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Exploring the potential impact of household photovoltaic systems on low-carbon production behavior in rural areas: unveiling the pro-environmental spillover effect

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Introduction: China, as the world's largest emitter of carbon dioxide, faces significant challenges in agricultural greenhouse gas emissions. The Chinese government has been actively promoting household photovoltaic (PV) power generation, which has great potential for application in rural areas. This study aims to explore whether the promotion of household PV systems in rural areas has a positive impact on farmers' low-carbon production behavior and to analyze the influencing factors and mechanisms. This research fills the research gap in the analysis of the promotion of household PV systems and farmers' low-carbon production behavior, providing scientific evidence to support policymakers in promoting widespread use of household PV systems and facilitating the transition of farmers to low-carbon production methods.

Methods: This study adopts a qualitative research method and analyzes interview data and semi-structured questionnaire survey data from 48 farmers. By collecting, organizing, comparing, and extracting information and employing the research process of grounded theory, the researchers summarize the model of household PV-driven low-carbon production behavior.

Results: The study finds that the installation of household PV systems indeed promotes farmers to adopt more low-carbon production behaviors. Farmers who install household PV systems show a greater willingness to reduce the use of fertilizers and pesticides, conserve water resources, and improve land utilization, among others. They perceive the positive effects of household PV systems and their own capacity for environmental protection, enhancing confidence and motivation to engage in low-carbon production behaviors.

Discussion: Existing research methods have mainly relied on theoretical deduction combined with quantitative empirical approaches when exploring farmers' pro-environmental spillover behaviors. However, these methods often start from the perspectives of either egoism or altruism, resulting in biased tendencies toward negative spillover or positive spillover. Nevertheless, neither egoism nor altruism fully captures the decision-making process when deeply understanding farmers' production, life, and decision-making processes. The installation of household PV systems can change factors such as farmers' knowledge, skills, cognition, and resources, enhancing their green self-efficacy and helping them acquire more knowledge and skills in renewable energy. Therefore, this research adopts a qualitative research method to more accurately reflect farmers' decision-making process and provides practical recommendations to promote farmers' active transition to pro-environmental spillover behaviors.

Conclusion: This study fills the research gap in the analysis of the promotion of household PV systems and farmers' low-carbon production behavior, providing practical recommendations for policymakers to facilitate farmers' positive behavioral changes. Qualitative research methods enable a more realistic understanding and promotion of farmers' pro-environmental spillover behaviors by deeply understanding their contexts. The study offers targeted suggestions to policymakers to drive farmers' transition to low-carbon production methods.

KEYWORDS

household photovoltaic system, low carbon production behavior, qualitative research, grounded theory, household PV systems promoting low-carbon production

1 Introduction

China, as the world's largest carbon emitter, is projected to reach a carbon emission of 110.39 billion tons by 2022, accounting for 28.87% of global emissions (Datasets, 2022). In light of this severe situation, Chinese leadership expressed his concerns as early as 2020. During the 75th United Nations General Assembly, President Xi Jinping announced China's targets of peaking carbon emissions by 2030 and achieving carbon neutrality by 2060, known as the "dual-carbon goals."

To achieve these objectives, China has submitted its nationally determined contributions (NDCs), which explicitly state a target of reducing CO2 emissions per unit of GDP by 60%–65% compared to 2005 levels by 2030 (Li et al., 2020). The restrictions imposed by these dual-carbon goals are increasing the pressure to reduce carbon emissions in the agricultural sector, which accounts for 14.9% of global greenhouse gas emissions, making it the second-largest emitter (Laborde et al., 2021). In China, this proportion is close to 17% and continues to rise annually (Rehman et al., 2020). Therefore, the transition from high-carbon to low-carbon agriculture and the reduction of agricultural greenhouse gas emissions have become new directions and requirements for modern agricultural development. Previous studies have shown that households, as key decision-makers in production, directly affect the achievement of carbon emission reductions in agriculture through their low-carbon production behavior (Du et al., 2023; Zhang et al., 2023). Consequently, this study focuses on household low-carbon production behavior.

Meanwhile, in order to achieve the dual-carbon goals, the Chinese government has been promoting household photovoltaic (PV) systems on a large scale within the country (Wu et al., 2023). It is worth noting that in rural areas of China, households have independent property rights for their houses, making them more suitable for the installation of household PV systems. Therefore, the promotion of household PV systems mainly targets rural areas (Wang et al., 2021). In academia, a recent study has discovered a phenomenon called "behavioral spillover": when individuals engage in certain environmentally friendly behaviors, their willingness or extent of participation in other environmental activities also changes accordingly (Truelove et al., 2014; Nilsson et al., 2017). When the adoption of one behavior leads to the adoption of another related behavior, it is referred to as positive spillover. Conversely, if it results in the avoidance or cessation of another behavior, it is considered negative spillover (Xu et al., 2018b). Based on this principle, since the installation of household PV systems by residents can be regarded as an environmentally friendly behavior, it is possible that the installation and use of these systems can also promote residents' engagement in other eco-friendly behaviors. In fact, scholars have already begun to explore this phenomenon and attempt to clarify the underlying mechanisms. For example, Wang et al. (2023) found that the installation of household PV systems can promote residents' green purchasing behavior (Wang et al., 2023). Although this research is still in its early stages, based on the relevant principles of behavioral spillover, it can be concluded that the environmental behavior spillover effects resulting from residents' installation of household PV systems are not limited to green consumption behaviors alone. Given that household PV systems are primarily promoted in rural areas in China, and as mentioned earlier, low-carbon production behavior holds special significance for China's dual-carbon goals, this study further focuses on the effects of residents' installation of household PV systems on their low-carbon production behavior.

The above analysis not only theoretically examines the potential causal relationships between individual environmental behaviors but also goes beyond the limited scope of previous single-behavior studies by considering individual environmental practices as interconnected elements in a complex system. This methodology promotes theoretical innovation and progress in the field of environmental behavior and management (Galizzi and Whitmarsh, 2019). Moreover, it also provides practical strategies for policymakers in environmental protection, enabling them to pursue two types of goals simultaneously. Therefore, this study will specifically examine whether the promotion of household PV systems in rural areas has a positive impact on the adoption of low-carbon production behavior by households. It aims to answer three specific questions: 1) Does the installation of household PV systems affect households' low-carbon agricultural production behavior? 2) If yes, what specific effects does it result in? 3) If yes, what are the underlying mechanisms? To answer these research questions, the following research design will be adopted: Chapter 2 will conduct a literature review to summarize existing research and provide background information for this study. Chapter 3 will outline the research design, including methodology, research procedures, and data sources. Chapter 4 will present the research findings and conduct a detailed analysis. Chapter 5 will interpret and discuss the results from a theoretical perspective. Chapter 6 will provide conclusions and limitations, summarize the theoretical and policy implications of the study, propose policy recommendations, clarify the research limitations, and suggest potential directions for future research.

2 Literature review

In the field of behavioral science, researchers have found an intriguing phenomenon where one behavior of an individual can influence another behavior (Dolan and Galizzi, 2015). This phenomenon, known as the "behavioral spillover of pro-environmental behaviors," has also been observed in the domain of human environmental behavior. After engaging in certain environmentally-friendly actions, individuals' willingness or extent of involvement in other pro-environmental activities also undergoes changes (Maki et al., 2019; Carrico, 2021). Evidence of negative spillover between behaviors has been discovered by some scholars. For instance, Tiefenbeck et al. (2013) demonstrated through experiments that residents' weekly energy consumption increased significantly by 5.6% after participating in water conservation activities (Tiefenbeck et al., 2013). Additionally, Werfel (2017) found that residents who engage in household electricity savings may exhibit a 15% decrease in their support for government carbon taxation policies (Werfel, 2017). However, other studies indicate positive spillover effects, such as higher levels of environmental consciousness in energy usage, resource recycling, and transportation choices among residents who purchase green products (Lanzini and Thogersen, 2014).

Behavioral spillover effects provide researchers with a crucial avenue to observe and understand the complex ecological dynamics of individual environmental practices (Galizzi and Whitmarsh, 2019). Traditional research on environmental behavior often focuses on an individual's decision-making process regarding a single behavior and considers behavior outcomes as products of individual psychological representations (Clayton et al., 2016). In contrast, behavioral spillover analysis suggests a potential causal relationship between individual pro-environmental behaviors and treats them as interconnected elements forming a complex system. Therefore, behavioral spillover analysis goes beyond traditional research paradigms and stimulates fundamental theoretical innovations and research paradigm advancements in the field of environmental behavior and management (Galizzi and Whitmarsh, 2019). This novel perspective enables a more comprehensive examination of individual environmental practices, surpassing previous narrow research viewpoints.

However, the existing research on household PVs primarily focuses on residents' willingness to install them and explores factors that influence installation intentions, such as attitudes, perceptions, and motivations (Ahmad et al., 2017; Alipour et al., 2019). Some studies also investigate external factors such as government policies and residential environments that affect installation intentions. Currently, although a small amount of literature has touched upon the potential derived value from residents' installation of household PVs (Wang et al., 2023; Yin and Zhao, 2023), there is limited research exploring the subtle impacts that residents experience after installing them.

The current research on pro-environmental spillover effects mostly employs theoretical deduction to propose research models, which are then validated through data collection and modeling. This type of analysis is often referred to as quantitative analysis. Under quantitative analysis, different conclusions have been drawn regarding pro-environmental spillover effects. For instance, the "behavior consistency theory" and the "target activation theory" (Thøgersen and Noblet, 2012; Truelove et al., 2014) support positive spillover, while the "moral licensing theory" and the "single-effect bias theory" (Jordan et al., 2011; Carrico et al., 2018) propose negative spillover. However, these theories often rely on a binary assumption about human nature, assuming a dichotomy between self-interest and altruism. For example, in their study on the influence of residents' waste sorting behavior on other pro-environmental behaviors, Xu et al. assume that waste sorting is a purely altruistic behavior, and they also define spillover behavior as completely selfless actions, such as sacrificing one's time to participate in environmental organizations or donating money to environmental causes (Xu et al., 2018a). In reality, individuals are constrained by daily concerns such as livelihood issues. Their motivations and purposes for engaging in pro-environmental behaviors are complex. For instance, energy-saving behavior may be motivated by both cost-saving and environmental concerns, or it may simply be an unconscious habit (Steinhorst et al., 2015). Therefore, the binary perspective of these theories does not align with the actual complexity of environmental behavior. The focus of this study, household installation and use of solar panels, possesses elements of both self-interest and altruism, rather than being a strict binary choice. Thus, this study rejects the binary assumption about human nature and instead adopts a qualitative analysis approach by collecting firsthand data through interviews. By doing so, it aims to extract key factors influencing residents' motivation changes and develop a theoretical model of pro-environmental spillover that incorporates both self-interest and altruism.

This study is focused on analyzing the role of promoting household solar panels in rural areas in implementing low-carbon production behavior among residents. The aforementioned literature on residents' motivations for installing solar panels and related research on pro-environmental spillover effects have provided references for the topic selection and research design of this study. Based on the current gaps and limitations in existing research, this study will utilize qualitative research techniques to collect firsthand data from residents and analyze the relationship between the installation and use of household solar panels and the implementation of low-carbon production behavior. The aim is to provide a research outcome that is grounded in the realities of residents' lives and make contributions to the study of environmental behavior as well as the development and implementation of public environmental policies.

3 Research design

This study aims to delve into the changes in rural residents' production methods after installing and using household PVs. Given the lack of research in this area, we have chosen to use an in-depth interview approach grounded in theory and iterative coding methods to extract and identify the relevant experiential factors that residents acquire through the installation and use of household PVs. We collected oral interview data from residents who have installed and used household PVs and conducted a thorough analysis of these data using grounded theory analysis techniques. To achieve the research objectives, it is first necessary to provide a clear definition of "installing and using household PVs" and delineate the scope of the study population.

3.1 Theoretical analysis

Grounded theory is a qualitative research method in the field of social sciences, which corresponds to quantitative research. In quantitative research, theoretical assumptions are often needed to guide research direction, provide frameworks, and explain results. However, grounded theory emphasizes the openness and flexibility of theory. This means that researchers should maintain an open attitude, not limited to existing theoretical frameworks, and be able to discover new theoretical perspectives or patterns from research data. Therefore, the pioneers of grounded theory unanimously believe that grounded theory research should not presuppose theoretical frameworks (Glaser, 1978; Strauss, 1987; Charmaz et al., 2007).

In our study, when constructing the mechanism model of pro-environmental spillover effects of household photovoltaic installations using grounded theory, no theoretical assumptions were made. However, we still need to explore the theoretical aspects of the core questions proposed. Namely, what impact does residents' installation of household photovoltaics have on their other pro-environmental behaviors? What is the mechanism behind this impact? This step aims to verify the theoretical feasibility of the question. If the question is not theoretically feasible, the entire study will not need to continue. Through theoretical exploration, we will clarify the theoretical basis of the research question to ensure the scientific and accuracy of the study. Although we have reviewed relevant theories of pro-environmental spillover behaviors in the literature review section, except for those controversial theories, we believe the following theories can also be used to deduce the potential pro-environmental spillover behaviors generated by residents' use of household photovoltaics.

Firstly, technological determinism posits that the rise and progression of science and technology, along with their associated products, will alter human production methods, societal values, and ultimately, behaviors. For instance, the advent and widespread adoption of technological innovations like motor cars, computers, and smartphones have had a profound influence on human activities. Automobiles, for instance, have revolutionized transportation behavior, while computers and smartphones have transformed production methods and entertainment habits (Howcroft and Taylor, 2023). Since household photovoltaic power generation systems, one of the objects of our study, are themselves technological products, we believe they have a similar shaping function on user behavior as the aforementioned technological products.

Secondly, the theory of substantive participation suggests that forms of citizen participation in social affairs and expression of political demands can manifest in both political participation in social affairs and in daily consumption and lifestyles. An environmentally friendly lifestyle can express support for environmental protection issues, and conversely, the use of environmentally friendly technologies can be interpreted as users starting to participate in and support environmental protection. Primary participation can gradually induce citizens to engage in deeper substantive participation (Marres, 2012). Therefore, we believe that residents' installation and use of household photovoltaics will make them environmental participants, thereby encouraging them to engage more deeply in other pro-environmental behaviors.

Lastly, the theory of learning by doing suggests that practice is a very effective form of learning, and learning can change people's attitudes and actions (Walters and Holling, 1990). Installing and using household photovoltaics involves changes to users' living environment, and daily management and maintenance can be seen as green practical activities. Through continuous green practices, users can develop the effect of learning by doing, shaping their environmental attitudes and behaviors, and further influencing them to engage in more green practices.

Based on the theoretical analysis above, we can deduce the feasibility of generating pro-environmental spillover effects from residents' installation and use of household photovoltaics, theoretically demonstrating the viability of this topic. Building on the possibility established in theory, we can further develop our research plan based on grounded theory. It is worth mentioning that although the implementation of grounded theory does not require preconceived theoretical frameworks, the aim of grounded theory is to generate theory. Therefore, when explaining the theoretical implications of the theories generated in this study, we will still rely on existing literature and theory for clarification.

3.2 The connotation and extension of household PV use

The concept of household PVs discussed in this study refers to the installation of distributed PV systems on household buildings, through which residents can benefit financially (Wang et al., 2021). Similar concepts can be found in domestic and international literature, with three commonly used terms: household PV, roof PV, and distributed PV. Roof PV and distributed PV can be installed on the roofs and walls of household properties as well as non-household properties such as factories and office buildings. Compared to roof PV and distributed PV, distributed PV offers more flexibility in terms of installation areas, encompassing not only roofs and walls but also areas such as carports and RV roofs, making it a broader concept. On the other hand, household PV mainly refers

TABLE 1 Outline of open interview.

Order	Interview topic	Main content summary
1	Demographics	Gender, age, education, average annual income of family members
2	Information on the installation and use of household PVs	The time, form, investment, and income of household photovoltaic installation
3	The benefits felt during use after installing household PVs	Benefits include various economic benefits and convenient living conditions
4	Disadvantages felt during use after installing household PVs	The downside includes: everything you are concerned about
5	Has the installation of household PV subtly improved farmers' awareness of environmental protection during use	Changes in cognition, knowledge, skills, perception, etc
6	Changes in Production and Life of Farmers after Installing Household PVs	Changes in plans and behaviors

to the installation and use of distributed PV systems on the roofs and walls of household properties owned by residents. The objective of this research is to explore the influence of residents installing and using distributed PV on their environmentally friendly behaviors, focusing on the general population. Therefore, in this study, we adopt the concept of household PV to provide a more accurate description.

In alignment with the research questions and objectives of this study, the concept of household PV includes the following aspects: first, the study focuses on the general population; second, it includes households (and their members) that have installed distributed PV equipment on their household roofs and walls.

In addition to the aforementioned aspects, based on related literature and news reports, there are currently four main forms of household PV installation in China: 1. Installing a household PV system for self-consumption, where residents not only install PV systems but also energy storage systems, and the generated electricity is primarily used for household consumption. 2. Selling the electricity generated by the household PV system to the grid company by signing a grid connection agreement. 3. A mixed mode where residents first consume the electricity generated by the household PV system and sell the surplus electricity to the grid company. Additionally, there is a fourth mode: 4. Renting rooftops to third parties for the installation of PV power stations, from which residents receive rental income (Wang et al., 2023). Although in this case residents do not directly use the PV power station, they benefit from its installation, and some residents sign power purchase agreements with the third party. In this scenario, residents rent out their rooftops to the third party, who installs distributed PV power stations on them, and residents then purchase electricity from the third party. The third party is responsible for the daily maintenance of the PV power station and thus requires communication and negotiation with the residents. Therefore, we also include residents in this situation within the scope of our study.

3.3 Data and research methods

3.3.1 Data

Once the qualitative research is initiated, the primary task is data collection. When the research team adopts theoretical sampling, they will determine interview subjects guided by expected theoretical developments. In selecting interview subjects, the following factors are primarily considered: Firstly, areas with a higher number of installed household PV systems are chosen to ensure an adequate number of interview samples for this study. Secondly, the research team possesses sufficient social resources to engage in these interview areas. Additionally, due to the vast geographic expanse of China and dialectical differences between regions and even villages (Jiang and Troyan, 2022), the selected areas and corresponding interview subjects need to facilitate communication for the research team members. This means that the research team should be able to at least understand the dialect used by the interview subjects. Lastly, the selected research areas and subjects should also contribute to a smooth implementation of the research team's investigation.

Based on these principles, we initially consider selecting areas familiar to us and areas familiar to team members as interview subjects and research areas. Based on this consideration, we have chosen Jiashang village in Dongdi Township, Bijie City, Guizhou Province, and Gongshang village in Wuchong'an Town, Qian'an County, Hebei Province as research sites. We chose Jiashang village because it is one of the assistance recipients from the Revolutionary Committee of the Chinese Kuomintang (MinGe, in short) which is one of the eight major democratic parties in China, dedicated to poverty alleviation and providing free installation of household PV systems for the villagers. According to reports (2022), many households in the village have already installed household PV systems (Information, 2022). Furthermore, the village is adjacent to Qixingguan District, Bijie City, where three team members are located, with a distance of less than 120 km. Additionally, we chose Gongshang village in Wuchong'an Town, Qian'an County because a significant number of PV systems have also been installed in that village (Time, 2022), and it is an area familiar to some members of our team. The village is less than 300 km away from China University of Mining and Technology (Beijing), where the three authors are studying. The selection of these two research sites also takes into account the factor of north-south distribution, facilitating the collection of interview samples from different regions on the basis of convenience and feasibility, thus enriching the information collected.

Given that the installation and use of household PV systems are intrinsic to household behavior, their decision-making and implementation are often carried out by household members

TABLE 2 Demographic characteristics.

Item	Attribute	Number of samples (48)
Gender	male	23
	female	25
Age	25–30	15
	31–36	19
	37–42	7
	Above 43	7
Education level	Associate degree and below (including associate degrees)	28
	Undergraduate degree (including self-study examination)	19
	Graduate and above	1
Average annual income of family members	¥Below 12,000 yuan	2
	¥12001–30000	8
	¥30001–50000	19
	¥50001–100000	13
	¥Above 100001 yuan	6

who possess a certain level of dominance and decision-making power. Therefore, our interview subjects primarily target residents between the ages of 20 and 60. Individuals within this age range typically have a clear understanding of the professional questions raised during the interviews and can provide relevant answers. We will recruit interview subjects through personal connections, similar to a snowball sampling method, to conduct the interviews. In conducting in-depth interviews for qualitative research, it is often necessary to maintain an open attitude and not necessarily adhere to fixed content. However, it is still important to design an interview outline to prevent the conversation from deviating too much. Therefore, this study has designed an interview guide as shown in Table 1. In relation to this interview guide, the following examination and introduction are provided in this article. The first question pertains to general interview requirements, asking respondents for demographic information including gender, age, level of education, and average annual household income. This question is structured and requires respondents to fill in the information themselves. The second and sixth questions are relevant to the purpose of this study. The main objective of this research is to explore the role and impact of household photovoltaic (PV) installation on low-carbon behaviors. Therefore, the second question aims to understand the situation of household PV installation and usage, while the sixth question focuses on understanding users' low-carbon behavior. However, due to the intertwining of production and daily life in rural areas in China, making it difficult to distinguish between the two (Wu et al., 2023), we adopt an open attitude when asking questions. We also try to avoid deliberately leading residents to elaborate on changes in their agricultural production. Hence, we choose to broaden the scope of the interview and mainly inquire about the changes in participants' lives after installing household PV systems. The third and fourth questions mainly involve the user experience of the respondents. According to studies by Bénabou and Tirole, the experience of previous behaviors can influence the motivation for subsequent actions (Bénabou and Tirole, 2004) in the context of spillover effects in pro-environmental behavior. Therefore, this study includes questions related to the user experience of household PV systems. The fifth question primarily explores the changes in participants' inner worlds after using household PV systems. Literature on behavioral spillover suggests that previous behaviors shape the inner world of actors, thus influencing the intensity of subsequent actions (Van den Broek et al., 2017).

During the period from 25 November 2022, to 15 March 2023, we conducted interview work in Jiashang village, Dongdi Township, Bijie City, Guizhou Province, and Gongshang village, Wuchong'an Town, Qian'an County, Hebei Province. These interviews resulted in a collection of over 30,000 words. However, we found that the interviewed subjects exhibited similarities in terms of their living environment, household income, occupation, education level, and rooftop PV installation. Taking Jiashang village in Bijie City, Guizhou Province as an example, the area is relatively poor, mainly cultivating corn, potatoes, and rice. The average annual income for households ranges from 10,000 to 30,000 RMB. The installation of household PV systems for residents was all conducted for free through assistance from the Revolutionary Committee of the Chinese Kuomintang (MinGe), following the "self-use with grid connection" model. Therefore, the interview content also showed certain convergence. For instance, in Dongdi Township, Guizhou Province, due to its mountainous location and hot and humid climate, local residents mainly rely on traditional agricultural tools for farming and demonstrate less interest in substituting fuel-driven tools with electric ones. Conversely, in Gongshang village, Wuchong'an Town, Qian'an County, Hebei Province, located in a plain area, the households showed a higher level of interest in this regard. Additionally, due to the weaker sunlight levels in Guizhou Province, residents in that area hold a cautious attitude toward the benefits of PV installation, with a significantly lower level of acceptance compared to residents in Gongshang village, Wuchong'an Town, Qian'an County.

During the on-site interviews, we found that female households were more willing to participate in in-depth interviews and provide more information. We collected a total of ten on-site interview samples, with only two records from male respondents. This may be because men are generally less inclined to engage in lengthy conversational interviews compared to women. Additionally, we discovered that residents who installed household PV systems would often establish a dedicated WeChat group for discussing PV installation, usage, and maintenance. To expand the sample coverage, we changed our strategy and designed a semi-structured online questionnaire, which we distributed through WeChat groups where we had established a certain level of trust with the residents. In addition, we provided cash incentives to participants. Ultimately, we collected 38 online questionnaire samples, covering areas such as Shandong, Shanxi, Hebei, Liaoning, Fujian, and Guangdong. Through this approach, we obtained more data from male respondents as well. Combined with the data from on-site interviews, we compiled a total of 48 interview materials, exceeding 90,000 words. The demographic information of the collected samples is presented in Table 2.

In the process of organizing and collecting the aforementioned data, we fully respected the wishes and privacy of each interviewee. The interview content did not touch upon the interviewees' health or other sensitive topics. Before each interview, we clearly explained the purpose of the interview, and all interviewees participated voluntarily. To protect the privacy of the interviewees, we assigned a unique identification number to each interviewee, rather than disclosing their names (except for cases of familiar face-to-face interviews where providing name information was not necessary for other interviewees). The numbering rule is as follows: serial number - year of visit + initials of the capital letter of the province + initials of gender + age + installation year and month. For example, 1-2022GZM33202004 represents the first interviewee, visited in the year 2022, located in Guizhou province (GZ), male (M), aged 33, with the installation taking place in April 2020. This numbering system facilitates data processing.

3.3.2 Research methods

In social science research, there are often three methodological positions: positivism, constructivism, and critical theory. Positivism is the most common methodological position, emphasizing the revelation of objective reality and facts through observation and empirical research. It advocates the application of scientific methods in both social and natural sciences, aiming to construct knowledge through quantitative data and empirical evidence. Correspondingly, the current use of quantitative research methods in the social science field represents the positivist paradigm, emphasizing neutrality, objectivity, and verifiability in research conclusions. Commonly used methods such as Likert scale questionnaire surveys, statistical analysis, game theory, and quantum entanglement fall into this category (Sullards et al., 2007; Yu et al., 2023).

Constructivism, on the other hand, emphasizes that our understanding of reality is formed through social and individual interactions and subjective interpretations of experiences. It believes that knowledge and meaning are constructed and shaped through the interaction of individuals and society. In correspondence with this standpoint, qualitative research methods have emerged under the constructivist paradigm. These methods focus on the description and interpretation of phenomena, obtaining detailed specific information through in-depth observation, interviews, and textual analysis, revealing underlying meanings and implications. Specific methods derived from qualitative research include ethnography, narrative research, and grounded theory (Hatch, 1996; Timmermans and Tavory, 2012).

Critical theory primarily focuses on studying issues related to social power distribution and social institutional structures (Fàbregues et al., 2021; Ryba et al., 2022). However, as it is not relevant to the scope of this article, it will not be further discussed.

The main objective of this study is to investigate the changes in rural residents' production modes after installing household photovoltaics (PV). It is necessary to extract key factors from the residents' life experiences in using household PV and construct corresponding theoretical models. Hence, we adopt a constructivist standpoint. Qualitative analysis under the constructivist paradigm is a process of examining and interpreting data aimed at discovering meaning, enhancing understanding, and developing experiential knowledge. It commonly employs research techniques such as observation and in-depth interviews, making it an exploratory research method (Zhou et al., 2023). Through these open-ended research activities, researchers comprehensively collect primary information relevant to the research subjects and content, and use inductive methods to interpret and analyze the data, revealing the underlying reasons behind visible phenomena (Bleiker et al., 2019. Through such exploration, we can investigate the causes and significance behind social phenomena and formulate relevant theories (Mcgowan et al., 2020). Unlike quantitative research methods, qualitative research focuses more on serendipitous discoveries and exploring patterns in unstructured information (Chen and Liu, 2023). The impact of household PV on the production and daily lives of rural residents is the result of complex factors and interactions between residents. This outcome is influenced by various factors (Grilli and Curtis, 2021). To better adapt to the characteristics of rural residents in China installing and using household PV, and to overcome the limitations of solely extracting research variables from literature, this study will collect residents' life experiences data through field interviews. Exploratory qualitative analysis techniques will be applied to extract the production and lifestyle changes brought about by rural residents installing and using household PV, gradually constructing a comprehensive theoretical model.

In qualitative research, the Grounded Theory method proposed by Glaser and Strauss (1967) has been widely applied and considered as one of the cutting-edge methods in qualitative research (Glaser and Strauss, 1967). Grounded Theory is an experiential-based method for theory construction used in data analysis and induction in qualitative research. As shown in Figure 1, practitioners of Grounded Theory derive concepts and categories through direct observation and raw data, gradually refining them into core concepts that reflect specific social phenomena, and construct relevant social theories based on the inherent relationships between these concepts. Strauss and Corbin (1994) divided the Grounded Theory method into three steps: open coding, axial coding, and selective coding. In the open coding phase, collected data is categorized, inducing concepts that describe the

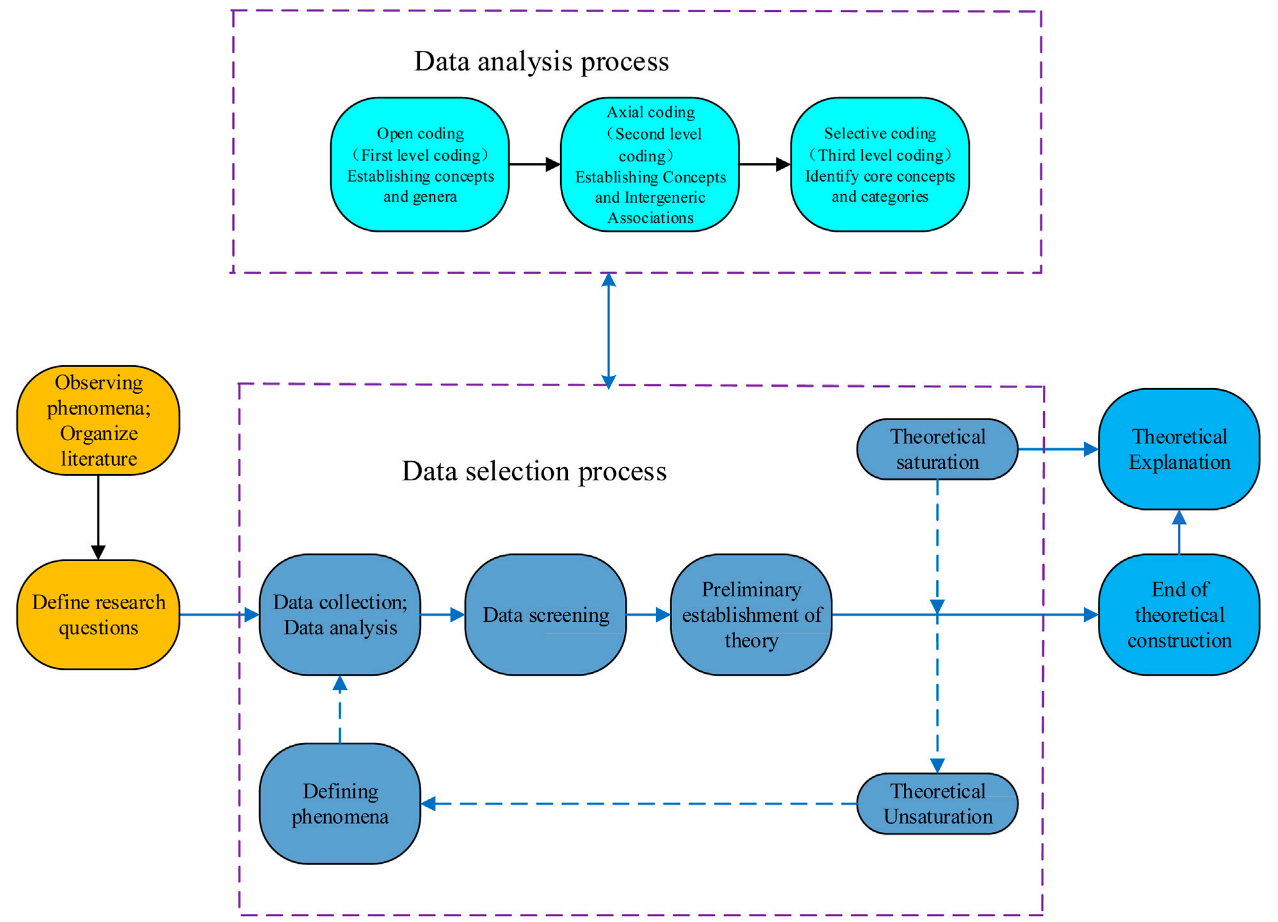

FIGURE 1
Flowing chart of the grounded theory.

phenomenon, and further categorizing them. The axial coding phase explores the relationships between categories and subcategories to form core categories. The selective coding phase involves extracting core categories, further refining extracted concept categories, and selecting a central category for subsequent analysis of related codes, concepts, and categories (Strauss and Corbin, 1994). Due to its advantages in theory construction, many scholars have adopted this method as the primary means for qualitative research (Gullo and Beachum, 2020).

After organizing and validating the interview records, following Bowen's recommendation (Bowen, 2008), we plan to conduct grounded coding analysis on 70% of the samples and reserve the remaining 30% for saturation testing. We collected a total of 48 samples, and approximately 33 samples, representing 70%, will be used for grounded coding analysis, while the remaining 15 samples will be used for saturation testing.

There are four common forms of household solar panel installation: 1) leasing the roof to a third party for installation; 2) self-installation and grid connection, selling electricity back to the utility company only; 3) installation with energy storage mainly for self-consumption; and 4) self-consumption with grid connection, selling electricity back to the utility company. Among the respondents, only one person adopted the "self-installation and grid connection, selling electricity back to the grid" approach, and only four people adopted the "installation with energy storage mainly for self-consumption" approach. Although these two types of residents are relatively small in number, they represent different installation forms, so we will include them in the grounded coding of the selected 33 interviewees. The remaining 28 interviewees and the 15 interviewees for saturation testing will be randomly selected. To ensure the rigor and effectiveness of the study, we will strictly follow the three-stage process of grounded theory for standardized coding. In addition to individual coding, we will actively consider expert opinions to jointly establish concepts and categories, establish logical relationships between concepts, and reveal core categories, drawing upon multiple sources of wisdom.

4 Research results and analysis

In the implementation process of the Grounded Theory research approach, we followed the high-frequency academic vocabulary mentioned in existing literature and theoretical foundations to describe the concepts in the grounded interviews. Furthermore, we investigated the logical causal relationships between the core categories and main categories. For contentious concepts and categories, we engaged five professional researchers, each with expertise in distributed photovoltaics and rural agriculture, to

TABLE 3 Correspondence and relationship connotation between main category and sub category of spindle encoding.

Order	Main category	Subcategory	Relationship connotation
1	Installation and use of household PVs	Only for self-use in power generation	In this study, the term "installation and usage" is broadly understood to include any households that have installed distributed photovoltaic power stations on their rooftops. Based on interview data and relevant news reports, it is evident that the installation of rooftop distributed photovoltaics by households can be categorized into four main forms. Firstly, some households rent out their rooftops to third parties for the installation of distributed photovoltaic power stations, while only collecting rental fees themselves. Secondly, some households install distributed photovoltaic systems solely for self-consumption. Thirdly, some households install distributed photovoltaic systems and sell the generated electricity to the power grid company. Lastly, there are cases where households both consume the generated electricity for self-use and sell the excess electricity to the power grid, combining both the second and third forms
		Only connected to the grid for electricity sales	
		Rental roof	
		Self-consumption plus selling electricity	
2	User Experience	Value Experience	In the context of user experience, both value experience and risk experience can be explained using consumer value theory and the Information-Processing Model. Consumer value theory suggests that consumers perceive the value of a product or service based on their evaluation of factors such as price, quality, and other related aspects. Specifically, consumers consider different dimensions of value, including economic value, functional value, emotional value, and social value, to form their own value experience (Zeithaml, 1988). In this study, we specifically refer to the perceived economic value and utility value that users perceive when installing and using household PV systems
		Risk Experience	On the other hand, risk experience can be related to the concept of perceived risk in the Information-Processing Model. Perceived risk refers to an individual's subjective perception and evaluation of potential risks associated with specific information or decisions (Lee et al., 2021). In the context of this study, we specifically refer to the quality risks associated with household PV systems, the engineering risks associated with installation, policy risks arising from uncertainties in relevant policies, and the potential safety risks during the use of household PV systems that users perceive after deciding to install them
			Therefore, user experience encompasses both the perceived value experience and risk experience, which can be explained using consumer value theory and the Information-Processing Model
3	Green self-efficacy	Environmental cognition	The concept of "Green self-efficacy" originates from the sociocognitive theory of self-efficacy and refers to an individual's perceived effectiveness in taking actions related to environmental protection or sustainable development. It involves the subjective assessment of an individual's influence and effectiveness regarding their environmental behavior. In simple terms, Green self-efficacy is the belief that individuals have in their ability to generate positive impacts through environmentally friendly actions (ER-Chen et al., 2015). Generally, individuals with more resources and greater proficiency in environmentally friendly practices tend to possess stronger Green self-efficacy (Hay et al., 2013)
		Environmental resources	In the context of this study, it refers to household PV system users enriching their environmental awareness through the installation and usage of such systems. Additionally, the installation of household PV systems empowers users with the ability to produce clean energy, which falls under the category of environmental resources. The improvement in environmental awareness and possession of more environmental resources than the average person can lead to higher Green self-efficacy among users compared to others
4	Low carbon production behavior of farmers	Resources recycling	Farmers' low-carbon production behaviors can be defined as the actions taken by farmers during agricultural production aimed at reducing greenhouse gas emissions and minimizing energy consumption. These behaviors include, but are not limited to, the following aspects
		Electrification of agricultural tools	1. Energy conservation: For example, using efficient agricultural machinery, optimizing energy usage schedules, and selecting low-energy-consumption equipment
			2. Optimal fertilizer management: Adopting scientific fertilization techniques, properly allocating fertilizers, and avoiding excessive or wasteful application
			3. Smart water resource management: Using water-saving irrigation techniques to reduce wastage of water resources in farmland
			4. Recycling of agricultural films: Proper use of agricultural films and recycling and reusing of discarded films
			5. Reduction of greenhouse gas emissions: Implementing measures to reduce greenhouse gas emissions in agricultural activities, such as managing livestock manure

(Continued on following page)

TABLE 3 (*Continued*) Correspondence and relationship connotation between main category and sub category of spindle encoding.

Order	Main category	Subcategory	Relationship connotation
			more efficiently, and reducing methane emissions caused by certain rice field drainage methods (Du et al., 2023)
			In this study, the focus is primarily on farmers' behaviors related to resource recycling and the adoption of clean energy utilization, such as electrification of agricultural tools, during the agricultural production process

organize and revise the interview data. The purpose of this approach was to avoid the subjective influence of the coders' opinions on the coding results, thereby enhancing the objectivity and persuasiveness of the coding.

4.1 Open coding: extracting concepts and categories

We conducted our work following the coding steps of Grounded Theory. Firstly, we performed open coding by breaking down all the data materials used for theoretical construction. Each member of the research team then individually extracted concepts and categories (further conceptual induction) from the data. During this process, we required team members to summarize the frequency of concepts and provide a list of the frequency of concept occurrence, theoretical basis for concept and category extraction, and typical statements. After each member completed their coding, the team leader oversaw the coordination and summarization of all members' coding results. In cases where consensus on concepts and categories could not be reached, discussions were held until agreement was achieved (Walker and Myrick, 2006).

Among the participants, only one person adopted the form of "self-installation, solely selling to the grid," while only four individuals chose "installation of energy storage system, primarily for self-use of photovoltaic electricity." Although these two types are less commonly adopted by households in reality, they represent different installation forms and are considered representative. Other codes followed the selection criteria from relevant literature (Luca et al., 2022). The research team eliminated initial concepts with an occurrence frequency below four and removed ambiguous statements and initial concepts expressed in the original data. The deleted concepts were saved in a separate document for preservation. If any concept appeared more than five times (inclusive) during the process of testing theoretical saturation, it was treated as a new concept for theoretical construction.

Through the efforts of the research team members, we eventually compiled 680 original descriptive statements along with corresponding initial concepts. To facilitate coding organization and synthesis, each code was assigned a number using the sample number and code number format. For example, 24–8 represents the eighth code in the interview record of the 24th sample. The research team further refined and consolidated lower-level and cross-complex initial concepts, achieving categorization of the initial concepts. There were four installation forms of household PVs, which underwent related coding operations in NVivo12 software. Ultimately, 12 initial categories were abstracted, namely: 1. Forms of household PV installation, 2. Economic benefits provided by household PVs to farmers, 3. Utilitarian value provided by household PVs to farmers, 4. Concerns about the quality of PV equipment, 5. Concerns during the installation and construction process of PV equipment, 6. Concerns about policy changes after PV installation, 7. Concerns about potential safety risks during the use of PV equipment, 8. Environmental awareness, 9. Environmental knowledge and skills, 10. Clean energy independence, 11. Price advantages of clean energy, 12. Behavioral changes. Appendix1presents the initial concepts obtained from the original interview records, as well as some initial categories. Due to space limitations, only typical statements corresponding to the initial categories are provided in this paper.

4.2 Axis coding: select the main category

The purpose of my open coding was to discover categories, and the next step was axial coding. The purpose of axial coding was to establish connections between different categories and develop core categories. In this stage, we utilized the grounded theory's axial coding analysis method, following the paradigmatic analysis model of "causal conditions—phenomenon—context—intervening conditions—action strategies—consequences." In the paradigmatic analysis, we initially assumed the existence of certain relationships between categories and then used relevant data to validate this idea. The specific approach involved clustering the categories developed during the open coding stage and analyzing whether there were potential relationships between these categories, in order to develop and establish logical connections among independent categories (Walker and Myrick, 2006).

Through axial coding analysis of 20 concepts and 12 initial categories, as shown in Table 3, we obtained four core categories. Table 3 presents these four core categories, ten subcategories, and the contextual implications corresponding to each core category.

4.3 Selective encoding

The primary objective of selective coding is to establish connections between categories identified during the axial coding phase, and further identify the core category. This process involves summarizing the relationships and contextual conditions between the core category, main categories, and other categories, also known as the "storyline" or typical relational structure (Walker and Myrick, 2006). By elucidating these relationships and contextual conditions in the form of a storyline, a new theoretical framework is developed to answer questions such as "which factors are involved, where, how, why, and with what consequences?" (Creswell, 2013).

Through further analysis of the original interview records and careful comparison of each piece of data, combined with the three

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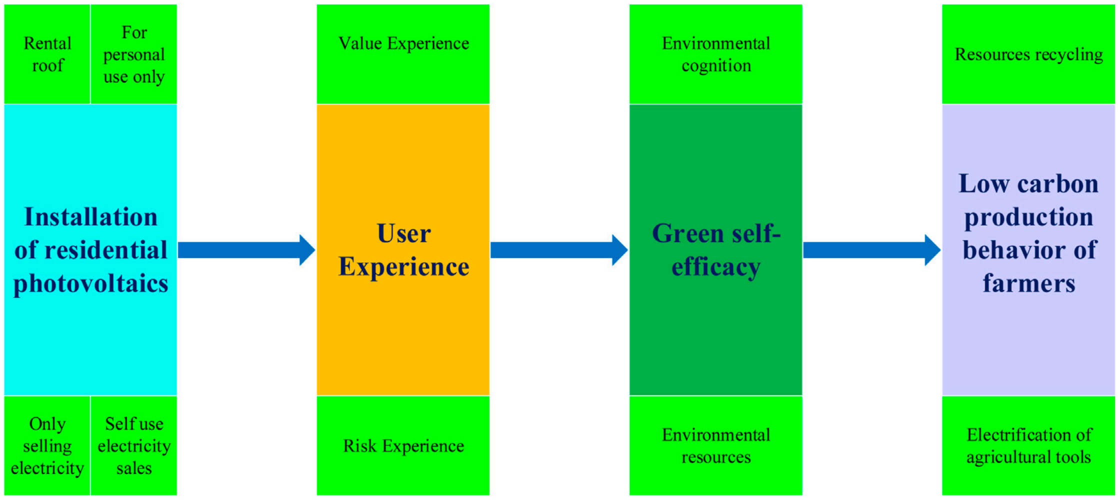

FIGURE 2
Mechanism of household PV-driven low-carbon agricultural production behavior.

TABLE 4 Core categories and typical relationships of selective encoding.

Core categories	Typical relationship structure and frequency	Typical sentence citation
Mechanism of formation of green self-efficacy	Adopting photovoltaics →User experience (192)	12–10: After learning how to use and maintain photovoltaic equipment, I am very happy when there is a profit. I think it has many positive aspects. After all, having profit is not only beneficial but also environmentally friendly
		13–4: Currently, the impact is mostly positive. The only downside is that I can no longer install it on the rooftop. On the bright side, it brings in extra income and reduces expenses
	The interaction between perceived value and perceived risk. (72)	12–5: In recent years, during the Spring Festival period, Shandong Province has refrained from purchasing electricity and required distributed photovoltaic system owners to participate in peak shaving. Later, we installed an energy storage system to facilitate self-consumption of the generated electricity
		16–4: Whether the product lifespan can actually exceed 20 years as advertised, and if the quality remains unchanged over that period, it would indeed be a very cost-effective investment
	User experience→ Acquisition of green self-efficacy. (153)	3–4: We also pay attention to changes in national environmental policies. For example, when the national subsidies were canceled last year, we were very concerned. We also compare various policies currently being implemented in rural areas, such as the straw burning ban and recycling policies. We hope that various policies can be relatively stable, and even if there are changes, it would be preferable to have a transition period
		1–2: My understanding of environmental protection concepts has deepened, and I have gained a lot of knowledge about environmental conservation, such as understanding what greenhouse effect is and why clean energy development is necessary
Mechanism of how green self-efficacy promotes farmers' low-carbon production behaviors	Acquisition of green self-efficacy → Farmers' low-carbon production behaviors. (153)	15–15: I used to work as an electrician, and I observed that installing solar panels is not that difficult. I plan to install solar panels in my own fish pond to generate electricity for powering the aeration system
		6–15: Now that electricity is more convenient, I plan to buy a power-driven straw shredder for straw crushing and returning it to the field

TABLE 5 Evidence of original statements for theoretical saturation verification.

Original sentence code	Main category	Subcategory	Original sentence reference example
47–1	Installing Photovoltaics	Self-consumption plus selling electricity	Both self-consumption and selling excess electricity to the grid company
48–5	User Experience	Value Experience	The neighbors who have installed household solar panels often communicate and share information about power generation and selling electricity to the grid. We have created a WeChat group to discuss the installation and usage of household solar panels
47–5		Risk Experience	In the past 2 years, I have been worried that during certain peak and off-peak periods, the grid may refuse to purchase electricity, so I have to equip myself with an energy storage system and increase my investment. It feels like the grid is shifting the burden of energy storage onto ordinary users
48–10	Green self-efficacy	Environmental cognition	After installing solar panels, I have gained a more detailed understanding of the country's low-carbon environmental policies. I have started to feel empowered to address some environmental issues myself, such as building a biogas digester or composting
46–3		Environmental resources	I recently learned about our country's green certificate trading system and I hope that small-scale distributed power stations like ours can also participate in green certificate trading. It would be beneficial to earn additional income each year
48–8	Farmers' low-carbon production behaviors	Resources recycling	My home has a vegetable greenhouse, and it is inconvenient for us to access water here. I plan to install a drip irrigation system in the vegetable greenhouse to make it more convenient, labor-saving, and save water resources
45–5		Electrification of agricultural tools	This household solar power system is actually more convenient for commercial use. I want to buy an electric rice mill that can not only help with dehusking our own rice but also assist our neighboring residents, while also earning some extra income

questions proposed in the introduction, this study found that the primary storyline of "Installation of household PVs—User experience—Green efficacy perception - Changes in low-carbon agricultural production behavior" accurately explains the changes in rural households' agricultural production behavior after installing and using household PVs. It should be noted that this study discovered that in the vast rural areas of China, production and daily life are not completely separated, as in urban households. Rural homes in China often have self-built vegetable gardens, fish ponds, and other facilities, as well as agricultural facilities such as pigsties and mushroom cultivation rooms nearby. While cooking in the kitchen, rural households may also prepare feed for pigs and even raise chickens and ducks. Vehicles in rural areas can be used for both daily life and production purposes. Therefore, we believe that the boundary between production and daily life is not clear in Chinese rural households. Although some production activities also take the form of lifestyle choices, we have unified them under the category of production behavior. Based on the mechanism constructed through the storyline, we refer to it as the "Household PV-Driven Low-Carbon Agricultural Production Behavior" model. This model explains that after households start installing household PVs, the gradual formation of green self-efficacy motivates some households to adopt low-carbon production behavior. We represent this process in Figure 2 and Table 4 divides the "Household PV-Driven Low-Carbon Agricultural Production Behavior" model into mechanisms for the formation of green efficacy perception and mechanisms for promoting low-carbon production behavior among households. It provides typical relational structures and typical quotes as evidence. The frequencies listed in Table 4 for the typical relational structures do not match the total number of codes mentioned earlier (680), as Table 4 only counts the number of codes related to the listed typical relational structures, totaling 570.

According to the research procedure of grounded theory, it is also necessary to conduct a theoretical saturation check on the research findings. Therefore, in the next section, we will proceed with this examination and in the following chapter, discuss and interpret the "Household PV-Driven Low-Carbon Agricultural Production Behavior" model based on interview data.

4.4 Theoretical saturation verification

This study conducted theoretical saturation verification using the remaining 15 sets of primary data, which comprised a total of 321 original statements. Following the procedures of grounded theory, open coding, axial coding, and selective coding were performed, comparing them with the concepts, categories, and relational paths derived during the theoretical construction process (including concepts that were previously excluded due to appearing less than four times). The aim was to explore the presence of new concepts, categories, main categories, core categories, and relational paths.

After data coding and analysis, no new concepts, categories, or relational paths were identified. The theoretical saturation verification was successfully completed, indicating theoretical convergence. Therefore, the previous grounded theory analysis results meet the requirements for saturation verification (O Reilly and Parker, 2012). Table 5 provides some representative original statements as evidence.

5 Theoretical elaboration

Chapter 4 constructs a model of household PV-driven low-carbon agricultural production behavior based on the research process of grounded theory. This model describes the process by which households transition from installing household PV systems to engaging in low-carbon agricultural production behavior. In Table 4 of Section 4.3, this mechanism is divided into two parts: the formation mechanism of green efficacy perception and the mechanism of green efficacy perception promoting low-carbon agricultural production behavior. This chapter will provide theoretical elaboration and discussion based on these two components.

5.1 Formation mechanism of green efficacy perception

According to Figure 2, the formation process of green efficacy is as follows: household installation of household PVs, followed by user experience, which in turn contributes to the formation of green self-efficacy. Firstly, let's analyze the formation of user experience. After households install household PV systems, they begin to use them, leading to the formation of user experience. User experience can be divided into two categories: value experience and risk experience. In this study, value experience primarily refers to the economic value and functional value, while risk experience includes the perception of four types of risks: quality, engineering, policy, and installation. First, we will interpret the value experience section.

Consumer value theory examines consumers' consumption behaviors and related decision-making processes, exploring the values and satisfaction pursued by consumers when purchasing products or services. Among these theories, a widely accepted consumer value theory is the "Customer Perceived Value Model" proposed by Zeithaml, which first appeared in a 1988 article. The model suggests that consumers' value experiences of products or services are based on their evaluations of price, quality, and other relevant factors. Specifically, consumers consider the economic value, functional value, emotional value, and social value across different dimensions to form their own value experiences (Zeithaml, 1988). Based on consumer value theory, the perceived economic value, functional value, social value, and cognitive value that households can perceive after installing and using household PV systems can be explained as follows: 1. Economic value: After installing and using household PV systems, households can experience economic value, including energy cost savings, reduced electricity expenses, and potential income from selling surplus electricity to the grid. 2. Functional value: After installing and using household PV systems, households can benefit from functional value, such as self-sufficient energy supply and reliability. PV systems convert solar energy into electricity, providing households with sustained and stable power supply, reducing dependence on utility companies. These explanations are based on consumer value theory and illustrate the economic value and functional value that households can perceive after installing and using household PV systems.

The risk experience is explained using the Information-Processing Model. The Information-Processing Model is a framework for understanding individuals' perceptions and attitudes towards risks. In this context, risk experience refers to individuals' subjective perception of the negative outcomes or losses that may result from specific behaviors, decisions, or situations. During the purchase decision-making process, consumers evaluate the level of risk and potential losses associated with a product or service. The concept of risk experience is widely applied in consumer behavior research, particularly in areas such as purchase decisions, brand choices, online shopping, and financial investments. By understanding consumers' perception of risks associated with a product or service, companies can take appropriate measures to alleviate consumer concerns and increase purchase intention (Lee et al., 2021). Household PV systems are durable products, and consumers gradually develop awareness of their risks during the usage process. Based on the qualitative research findings from Chapter 3, consumers may perceive the following four types of risks: quality risk, engineering risk, policy risk, and safety risk. 1. Quality risk: During the information acquisition stage, consumers may learn about aspects such as the quality, design, and manufacturing of photovoltaic system components. They may consider quality issues related to the reliability of components, performance stability, and manufacturer reputation. Such concerns can influence their risk experience regarding the quality of the photovoltaic system and might lead to concerns about system failures. 2. Engineering risk: Consumers gain knowledge about potential technical and procedural issues during the installation process of photovoltaic systems, such as incorrect placement selection, improper cable routing, connector failures, and grid connection problems. These issues can affect the operational efficiency and safety of the photovoltaic system. Consumers may perceive engineering risks associated with the photovoltaic system, worrying about potential problems during the installation process that could result in system malfunctions or safety hazards. 3. Policy risk: Consumers gather information about subsidies, tax incentives, and government support related to photovoltaic systems through various channels. However, policies can change, including reductions or eliminations of subsidies and modifications to tax policies. Such uncertainties can impact consumers' expectations of return on investment and their risk experience regarding the photovoltaic system. They may be concerned that policy changes could make the investment unprofitable or prevent them from achieving the expected economic benefits. 4. Safety risk: Consumers may become aware of safety hazards associated with the use of photovoltaic systems during the information acquisition stage, such as electrical equipment failures, fire risks, and electric shock hazards. They may be concerned about these potential safety issues, leading to a risk experience regarding the safety of themselves and their families, and they may need to take corresponding safety measures.

Household PV users typically engage in enhanced learning to mitigate potential harm once they perceive both value and risk experiences. This phenomenon can be explained through the Expectancy-Value Theory. According to this theory, individuals' decision-making processes are determined by two primary factors: expectancy effects and value judgments. Expectancy effects refer to individuals' expectations regarding the outcomes or consequences of their choices, including expectations related to success, failure, satisfaction, difficulty, and other aspects. Value judgments involve individuals' subjective evaluations of the importance or value of these outcomes or consequences, including their preference levels and significance for different outcomes. The Expectancy-Value Theory states that individuals' decision outcomes are the multiplication of expectancy effects and value judgments, in other words, determined by calculating utility values. In other words, individuals tend to choose options that produce the highest utility value. If a choice has both high expectancy effects and high value judgments, individuals are likely to select that option as the optimal solution (Eccles and Wigfield, 2020).

However, obtaining the optimal solution is not cost-free. In the process of installing and using household PV systems, there is an interaction between risk experience and value experience, which can be explained as the decision-making process of individuals in learning more knowledge and skills. When individuals perceive certain risks associated with the installation and use of household PV systems (risk experience), and at the same time realize that they can better cope with these risks and gain more benefits by learning more knowledge and skills (value experience), they are more likely to actively engage in the learning process. As individuals acquire more knowledge and skills, becoming more proficient, they move closer to the optimal solution. By learning more about household PV systems, individuals can enhance their awareness and understanding of system quality, engineering safety, policy changes, and other aspects, thereby reducing risk experiences and better pursuing their own interests. Therefore, they are more likely to proactively learn relevant knowledge and skills, in order to increase their gains and reduce potential risks.

The influence of value experience and risk experience on user experience can promote users' learning motivation. Additionally, using household PV systems and accumulating experience is a form of learning. This learning method is known as the Learning by Doing theory, which emphasizes the importance of practical involvement and experiential learning. Compared to solely relying on listening, reading, and observing, deepening understanding and cultivating skills through firsthand experiences and practice. Practical learning emphasizes practical application and problem-solving processes, where individuals can better comprehend concepts and principles and apply them to practice. Practical learning is often associated with interactivity, practicality, and feedback, which can facilitate individuals' active learning and autonomous development (Cai et al., 2022).

The phenomenon of improving households' green self-efficacy through the installation and use of household PV systems can be explained by the Learning by Doing theory. The theory refers to the process in which individuals gradually grow and develop within a social environment, forming self-efficacy and behavioral control capabilities. Firstly, through the installation and use of household PV systems, households can enhance their awareness and understanding of green energy. Understanding the principles and value of photovoltaic technology enables households to recognize the benefits of using solar energy as a renewable energy source and the positive impact of reducing reliance on traditional energy sources on the environment. This awareness stimulates an increase in households' environmental consciousness and strengthens their belief in engaging in environmental actions. Secondly, the installation and use of household PV systems can improve the skill levels and self-efficacy of households. Households need to learn the proper installation, operation, and maintenance of PV systems, which involve a learning process of acquiring a range of skills and knowledge. Through learning and practice, households can enhance their skills and gradually develop confidence and mastery in using photovoltaic systems. This self-efficacy inspires households to actively participate in and promote the use of green energy. Thirdly, the installation and use of household PV systems can yield tangible environmental benefits, further enhancing households' green self-efficacy. Through solar power generation, families can reduce their consumption of traditional energy, lower carbon emissions and pollutants, thus alleviating the burden on the environment. When households personally experience the positive impact of their actions on the environment, their sense of green self-efficacy is further heightened, motivating them to sustain their commitment to using and promoting green energy. Therefore, the Learning by Doing effect can be achieved through user experience, enhancing green self-efficacy. Overall, the installation and use of household PV systems have a positive impact on households' green self-efficacy in terms of cognition, skills, and environmental benefits. The Expectancy-Value Theory and the Learning by Doing theory can explain the increase in green self-efficacy resulting from enhanced environmental awareness among households. Finally, according to social cognitive theory, self-efficacy refers to individuals' confidence and ability assessment in accomplishing specific tasks or dealing with specific situations. Self-efficacy is closely related to individuals' self-esteem, self-confidence, motivation, and behavioral performance, and personal resource advantages can enhance individuals' self-efficacy (Denoble et al., 2007; Jordan et al., 2011). The installation of household PV systems can contribute to an increase in individuals' green self-efficacy. This is because the possession of more environmental resources, which aid in accomplishing environmental tasks, can boost individuals' confidence and enhance their evaluation of their abilities in the environmental domain. By installing household PV systems, rural users gain the ability to generate green electricity, granting them a distinct advantage in terms of accessing green resources compared to ordinary households. Consequently, we contend that the installation of household PV systems provides households with a heightened sense of green self-efficacy in comparison to the general population.

5.2 Mechanisms of green self-efficacy in promoting low-carbon production behavior among farmers

The promotion of low-carbon production behaviors among farmers through green self-efficacy can be explained by Hobfoll's, (1989). This theory suggests that individuals and organizations tend to protect existing resources and seek new resources to cope with challenges. Loss or lack of resources may result in negative impacts such as emotional stress, fatigue, and decreased efficacy. Therefore, individuals and organizations adopt a range of strategies to maintain, increase, and protect resources (Ye et al., 2021). Subsequently, the concept of resources has been expanded to include various individual characteristics, such as intelligence, self-efficacy, and optimism, representing the skills and traits individuals possess to resist stress (Hobfoll, 1989). Self-efficacy is also considered as a resource. Halbesleben et al. (2014) further deepened the meaning of this theory by stating that individuals with more initial resources are less likely to suffer resource loss and have greater ability to acquire new resources. Conversely, individuals with fewer initial resources are more prone to resource loss and have relatively weaker ability to obtain new resources. Initial resource loss triggers further resource loss, accelerating the development of the resource loss spiral and accompanied by stronger negative impacts. This is because individuals in a state of resource loss find it more difficult to engage in effective resource investment activities, thereby making it harder to prevent further resource loss. Additionally, under the influence of the "loss aversion" principle and accompanying tension and stress responses, individuals and organizations have fewer resources available in the stress cycle to prevent resource loss. The acquisition of initial resources contributes to the acquisition of subsequent resources, although the development of the resource acquisition spiral is relatively slower (Halbesleben et al., 2014).

According to the Conservation of Resources Theory and its implications, the green self-efficacy generated by farmers installing and using household photovoltaic power generation equipment is regarded as a personal characteristic resource. This implies that farmers are motivated to protect and enhance their green self-efficacy resource. Therefore, it can be inferred that a self-reinforcement effect occurs after farmers develop green self-efficacy. Specifically, individuals internalize experiences and behaviors related to green self-efficacy through self-reinforcement mechanisms and further strengthen and enhance this efficacy. When individuals achieve positive outcomes through engaging in low-carbon production behaviors, they are more motivated to continue these behaviors. These positive outcomes include resource conservation, economic benefits, reduced energy consumption, decreased dependence on traditional energy sources, and carbon emissions reduction. There exists a feedback loop between an individual's green self-efficacy and low-carbon production behaviors. More low-carbon production behaviors enhance an individual's green self-efficacy, further motivating them to engage in even more low-carbon production behaviors. This positive cycle strengthens an individual's confidence and willingness to participate in environmental protection actions, driving their active involvement in environmentally beneficial activities. By applying the Conservation of Resources Theory to explain the green self-efficacy generated by farmers installing household photovoltaic power generation equipment, we can better understand the decision-making process of individuals regarding sustainable development and environmental protection, deepening our understanding of their behavioral choices.

In this section, we have utilized five theories—Consumer Value Theory, Information-Attitude Model, Expected Utility Theory, Theory of Planned Behavior, and Conservation of Resources Theory—to provide a theoretical overview of the model of farmers' low-carbon production behavior driven by household photovoltaic energy. This establishes a theoretical foundation for our research findings. Subsequently, we will further discuss and analyze this model.

6 Conclusion and discussion

6.1 Conclusion

This research aims to explore the impact of promoting household PV systems on farmers' adoption of low-carbon production behavior in rural areas. It adopts a grounded theory approach, analyzing data obtained from 48 interviews and semi-structured questionnaires. The findings indicate that the installation and utilization of household PV systems by farmers can effectively promote their engagement in low-carbon production behavior. This influence primarily stems from user experience and the development of green self-efficacy. These factors are encapsulated within the proposed model of household PV-driven farmers' low-carbon production behavior, which addresses the three research questions outlined in the introduction: 1) the effect of household PV installation on farmers' agricultural production behavior; 2) the nature of this effect as facilitating; and 3) the specific mechanisms involved, namely user experience and subsequent development of green self-efficacy.

6.2 Discussion

In terms of the research topic, this study provides the first analysis of the mechanisms through which household installation of household photovoltaic (PV) systems promotes low-carbon production behavior among rural residents. While there are existing studies that have begun to examine the various impacts of renewable energy adoption in rural China (Dong et al., 2023; Yin and Zhao, 2023), exploring the influence of household adoption of PV systems on low-carbon production behavior from an environmental behavioral perspective is a novel contribution. The findings of this study offer a fresh policy approach for driving the green transformation of production practices among rural residents in China. It suggests leveraging the positive spillover effects and utilizing the "behavioral leverage" principle to promote the generalization of low-carbon production behavior among rural residents, while simultaneously promoting the widespread adoption of household PV systems in rural areas (Galizzi and Whitmarsh, 2019).

The process of behavior changes among farmers described in the model of low-carbon production behavior driven by household PV power bears similarity to the widely researched concept of "pro-environmental spillover behavior." However, previous studies have primarily employed theoretical deduction combined with quantitative empirical methods to examine individuals' pro-environmental spillover behavior, with limited qualitative research exploring and examining the literature on this behavior.

Existing research methods typically require abstract assumptions about human nature as a logical starting point during theoretical deduction. Starting from a self-interest perspective often leads to research conclusions that emphasize negative spillover, such as the moral licensing theory (Jordan et al., 2011) and the single-effect bias theory (Carrico et al., 2018). On the other hand, starting from an altruism-based assumption tends to yield research findings that support positive spillover, for example, the target activation theory (Thøgersen and Noblet, 2012) and the behavior consistency theory (Truelove et al., 2014).

The "moral licensing" theory suggests that individuals reinforce their moral self-image after engaging in environmentally friendly behaviors (Jordan et al., 2011). When faced with subsequent environmental decisions, individuals tend to provide themselves "moral rewards" as a way to exempt themselves from future inaction or even unethical behaviors (Truelove et al., 2014; Truelove et al., 2016). Alternatively, individuals may give themselves "moral credentials" to alter their negative understanding of engaging in subsequent morally ambiguous behaviors, thereby alleviating inherent pressure and discomfort caused by cognitive dissonance (Effron et al., 2009; Merritt et al., 2010). The "single-effect bias" theory suggests that individuals, after participating in environmental practices, tend to believe that they have done what is within their capacity, leading to "blind confidence" that reduces their perceived necessity and willingness to engage in subsequent environmental behaviors (Weber, 2006; Truelove et al., 2014).

The target activation theory posits that residents, after engaging in initial pro-environmental behaviors, experience the activation of their environmental goals as a result of these initial behaviors. In order to continue achieving their environmental goals, individuals continue to engage in pro-environmental behaviors (Thøgersen and Noblet, 2012). Emphasizing individuals' inherent inclination to maintain behavioral consistency (Bem, 1967), environmental self-identity is an essential motivational factor driving individuals to participate in various environmental behaviors (Whitmarsh and O'Neill, 2010). Furthermore, past environmental experiences enhance individuals' environmental self-identity (Van der Werff et al., 2014), and the stronger individuals' identification with environmentalism, the higher their perception of personal ecological norms (Van der Werff et al., 2013). As a result, their tolerance for cognitive dissonance caused by inconsistent behavior decreases (Thøgersen, 2004), making them more inclined to participate in subsequent environmental behaviors.

In conclusion, the model of low-carbon production behavior among farmers driven by household PV power exhibits similarities to the concept of pro-environmental spillover behavior. The integration of various theoretical perspectives enhances our understanding of the underlying factors influencing farmers' decision-making processes and provides valuable insights for promoting sustainable development and environmental protection.

The aforementioned theoretical approaches, characterized by extreme abstraction in their treatment of human nature, detach researchers from specific contexts. They consider either egoism or altruism assumptions as universal perspectives or standards, using them as logical starting points for research questions, similar to a "God's eye view." However, when we delve into the production and daily lives of farmers and understand their decision-making processes, neither egoism nor altruism can fully align with their decision-making processes. Overemphasizing egoism in individual decision-making portrays humans as extremely rational and selfish agents, which can lead to the naturalistic fallacy (Yang and Zhang, 2020). On the other hand, altruism assumptions, emphasizing environmental justice and moral values, overemphasize personal altruistic motives while neglecting individuals' selfish needs, violating limited morality assumptions and resulting in the moralistic fallacy (Irawan and Benius, 2022).

In reality, when we deeply understand the production and daily lives of farmers and their decision-making processes, neither egoism nor altruism can fully align with those processes. The decision-making processes of farmers are closely related to their knowledge, skills, cognition, and available resources. The installation of household PV systems can change these factors, allowing farmers to acquire more knowledge and skills, increase their awareness and understanding of environmental impact and sustainable development, and enhance their mastery of renewable energy resources. We categorize this change as an enhancement of green self-efficacy. Only by gaining an in-depth understanding of the production and daily lives of farmers and their specific decision-making processes can we authentically reflect their decision-making processes. Therefore, we employed qualitative research methods to investigate in detail the installation behavior of household PV systems among farmers and their low-carbon production behavior. This perspective is closer to an "ordinary person's viewpoint."

By conducting in-depth research on the installation behavior of household PV systems and low-carbon production behavior among farmers using qualitative research methods, we can more accurately reflect their decision-making processes and understand and promote the development of pro-environmental spillover behavior from a more realistic perspective. This "ordinary person's viewpoint" research method tightly connects researchers with the actual contexts of farmers, facilitating the formulation of practical recommendations to foster positive transformations in farmers' actual behaviors.

6.3 Managerial implication

The significant findings of this study offer valuable insights for guiding rural low-carbon production behavior and informing policy formulation. Drawing on system theory, which views the interactions among various elements as constituting a complex whole or system, external factors such as government policies have the ability to influence the system's background (environmental conditions) and subsequently impact the synergistic relationships among its elements (Uriona and Saartjie Grobbelaar, 2019). In the context of this study, a positive synergistic relationship is observed between farmers' adoption of household PV systems and their engagement in low-carbon production behavior. Therefore, policymakers can capitalize on this relationship to achieve positive policy outcomes. Adopting a system theory perspective, where the household PV-driven model of farmers' low-carbon production behavior represents the interplay of internal elements and government policy variables as external factors, governments can strategically allocate resources to these internal elements in order to steer the system towards more favorable outcomes. These resources can encompass financial subsidies, preferential taxation policies, information dissemination, knowledge enhancement, skill development, and more (Dong et al., 2019). Thus, policymakers can consider measures such as providing financial incentives or tax benefits to alleviate the economic burden associated with PV system installation, thereby further promoting farmers' adoption of low-carbon production methods. Additionally, the government can organize relevant training and educational activities, particularly focusing on the application of PV technology in agricultural production, to enhance farmers' technical capabilities and knowledge levels, ultimately enabling them to effectively utilize PV technology in their farming practices.

6.4 Practical implications

In light of the Chinese government's gradual reduction in subsidies for household PV systems (Wang et al., 2023), it is advisable to provide more comprehensive technical training to mitigate any potential negative repercussions resulting from subsidy reductions. These policies and measures can contribute to improved resource utilization efficiency among farmers, thereby driving low-carbon production behavior in rural areas. Consequently, this study offers critical insights for policymakers, aiding in the promotion of rural areas' transition towards a low-carbon economy and the achievement of sustainable agricultural development and environmental protection goals. Policymakers can adopt a systemic approach, viewing the household PV-driven model of farmers' low-carbon production behavior as an interplay of internal elements, and inject resources strategically to steer the development of rural low-carbon production behavior. Through effective policy design and implementation, positive changes in farmers' low-carbon production behavior can be facilitated, fostering sustainable agricultural development and achieving economic, social, and environmental cohesion.

7 Limitation and future work

This study employs qualitative research methods and data collection approaches, which warrant acknowledging certain limitations. Firstly, the sample size is relatively small, consisting of 48 interview records and semi-structured questionnaires, potentially limiting the representation of rural areas and thus constraining the generalizability of the research findings. Secondly, relying on self-reporting from farmers for data collection may introduce inherent subjective biases and information distortion. Furthermore, as the data used in this study primarily comprises interview data from household photovoltaic (PV) users in China, it is influenced by the specific language, policies, and culture of the Chinese context. Therefore, the conclusions drawn from this study may only be applicable within China. Lastly, this study solely focuses on the impact of household PV systems on farmers' adoption of low-carbon production behavior, without considering other potential influential factors such as socio-cultural and economic aspects. To enhance the model, future research endeavors could further refine these considerations.

To further advance research in this field, there are several potential directions for future investigations. Firstly, expanding the sample size and diversifying the research areas and participants would enhance the reliability and generalizability of the research findings. This could involve including more regions and a larger number of participants to capture a broader representation of rural areas. Secondly, employing a variety of research methods and data collection approaches, such as quantitative analysis and field observations, would provide a more comprehensive and objective understanding of the topic. Combining different techniques can yield richer and more robust research results. Additionally, considering the influence of other relevant factors, such as the policy environment and social capital, would contribute to a deeper understanding of the complexity and multidimensional mechanisms behind farmers' low-carbon production behavior. Examining how these factors interact and shape behavior patterns can provide valuable insights.

Furthermore, conducting longitudinal tracking studies on actual low-carbon production behavior following the installation and utilization of household PV systems would enable the evaluation of their sustainability and effectiveness over time. This longitudinal perspective would provide valuable information on long-term trends and impacts. Moreover, exploring specific policies and implementation strategies to promote rural low-carbon production behavior, involving government agencies and other stakeholders, is crucial for facilitating sustainable agricultural development and achieving environmental protection goals. Understanding the practical steps and interventions required to support farmers in adopting low-carbon practices would be beneficial in driving positive change. Finally, it has been shown that the combination of digital technology and new energy technologies can generate rich derived social effects in rural areas in China (Yu et al., 2022). Therefore, investigating the derived effects of promoting the combination of digital technology and new energy technologies in rural areas could also be considered as a next step in research planning. Overall, these proposed avenues for future research would help advance our knowledge in this field and contribute to the development of effective strategies that promote rural low-carbon production behavior.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

Ethics statement

The studies involving human participants were reviewed and approved by the Academic Ethics Committee of Guizhou University of Engineering Science (20 September 2022). Written informed consent to participate in this study was provide by the participants.

Author contributions

YW: Investigation, Project administration, Supervision, Writing–original draft. SW: Conceptualization, Data curation, Software, Writing–original draft, Writing–review and editing. RZ: Conceptualization, Methodology, Writing–original draft, Validation. HM: Supervision, Validation, Writing–review and editing. AH: Software, Writing–review and editing. JW: Formal Analysis, Investigation, Writing–original draft. BY: Formal Analysis, Validation, Writing–original draft. SF: Project administration, Software, Writing–original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenrg.2024.1297575/full#supplementary-material

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