are selected to indicate the validity and internal consistency of these items. The above analysis is achieved by the software SPSS 23.0.

4. Results

4.1. General Attitude Analyses of Energy Demand Response

Combining of spiritual incentive and material incentive, the questionnaire surveyed public attitude (from strong unwillingness to strong willingness) to participate in energy demand response in three different scenarios: Compensation for slashing power consumption during peak periods, implementing dynamic electricity prices, and issuing honorary certificates for customers who actively cut down power consumption during peak periods. As shown in Figure 2a, under the three scenarios of compensation, dynamic electricity price, and honorary citizen certificate, the proportion of respondents who refused to participate in the demand response is very small, which is 3.1%, 4.9%, and 4.6%, respectively. The

proportion of respondents who maintain a neutral attitude are 10.8%, 20.4%, and 25.9%, respectively, and the proportion of respondents who want to participate is quite large, which are 86.1%, 74.7%, and 69.4% respectively. Using a 1–5 Likert scale to score the three items, the average score of each item is 4.15, 4.01, and 3.88, respectively, in Figure 2b, which indicates that the public WTP in demand response is quite high and residential demand response has broad market potential. With comparison on the three scenarios, it is found that public WTP is the highest in the scenario of compensation, and the proportion of respondents who are strongly willing to reach nearly one third, while the proportion of respondents who remain neutral and refuse to participate is only 10.8%. In the scenario of dynamic electricity price, public WTP is second, and in the scenario of honorary citizen certificate, public WTP is the lowest, and the number of respondents who remain neutral and reject has reached 30.5%. It shows that, compared with a spiritual motivation, material motivation has a greater impact on public WTP. On the other hand, it also reveals that the public is less sensitive to changes in electricity prices than direct compensation. The awareness of social responsibility should be popularized for the public and engaged in accepting spiritual incentives.

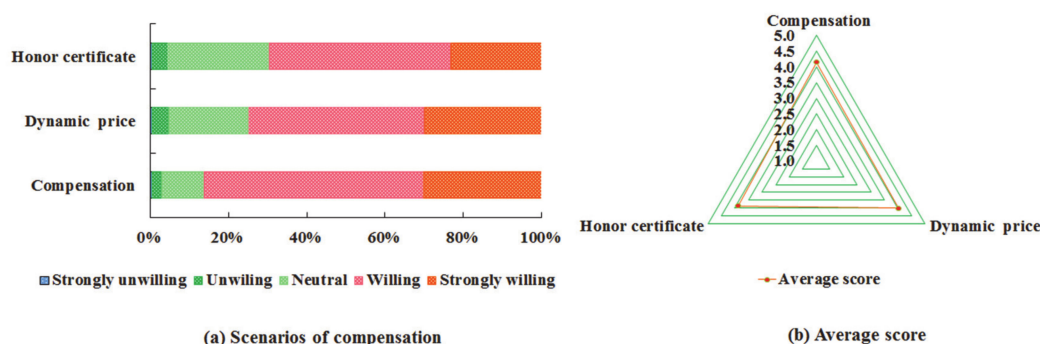


Figure 2. The general attitude of public participation in energy demand response. (a) Percentage of respondents with different degrees of willingness in the three scenarios. (b) Respondents' average willingness scores in the three scenarios.

4.2. Conditional Support Analysis of Public Willingness to Participate

To further explore the mechanism of public participation willingness, this research sets clear compensation and dynamic electricity price target values, and calls the public participation willingness at this time as the public participation in demand response with conditional support. With the help of public participation intention under different conditions, the change mechanism of public participation willingness is further explored. The research sets up related questions for two scenarios, and the statistical results are shown in Figure 3. The results show that when the compensation of 1 RMB/kWh was explicitly proposed for the electricity saved during peak periods, compared with the scenario without explicit compensation amount, it is clear that the level of public WTP was improved obviously, and the proportion of respondents who were strongly willing to participate increased from 29.9% to 40.1%. From the perspective of the public pursuit of utility maximization, the respondents think that the amount of compensation is greater than the reduction of utility caused by inconvenience and additional labor. However, when it was explicitly proposed that the electricity price during the peak periods would increase twice and the electricity price during the off-peak periods would decrease twice, the level of public WTP declined, and the proportion of respondents who were strongly WTP decreased from 29.6% to 12.35%. This may be because the public thinks that the electricity price-setting method cannot achieve the purpose of reducing electricity bills, or that the electricity price reduction achieved by this method cannot completely compensate for the decline in utility caused by the response in power consumption, such as bad comfort, additional labor, etc.

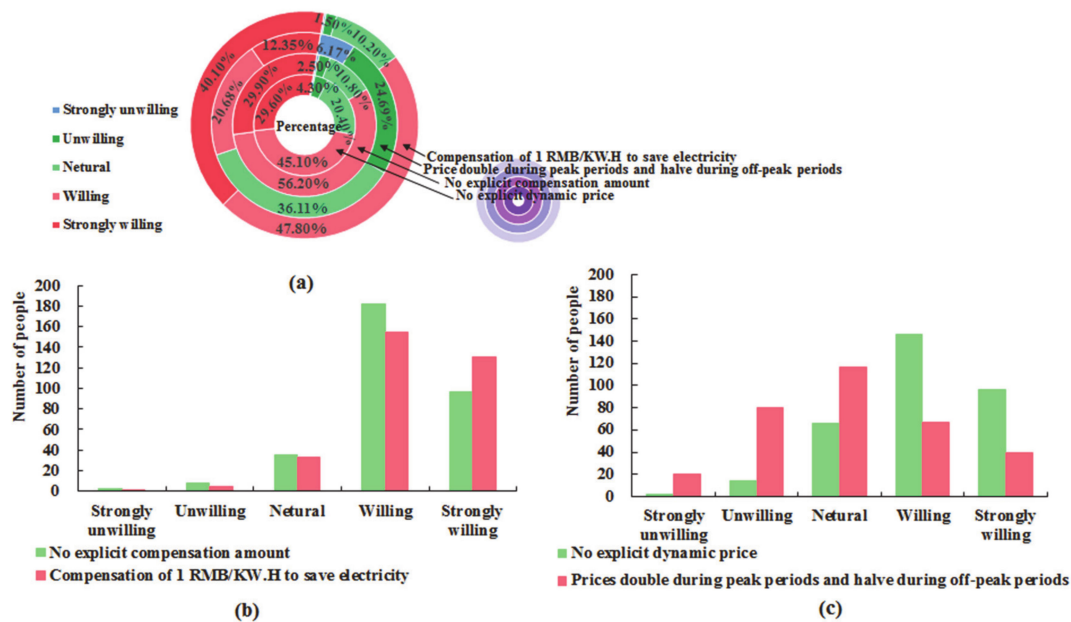


Figure 3. Conditional and unconditional support for public willingness to participate. (a) Percentage of respondents with different degrees of willingness in conditional and unconditional support. (b) Number of respondents with different degrees of willingness with and without clear compensation amounts. (c) Number of respondents with different degrees of willingness with and without clear dynamic prices.

By comparing and analyzing changes in the level of public WTP in both conditional and unconditional support, it can be found that how to set a reasonable amount of incentive compensation and dynamic electricity prices to achieve optimal allocation of resources is the key to the successful implementation of residential demand response. On the one hand, demand response policies should be able to increase public WTP. On the other hand, they should ensure that the benefits of slashing peak demand and potential social benefits can compensate the power company for the additional incentives provided to residents, such as reducing the high supply costs, and power system operation and maintenance costs during peak periods, and reducing carbon emissions [10]. Therefore, when formulating the policy of residential energy demand response, comprehensive consideration should be given to the utility of the public, the profits of power companies, and the social benefits.

4.3. Public Preferences for Participation Forms and Measures

There are three main measures for residents to participate in energy demand response. (1) Change load time, such as adjusting dishwasher, washing machine, energy storage equipment, and other equipment to use during off-peak hours. (2) Slash load power consumption, such as adjusting the temperatures of refrigerators, air conditioners, and water heaters. (3) Interrupt the load power supply, such as turning off TVs, audio entertainment facilities, and other charging equipment during peak period. The results suggest that the number of respondents willing to shift load from peak periods to off-peak periods is the largest, accounting for 82.41%. The respondents willing to slash the load power consumption account for 74.38%, and the percentage of respondents willing to interrupt the load is the least by 67.29% in Figure 4. As for the three demand-side response measures, it suggests that when the public participates in demand response, they are more willing to take measures that have less impact on quality of life and are more convenient. Therefore, when formulating residential demand response policies, full consideration should be given to the convenience and comfort of residents.

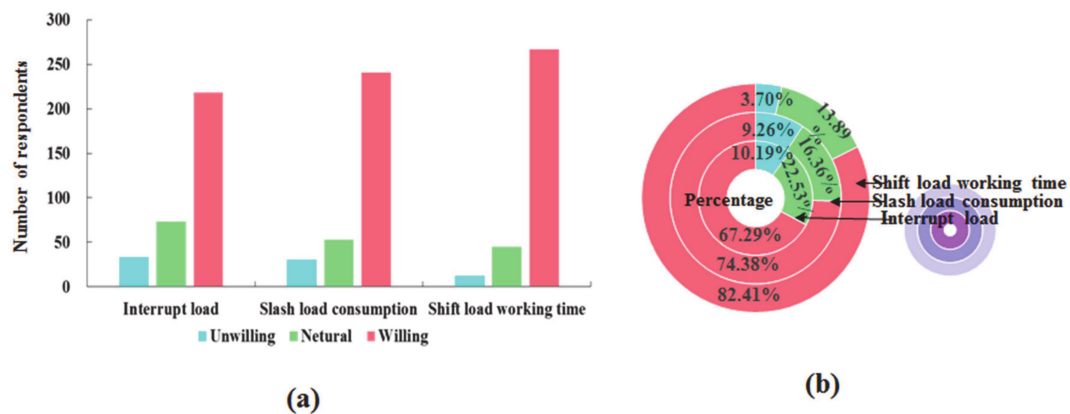


Figure 4. Public willingness to three main participation measures. (a) Number of respondents with different levels of willingness under the three main participation measures. (b) Percentage of respondents with different willingness levels under the three participation measures.

4.4. Public Perception of Difficulties and Forms in Participating in Demand Response

To investigate the public awareness on the difficulties of participation in demand response, the research considers five aspects of measurement feedback technology, operability, living standard, participation time, and trust in power companies. These concerns are mainly rooted in real-time feedback inquiry of timely household electricity consumption, manual operation of equipment, the possible trouble in home comfort by limited electricity consumption, time cost in demand response during the peak period, and the achievement of the compensation. Figure 5a demonstrates that more than 60% of respondents believe that failure to query and report changes in household electricity consumption in time is the main difficulty in participating in demand response; that is, residents do not know how much electricity they have slashed. In addition, 53% of the respondents are worried about whether the compensation can be paid in the right amount and on time, and 51% of respondents concern that the manual operation of loading equipment is too cumbersome. The number of respondents who believe that participating in demand response will affect family comfort also reaches 46%. However, only 15% of respondents feel that they have no time to participate. This fact indicates that the public believes that the main difficulty in participating in demand response at this stage is the lack of support for measurement feedback technology, inconvenience in operation, and the availability of subsidies.

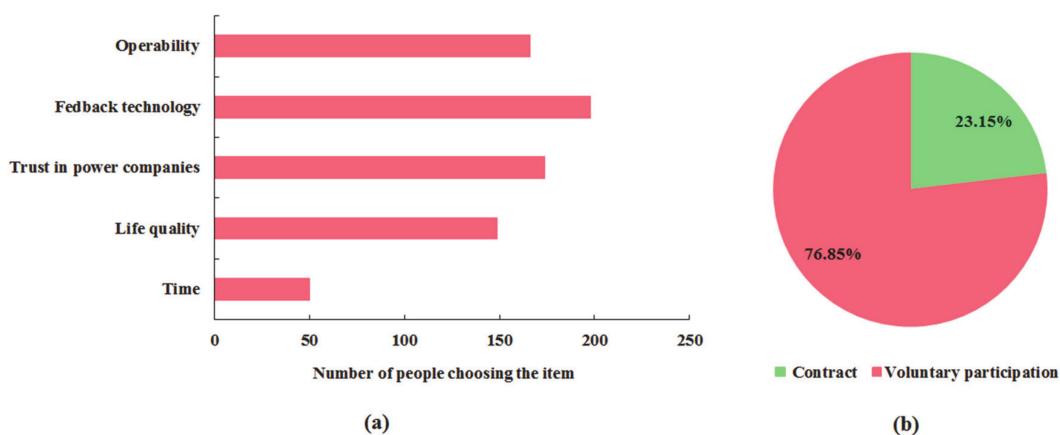


Figure 5. Public perception of difficulties and forms in participating in demand response. (a) Number of respondents under different difficult conditions. (b) Percentage of respondents under different forms of participation.

By investigating public preferences for participation forms, it was found that only 23.15% of respondents chose a contract-based participation form (as shown in Figure 5b), which indicates that residents are more willing to choose flexible participation methods, rather than the reduction of the power load and the response duration agreed in the contract. Therefore, it is helpful to follow the principle of gradual progress and adopt the form of voluntary participation of end-user customers to promote the implementation. Implementing flexible participation will greatly increase the uncertainty of demand response and the difficulty of monitoring and accounting. However, in the context of the continuous development of the Energy Internet, the State Grid of China has definitely put forward the strategic goal of integrating the Strong Smart Grid with the Ubiquitous Electric Internet of Things (UEIOT). This makes it possible for power companies to interact flexibly with consumers and electrical equipment, and to collect, store, monitor, and feedback in real-time. Therefore, with the development of key technologies of the Energy Internet and the construction of the corresponding infrastructure, both flexible public participation and even automatic demand response can be achieved [46]. This will further increase the public's enthusiasm to participate in demand response and promote the popularization of residential demand response.

5. Discussion

5.1. Reliability and Validity for Determinants of Public Willingness to Participate

To verify the validity and reliability of the measurement items, this study analyzed the validity and reliability of the questionnaire. Validity refers to the level at which the measurement items can accurately measure the factors, and reliability refers to the internal consistency of the measurement items, which is reflected by the correlation of several items in a certain index. To measure the validity of the measurement items, a principal component factor analysis method with Varimax rotation and other statistics of mean and Root-Mean-Square (RMS) were applied to verify the 12 measurement items of the four influencing indexes. The results from the mean and RMS statistics suggest the credibility of the survey data.

As can be seen from Table 3, the 12 measurement items are divided into three factors. The correlation between the three measurement items of energy-saving attitude was the strongest, with factor loads of 0.780, 0.767, and 0.584, which were classified as the same factor. In addition, the three measurement items of behavior ability were also classified into the same factor, and the factor loads are 0.784, 0.764, and 0.711. However, external motivating factors, and energy-saving technologies are combined into the same factor, with factor loads are 0.756, 0.726, 0.697, 0.682, 0.619, 0.521, respectively. It is because external motivating factors and energy-saving technologies are external factors that promote changes in personal energy consumption behavior. Therefore, external motivating factors and energy-saving technologies are considered as the same type of influencing factors, collectively referred to as external factors. It was found that the factor load of all measurement items exceeded the recommended value of 0.5, indicating that the scale was valid. Secondly, in order to measure the reliability of the measurement items, the Cronbach's α coefficient is used for detection. The commonly used standard is that when α is greater than 0.7, reliability is better; when α is greater than 0.6, reliability is acceptable [38]. It can be seen from Table 3 that the Cronbach's α coefficients of energy-saving attitudes and behavior ability are 0.683 and 0.674, respectively, which are greater than 0.6. The Cronbach's α coefficient of external motivating factors and energy-saving technology is 0.786, which is greater than 0.7. Therefore, the scale demonstrated adequate validity and reliability.

Table 3. Factor analysis and reliability test of each measurement item.

Variables	Factor Loading			α	Mean	RMS
	1	2	3			
1. Energy-saving attitude				0.683		
✓No matter what others do, I have a moral obligation to reduce power consumption.	0.155	−0.197	0.780		4.302	4.335
✓I think my energy-saving actions can help reduce air pollution and alleviate power shortages.	0.219	−0.046	0.767		4.287	4.355
✓I see energy waste and often consciously reduce it.	0.247	−0.392	0.584		4.352	4.421
2. Behaviour ability				0.674		
✓I think it is troublesome to save electricity.	−0.186	0.784	−0.183		4.182	4.260
✓I don't think I know how to save electricity.	−0.069	0.764	−0.038		3.775	3.889
✓I don't think I can reduce my electricity use because it will reduce home comfort.	−0.051	0.711	−0.142		3.741	3.812
3. External motivating factors/Energy-saving technology				0.786		
✓Providing a discount price for consumers who save electricity, I tend to reduce electricity consumption.	0.697	−0.119	0.249		4.105	4.175
✓Providing subsidies for smart energy-saving appliances, I will be willing to move to energy-saving appliances.	0.682	−0.084	−0.013		4.031	4.128
✓Providing monetary rewards to consumers who save electricity, I would be more willing to save electricity.	0.619	0.009	0.236		4.176	4.256
✓The rules and regulations require saving electricity, and I will resolutely implement it.	0.521	0.037	0.316		4.034	4.119
✓Using smart meters to monitor and feedback the saved electricity in real-time, I will tend to save electricity.	0.756	−0.202	0.137		4.145	4.223
✓Using APP to achieve remote energy-saving control of electrical equipment, I will tend to save electricity.	0.726	0.726	0.129		4.133	4.206

5.2. Multiple Linear Regression Analysis for Determinants of Public Willingness to Participate

In this research, the average willingness to participate in respondents in these three scenarios was taken as the predicted variable, while gender, age, family size, income level, education level, energy-saving attitudes, behavior ability, and external factors were used as explanatory variables. Among them, energy-saving attitudes, behavior capabilities, and external factors are the weighted average of the respective measurement items. The remaining explanatory variables are coded as male 1, female 2, age and income 1–5 from low to high, and education 1–4 from low to high. It was found from Table 4 that the F value was 26.045, and the adjusted R² was 0.383. The overall model had a high significance level, which can explain the change of 38.3% of public WTP. Among these explanatory variables, the impact of income level, energy-saving attitudes, behavior ability, and external factors on public WTP was significant ($p < 0.05$).

Table 4. Regression coefficients for different factors governing demand-side response.

	Unstandardized Coefficients	Standard Errors	Standard Coefficients	T-Value
Constant	0.750 **	0.337		2.228
Gender	−0.017	0.059	−0.013	−0.778
Age	0.021	0.030	0.035	0.702
Family size	0.020	0.037	0.025	0.539
Monthly income	−0.067 **	0.034	−0.102	−1.969
Education	−0.027	0.046	−0.031	−0.582
Energy-saving attitude	0.173 **	0.059	0.160	2.940
Behavior ability	0.098 **	0.047	0.101	2.078
External factors	0.541 ***	0.059	0.489	9.215
F-value		26.045 ***		
Adjusted R ²		0.383		

Note: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.10$.

Results from the coefficient of each explanatory variable suggest that there is a significant negative correlation between income level and public WTP ($\beta = -0.067$, $p < 0.05$), which indicates that the higher the income of residents, the lower their WTP. Generally, as income levels fall, the proportion of household electricity expenditures will increase. Compared with high-income residents, low-income residents tend to reduce electricity consumption during peak hours, due to price increases or compensation. In addition, energy-saving attitudes ($\beta = 0.173$, $p < 0.05$), behavior ability ($\beta = 0.098$, $p < 0.05$), and external factors ($\beta = 0.541$, $p < 0.001$) are a significant positive correlation with public WTP. The most salient factors are external factors, followed by energy-saving attitudes. This means that external incentives, policies, and energy-saving technologies, such as real-time feedback and intelligent autonomous control, play a more critical role in driving residents' participation in demand response than socio-demographic and psychological factors. However, continuously improving the public's awareness of energy conservation and popularizing demand response methods and the economic and social benefits of demand response will further greatly improve residential responsiveness.

6. Conclusions

6.1. Conclusions

This research not only discusses public WTP in energy demand-side response, public preferences for measures, and perception of difficulty in participating, but also investigates the determinants of WTP in DSM from the perspective of social, psychological, and external environmental factors. It also explores how these determinants affect public WTP. Major conclusions are summarized as follows.

- (1) Public willingness to participate in demand response is quite high in these three scenarios, and compared with spiritual incentives, material incentives have a greater impact on promoting public WTP. In terms of material incentives, the public is less sensitive to changes in electricity prices than direct incentive compensation. In addition, by comparing and analyzing whether

there is a clear target value for compensation and dynamic electricity price, it is found that the amount of compensation and dynamic electricity price will make public WTP change in different directions. How to set a reasonable reward compensation amount and dynamic electricity price to achieve the optimal allocation of resources is an important part of the successful implementation of residential demand response.

- (2) Compared with the traditional participation method of signing a contract with the end-user customers in advance and responding according to the agreed time and quantity, the public prefers a flexible approach to participation. Flexible participation methods, however, face greater uncertainty, which requires the support of advanced measurement systems. Among the main measures for residents to participate in the demand response, the public is most willing to delay the use of load equipment, such as washing machines and dishwashers, rather than interrupt the work of load equipment. This fact indicates that the public is more willing to take measures that do not affect the quality of life and are more convenient. In addition, it was found that more than 50% of respondents believe that the main difficulty in participating is the need for innovative measurement feedback technology, the inconvenient operation, and the difficulty in providing promissory subsidies. Flexible participation should involve the intelligent and convenient equipment, performance assessment of the implementation, and risk management on fulfillment mechanism.
- (3) By exploring the influence of socio-demographic characteristics, psychological factors, and external environmental factors on public WTP, it is found that compared with high-income residents, low-income residents are more inclined to reduce electricity consumption during peak periods because of dynamic prices or compensation. This fact is meaningful for the balance between the potential of demand-side in the rich and the willingness of the poor in participation. The factors of energy-saving attitudes, behavior ability, external motivation, and energy-saving technologies have a positive effect on public WTP. Furthermore, external motivating factors and energy-saving technologies have the strongest driving effects on WTP in demand-side management. With the support of intelligent control, information interaction technologies, and greater incentives, there is still plenty of room for relevant departments to increase public participation. However, facilitating residential responsiveness requires continuous improvement of the public awareness of energy-saving, as well as the ability to perceive and act on demand response.

6.2. Policy Implications

Giving full play to the responsiveness of residents is an important guarantee for the successful implementation of demand response. The findings from this research could provide references for building incentive mechanisms, infrastructure management, and public awareness for active participation in DSM. According to the above conclusions, the following policy recommendations are formulated for the power sector and the resident.

- (1) The combination of material incentives and spiritual incentives to establish a reasonable incentive mechanism from different aspects is an effective means to stimulate public participation in demand response, such as compensation, dynamic electricity prices, and social reputation. According to empirical results, the public WTP in energy demand response has a negative correlation with the income level. Generally speaking, the most urgent need is the main reason and motivation to motivate people to act. When the income of residents reaches a certain level, their pursuit of the spiritual level will occupy a dominant position, thus playing a decisive role in behavior. By developing spiritual incentives, the demands for respect and self-fulfillment of wealthy family members can be satisfied to a certain extent so as to promote the extensive participation by wealthy families.

- (2) The research and development of advanced measurement system technologies, such as intelligent acquisition, intelligent interaction, and autonomous control, should be strengthened to improve the convenience of public participation and reduce the impact on quality of life. Our results indicate that the public prefers flexible forms of participation and measures with little impact on life, and energy-saving technology has a positive relationship with public participation. It is essential to realize automatic demand response through the R&D and application of the China Electric Power Advanced Measurement System.
- (3) The power sector should strengthen publicity and education, and popularize the knowledge of energy demand response and social benefits, so as to improve public perception of demand response and their ability to act. Our empirical study indicates that energy-saving attitudes and behavior abilities have a positive relationship with public WTP. The impartial promotion of energy demand response is not only conducive to the comprehensive understanding of energy demand response, but also can further improve public awareness of environmental issues and power safety, which is of great significance for achieving sufficient residential response.

This research attempts to explore the relationships between public willingness to participate in energy demand response and its influencing factors. Investigation on these factors may help to a better understanding of the public's motivations to participate in energy demand response and achieve sufficient residential demand response. However, there is much room for improvement in this research. First, the number of measurement items for each influencing factor should be developed to obtain better reliability and validity. Second, the influencing factors are further subdivided or expanded to obtain a higher explanatory variance for the regression model. Besides, Structural equation modeling can be employed in further research. It is important for further researches on how to build an efficient incentive policy with motivations from spiritual and material rewards and to find a flexible mechanism to generate a real-time electricity price under demand-side response management with equity, incentive, and contractual relationship.

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