



OPEN Study on the key factors of public participation in low carbon city construction and willingness to pay

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The popularity of urban distributed photovoltaics is crucial for building low-carbon cities. Retrofitting roofs with photovoltaic tiles is a new option. However, whether the public supports this initiative needs to be understood. Assessing willingness to pay is a critical way to measure public acceptance. Therefore, this paper assesses Chinese urban households' willingness to pay to support photovoltaic tiles retrofit roofs to promote the construction of low-carbon cities. To obtain factors that better explain the willingness to pay, variables such as personal of interest perception, moral perception and policy perception are added to the initial theory of planned behavior psychological interpretation framework for willingness to pay and the extended theory of planned behavior psychological explanatory framework for willingness to pay is constructed. It is encouraging to note that the expanded framework has increased the explanatory power of willingness to pay, where the personal of interest perception is the dominant variable in explaining willingness to pay. We believe that we should pay attention to the impact of the personal of interest perception on willingness to pay and increase the publicity of the importance of photovoltaic tiles retrofitting roofs to promote low-carbon city construction through Internet means and increase individual personal of interest perception, policy perception, and moral perception, which may help promote better public participation in low-carbon cities.

Keywords Theory of planned behavior, Photovoltaic tiles, Structural equation model, Willingness to pay, Low-carbon city construction

As an essential renewable energy source, solar energy is vital in constructing low-carbon cities and sustainable social development in various countries worldwide^{1,2}. Global PV capacity additions are expected to increase 25% to 197GW by 2022 compared to 2021^{3,4}. With the soaring global fossil energy prices caused by the “Russo-Ukrainian War” and the “carbon-neutral” development route advocated by the UN climate conference in 2020, solar energy is bound to see even more booming development. China is the world's largest PV market, with an installed PV capacity of 75GW in 2022, accounting for about 38% of the world. The installed capacity of centralized PV is 42GW, and the installed capacity of distributed PV is 33GW. The share of distributed PV has increased from 13% in 2016 to 44%, rapidly growing.

In China, distributed PV has received much attention due to its easy siting and installation, but it still has significant limitations⁵. (1) Traditionally distributed photovoltaic installations need a bracket or concrete base support, resulting in the waste of roof space. (2) Its installation is constrained by China's “*Interim Measures for the Management of Distributed Photovoltaic Power Generation Projects*” (the highest point of the photovoltaic modules shall not be higher than 2.8 m from the laying plane, shall not build structures unrelated to photovoltaic power generation equipment, and shall not affect the aesthetics of the surrounding buildings), which is not easy to implement in cities^{7,9}. This creates a negative impact for the construction of urban distributed PV, which is not conducive to the construction of low-carbon cities.

With the development of Building Integrated Photovoltaic technology, using photovoltaic tiles to retrofit roofs is becoming a new solution to solve the distributed solar PV shortage in promoting the construction of low-carbon cities^{6–8}. The photovoltaic tiles give building materials photovoltaic properties by integrating photovoltaic cells into building materials and can be used as building shells^{8,9} (Fig. 1) Not only does it completely solve the drawbacks of conventional PV installation (requiring a steel frame or concrete foundation for fixation),

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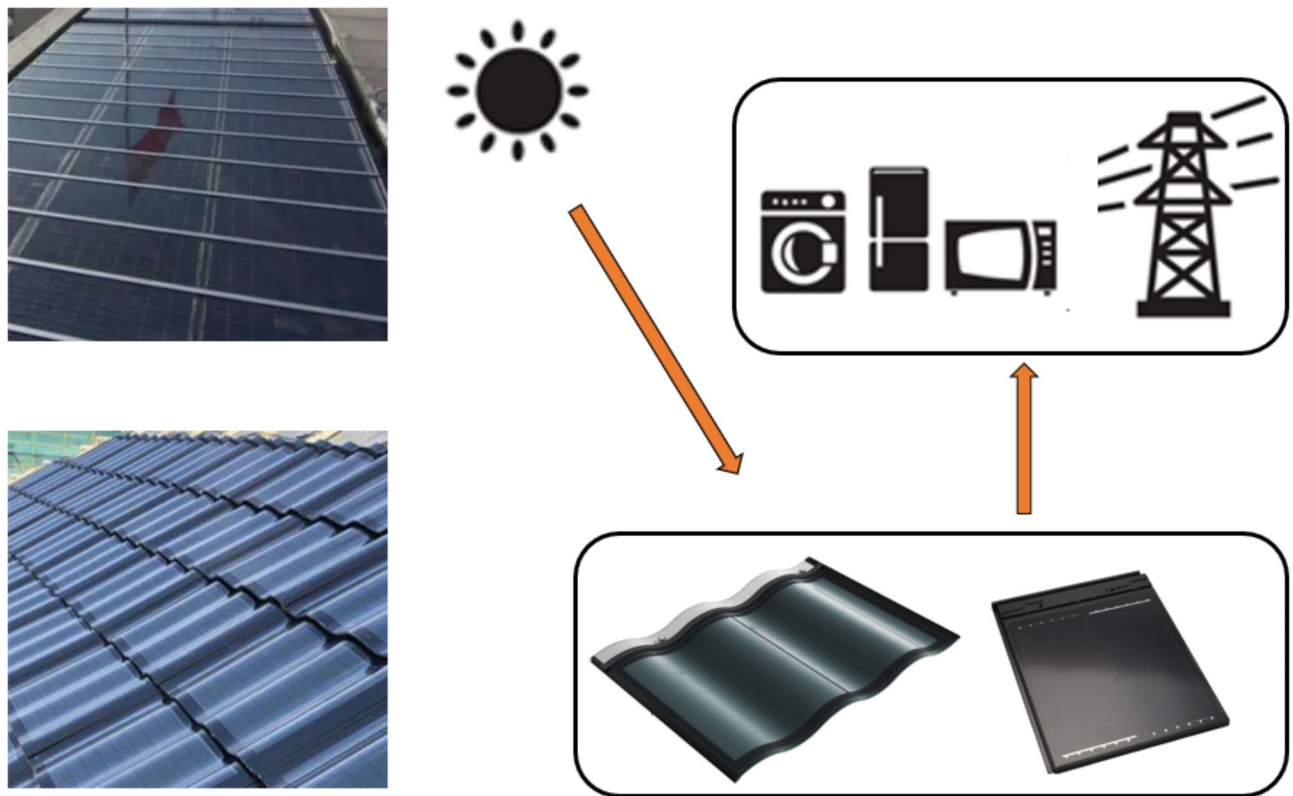


Fig. 1. Solar photovoltaic tiles.

but it has also received much attention from researchers in various countries due to its architectural aesthetic advantages and significant space-saving and PV conversion capabilities^{8,10–12}. Currently, the installation of photovoltaic tiles uses the rooftops of apartment buildings as the installation area, and the calculation is carried out based on each household in a single apartment building. Under normal circumstances, a large inverter and an energy storage box are set up in the apartment building, and then the generated electric energy is used by all the households in this apartment building (there are also cases where energy storage devices are installed in each household, but the cost is relatively high). On the premise that the housing area is the same, the cost in this regard is shared equally among all households.

In May 2022, China's Development and Reform Commission promulgated the Implementation Plan for Promoting the High-Quality Development of New Energy in the New Era, which requires that the coverage rate of distributed PV on newly constructed rooftops in cities exceeds 50% by 2025 and deepen the rooftop distributed PV transformation of existing buildings to promote the construction of low-carbon cities. However, the implementation of this policy still faces significant challenges. (1) Conventional PV is difficult to popularize widely in Chinese cities due to its limitations (mentioned previously). (2) Although the photovoltaic tiles have been more widely used in some developed countries^{13,14}, its application in China cities is still limited, and there are no corresponding case studies. The Chinese researchers have focused their attention on PV more on seeking technological breakthroughs, evaluating the effects of carbon reduction, and evaluating the benefits of the product in the context of government subsidies^{79,97–99}. Research on behavioral preferences for PV products has been conducted, but mostly on traditional PV product. This is not conducive to the promotion of photovoltaic tiles in Chinese cities and the construction of low-carbon cities. In a previous study, we assessed the willingness to pay for solar photovoltaic tiles among rural households in Shandong Province, China⁷⁹. While it can provide a valuable reference value for this study, it is difficult to consider the findings of the previous study representative of urban households given the policies and the demographic differences in the populations to which they belong. Policymakers need to understand urban public attitudes toward photovoltaic tiles and the factors motivating them participation in photovoltaic tiles construction, as this will contribute to constructing low-carbon cities.

Capturing the variables that promote individual participation by studying the behavioral drivers of individuals and developing policies based on these variables is an effective way to help reduce time and investment costs and increase individual participation, which is of great importance^{15–17}. In studies related to solar PV, researchers have used several theories to explore individual behavioral drivers^{18–20}, with the theory of planned behavior being the most widely used and efficient model^{21–23}. It is a framework for explaining psychologically relevant behaviour. The validity of the main variables (attitudes, subjective norms, and perceived behavioral control) for explaining individual environmental behavior has been demonstrated several times²⁴. As research progressed, some researchers began to try to obtain better explanatory power by adding additional variables to the theory of planned behavior, and promising results were obtained. The explanatory power of the expanded theory of

planned behavior has been improved to different degrees^{25,26}. Assessing willingness to pay is a critical measure of individual participation in public environmental products and is very important^{27,28}. The photovoltaic tiles roofs have positive environmental externalities (reduction of urban carbon emissions, cleaner production, etc.), so they can be considered public environmental products. The conditional value approach can obtain their willingness to pay and environmental value. Unfortunately, their willingness to pay and environmental value have not received sufficient attention, and such studies are still lacking. This is not conducive to policymakers in formulating policies related to photovoltaic tiles promotion and the construction of distributed PV in Chinese cities. The willingness to pay also represents the public's willingness to support the project financially²⁹, and the promotion of photovoltaic tiles is also in great need of the public's financial support in China's downward economic environment influenced by COVID-19. Therefore, the public's willingness to pay to support photovoltaic tiles to retrofit roofs should be given due attention.

This study focuses on the psychological factors that explain the willingness of Chinese urban families to pay for photovoltaic tiles roof retrofitting to promote the construction of low-carbon cities. To obtain better model explanatory power, we added expansion variables to the initial theory of planned behavior psychological interpretation frame for willingness to pay and constructed an extended theory of planned behavior psychological explanatory framework for willingness to pay, which significantly improved the explanatory power of the model compared with the initial model. The conditional value method is adopted as the evaluation method of willingness to pay. This method has been widely used in the environmental value evaluation in the public environment field, including vertical greening, heat island effect mitigation, and the use of new energy^{30–32}. Due to a higher zero response (willingness to pay = 0), We estimate the willingness-to-pay based on the double-boundary dichotomous choice conditional value method combined with the Spike model and obtain better model fitting results. The application of this valuation method in PV field research is still relatively limited, especially in China.

Compared to previous studies the present study differs in three major ways.

- 1) This study explores the willingness to pay of urban residents in China to promote low-carbon urbanization through solar photovoltaic tiles, and further discusses the psychological factors that influence willingness to pay, contributing to the expansion of existing literature.
- 2) The willingness to pay and environmental values of photovoltaic tiles are estimated, which can help decision makers to formulate relevant policies.
- 3) Based on the initial theory of planned behavior psychological interpretation frame for willingness to pay was supplemented with the perception of personal of interest perception, moral perception, and policy perception. An extended theory of planned behavior psychological interpretation frame for willingness to pay was constructed. The effects of these variables on willingness to pay and the relationship between the variables are discussed.

The remainder of this paper is structured as follows: Section II is the literature review, and the hypotheses are formulated for the review; Section III describes the research methodology; Section IV is the estimated results; Section V Analysis and discussion of the results; and Section VI Summarize the conclusions of the whole paper and provide implications for policy.

Research hypothesis and literature review

Initial theory of planned behavior psychological interpretation Frame for willingness to pay

To explore urban households' acceptance of photovoltaic tiles for retrofitting roofs to promote low-carbon city construction, we applied the theory of planned behavior psychological explanatory framework of behavioural intentions substitution behavioural to investigate the willingness to pay for photovoltaic tiles. The traditional theory of planned behavior model was first proposed by Ajzen³³ and was initially applied mainly in sociological and psychological research. It contains three main variables, attitudes, subjective norms, and perceived behavioural control. Ajzen argued that an individual's behavioural intentions is the most proximal factor explaining behaviour, while attitudes, subjective norms, and perceived behavioural control can jointly determine behavioural intentions. where perceived behavioural control also impacts behaviour³⁴. However, some researchers believe the traditional model has some limitations^{35,95,96}. Taking willingness to pay as an example, the traditional model is not suitable when the object of study is the willingness to pay. Because the willingness to pay is the behavioural intentions of individuals to pay for public environmental products rather than the actual payment behaviour, the willingness to pay occurs before the payment behaviour. McEachan³⁵ analysed 206 theory of planned behavior - related papers through a meta-literature analysis and found that models using behavioural intentions alternative behaviours were significantly higher in explanatory power than traditional models. Armitage³⁶ also analysed 185 theory of planned behavior literature. Armitage argued that the hysteresis of behaviour affects the explanatory power of theory of planned behavior models and that models using behavioural intentions alternative behaviours might have better explanatory power. In subsequent studies, several researchers have also confirmed their findings^{37,38,91,92,94}. For example, Tan et al.⁹³ refined the traditional theory of planned behavior in their study of the impact of carbon inclusion on residents' low-carbon behavior. By applying the model with behavioral intention as the research objective, the predictive performance of the model has been greatly improved and proved that attitudes, subjective norms, and perceptual-behavioral control in the Theory of Planned Behavior can be a good explanation for willingness to pay. Tao et al.⁴¹ used the extended model of the theory of planned behavior with behavioral intention to substitute behavior to study Chinese consumers' willingness to compensate for carbon and came to similar conclusions. Therefore, we applied the Theory of Planned Behavior model of Behavioral Intention to Replace Behavior as a basic framework to study

the willingness to pay of Chinese urban households to support PV rooftop retrofits to promote low-carbon city construction (Fig. 2). And the following hypotheses are proposed:

- H1: When city residents have more positive attitudes for promoting low-carbon city construction, their willingness to pay for photovoltaic tiles retrofit roofs will increase.
- H2: When city residents have more positive subjective norms for promoting low-carbon city construction, their willingness to pay for photovoltaic tiles retrofit roofs will increase.
- H3: When city residents have more positive perceived behavioural control for promoting low-carbon city construction, their willingness to pay for photovoltaic tiles retrofit roofs will increase.

Expanded variables of the theory of planned behavior

Although the applicability of theory of planned behavior has been demonstrated, some other researchers believe that the traditional theory of planned behavior have difficulty explaining lots of variances^{24,88}, it does not explain individual behavioural intentions or behaviours well^{39,40}, and needs to be improved by adding extended variables^{41,96}. Among them, Moral Perception, Policy Perception, and Perception of personal interest are three more discussed variables in the expanded theory of planned behavior and have superior explanatory power for enhancing the theory of planned behavior model.

Thøgersen⁴² argued that an individual's behaviour is not only determined by the variables among theory of planned behavior but should also be constrained by the individual's moral perception. In studies of normative activation theory, the moral perception is the dominant variable in explaining behaviour⁴³. Therefore, the influence of moral perception on individual behaviour in theory of planned behavior should not be ignored. Manstead⁴⁴ questioned that theory of planned behavior does not contain an ethical element. He argues that moral perception is an obligation for environmental protection and has great importance, and his view is shared by relevant researchers^{45,29}. For example, Zhang et al.¹⁵ also proved the importance of moral perception in explaining behavioral intention in the study of residents' behavioral preference for heat-island mitigation. Although the importance of moral perception for theory of planned behavior expansion has been demonstrated in many studies, the discussion of the relationship between moral perception and other variables continues. One important argument is that moral perception can directly affect behavioural intentions, with solid moral perceptions directly motivating individuals to engage⁴¹, and many researchers have demonstrated the validity of this argument^{15,46,47}. It covers a variety of studies of pro-environmental behavior. Therefore, we adopted the above researcher's viewpoint and studied moral perception as a direct influence on behavioural intentions in order to explore the factors explaining the public's willingness to pay and to formulate the following hypotheses:

- H4: When city residents have stronger moral perception for promoting low-carbon city construction, they will have stronger willingness to pay for photovoltaic tiles retrofit roofs.

Tan²⁷ argued that individuals' perceptions of policies might impact behavioural intention, especially in China. It is also proved that the policy perception can significantly increase the explanatory ability of theory of planned behavior. He believes that China has had a top-down management model for a long time, which leads to people who are sensitive to or show interest in the policy being more likely to implement the content of the policy. Nguyen⁴⁸ added the variable policy perception in applying theory of planned behavior to explain the energy-saving behaviour of Vietnamese households. The results showed that the model's explanatory power was significantly improved by adding policy perception. Ali⁴⁹ discussed the determinants of consumer purchase of energy efficient appliances in Pakistan through a policy perception extended theory of planned behavior model and demonstrated that policy perception significantly influences the purchase of energy efficient appliances.

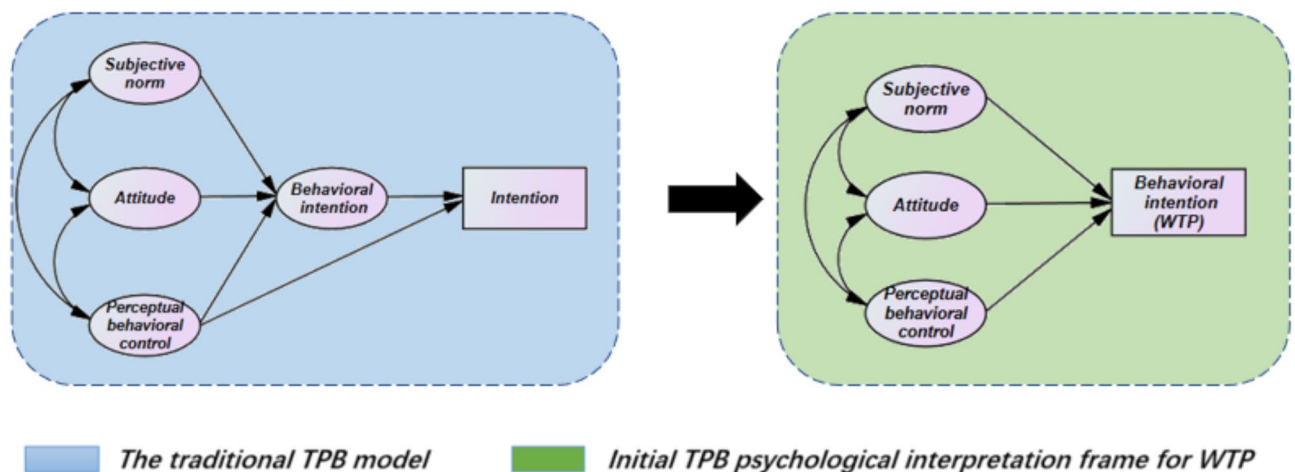


Fig. 2. Initial theory of planned behavior psychological interpretation framework for willingness to pay.

Tian⁵⁰ compared the differences in residents' waste sorting behaviour in China between areas where waste sorting policies were implemented and those where they were not and demonstrated that individual policy perception could impact behaviour. In summary, there are three main perspectives on the correlation between policy perception and the variables; (1) The policy perception directly influences individuals' behaviour^{51,52}; (2) The policy perception impacts attitudes and, thus, behavioural intentions^{53,54}; (3) Policy perceptions can directly influence behavioural intentions²⁷. Since we used a model of behavioural intentions alternative behavior. Therefore, only the effect of policy perception on attitudes and behavioural intentions (expressed as willingness to pay) is discussed in study and proposes the following hypotheses:

H5: Policy perception can have a positive impact on the attitudes of city residents to promote low-carbon city construction.

H5a: Policy perception can indirectly influence urban residents' willingness to pay for promoting low-carbon city construction through attitudes.

H6: When city residents have more positive policy perception about promoting low-carbon city construction, their willingness to pay for photovoltaic tiles retrofit roofs will be stronger.

In the case of photovoltaic tiles, its positive environmental externalities (carbon reduction, clean energy) must be considered. The perceived behavioural control refers to past experiences and expected obstacles. Its explanatory power for behavioural intentions is more potent when individuals perceive more resources and opportunities and fewer expected obstacles³³. The personal of interest perception mainly includes several aspects, such as money, environment, health, and time. In contrast, the perceived behavioural control can identify specific behavioral intentions through perceived barriers to engaging in specific behaviors⁵⁵, meaning the personal of interest perception can directly impact perceived behavioural control. Wolske⁵⁶ analyzed the literature on structural equation modelling through meta-literature analysis and found that the personal of interest perception is the most dominant variable influencing the intention to adopt residential PV facilities. Korcaj⁵⁷ and Zander⁵⁸ also found that the personal of interest perception can positively affect the promotion of PV-based products. Adam Smith's assumption of individual "economic beings" in the theory of labor exchange similarly supports this view. Thus, it can be assumed that the personal of interest perception affects behavioural intentions. Therefore, in our study, personal of interest perception, as a variable that directly affects perceived behavioural control and behavioural intentions and indirectly affects behavioural intentions through perceived behavioural control, was included in the initial theory of planned behavior psychological explanatory framework of willingness to pay and the following hypotheses were formulated:

H7: The personal of interest perception have a positive impact on perceived behavioural control of urban residents to promote low carbon city construction.

H7a: When city residents have a more the positive personal of interest perception for promoting low-carbon cities they will have a stronger willingness to pay for photovoltaic tiles retrofit roofs.

H8: The personal of interest perception have a positive impact on willingness to pay of urban residents to promote low carbon city construction.

Correlations between moral perception, policy perception, and personal of interest perception have also been frequently mentioned in psychology-related research. For example, there are correlations between policy perception and moral perception^{59,60}, between moral perception and personal of interest perception^{61,62}, and between policy perception and personal of interest perception^{63,64}. Since the above three variables are exogenous in this study. Therefore, in the extended theory of planned behavior psychological interpretation frame, we treat the three variables as having interrelatedness and discuss the effects of these factors on willingness to pay. With the addition of new variables, the relationship between attitudes, subjective norms, and perceived behavioural control may change due to the addition of other variables, so attitudes, subjective norms, and perceived behavioural control are no longer considered as interrelated in the extended theory of planned behavior psychological interpretation frame for willingness to pay. The conceptual framework is shown in (Fig. 3).

Measurement scale

To ensure the reliability and validity of the measurement instrument, we designed a measurement scale (Table 1) based on existing content in the relevant scientific literature, which contains eighteen measurement indicators. The purpose is to explore the factors that explain Chinese urban households' support for photovoltaic tiles retrofitting roof willingness to pay to promote low-carbon city construction.

Research methodology

Survey site

On October 31, 2022, China's Development and Reform Commission promulgated the "Implementation Plan for Establishing a Sound Carbon Dumping and Carbon Neutral Standard Measurement System", further emphasizing the importance of solar PV construction for achieving carbon neutrality, with Shandong Province being the critical region for solar construction in China (Fig. 4). In September 2021 China issued a "public notice on the entire county's (city's, district's) rooftop distributed photovoltaic power generation development pilot list" in Shandong Province under a number of urban areas were selected into the pilot list, accounting for the highest proportion of the whole China. Shandong Province has the third highest GDP in China, the second highest population, and the highest carbon emissions in China. The selection of Shandong province as the study population ensures that urban households have a good income level to support photovoltaic tiles

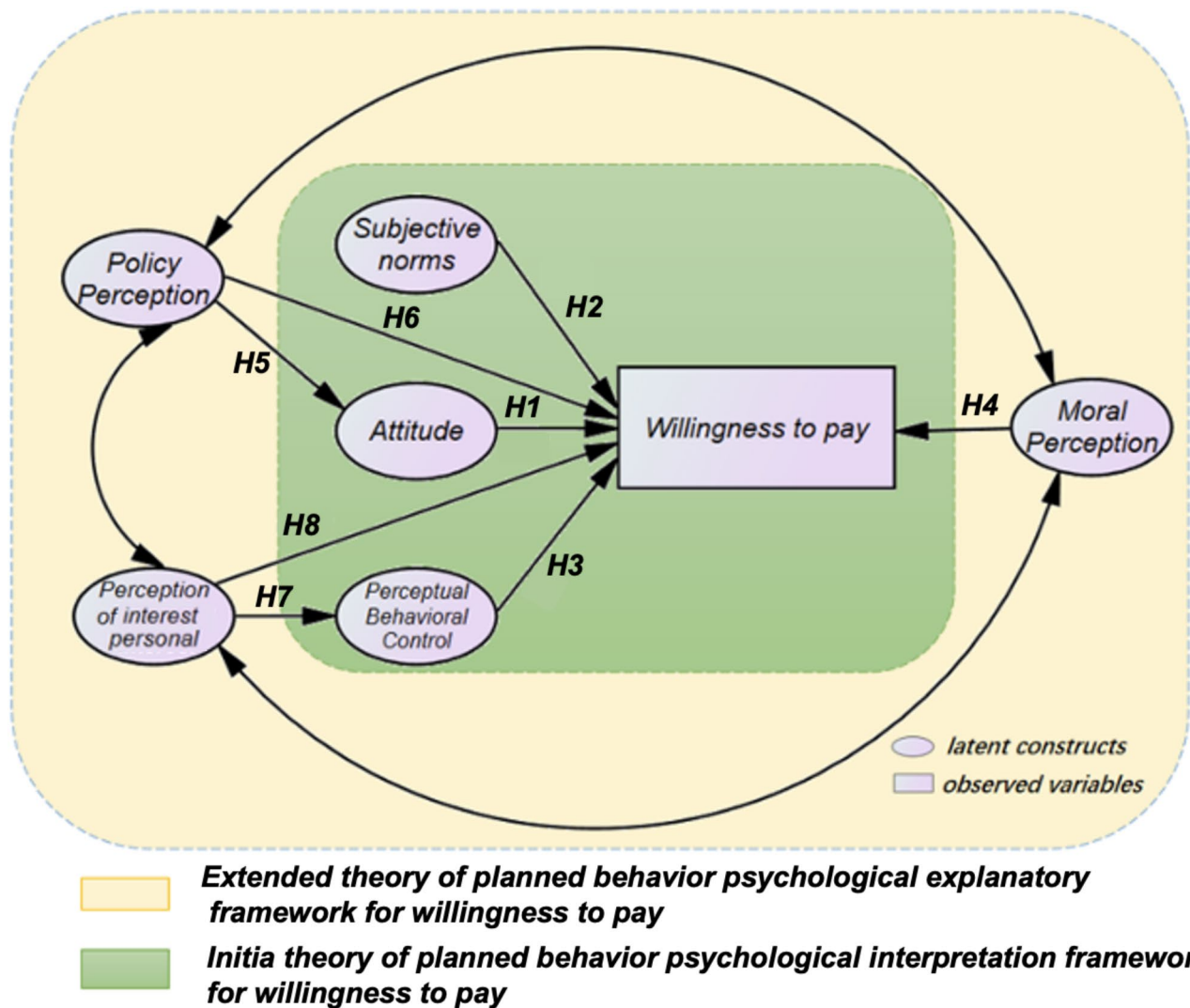


Fig. 3. The extended theory of planned behavior psychological interpretation frame for willingness to pay.

roof retrofitting, avoiding errors in the study due to income levels. As several urban areas were selected for the pilot list, local governments increased their efforts to promote solar development policies, which helped better to study the impact of policy perception variables on willingness to pay. Finally, Shandong province has the highest carbon emissions in China, and some counties and cities still burn biomass and coal in winter. It is more representative to choose Shandong province as the research object. Therefore, we use Shandong province as the research object.

Sample size

The Schaeffer-equation is an important tool for determining the sample size of the study area^{27,65,79}. Schaeffer, the author of this equation, believes that the sample size is determined by the population size, the accuracy and reliability of sampling and the heterogeneity of the population. Under a certain heterogeneity level of the total, the sample size can be determined using this Equation²⁹:

$$w = X / \{ (X - 1) i^2 + 1 \} \quad (1)$$

where w is the sample size, X is the total number of samples, and i is the acceptable error (generally considered to be 5%)²⁹.

The urban population of Shandong province is about 66 million, and there are about 22.50 million households ($w \approx 22.50$ million), $i^2 \approx 0.05^2$, so the minimum threshold of the sample in the ideal state is $X = 400$. Considering the bias generated in the interview questionnaire, the minimum sample size should exceed 50% of the ideal state^{29,94}. in order to reduce the deviation between the estimated and actual values to within 15 percent^{29,66,92,94}, which means that the sample size should not be less than 600. To ensure the reliability of the sample distribution, we refer to the official population distribution data of the Shandong Provincial Bureau of Statistics to ensure that the distribution of valid questionnaires in each city is consistent with the official data.

Variable	Item	References
Attitudes	(1) Paying for photovoltaic tiles retrofit roofs is good for promoting the construction of low-carbon cities.	[41]
	(2) Paying for photovoltaic tiles retrofit roofs is important for promoting the construction of low-carbon cities.	[33]
	(3) Paying for photovoltaic tiles retrofit roofs is wise for promoting the construction of low-carbon cities.	[38]
Subjective norm	(1) People who are important to me will support me to pay for photovoltaic tiles to retrofit roofs to promote the construction of low-carbon cities.	[15]
	(2) People who are important to me will pay for photovoltaic tiles to retrofit roofs to promote the construction of low-carbon cities.	[33]
	(3) People who are important to me will convince me to pay for the photovoltaic tiles to retrofit roofs to promote the construction of low-carbon cities.	[89]
Perceive behavioral control	(1) I have the time and money to support photovoltaic tiles retrofit roofs to promote the development of low-carbon cities.	[90]
	(2) I'm sure that paying for photovoltaic tiles 's rooftop conversion will promote the development of low-carbon cities.	[33]
	(3) It is not difficult for me to support photovoltaic tiles to retrofit roofs to promote the construction of low-carbon cities.	[41]
Moral perception	(1) Morally I want to contribute to promoting the construction of low-carbon cities.	[79]
	(2) Participation in activities related to constructing low-carbon cities is part of my ethical standards.	[15]
	(3) I am responsible and obligated to participate in activities related to low-carbon city construction	[15]
Policy perception	(1) I am intrigued by and keep an eye on existing policies related to low-carbon city construction.	[79]
	(2) I will take notice of the policies related to the construction of low-carbon cities and support them	[27]
	(3) Following the Low carbon city construction-related policies will enable me to participate better in clean energy use activities.	[27]
Perception of	(1) The solar power converted from the photovoltaic tiles roof will bring me economic benefits.	[79]
	(2) Using solar power converted from photovoltaic tiles roofs can reduce pollution and benefit my health.	[88]
	(3) Using photovoltaic tiles roofs can promote the construction of low-carbon cities and improve the urban environment, improving my quality of life.	[90]

Table 1. Questionnaire scale.

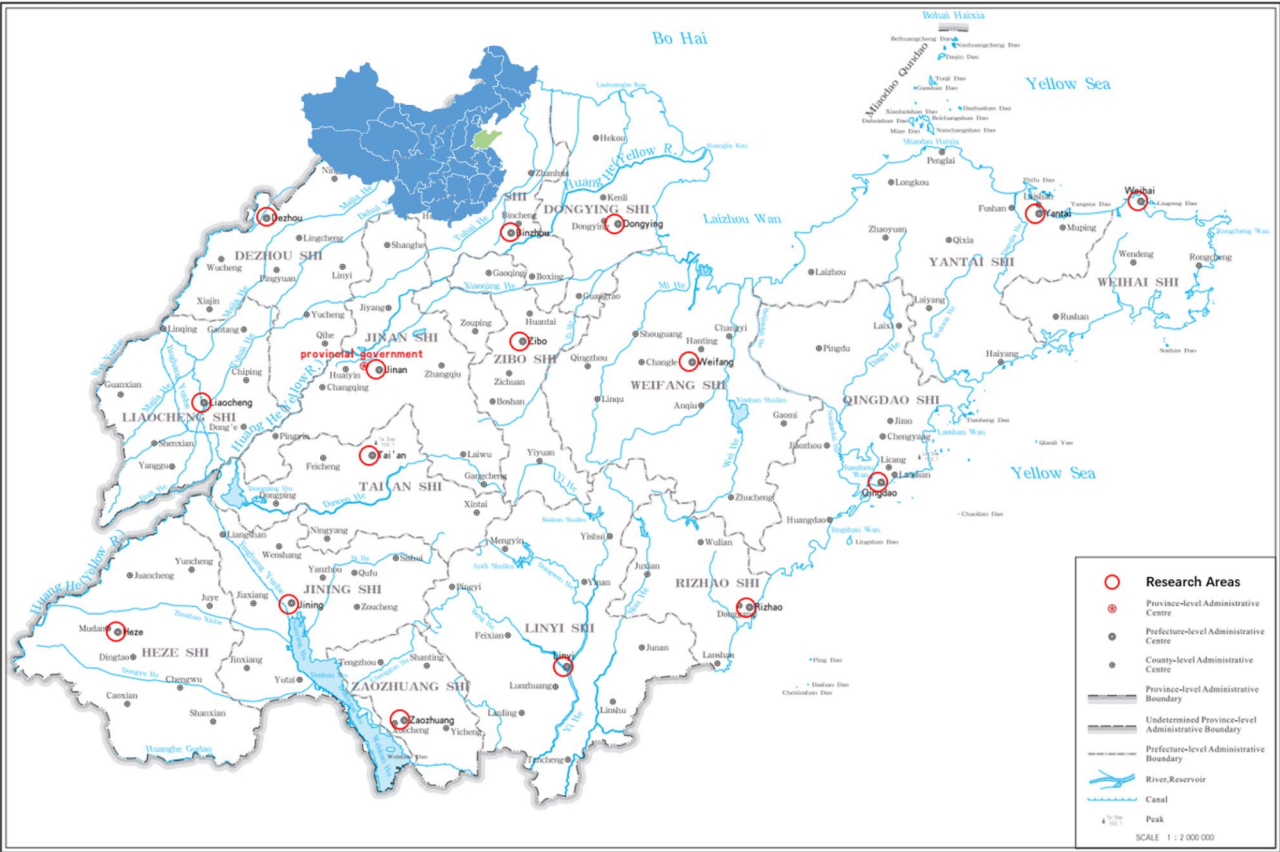


Fig. 4. Map of the study area Shandong province (<https://www.sdmap.gov.cn/map.html>).

The population distribution and the distribution of valid interview questionnaire samples in each municipality are shown in Fig. 5. We can assume that the obtained distribution of valid interview questionnaires does not deviate significantly from the actual population distribution.

Survey design

To determine the range of willingness to pay bidding values and to ensure that the respondents easily understand the measured variables, we started with a small sample size of respondents in a preliminary survey. (sample size of 70). The contents of the preliminary survey are shown in Table A1. The preliminary survey was executed under the supervision of three statistically relevant persons with the aim of optimizing the interview questionnaires items based on the feedback content. The final bid points obtained were 15, 30, 60, 120, 240 and 480 CNY.

Based on the preliminary survey results, the bid values were divided into four groups (15,30,60), (30,60,120), (60,120,240) (120,240,480). Based on the official data of the proportion of the population of each city in Shandong Province in the total population of Shandong province, we determined the number of interviews in each city under the overall sample size (for example, the population of Qingdao in Shandong Province accounts for 10% of the total sample size, then the number of interviews in this region is 10% of the total sample size) to reduce the impact of uneven population distribution on the accuracy of the study. Random sampling was then conducted in 16 urban areas based on the identified number of people. In the event that the number of respondents in the city cannot be evenly divided into four groups, the remaining respondents will choose their bidding group by drawing lots. Considering the potential protest responses in the questionnaire and the questionnaire recall rate issue. A total of 1100 questionnaires were distributed in order to minimize research bias in our study with limited research funding. Two interviewers were responsible for each group, one for answering the questions asked by the respondents and the other for the statistics. The interviewers were professionally supervised, required to be familiar with the research content, and had relevant expertise.

The formal survey was conducted from December 1, 2022, to December 16, 2022, using a questionnaire in the form of a face-to-face interview as recommended by NOAA (Semi-structured interview questionnaire⁶⁷). Semi-structured face-to-face interview questionnaires not only have the advantages of a higher response rate compared with online questionnaires and those distributed through telephone interviews, but also allow interviewers to flexibly adjust questions and their order according to the actual interview situations but also help to improve the accuracy of the questionnaires by answering the respondents' questions in the first instance^{28,30}. In order to guarantee the number of valid interview questionnaires, we controlled the age range of respondents to 18–65 years old to avoid cognitive differences due to age that could affect the accuracy of the interview questionnaire. Because the study was conducted with families, respondents were asked to be able to respond on their or their family's behalf.

Currently, the Likert five-point scale and the Likert seven-point scale are mainly used for questionnaire measurement. The Likert seven-point scale is more often used for in-depth data analysis and for uncovering the potential relationships among variables. On the other hand, the advantage of the Likert five-point scale lies in its

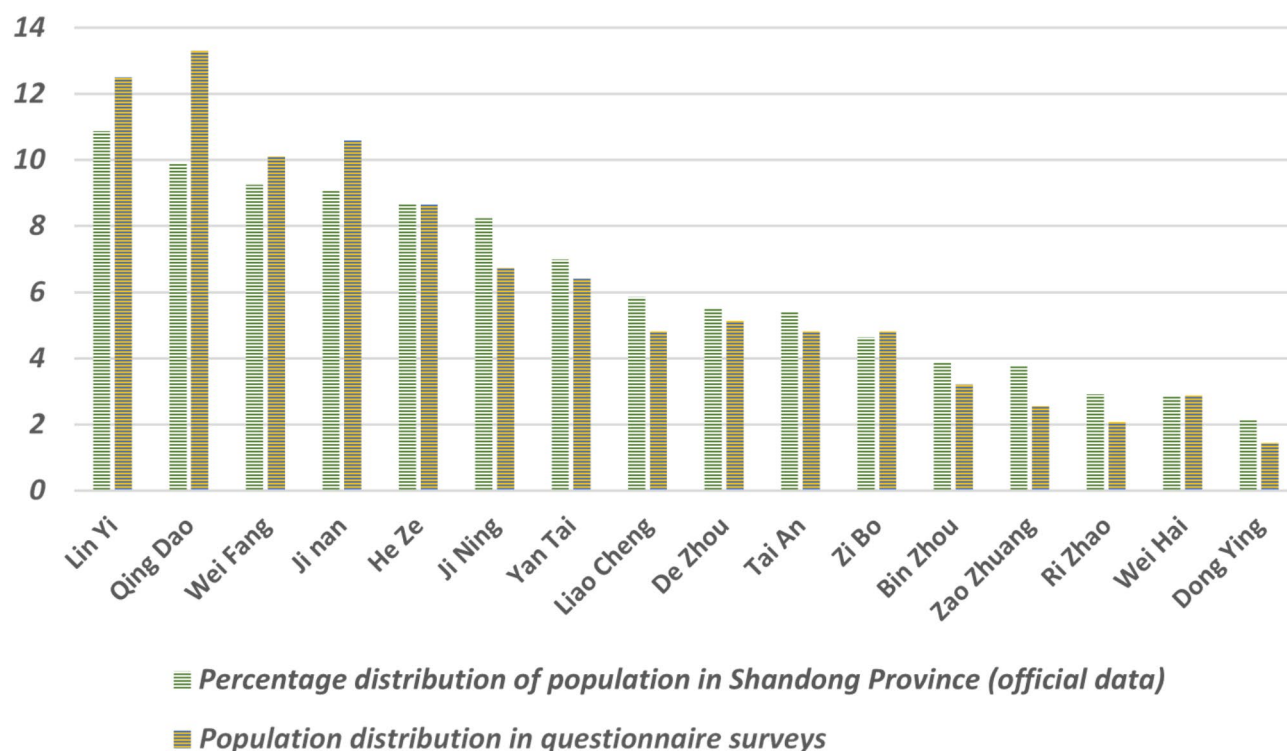


Fig. 5. Population distribution of sample locations.

good performance in quickly collecting a large amount of data for preliminary screening or simple descriptive statistical scenarios. Since our research needs to explore the relationships among latent variables, we have chosen the Likert seven-point scale as the measurement scale^{79,93}.

Participant consent statement

Before the interview each respondent provided informed consent. The interviewees were before signing the document informed that their answers will be used in are search project, that their contribution was voluntarily, that their data will be treated confidentially and stored securely.

Ethical approval

All materials and methods are performed in accordance with the instructions and regulations and this research has been approved by Zhejiang University City College Ethics Society (No: 010105). All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Interview process

The flow of the formal interview questionnaire is as follows:

Part 1 Screening respondents who do not meet the age limit, do not live in the local urban area, and cannot answer on behalf of the household will not be interviewed (Table A2).

Part 2 Eligible respondents were given a graphic presentation on the significance and impact of the study and the benefits they could gain through photovoltaic tiles.

Part 3 Collection of demographically relevant information on respondents (Table A3).

Part 4 Inquire about the measurement scale's assumptions (using the seven-point Likert scale as the quantifying unit of respondents' responses. 1 = strongly disagree, 7 = strongly agree).

Part 5 Inquire about willingness to pay 's central issues. Assume the government will retrofit photovoltaic tiles on city rooftops to promote the construction of low-carbon cities (the government will fund the project). Considering the positive environmental externality of photovoltaic tiles roofs and the current financial pressure of government programs due to the impact of COVID-19, would your house hold be willing to pay an extra portion of your monthly electricity rate to support the retrofitting of photovoltaic tiles roofs for the construction of low-carbon cities, considering your household's financial situation? The payment term is five years because the central government develops a major strategic deployment every five years.

Part 6 Respondents were surveyed on their current primary means of accessing information.

Willingness to pay elicitation method

For willingness to pay, we use the conditional value method as the valuation method. The conditional value method is the most widely used willingness-to-pay estimation method at this stage³², which mainly includes payment card-based, open-ended, single-boundary dichotomous choice (SBDC) and double-boundary dichotomous choice. The limitation of the payment card approach is the presence of rounding, which reduces the accuracy of the valuation⁶⁸. The limitation of the open-ended conditional value method is that the maximum willingness to pay is directly presented within the acceptable range of the respondent, but this method lacks a reference standard for the maximum willingness to pay and therefore often leads to low response rates⁶⁹. The dichotomous choice format approach is an incentive compatible approach that only requires an "Agree" or "Disagree" response to a question's outgoing value without specifying a specific willingness to pay, thus helping to reduce strategy bias⁷⁰, the double-boundary dichotomous choice has more precise control over the bid range when the willingness to pay questions are asked compared to SBDC, neither double-boundary dichotomous choice nor SBDC can handle the zero response problem (zero willingness to pay) for willingness to pay²⁸. Considering the current economic downward environment, the proportion of zero response is higher (and the comparison of zero response is also higher in our study). Therefore, we used the Spike model proposed by Kristrom⁷¹ combined with the double-boundary dichotomous choice to estimate the willingness to pay. The advantage of this estimation method is that it allows respondents with a non-zero willingness to pay but not in the bidding range to take a non-zero positive decimal value of willingness to pay, addressing the limitation due to the bidding range⁷¹.

The double-boundary dichotomous choice model assumes that the initial bid amount is represented by W_i ($i=1, \dots, n$) and that respondents who answer "yes" are asked an additional question with a higher bid value W_i^H . Respondents who answer "no" are asked a low bid question W_i^L . Respondents will have four possible responses: yes-yes, yes-no, no-yes, and no-no. The relevant binary-valued indicator variables are M_i^{YY} , M_i^{YN} , M_i^{NY} , M_i^{NN} . Spike model is a follow-up question to ask respondents if they are willing to join the market again when they answer no-no in the double-boundary dichotomous choice model (M_i^{NN}). If willing then the binary indicator variable is denoted as M_i^{NNY} , if rejected then it is denoted as M_i^{NNN} . A protest response determination is required for respondents who again refuse to pay, and the protester will be dropped from the sample. $G_c(W; X)$ is the cumulative distribution function (CDF) of willingness to pay, X is the unknown parameter to be valued, and W is the value of the bid, then the logarithmic fit formula of double-boundary dichotomous choice + Spike model is expressed as

$$\ln L = \sum_{i=1}^N \{M_i^{YY} \ln[1 - G_c(W_i^H; X)] + M_i^{YN} \ln[G_c(W_i^H; X) - G_c(W_i; X)] + M_i^{NY} \ln[G_c(W_i; X) - G_c(W_i^L; X)] + M_i^{NNY} [\ln G_c(W_i^L; X) - G_c(0; X)] + M_i^{NNN} [G_c(0; X)]\} \quad (2)$$

In spike model estimation, the maximum likelihood estimation method has the best fitting properties and is widely used by researchers^{72–74}. Assuming that α and β are parameters of the logistic function, the parameters α and β are obtained by applying a maximum likelihood method for valuation. In Eq. (2) the Spike value is defined as $[1 + \exp(\alpha)]^{-1}$

$$G_c(W; X) = \begin{cases} 0 & \text{if } W < 0 \\ [1 + \exp(\alpha)]^{-1} & \text{if } W = 0 \\ [1 + \exp(\alpha - \beta A)]^{-1} & \text{if } W > 0 \end{cases} \quad (3)$$

Therefore WTP_{mean} can be expressed as

$$WTP_{mean} = \bar{C} = (1/\beta) \ln[1 + \exp(\alpha)] \quad (4)$$

Structural equation modeling

With the help of AMOS 28.0 software, we used structural equation modelling to reveal the correlation hypotheses and the relationship between variables between the traditional and expanded theory of planned behavior psychological explanatory framework and willingness to pay, respectively. The structural equation modelling is a crucial method for investigating the relationship between hypothetical, unknown, and known variables, and is also widely used in the discussion of the correlation between each variable and willingness to pay^{15,75}. To verify the plausibility of the proposed hypothesis, we also tested the fit of the measurement model using the confirmatory factor analysis proposed by Anderson and Gerbing⁷⁶.

Results

Of the 1100 interview questionnaires distributed, 1028 were recovered, with a return rate of 93.4% (72 questionnaires were invalidated because the respondent stopped the interview in the middle). The number of valid questionnaires obtained from the validity and protest response determination of 1028 questionnaires was 832. The interview questionnaires' effective response rate was 80.9%, which met the criteria recommended by the NOAA Review Committee^{70,79}. We excluded 51 samples that did not meet the validity of the questionnaire (e.g., those with Ph.D. degrees but whose income did not match their age, those with too high a proportion of the same choices, those with too short a response time, etc.) and 145 samples that refused to pay any fees and questioned the program.

The social characteristics in the interview questionnaire included age, gender, education level, and monthly household income (Table 2). The age of the respondents is more concentrated between 26 and 45 years old, accounting for about 53.3% of the total respondents. The proportion of female respondents is 53.6% higher than that of males, 46.4%. In terms of education, most of the respondents are well educated, with 64.4% of them having a university education or above. About 49.3% of the respondents have a household income of more than 7,000 CNY.

Respondents' willingness to pay

Table 3 reveals the statistical results of willingness to pay, with 620 respondents out of 832 valid questionnaires with a willingness to pay greater than zero and 212 respondents who refused to pay, representing approximately 25.5% of the sample size (actual zero response), most respondents with low income or who did not think they would benefit from the photovoltaic tiles roof. According to the protest response determination criteria, respondents (145) who believed that the project does not make sense, that constructing a low-carbon city was irrelevant to them, and that the project should be the government's responsibility were judged as protest-responses⁷⁰. To reduce the protest sentiment affecting the accuracy of the interview questionnaire, we excluded protest responses from the data analysis.

The average willingness to pay of households was estimated using the Maximum likelihood valuation method, and the results showed that the average willingness to pay of households in Shandong Province to support photovoltaic tiles retrofitting roofs to promote low carbon city construction was 108.71 CNY (15.78 USD) per month (Table 4). The Spike value of the model is 27.6%, which is closer to the percentage of respondents who refused to pay, 25.5%. Therefore, the fit of the peak model is more satisfactory. The parameter bootstrap approach proposed by Krisky⁷⁷ (including five thousand replications) was used to obtain 95% confidence interval values of 99.75 to 117.96 CNY (14.48–17.12 USD) and 99% confidence interval values of 97.62 to 122.85 CNY (14.17–17.83 USD), respectively. According to the seventh census data, about 22.5 million urban households are in Shandong Province. Extending the results to Shandong province, the total amount of willingness to pay is about 2.43 billion per month. Since the non-standardized environmental value is estimated by the willingness to pay^{28,31}, the environmental value of urban photovoltaic tiles retrofitting roofs in Shandong province is 2.43 billion CNY per month.

Kendall's tau-b correlation analysis was used to examine the relationship between demographic variables and willingness to pay (Table 5). The Kendall's tau-b coefficient is a statistical measure used to evaluate the

Urban characteristics	Response	Frequency	Percentage (%)
Gender	Male	386	46.4
	Female	446	53.6
Age(years)	18–25	153	18.3
	26–35	238	28.6
	36–45	206	24.7
	46–55	138	16.5
	55–65	97	11.6
Education level	Below-university diploma	296	35.6
	Bachelor's degree	399	48.0
	Master's degree	127	15.2
	Doctor's degree	10	1.2
Monthly household income	< 3000 CNY	37	4.4
	3001–5000 CNY	163	19.6
	5001–7000 CNY	194	23.3
	7001–9000 CNY	200	24.0
	9001–11,000 CNY	130	15.6
	> 11,000 CNY	108	13.0

Table 2. Demographic characteristics of respondents.

Bid amount	Positive willingness to pay					Zero willingness to pay (Refusal to pay)			Sum
	Y-Y	Y-N	N-Y	N-N-Y	Total	Protest response	Zero response	Total	
(15/30/60)	55	42	47	35	179 (86.1%)	30 (delete)	32	32 (13.9%)	208 (100%)
(30/60/120)	41	36	63	19	159 (76.4%)	37 (delete)	49	49 (23.6%)	208 (100%)
(60/120/240)	30	31	51	22	134 (64.4%)	35 (delete)	74	74 (35.6%)	208 (100%)
(120/240/480)	26	51	57	14	148 (71.2%)	43 (delete)	60	60 (28.8%)	208 (100%)
Sum	152	160	218	90	620 (74.5%)	145 (delete)	212	212 (25.5%)	832 (100%)

Table 3. Data statistics of returned interview questionnaires.

Variables	Coefficient	T values	P values
Constant	0.770	11.421	0 ***
Beta	0.010	24.340	0 ***
Spike	0.276	21.689	0 ***
Willingness to pay(mean)	108.711 CNY	22.933	0 ***
Interval_95	99.755 7.968 CNY		
Interval_99	97.621 22.856 CNY		
Wald-statics	594.011		0 * **
Log-likelihood	−1530.632		

Table 4. Estimation result of the willingness to pay. Note: Relevance * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

rank correlation between two variables, and it is especially applicable to handling ordered categorical scale data. With the assistance of the SPSS software, we estimated the correlation between the willingness to pay and the demographic data by using this method³². Similar to the findings obtained by most researchers, income level and educational attainment had a significant positive correlation with willingness to pay at the 1% level^{24,27,32}. This indicates that the higher income and higher education groups place more importance on using solar facilities and constructing low-carbon cities, which may be related to the knowledge they have learned during their school years. Higher education leads to higher earnings, which is consistent with our findings¹⁷. The negative correlation between willingness to pay and age was significant at the 5% level, which may be caused by the fact that older respondents tend to be less receptive to new things and tend to be conservative. Surprisingly, age was negatively correlated with income level and was significant at the 5% level, which is inconsistent with the findings of many researchers^{15,30}, possibly due to sampling bias caused by the low proportion of older respondents or the gradual rejuvenation of the higher income group. Age was not significantly related to willingness to pay in our study.

	Household income	Age	Level of education	Gender	Willingness to pay
Household income	1.000				
Age	−0.057**	1.000			
Level of education	0.430***	−0.335**	1.000		
Gender	−0.018	−0.044	0.008	1.000	
Willingness to pay	0.494***	−0.150**	0.438***	−0.018	1.000

Table 5. Kendall correlation coefficient between demographic variables and willingness to pay. **, ***: Indicates statistical significance at the 5% and 1% levels, respectively.

Hypothesis testing

Excessive correlation among the hypothetical variables in each group affects the accuracy of the estimation results⁷⁹. Since the data are generally normally distributed, we determined the correlation among the hypothetical variables in each group using Kendall's tau-b correlation analysis before confirmatory factor analysis. The results showed that the correlations between the variables in each group were less than 0.6 and significant at the 1% level. Therefore, there is no over-correlation among the hypotheses. The analysis of the multicollinearity detection results showed that $VIF < 5$, and the data could be considered free of multicollinearity and suitable for the next step of confirmatory factor analysis.

The reliability and validity of the model were tested by confirmatory factor analysis using the maximum likelihood estimation method. The results of the confidence, convergent validity and discriminant validity of the latent variables are shown in Table 6. Cronbach's alpha and Composite Reliability (CR) were used to detect the internal consistency of each hypothetical variable of the model (coefficients greater than 0.7 indicate good internal consistency of the model). Convergent validity is the degree to which hypothesized variables are theoretically correlated with each other and is usually measured using constructed factor loading and average variance extraction (AVE)⁷⁵ (suggested benchmark value of 0.5).

In our study, the range of AVE scores was greater than the baseline value of 0.5. The lowest value of the factor load recorded was 0.71 and the highest was 0.78 (both above the recommended threshold of 0.7). With these satisfactory reliability conditions in place, the next step involves further examination of the AVE and CR of each dimension of the scales. This validation process entails calculating the standardized factor loadings of each measurement item on the corresponding dimension, using the established confirmatory factor analysis model. Discriminant validity is the degree to which two or more constructs are independent, with the square root of the AVE of each construct having a value greater than the correlation factor between that construct and any other construct⁴¹. As per the analysis results in Table 6 and in the validity test, the AVE values of each dimension are more than 0.5, the discriminant validity of each variable is less than the AVE's square root (Table 7 right side bolded diagonal), indicating that the scales are internally consistent and have good reliability and validity, and the CR values exceed 0.7, indicating that each dimension demonstrates good convergent validity and composite reliability.

To ensure that the model has a good fit, the fitness of the model needs to be checked. Usually the fitness coefficient contains the following indicators: chi-square/degrees of freedom (χ^2/df), robustness of mean squared error approximation (RMSEA), comparative fitness index (CFI), normative fitness index (NFI), fitness index (GFI), relative fitness index (RFI), and adjusted fitness index (AGFI)^{41,78}. The fitness coefficients are shown in the first row of Table 7. The indicators of the extended theory of planned behavior psychological explanatory framework are shown in the second row. Meeting the range of values of the fitness coefficients can prove that the model has good fitness. The results show that all the fitnesses of the model meet the range of values of the fitness coefficients.

The data fit the initial theory of planned behavior psychological interpretation frame for willingness to pay (Fig. 6) well (chi - square = 34.392, RMSEA = 0.015, AGFI = 0.979, RFI = 0.975); most of the coefficients were statistically significant ($p < 0.05$) with attitudes ($H1 = 0.28$, $p < 0.001$) with perceived behavioural control ($H3 = 0.63$, $P < 0.001$) but the subjective norms showed a non-significant negative correlation with willingness to pay and the subjective norms was rejected because the correlation of subjective norms could not be confirmed. $r^2 = 0.61$ indicates that the initial theory of planned behavior psychological interpretation frame explains 61% of willingness to pay.

The fit of the data in willingness to pay's extended theory of planned behavior psychological interpretation frame for willingness to pay (Fig. 7) was excellent (Chi-Square = 640.661; RMSEA = 0.065; CFI = 0.930, TLI = 0.915). The six variables influencing willingness to pay (attitude, subjective norm, perceived behavioural control, perceived policy, perceived ethics, and perceived personal interest) explained 75% of the willingness to pay ($R^2 = 0.75$). A 14% increase in interpretation capability over the initial theory of planned behavior psychological interpretation frame for willingness to pay. Among the direct effects, attitudes ($H1 = 0.14$, $p < 0.001$), perceived behavioural control ($H3 = 0.18$, $p < 0.001$), policy perception ($H6 = 0.17$, $p < 0.001$), moral perception ($H4 = 0.18$, $p < 0.001$) and personal of interest perception ($H8 = 0.35$, $p < 0.001$) were essential variables in predicting willingness to pay, and personal of interest perception was the dominant variable in predicting willingness to pay. There is a negative relationship between subjective norms and willingness to pay, and since the H2 pathway did not show a statistically significant relationship with willingness to pay, H2 was excluded.

Table 8 displays the results of the indirect effects. Combined with Fig. 7, the overall effect of policy perception on attitudes ($H4 = 0.560$, $p < 0.01$) and the indirect effect of policy perception on willingness to pay via attitudes ($H4a = 0.043$, $p < 0.01$) were both significant, proving the validity of hypotheses H4 and H4a. The overall effect

Construct	Cronbach's Alpha	CR	SRW			AVE	Discriminant validity				Perception of personal interest			
			(1)	(2)	(3)		Attitude	Subjective norms	Perceptual behavioral control	Moral perception	Policy perception	Perception of personal interest		
Attitude	0.80	0.81	0.78***	0.76***	0.75***	0.58	0.76							
Subjective norms	0.79	0.80	0.75***	0.77***	0.76***	0.56	0.50	0.75						
Perceptual Behavioral Control	0.79	0.79	0.74***	0.75***	0.73***	0.55	0.48	0.64	0.74					
Moral Perception	0.77	0.78	0.74***	0.72***	0.72***	0.52	0.38	0.42	0.64	0.72				
Policy Perception	0.78	0.78	0.71***	0.75***	0.73***	0.53	0.52	0.61	0.68	0.70	0.73			
Perception of personal interest	0.80	0.80	0.74***	0.75***	0.76***	0.56	0.54	0.58	0.73	0.61	0.71	0.75		

Table 6. Confirmatory factor analysis. Notes: SRW stands for Standard regression weight; Values in the diagonal row (in bold) are the square roots of AVEs; (1) (2) and (3) represent the measured variables in Table 1.

Fit statistics	χ^2/df	RMSEA	CFI	RFI	GFI	NFI	AGFI
Decision criteria	<3.00	<0.08	>0.80	>0.80	>0.80	>0.80	>0.80
Result	4.512	0.065	0.930	0.894	0.932	0.912	0.909

Table 7. The structural model’s fit indices.

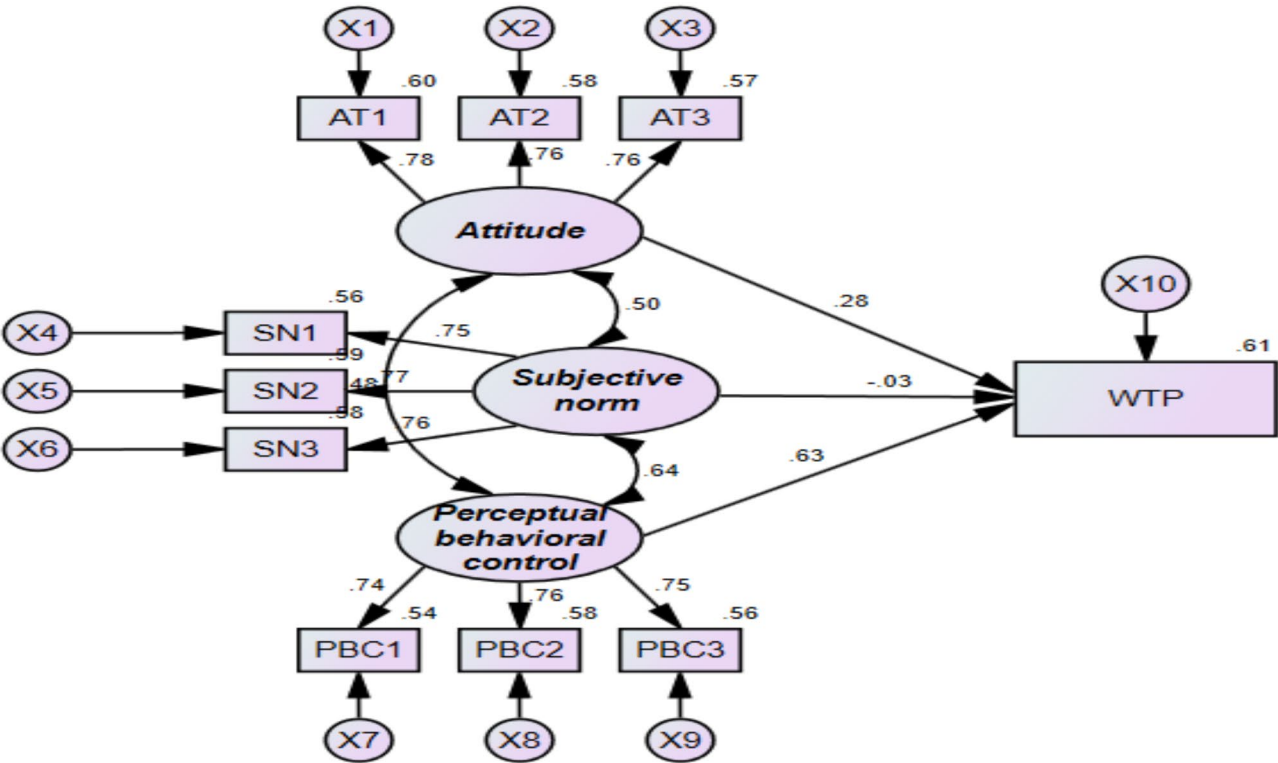


Fig. 6. Standardized direct effect estimation in structural equation models (Traditional frame).

of the policy perception on willingness to pay was 0.134, with indirect effects accounting for 31.8%. The indirect effect of personal of interest perception on perceived behavioural control ($H6 = 0.800, p < 0.01$) and the indirect effect of personal of interest perception on willingness to pay through perceived behavioural control ($H6a = 0.076, p < 0.01$) were both significant, proving the validity of hypotheses H6 and H6a. The overall effect of personal of interest perception on willingness to pay was 0.256, with indirect effects accounting for 29.5%.

A rational approach to information dissemination helps decision makers to choose a more rational medium for information dissemination⁷⁹. Since photovoltaic tiles roofing is still relatively new, research on its information access methods has been limited. In order to better understand the way respondents access relevant information, we surveyed the information access habits of all respondents to provide a referable way of information dissemination for decision-makers. The results are shown in Fig. 8. About 41% of the respondents said their primary access to information is through cell phone surfing online. About 21% of the respondents said their access to information is through computer surfing online. More than 60% of the people in urban households have access to relevant information online. In contrast, traditional ways of accessing information, such as books, TV, and newspapers, account for 4%, 10%, and 2%, respectively. It shows that with the development of network technology, access to information has changed significantly compared with the traditional mode, and policymakers should pay attention to information dissemination through the network. Some respondents have not heard of photovoltaic tiles roofing, accounting for 19% of the respondents.

Discussion
About willingness to pay

Shandong Province’s urban households’ monthly willingness to pay to support photovoltaic tiles retrofit roofs to promote low-carbon cities is 108.71CNY (15.84USD), which is slightly lower than the willingness to pay of rural households in China to support photovoltaic tiles roofs at 133.55CNY (19.47USD) per month⁷⁹. This is not consistent with the findings that income level is significantly and positively correlated with willingness to pay^{15,30}. Since the personal of interest perception is the dominant variable determining willingness to pay in our study, and Chinese rural households tend to have larger roof areas (one household builds mainly),

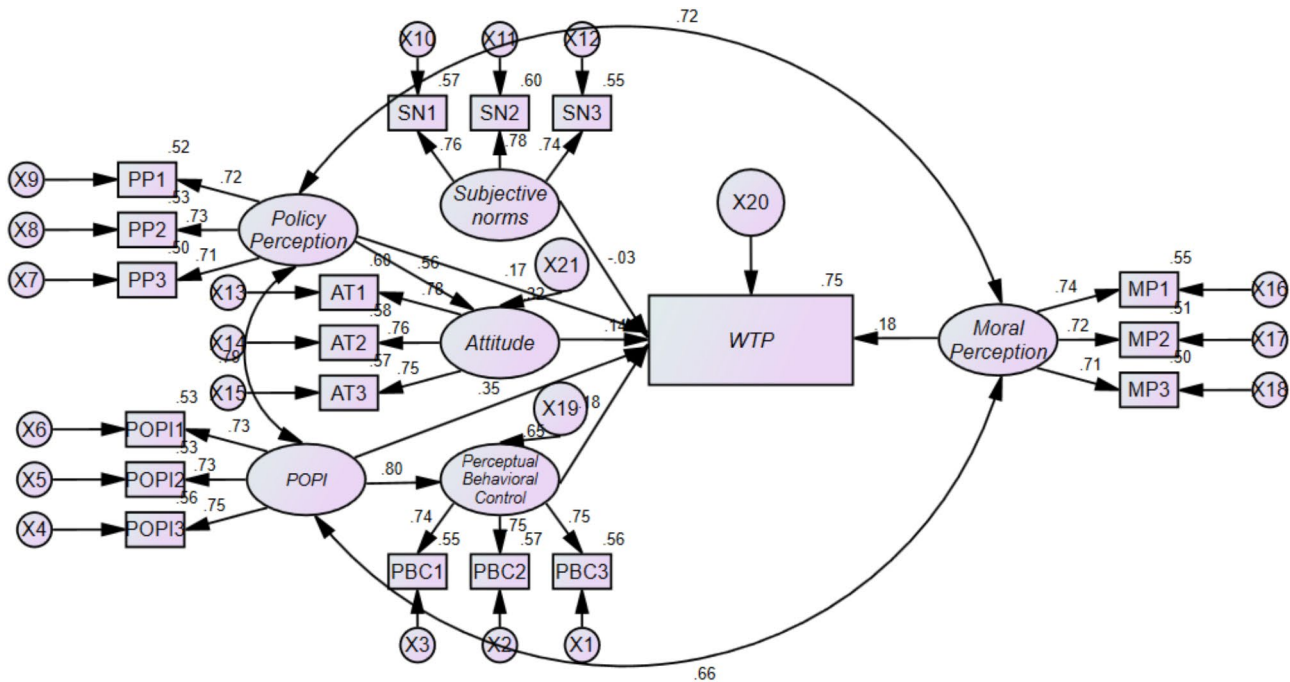


Fig. 7. Standardized direct effect estimation in structural equation models (Extension framework).

Indirect effect	Estimate	S. E.	95% CI	Supported	P
PP → AT → WTP	0.078	0.009	0.023–0.060	Confirm	0.007
POIP → PBC → WTP	0.144	0.023	0.032–0.119	Confirm	0.004

Table 8. Standardized indirect effect estimation in the structural equation modelling. Personal of interest perception (POIP); willingness to pay (WTP); attitudes (AT); perceived behavioural control (PBC); Policy perception (PP).

therefore the benefits per unit household through photovoltaic tiles roofs are higher than urban households (roof apportioned area), which may be responsible for the higher willingness to pay of rural households. The WTP of urban households in Shandong Province is also lower than the willingness to pay of the general public in New Jersey for solar products (31.10 USD per month)⁸⁰, which may be due to the influence of education level and income level. Because willingness to pay and income level and education level in our study showed a significant positive correlation, which is also consistent with the conclusions reached by many researchers^{29,81}, in contrast, the United States, as a developed country, has higher education and income levels than China, so respondents in New Jersey, USA, have higher willingness to pay. The willingness to pay was greater than zero for approximately 74.5% of respondents, higher than the willingness to pay for a solar roof among rural Chinese households⁷⁹, which we speculate may be caused by the higher education level of urban households and a more comprehensive understanding of the positive environmental externalities of photovoltaic tiles. This percentage is also higher than that of fellow developing countries Myanmar (62%) and India (60–71%)^{82,83} but less than the percentage paid by New Jersey residents⁸⁰. Approximately 40.6% of respondents who refused to pay were protest responders, most of whom believed that the photovoltaic tiles roof retrofitting was a government project unrelated to them. This percentage is slightly higher than the percentage of protest responses among those who refused to pay predicted by Canson⁸⁴. This may be due to the relatively new concept of photovoltaic tiles and the lack of public understanding.

The Spike model reduces the percentage of refusers by asking whether they would like to join the market again, which can reduce respondents' refusal due to the bid range setting to some extent. In our study, 90 respondents were willing to rejoin the market (Table 4), representing about 10.8% of the total sample size. Moreover, other researchers have reached similar conclusions^{24,27,28,85}. We guess in future willingness to pay studies, the Spike model will replace the existing double-boundary dichotomous choice conditional value method as the dominant valuation model for willingness to pay.

The retrofit cost of photovoltaic tiles roofs in China in 2023 is about 1,960 CNY per square meter (284.8 USD). The power production per square meter is about 0.26 kw/h. Assuming a roof area of 1,000 square meters for a collection of urban houses with 20 occupants, photovoltaic tiles is installed on the roof in a flat lay (tilt angle of 0 degrees) with no building shading, and the average daily sunshine duration is 6 h. The generation of consistent power on a daily basis is about 260 kw/h. The electricity price for urban consumers in China is about

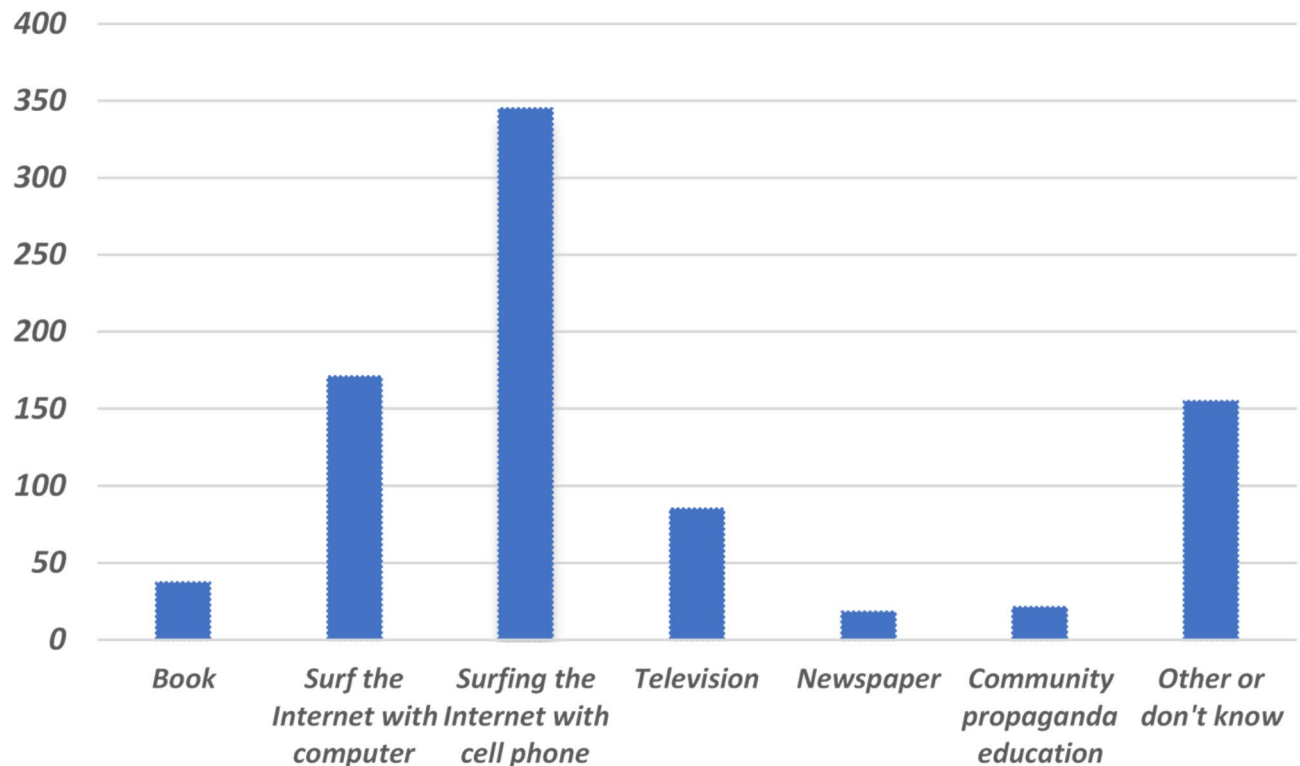


Fig. 8. Access to public information.

0.6CNY/kwh, and the power generation revenue from a 1000 square meter photovoltaic tiles roof is about 936 CNY (136.01USD). The payback is about 5.7 years without considering the willingness to pay. If the willingness to pay is considered, the cost recovery time is 5.3 years. Therefore, policymakers must pay attention to the estimated results of willingness to pay when formulating policies related to photovoltaic tiles roofs because it will reduce the cost recovery time to some extent.

Explanation model of willingness to pay

Ajzen³³, the proposer of theory of planned behavior, argued that individuals' attitudes, subjective norms, and the perceived behavioural control will directly affect their behavioural intentions. Our results show that the perceived behavioural control in the initial theory of planned behavior psychological interpretation frame for willingness to pay is the dominant variable in explaining willingness to pay, while behavioural intentions is also significant in predicting willingness to pay, which is consistent with the findings obtained by many researchers^{15,79}. However, there is a negative correlation between subjective norms and willingness to pay, and the path was insignificant. This is not consistent with the conclusion reached by Ajzen³³ nor with the collectivist way of thinking in traditional Chinese culture⁴⁶. The reason might be due to the limitations of the sample, or it may be caused by the decision-making independence of the sample's family representative (interviewees).

Demographic variables are also considered to be essential factors influencing individuals' behavioural intentions⁸⁶. Zhang³¹ argued that individual behavioural intentions is directly related to income level and education. López-Mosquera⁸⁷ obtained similar conclusions, consistent with our Kendall tau-b correlation analysis findings. However, it is worth noting that age was significantly negatively associated with willingness to pay in our study, contrary to the conclusions obtained by some researchers^{27,30}. The results in Table 6 show a significant negative correlation between income level, education level and age as well, which we speculate may be due to the lower education and income levels of the older individuals in the sample, leading to a lower acceptance of photovoltaic tiles among the older individuals, which in turn affects their willingness to pay. Increasing the income level of the elderly is not easy to achieve in the short term. However, it is possible to increase their willingness to pay by increasing their awareness of the importance of photovoltaic tiles through promotional means.

The extended variable personal of interest perception in the extended theory of planned behavior psychological interpretation frame for willingness to pay is the dominant variable to directly explain willingness to pay, which is consistent with the conclusion obtained by Nketiah⁸⁸ and Wolske⁵⁶. Nketiah believes that publicity should be used to increase individuals' perceptions of environmental values and thus increase their personal of interest perception. We argue that increasing the perceived environmental value of photovoltaic tiles is only one aspect of personal of interest perception and that the tangible economic benefits of photovoltaic tiles rooftop use (the revenue generated by photovoltaic tiles electricity) should not be overlooked, as tangible economic benefits are often more motivating for individual personal of interest perception⁷⁹. The policy perception

and moral perception are also essential factors in directly explaining willingness to pay, which is consistent with Tan²⁷ and Thøgersen⁴², who concluded that individuals have stronger willingness to pay when they show stronger perceptions of policy and possess stronger moral identity. Policymakers must emphasize the existing policies related to photovoltaic tiles and low-carbon city construction when formulating new photovoltaic tiles promotion policies to increase individual policy perception and publicity on the ethical aspects of low-carbon city construction and clean energy use to improve individual moral perception. The correlation between policy perception, personal of interest perception, and moral perception was also confirmed. The results showed significant correlations between policy perception and personal of interest perception, personal of interest perception and moral perception, and moral perception and policy perception, which further confirmed the researchers' findings^{59–64}. There is a correlation between the three variables policy perception, personal of interest perception, and moral perception. This helps to provide a reference value for relevant researchers in future studies of low-carbon cities.

In the study, we found that the explanatory power of the traditional theory of planned behavior for willingness to pay is $R^2=0.61$, which explains 61% of willingness to pay, while the R^2 of the expanded model with the addition of the expanded variables is $R^2=0.75$, which explains 75% of willingness to pay. Therefore, we conclude that the explanatory power of the model increases by 14%, and the performance of the model improves by 21%. This also visualizes the effectiveness of the expansion for theory of planned behavior from the data.

Low-carbon city construction is an important issue worldwide, and photovoltaic tiles is an important solution to promote low-carbon city construction. This study takes a behavioral perspective as an entry point to explore the key factors that drive residents to participate in low-carbon city construction. At the theoretical level, our research proves the effectiveness of moral perception, the policy perception and personal of interest perception in explaining residents' participation in low-carbon city construction, and expands the application scope of theory of planned behavior. At the practical application level, moral perception, the policy perception and personal of interest perception can serve as anchoring factors for external intervention, and further formulate corresponding policies and boost intervention measures to promote residents' participation in low-carbon city construction. To summarize this study is important at both theoretical and practical levels.

Conclusions and policy implications

Conclusion

This study examines the factors explaining the willingness to pay of urban households in China that support photovoltaic tiles retrofitting of rooftops to promote low-carbon city construction. It contributes to the construction of low-carbon cities in China, the promotion of photovoltaic tiles, and the development of related policies. In total, the results of this study were three-fold.

- 1) We proposed an extended theory of planned behavior psychological explanatory framework for willingness to pay, including policy perception, personal of interest perception, and moral perception, based on the initial theory of planned behavior psychological explanatory framework for willingness to pay and achieved a pleasing willingness to pay interpretation result. Compared with the initial framework, the explanatory power of willingness to pay increased by 19%. Among them, P OPI is the dominant variable in explaining willingness to pay, and the strength of the explanatory power for willingness to pay is personal of interest perception > moral perception > perceived behavioural control > policy perception > attitudes. The effect of subjective norms on willingness to pay is not significant.
- 2) In terms of demographic variables, the household's income level and the household representative's educational level were significantly and positively correlated with willingness to pay, and age was significantly and negatively correlated with willingness to pay. There was no correlation between gender and willingness to pay.
- 3) The final willingness to pay of Shandong Province urban households supporting photovoltaic tiles retrofit roofs to promote low-carbon city construction is 108.711CNY per month. The environmental value generated by photovoltaic tiles retrofitted roofs in urban Shandong Province is approximately 2.43 billion CNY monthly.

Policy implications

This paper puts forward the following four policy recommendations based on the above research results.

- 1) Since the personal of interest perception is the dominant variable in explaining willingness to pay, it is important to pay attention to the impact of personal of interest perception on willingness to pay. This can be divided into two areas, increasing awareness of the positive environmental externalities and environmental values of photovoltaic tiles at the environmental level. Raise individual awareness of the environmental benefits of photovoltaic tiles. At the individual benefit level, we should highlight the economic value of photovoltaic tiles roofs and promote it in a way that incorporates the current mainstream information access (computer networks and cell phone networks). For example, the application of China's largest Tiktok short-video media publicity platform and the information interaction software Wechat for the broadcasting of the city's low-carbon construction publicity video; the photovoltaic tiles as well as pop-ups from public numbers of related apps.
- 2) Forming individual moral perception often requires a continuous process, so it is necessary to strengthen the education on environmental ethics during the school years and develop an awareness of them. Encourage the organization of various in-school activities related to low-carbon city building and environmental protection to develop their moral perception. For example, experience classes on environmental protection and lectures on low-carbon urban construction.

- 3) Public willingness to pay can quantify the environmental value of photovoltaic tiles to a certain extent, so public willingness to pay is necessary to mention when formulating policies promoting low-carbon city construction through photovoltaic tiles. This helps policymakers and investors better evaluate photovoltaic tiles' business value and increase their interest in investing in it.
- 4) Age is significantly and negatively correlated with willingness to pay, so it is necessary to organize unique campaigns for the elderly in the community to increase their awareness of the importance of low-carbon city buildings and photovoltaic tiles. For example, seminars on the importance of low-carbon urban construction for the elderly were held in community activity centers; Carry out photovoltaic tiles experience activities.

We must recognize that there are some limitations to this study. (1) There are regional income differences because different urban areas in Shandong Province, China, have different levels of development. We estimated the average willingness to pay of households in Shandong province based on a sample size level of 1,000 persons, but did not further discuss the differences in willingness to pay across urban areas in Shandong province and the impact of regional development levels on willingness to pay. This limitation may challenge the accuracy of the willingness to pay estimates in this study. We believe that with sufficient funding, a large-scale empirical study of willingness to pay incorporating information on regional development GIS for cities in Shandong Province may explain these issues and reveal the inherent patterns between regional development levels and willingness to pay. In the case of financial constraints, predictive research through machine learning combined with regional development GIS information is not an ineffective solution. (2) Although theory of planned behavior is the most widely used behavioral explanation framework, there are many theoretical models to explain individual behaviors besides theory of planned behavior. We only studied theory of planned behavior, which is one of the limitations of this study, and applying rootedness theory to construct a theoretical model through in-depth interviews may maximize the solution to this problem. We will explore further around the above research limitations to further improve our study.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Author contributions

Authors' contributions: All authors contributed to the study's conception and design Yang Tan: Conceptualization, investigation, writing, and modification. xiaoyu Ying: writing— Conceptualization, review, and editing. Jian Ge: ConceptualizationWeijun Gao: AnalysisXueyuan Zhao: Supervision Shuai Wang: methodology.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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