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Impact of energy affordability on the decision-making of rural households in ecologically fragile areas of Northwest China regarding clean energy use

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Abstract

Background Highly carbonized energy use in ecologically fragile areas of Northwest China seriously endangers the health of residents and the ecological environment. However, poor energy affordability remains a major obstacle to the promotion of clean energy use in rural households in this region.

Methods Based on survey data of 1118 households in ecologically fragile areas of Northwest China, this study constructed a household-level database of energy use, measured energy affordability in two dimensions: endogenous income (annual per capita household income) and external inputs (government energy subsidies). It uses logistic and threshold regression to empirically test the impact, threshold, and heterogeneity of energy affordability on the decision-making of rural households regarding clean energy use for cooking, heating, and heating water.

Results (1) The energy use structures of rural households in different ecologically fragile areas differ because of different household characteristics. (2) Energy affordability affects cooking significantly more than it affects heating and subsidy growth is a stronger incentive than income growth. Moreover, for both cooking and heating, energy affordability has a greater impact on electricity use than on gas use. (3) The thresholds for energy transformation for heating are greater than those for cooking and heating water. When the subsidy increases by 2400 yuan/year, heating can catch up to other types of use, whereas, based on the current level of income growth, it requires more than 5 years. (4) This effect is higher in high-income, purely agricultural, highly educated, young, and middle-aged households.

Conclusions Promoting the use of clean energy in rural households only by increasing income will be a slow process. Subsidies should be used to accelerate this process by improving the energy affordability of rural households and a compensation policy should be implemented considering the energy types and periods. Taking into account the differences in the basic characteristics of rural households in different ecologically fragile areas, clean energy policies should be adopted from various perspectives to better leverage the enhancement effect of energy affordability.

Keywords Energy affordability, Ecologically fragile area, Clean energy, Decision-making regarding usage, Logistic regression

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Background

The heavy use of traditional solid energy sources such as coal and firewood has caused high emissions and pollution and the air pollutants emitted by their combustion have caused considerable damage to the ecological environment, hindering the sustainable development of the economy and threatening human health and life [1–3]. Conversely, clean energy involves considerably less exhaust gases and environmental pollution and is conducive to health, productivity, and the environment [4, 5]. However, the cost of clean energy is greater than that of traditional solid energy, which slows the process of replacing traditional solid energy, especially in economically lagging rural areas [6].

In China, Northwest China is the region with the lowest-ranked economy in the country and the affordability of energy for rural households in Northwest China is poor, hindering the promotion of clean energy [7, 8]. Traditional solid energy such as fuelwood and livestock manure are still the main energy on which rural households in Northwest China rely heavily due to their characteristics of "easy access and low cost" [9, 10]. However, poverty-stricken areas coincide geographically with ecosystems. Most rural areas in Northwest China are in ecotones, transition zones between different ecological systems. These transition zones in Northwest China include ecol. fragile areas, such as the Loess Plateau, the Northwest Arid Desert and the Qinghai-Tibet Plateau, which face poor ecosystem stability and limited natural recovery capacity [11]. Carbon-intensive energy consumption poses health threats to women, newborns, and elderly individuals in these ecologically fragile and seriously harm local ecosystems [12, 13]. Therefore, examining the influence of energy affordability on clean energy adoption decisions among rural households of ecol. fragile areas of Northwest China is imperative.

More than 30 years ago, Hughes-Cromwick indicated that affordability was the most important decision criterion for poor households [14]. Existing research has mainly measured the impact of energy affordability on endogenous income, such as income and assets [15, 16]. However, besides income, the energy affordability of rural households can be affected by government subsidies, which can increase income and lower energy prices compared with reference prices, effectively improving the energy affordability of rural households [17]. In addition, there is a lack of empirical analyses using data from ecol. fragile areas of Northwest China and the impacts of energy affordability have not been quantified in detail. Furthermore, the clean energy transformation of rural households is a multi-dimensional process involving cooking, heating, and producing hot water and there are differences in the current status of energy use with regard to different types of use; therefore, it is essential to analyze decision-making regarding clean energy use [6].

Given the above, we surveyed 1118 rural households in ecol. fragile areas of Northwest China and innovatively constructed a theoretical framework for energy affordability and decision-making regarding clean energy use in rural households from two dimensions: endogenous income (annual per capita household income) and external inputs (government energy subsidies). At the same time, a logistic regression model was used to empirically test the differences in the sensitivity of rural households to energy affordability and decision-making regarding different types of clean energy use, overcoming the shortcomings of existing studies. Based on this, a threshold regression model was used to explore the extent to which rural households would switch to clean energy when per capita annual household income and government energy subsidies increased. Finally, the heterogeneity of the impact of energy affordability on clean energy adoption decisions among different types of rural households was discussed to explore how energy payment capacity affects the clean energy usage decisions of rural households in ecol. fragile areas of Northwest China. This analysis aims to provide policy implications for the promotion and utilization of clean energy in rural areas of Northwest China, which is of great practical significance for energy transition, healthy sustainable development, and ecological environment improvement.

This study makes both theoretical and practical contributions to the literature. Theoretically, this study analyzes the impact of energy affordability from two dimensions, endogenous income and exogenous inputs, and discusses the influence of energy payment capacity during the clean energy transition process for different types of households. By broadening the research perspective and complementing the shortcomings of the existing literature, this study reveals the mechanism through which energy payment capacity affects the clean energy adoption decisions of rural households in ecol. fragile areas of Northwest China. Practically, this paper establishes a new household-level database that characterizes rural household energy use decisions in the ecologically fragile area of Northwest China. It explored the effects of energy payment capacity on clean energy adoption decisions from the perspectives of different decision-makers, income characteristics, and ecol. fragile areas. It also proposed clean energy promotion suggestions for different ecol. fragile areas to better leverage the enhancing effect of energy affordability. This provides support for the design and optimization of clean energy policies for rural areas in the ecol. fragile areas of Northwest China and has significant practical implications for energy transition, healthy sustainable development, and ecological

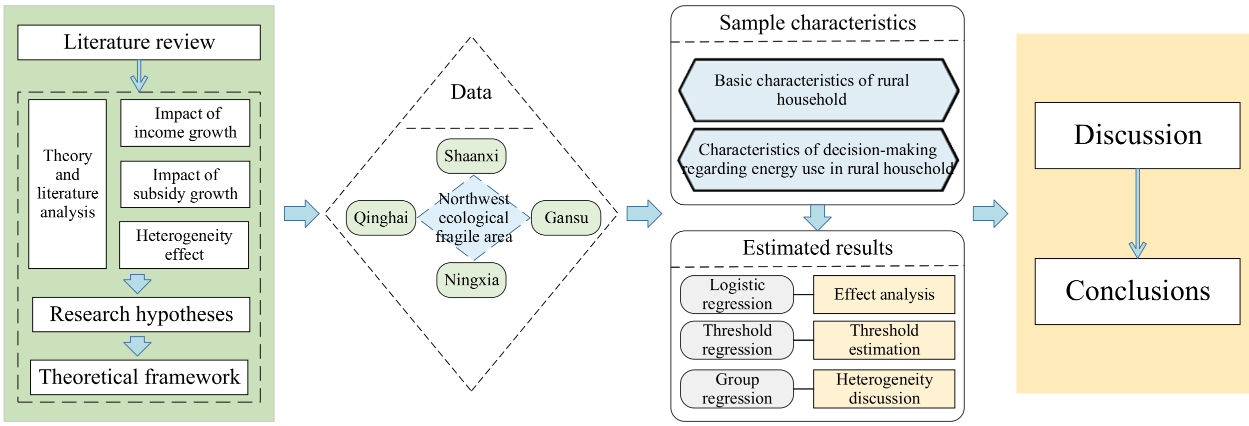

Fig. 1 Research framework

environment improvement in these areas of Northwest China.

The remainder of this paper is structured as follows (Fig. 1): Sect. 2 summarizes the existing literature; Sect. 3 presents the research hypotheses and the theoretical framework; Sect. 4 describes the data and research methods; Sect. 5 presents an analysis of the estimates; Sect. 6 discusses the results; finally, Sect. 7 presents the conclusions and policy implications.

Literature review

Characteristics of energy use and its ecological and environmental effects

In recent years, scholars have investigated the energy structure of rural households and found that the main fuels currently used in rural areas can be divided into solid fuels (i.e., straw fuelwood and coal) and clean fuels (i.e., biogas, natural gas, liquefied gasoline, and electricity) [18]. Wang and Jiang conducted a field survey on the energy use of 6000 rural households in 25 provinces in China and found that wood fuel is the most commonly used fuel in rural areas for cooking, whereas natural gas has been used in rural areas in the southeast [6]. Most rural residents use coal for heating in winter; however, Guangdong mainly uses natural gas, whereas Jiangsu, Zhejiang, and Shanghai mainly use electricity. Vihi et al. investigated the cooking energy preferences of households in the Jos North Local Government Area, Plateau State, and found that while kerosene was the main type of energy used by respondents, approximately 49.1% of households used at least two types of fuel for cooking [19].

With economic development and social progress, rural households are slowly turning to modern commercial energy sources such as cleaner electricity and natural gas. However, in China's economically poor rural areas, traditional solid energy is still widely used, accounting for approximately 41.8% of households [20]. A study in Bhutan showed that, in the past decade, many Bhutanese households have turned to cleaner energy sources, such as electricity and LPG, but poorer households still rely on polluting fuels, such as firewood and coal [21]. Similar results were found in a study in Brazil [22].

However, rural household energy use is closely related to greenhouse gas emissions and environmental quality [23–25]. The extensive use of traditional energy causes significant damage to the environment and ecology, whereas the consumption of renewable energy can help reduce carbon dioxide emissions [26–28]. Greenhouse gas and atmospheric pollutant emissions caused by the use of traditional solid fuels in households, such as carbon oxides, nitrogen oxides, particulate matter, sulfur dioxide, and volatile organic compounds, are not only important contributors to regional air pollution but also a direct cause of indoor air pollution for farmers [15, 29]. However, in the ecol. fragile areas of Northwest China, the use of traditional solid energy has seriously damaged the ecological environment. Biomass energy consumption in Tibet is approximately 1.41 million tons kgce every year, and approximately 1/3 of cow dung and straw are used as fuel, which loses many nutrients and destroys the material cycle of the Tibetan ecosystem [13]. Therefore, research on promoting clean energy use by farmers in ecol. fragile areas of Northwest China is not only conducive to improving the local energy structure, but also to protecting human health and promoting local ecological environment protection.

Impact of energy affordability on energy use

According to a detailed review, there are approximately 50 different factors in the literature that may influence household decisions on fuels and stoves [30], including external factors (i.e., policy regulation [31, 32], policy incentives [33, 34], social norms [35], and publicity [36]), internal psychological factors (i.e., environmental responsibility [37], values [38], herd mentality [39], and perceived behavioral control [40, 41]), demographic factors (i.e., income [15, 42], age [43, 44], gender [45], family structure [46], and education [47, 48]), and energy characteristics (i.e., energy prices [49, 50], energy availability and convenience [10, 17], and energy reliability [51]). Among them, two measures of energy affordability, household income and subsidies, have received considerable attention and are considered the most important [52, 53].

Numerous studies have analyzed the effect of energy affordability and found that it remains an important barrier to energy transition in rural China [54]. Hou et al. determined that a household's income determines its fuel affordability, measured the impact of energy affordability on household cooking fuel choices from the perspective of wealth (income and assets), and verified its important role in the energy transformation process [16]. In their study on energy choices for cooking and heating in rural Chinese households, Wu et al. identified the crucial role of energy affordability and highlighted income growth as a key factor in improving energy payment capacity [54]. However, energy affordability is measured not only by income levels, but also by factors such as government energy subsidies, which can increase income and keep energy prices below reference prices, effectively increasing rural households' energy affordability [17]. Household income and government energy subsidies have received much attention in studies on the factors influencing decision-making regarding clean energy use and have repeatedly been shown to be the most important influencing factors [52, 53].

Impact of income growth on energy use Income has always been an indispensable factor in the study of influencing factors of energy use [55, 56]. In their research on the consistency of renewable energy use intentions and behaviors, Fang et al. pointed out that income has a significant impact on the consistency of residents' support for renewable energy development and that this impact will be more obvious in rural areas [57]. This view has been confirmed in many studies on rural energy use and it has been pointed out that income is the decisive factor for farmers to spend on energy and use new energy, and is an important factor for achieving a clean transformation of rural energy consumption [6, 42]. Based on this, scholars have discussed changes in the rural household clean energy utilization rate with income changes. Chen and Liao indicated that coal consumption decreases by approximately 17% for every 10% increase in the income of rural residents and that the higher the income, the more sensitive it is [15]. Hou et al. considered income and examined the influence of assets on cooking fuel choices. They analyzed cooking fuel selection during wealth (asset and income levels) growth and compared the probabilities of households choosing clean fuel when assets and income increased by 10% below the average levels. They elucidated the differences in the sensitivity of fuel choice to per capita assets and income within households [16]. However, few studies have comparatively analyzed the impact of income and subsidies on the decision-making process regarding clean energy use in rural households.

Impact of subsidy growth on energy use The poverty level in rural areas is high and traditional solid energy is widely used. Therefore, relevant policies must be formulated and implemented to accelerate the elimination of traditional solid energy [42]. Relevant studies have indicated that the impact of environmental incentive policies is particularly important for low-income farmers [33]. Many scholars have conducted regression analyses on the relationship between subsidies and energy use and found that subsidies are an important factor in the implementation of biogas or residential solar photovoltaic power generation [58]. Moreover, the government's subsidy policy can indirectly affect purchase behavior intention through income and new energy product purchase attitude [59]. Some scholars have also studied changes in energy demand when subsidies change, indicating that if the subsidy amount continues to grow, the use of solar energy will increase, whereas the use of firewood and coal will continue to decrease [60, 61]. However, the existing literature primarily focuses on cooking and heating fuels or treats all clean energy usage decisions as dependent variables. There is limited research that specifically analyzes the impact of income and subsidies, among other factors, on clean energy usage decisions based on different purposes.

Methodologies Logistic or probit models are commonly used as estimation methods for energy decision-making [46]. The probit model is primarily used to study species with specific energies. Logistic models are more commonly used for research on energy conversion strategies. For example, Mensah and Adu set firewood, charcoal, LPG, and other solid energy sources as categorical variables and estimated them using a multinomial probit model [62], while Hou et al. used logistic regression to explore the impact of wealth on household fuel transitions [16]. Based on the number of available fuel types, these models can be categorized into binary models (two available fuel types) and multivariate models (three or more available fuel types). Simultaneously, some scholars began to use ordered models to study residents' energy consumption choices [63].

Although many studies have analyzed the impact of energy affordability on decision-making regarding clean energy use, they rarely measure energy affordability from the income side along two dimensions: endogenous income (annual per capita household income) and external inputs (government energy subsidies), and lack comparisons of differences in the extent to which income and subsidy growth affect decision-making regarding clean energy use and predictions of thresholds of effect. In addition, the existing literature focuses on the influence of cooking or heating fuels, or treats all decision-making regarding clean energy use as a dependent variable, with little discussion of the impact of factors such as income and subsidies on the decision-making of rural households regarding clean energy use and their heterogeneity across rural households [64]. Thus, the differences in the effects of income and subsidy increases need to be analyzed, the extent to which rural households choose to use clean energy as a result of income and subsidy increases also remains to be explored, and the heterogeneity of the effects of income and subsidy increases on decision-making regarding clean energy use needs to be discussed.

Moreover, although a few scholars have researched the impact of energy affordability on energy use, there is a lack of empirical analysis based on data from rural areas in the ecologically fragile regions of Northwest China [65]. Additionally, most of these studies focus on using regression methods such as the logistic model to explore the relationship between the two but fail to quantify the extent to which rural households switch to clean energy when energy affordability increases [46, 61]. However, several economic variables exhibited structural mutations. When one economic parameter reaches a certain value, it will cause another economic parameter to suddenly change to another form, and the threshold regression model can effectively detect the threshold value. You et al. used this method to analyze the threshold effect of population aging on the relationship between digital economic development and residents' health [66]. The present study considers rural households in ecol. fragile areas of Northwest China as the research object, and, based on logistic regression, uses the threshold regression model proposed by Hansen [67]. We explore the relationship between energy affordability and decision-making regarding clean energy use, the thresholds of income and subsidies that lead to changes in decision-making regarding clean energy use, and quantify the impact of energy affordability on decision-making regarding clean energy use.

Research hypothesis and theoretical framework

Impact of income growth

Income is a determining factor that influences clean energy usage decisions in rural households. The ability of a household to move up to a higher level, or "staircase", largely depends on its income level [46]. The "energy ladder theory" was first introduced by Hosier [68], who suggested that income plays an important role in the transformation of a household's energy structure. This process is divided into three stages and increases linearly with income, from the use of the most primitive biomass (firewood) to transitional fuels (coal), and finally to clean energy (gas and electricity) [69]. A significant improvement in the economy of a household generally results in the reduced use of energy with high emissions, low cost, inefficient combustion, and increased use of modern clean energy [19, 57]. Based on the given information and research context, the following hypothesis is proposed: H1: Income growth has a positive impact on clean energy usage decisions in rural households in the ecol. fragile areas of Northwest China.

Impact of subsidy growth

Compared to traditional solid energy, clean energy is convenient and efficient; however, it involves high costs and is difficult to obtain; hence, it is not easily adopted in rural households [9, 10]. The transition to clean energy is desirable; however, it is difficult to accomplish because of high upfront costs [8]. Energy subsidies constitute external income with regard to energy consumption, and their growth can improve household energy affordability and ease the plight of low-income rural households that cannot afford clean energy. Tian and Chang used coal consumption as a dependent variable to explore the impact mechanisms of subsidy growth and found that increasing subsidies led to the increased use of clean energy and was conducive to decreasing the use of traditional solid energy [60]. Incentive policies are particularly important for rural low-income households [33]. Based on the consideration of economic underdevelopment in the ecol. fragile areas of Northwest China, the following hypothesis is proposed: H2: Subsidy growth has a positive impact on clean energy usage decisions in rural households in the ecol. fragile areas of Northwest China.

Heterogeneity of the impact of energy affordability

Energy affordability is heterogeneous; that is, it has different effects on different groups. This heterogeneity has important implications for intervention in policy implementation, expanding policy effects, and achieving the optimal allocation of limited public resources

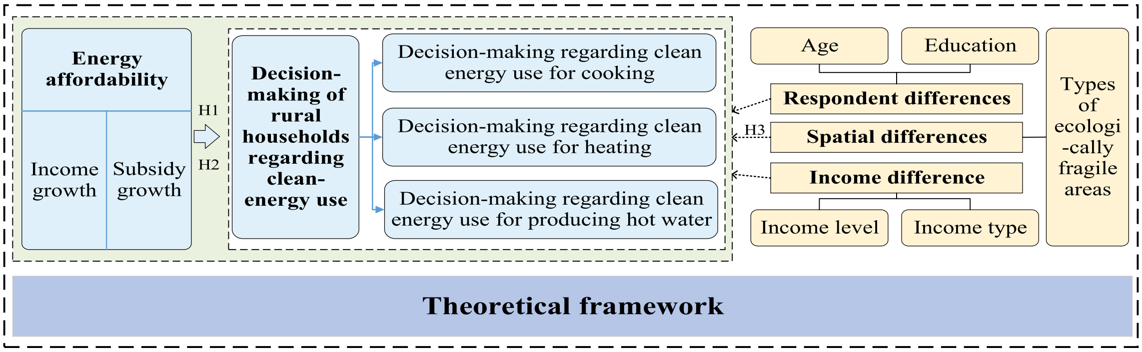

Fig. 2 Theoretical framework

[64]. Previous studies have shown that some households have already transitioned to cleaner energy, while others still rely on traditional solid energy [21]. Rural households have different energy payment capacities depending on their type. Therefore, the heterogeneity of rural households may lead to varying effects of energy payment capacity on clean energy usage decisions [70, 71]. The heterogeneity of rural households mainly includes differences in the individual characteristics of respondents (i.e., age and education), income characteristics (i.e., income level and type), and types of ecol. fragile areas [72, 73]. Thus, we propose hypothesis H3: The impact of energy affordability on rural households' decision-making regarding clean energy use in the ecol. fragile areas of Northwest China is heterogeneous.

Based on these hypotheses, we constructed a theoretical framework (Fig. 2).

Methods

Data

Overview of the study area

Ecol. fragile areas of China are widely distributed and poverty is concentrated [11]. There are different types of ecol. fragile areas of China, including arid desert areas in Northwest China, the Loess Plateau, and the Qinghai-Tibet Plateau; karst areas in Southwest China; and northern sand-blown areas [39]. Northwest China is vast and sparsely populated and its economic structure is dominated by resource-based industries, traditional agriculture, and animal husbandry. The five provinces (districts) that make up Northwest China, Shaanxi, Gansu, Ningxia, Qinghai, and Xinjiang, account for approximately 1/3 of China's land area; however, the resident population in Northwest China in 2021 is 103.52 million, accounting for only 7.33% of China's total population. In 2021, the GDP of Northwest China was 6389.69 billion yuan, accounting for 5.58% of the national GDP; the economy of Northwest China ranked last behind those of all other regions. Therefore, rural families in Northwest China are accustomed to using cheap straw fuelwood, livestock manure, and other traditional solid energy sources. We focused on villages in the ecol. fragile areas of Northwest China. The village details are presented in Table 1.

Northwest China has abundant water, soil, light, and heat resources. According to China Energy News, with the country's increasing demand for clean energy, the development of new energy industries, such as photovoltaic and wind power, is rapidly increasing, especially in

Table 1 Details on the investigated villages

Province	City	Type of ecol. fragile areas	Village
Shaanxi	Xi'an	Areas in the Loess Plateau	Xiaojiang, Yue, Xifan, Lanjiazhuang, Zhaijia, Shangzhai, Xiaozhai, Xipo, Dongnan, Dongbei
Gansu	Dingxi	Areas in the Loess Plateau	Maying, Youfang, Youfu, Dazhai, Youjiang, Mingxing, Nancha, Huangyao, Majiadian, Geligou, Wangjiaping, Jiaojiawan, Nanshilipu, Qianhe, Muhe, Xinkang, Gaoleng, Gaotaishan, Jiudian
Ningxia	Yinchuan	Arid desert areas in Northwest China	Jinxin, Tuanjie, Guanqu, Lianxing, Ligang, Yongxing, Weituan, Jinglong, Wuqu, Xuwang, Donghe, Nanfang, Xihe, Tongqiao, Yongqing
Qinghai	Haibei Prefecture	Areas in the Qinghai-Tibet Plateau	Hongshan, Gaqu, Hedong, Tangqu, Huancangxiuma, Rimang, Xiangyang, Huancanggongma, Yehemao, Qieji, Longlang, Dazhuang, Meihua, Talongtan, Siergou, Huangtian, Hantai, Chahandawu, Zhamatu, Ebao, Huangcaogou, Caodaban, Qingyanggou, Binggou, Dongcuotai, Hexi, Gezidong

Northwest China. In recent years, the energy consumption structure in ecol. fragile areas of Northwest China has been optimized and clean energy sources, such as electricity, liquefied petroleum gas, natural gas, and solar energy, have gradually become popular for cooking, heating, and hot water production. With government support, electricity has achieved 100% penetration, and rural, and the conversion of coal to electricity in ecol. fragile areas of Northwest China is subsidized by RMB 0–1000. Although some rural areas have implemented subsidies for the conversion of coal to gas, the price of gas is so high that its penetration is still very low, especially in rural households in ecol. fragile areas of the Qinghai-Tibet Plateau. Solar energy is mainly used in water-heating activities. The government provides subsidies of RMB 1000–1500 for the installation of solar water heaters and because of the abundant supply of solar energy and the maturity of solar equipment in ecol. fragile areas of Northwest China, solar water heaters are very common in Northwest China, far exceeding electricity and natural gas water heating equipment.

Data collection

The data used in this study were obtained from a social survey conducted by a research team in ecol. fragile area in Northwest China. Due to the COVID-19 pandemic and severe weather, the survey lasted longer than anticipated and was conducted from November to December 2021 and from February to June 2022 (7 months in total). The survey followed random and stratified sampling principles. First, according to the level of economic development, we selected ten counties (districts) in the four lagging-economy provinces of Shaanxi, Gansu, Ningxia, and Qinghai in the northwest, which were used as primary sampling units. Second, one to five townships were randomly selected based on the distance between each township government and the county (district) government. Third, based on the distance between each village committee and the township government, one to five villages were randomly selected for the investigation. Finally, more than ten interviewed households were randomly selected from each village and personal interviews were conducted with the main labor force in the households. A total of 1170 rural household questionnaires were collected from 71 villages. Each part of the questionnaire was strictly screened and questionnaires with incomplete data were excluded. Finally, 1118 valid questionnaires in line with the research theme were obtained, with an effective response rate of 95.56%. The authors also participated in a survey, thereby obtaining a clear understanding of the living conditions of the interviewed rural families.

The questionnaire was divided into two main sections (see Additional file 1: Appendix for specific questionnaires): (1) basic information on rural households, including the gender, age, and education levels of the respondents, as well as the family size, type of family income, and annual family income, and (2) characteristics of rural households' decision-making regarding energy use, including the main types of energy currently used by rural households for cooking, heating, and hot water purposes; the main types of energy used by rural households for cooking, heating, and hot water purposes when annual household income per capita and government energy subsidies increase; and the current subsidies for various types of clean energy use in ecol. fragile areas of Northwest China. Based on the characteristics of the study area, clean energy included electricity, liquefied petroleum gas, natural gas, solar energy, and biogas, whereas non-clean energy mainly included straw fuelwood, livestock manure, and coal. Following the method of [20], "liquefied petroleum gas" and "natural gas" are collectively referred to as "gas". Additionally, the proportion of households using biogas and other specified energy sources was too small to generate reliable results; therefore, these samples were removed from the dataset.

Sample characteristics

1. Basic characteristics of rural households

According to the personal characteristics of the respondents displayed in Fig. 3, the surveyed population did not include individuals below the age of 18 years and mostly consisted of individuals aged between 40 and 60 years, accounting for 54.56% of the total sample. In addition, the proportion of male and female respondents was relatively balanced and the overall educational level was relatively low; the majority (85.87%) of respondents were at the junior high school level or below, similar to other surveys [39].

Table 2 presents the basic characteristics of the sample households. From the perspective of household features, significant differences were observed among rural households in ecol. fragile areas. Compared with the ecol. fragile areas of the Loess Plateau and the northwest arid desert, the income level of rural households in the ecol. fragile areas of the Qinghai-Tibet Plateau is relatively high, with 42.99% of the households earning more than 50,000 yuan, which is higher than the overall income level of the ecol. fragile areas of Northwest China (21.11%), while only 11.29% and 14.42% of the households earned more than 50,000 yuan in the ecol. fragile areas of the Loess Plateau and northwest arid desert, respectively. Regarding family size, rural households in ecol. fragile

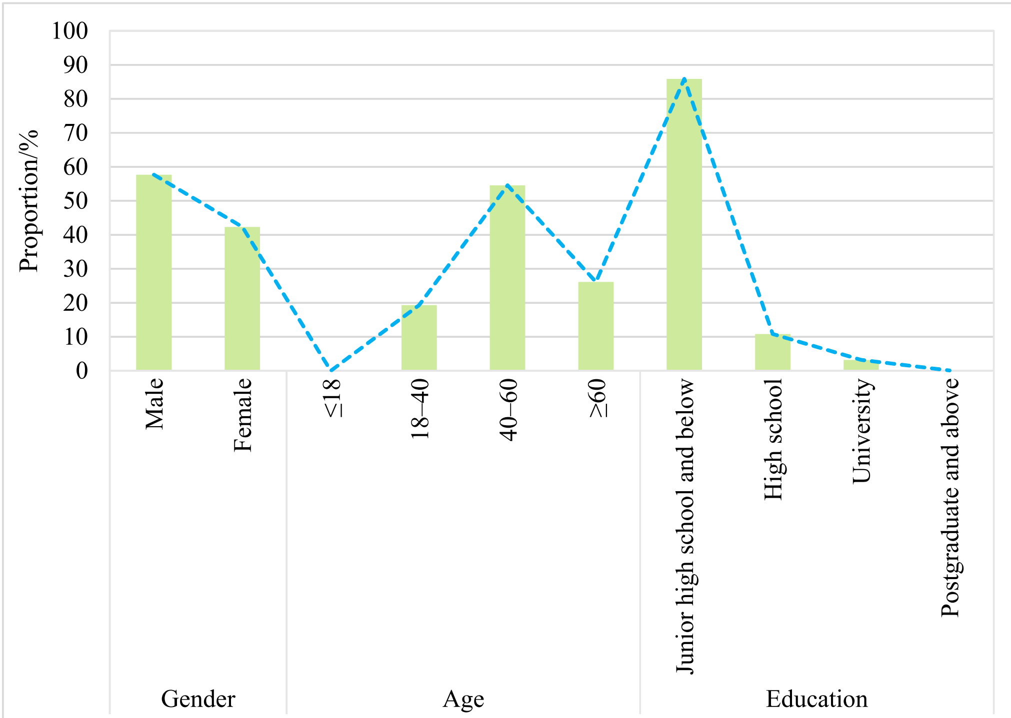

Fig. 3 Basic characteristics of respondents

Table 2 Basic characteristics of rural household

Type		Ecol. fragile areas in Northwest China	Areas in the Loess Plateau	Arid desert areas in Northwest China	Areas in the Qinghai-Tibet Plateau
Number of samples/household		1118	478	326	314
Income-level	≤ 10,000%	12.08	14.23	14.42	6.37
	10,000–30,000/%	35.96	40.38	41.10	23.89
	30,000–50,000/%	30.86	34.10	30.06	26.75
	50,000–100,000/%	15.65	9.83	11.35	28.98
	≥ 100,000/%	5.46	1.46	3.07	14.01
Family size/person		3.49	3.83	2.99	3.47
Income type	Purely agricultural/%	30.05	20.29	24.23	50.96
	Part-time agricultural/%	37.84	40.90	36.81	34.39
	Non-agricultural/%	32.11	38.91	38.96	14.65

areas of Northwest China contained 3.49 people on average, with a relatively small family size, especially in the arid desert areas in Northwest China.

Finally, in terms of income type, there were obvious differences between the different ecol. fragile areas. Nearly half of the rural households in ecol. fragile areas of the Qinghai-Tibet Plateau were completely dependent on agriculture and animal husbandry, far higher than those in ecol. fragile areas of the Loess Plateau (20.29%) and the northwest arid desert (24.23%), which is also the reason for the high income of rural households in the Qinghai-Tibet Plateau. In the field survey, we learned that grazing could bring a rich income.

2. Decision-making characteristics of energy use in rural households

During the field survey, we learned that traditional solid energy use by rural households in ecol. fragile areas of Northwest China accounted for a large proportion of

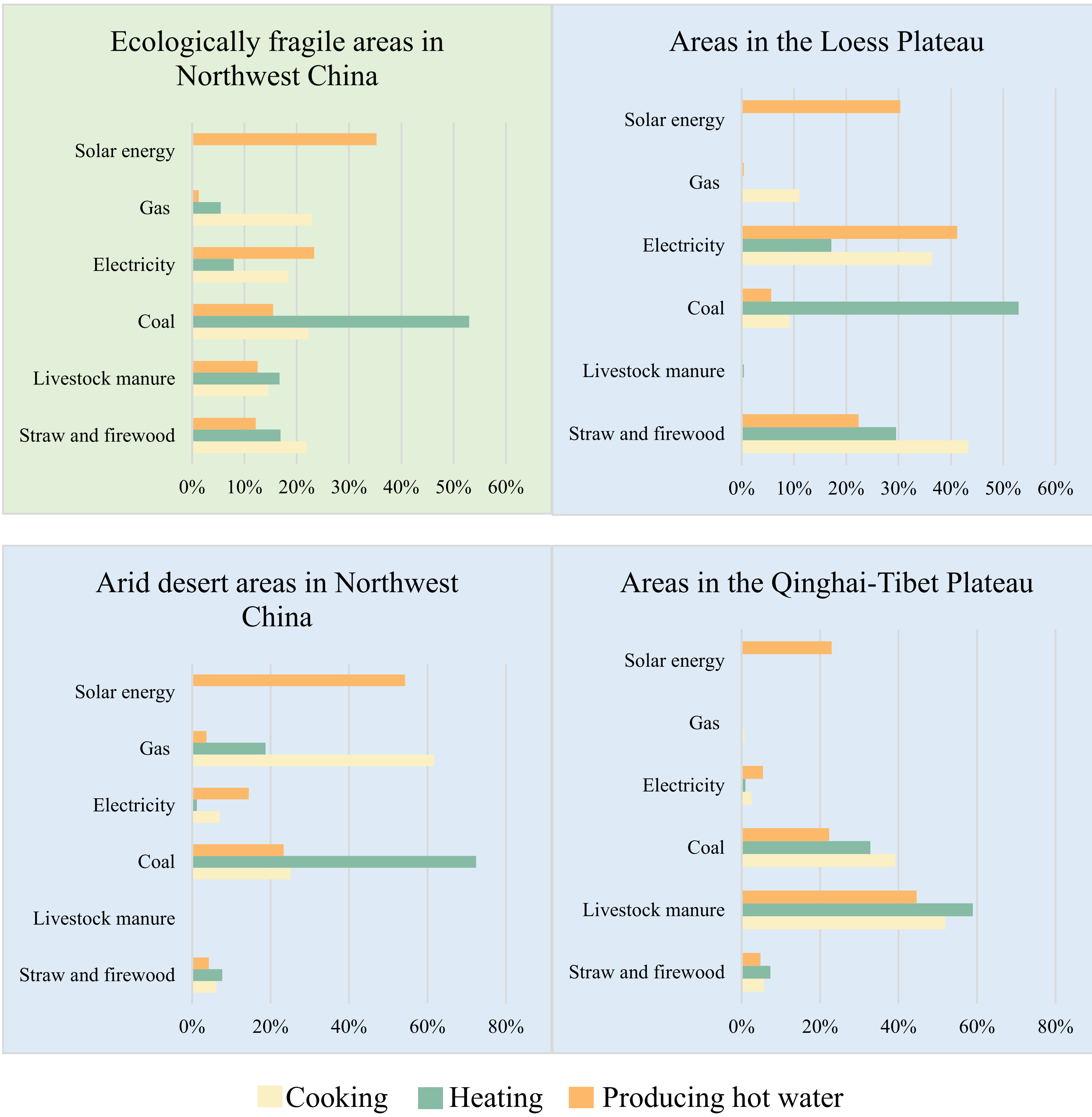

Fig. 4 Energy use structure of rural households in ecol. fragile areas of Northwest China

the use of cooking, heating, and hot water energy. However, owing to the different climates in each region and the degree of perfection of the local infrastructure construction, their energy-use characteristics are different. Figure 4 shows the energy-use structure of rural households in ecol. fragile areas. It can be seen that in terms of heating, rural households in ecol. fragile areas of Northwest China using traditional solid energy account for the highest proportion (i.e., 86.59%). Among them, the utilization rate of coal was the highest, accounting for 52.93% and 72.39% of rural households in the ecol. fragile areas of the Loess Plateau and the northwest arid desert, respectively. However, in rural households in the ecol. fragile areas of the Qinghai–Tibet Plateau, the utilization rate of coal was relatively low (32.80%), with the largest proportion (58.92%) of rural households using livestock manure. This is mainly because most rural households in this area are engaged in work related to agriculture and animal husbandry, making them rich in livestock manure.

In terms of cooking, 58.77% of rural households in the northwest ecol. fragile areas used traditional solid energy for cooking and the proportion of the three traditional solid energy uses was relatively balanced, which is related to the significant difference between cooking energy with the highest utilization rate among rural households in different ecol. fragile areas. Among rural households in the ecol. fragile areas of the Loess Plateau, the number of households using straw firewood for cooking was the largest (43.31%). As with heating, the highest utilization rate of cooking energy for rural households in the ecol. fragile areas of the Qinghai-Tibet Plateau was livestock manure (51.91%). However, the arid desert ecol. fragile areas of Northwest China have the largest number of households using clean energy for cooking and 61.66% of rural households use gas for cooking. This is because many rural households engage in nonagricultural work in this area. Most non-agricultural households make a living by working outside, which gives them a deeper understanding of the advantages of clean energy.

For producing hot water, more than half of the households surveyed used clean energy to produce hot water. Among them, most rural households in ecol. fragile areas of the Loess Plateau used electricity (41.21%), and the majority (54.29%) of rural households in the northwest arid desert ecol. fragile areas used solar energy. According to an actual survey, the energy consumption for producing hot water is lower and the cost of using solar energy and electricity for producing hot water is lower and more convenient. However, in ecol. fragile areas of the Qinghai-Tibet Plateau, livestock manure was still the main energy source for producing hot water (44.59%), owing to the impact of the large proportion of herders living in this region.

Variables

1. Dependent variables: decision-making regarding clean energy use

The construction of decision variables for clean energy use was according to [20]. Considering the different energy choices for different types of use, we divided clean energy use decisions according to the type of use. The China household energy consumption research report (2016) showed that cooking and heating are the most important types of use, followed by producing hot water and operating household appliances [74]. However, we mainly examined the substitution relationship between clean and non-clean energy consumption in rural households; hence, the energy used by household appliances was not taken into consideration since it is mainly electricity and does not involve clean energy substitution. We mainly covered the decision-making regarding clean energy for three types of use: cooking, heating, and producing hot water.

Table 3 Per capita disposable income and growth of rural residents in the five Northwest provinces in 2020

Income ranking	Region	Disposable income per capita	Increase %
	National	17,131	6.9
1	Xinjiang	14,056	7.1
2	Ningxia	13,889	8.0
3	Shaanxi	13,316	8.0
4	Qinghai	12,134	5.5
5	Gansu	10,344	7.4

Specifically, based on the subjective decision-making (a method that utilizes human knowledge, experience, and ability to provide decisions) of rural households, which involves choosing between traditional solid fuels and clean energy sources (i.e., gas, electricity, and solar energy) for cooking, the decision-making process regarding the use of clean energy for cooking was characterized. Following the same principles and methods, the variables were designed to represent the decision-making process of using clean energy for heating and hot water. The meanings, assignments, and descriptive statistics of the relevant variables can be found in Table 4.

2. Independent variables: energy affordability

Referring to the definition of affordability [66], this study defines energy affordability as the ability of a household to pay for the energy it needs to live with for a given period. Most existing studies measure a household's energy affordability in terms of endogenous income (annual per capita household income); however, energy affordability is influenced not only by annual per capita but also by external inputs, such as government energy subsidies, which can increase income and lower energy prices compared to the reference price, effectively increasing energy affordability [17]. Therefore, this study explores the effect of energy affordability from the income perspective in two dimensions: endogenous income and external inputs.

Whether a family can afford a specific type of clean energy depends on its income status and government energy subsidies; thus, we measure energy availability based on the growth rates of per capita annual household income and government energy subsidies.

Regarding income growth rate, based on the growth rates of per capita annual household income of rural

Table 4 Definition, assignment, and descriptive statistics of variables

Variable	Definition and assignment	Mean	St. dev	Min	Max	VIF
Cooking clean energy use decision	Energy choices for cooking: traditional solid energy = 0; clean energy = 1 (electricity = 1; gas = 2)	0.89	0.789	0	2	
Heating clean energy use decision	Energy choices for heating: traditional solid energy = 0; clean energy = 1 (electricity = 1; gas = 2)	0.33	0.598	0	2	
Hot water clean energy use decision	Energy choices for producing hot water: traditional solid energy = 0; clean energy = 1 (electricity = 1; gas = 2; solar energy = 3)	1.50	1.238	0	3	
Income growth	Growth rate of per capita annual household income: level 1 = 1,000; level 2 = 2,000; level 3 = 3,000; level 4 = 4,000; level 5 = 5,000	2500.00	1,707.952	0	5,000	1.000
Subsidy growth	Growth rate of government energy subsidies: level 1 = 600; level 2 = 1,000; level 3 = 1,500; level 4 = 2,000; level 5 = 2,400	1250.00	816.047	0	2,400	1.000
Gender	Respondent's gender: male = 1; Female = 0	0.58	0.494	0	1	1.026
Age	Respondent age: ≤ 18 = 1; 18–40 = 2; 40–60 = 3; ≥ 60 = 4	3.07	0.671	2	4	1.249
Education	Educational level of respondents: junior high school and below = 1; high school = 2; university = 3; postgraduate and above = 4	1.18	0.463	1	4	1.140
Family size	Number of individuals living at home all year round	3.49	1.620	1	10	1.216
Income type	Respondents' sources of household income: purely agricultural (farming and animal husbandry / low income insurance / relying on child allowance / pension) = 1; part-time (purely agricultural + income from self-employment / salary of teachers, cadres and other regular employees, etc.) = 2; non-agricultural (income from self-employment + salary of teachers, cadres and other regular employees, etc.) = 3	2.02	0.788	1	3	1.218
Income-level	Total household income last year: ≤ 10,000 = 1; 10,000–30,000 = 2; 30,000–50,000 = 4; 50,000–100,000 = 4; ≥ 100,000 = 5	2.66	1.051	1	5	1.402
Time dummy variable (based on 2021)	2022 = 1, other = 0	0.87	0.34	0	1	1.388
Area dummy variables (based on rural areas in ecol. fragile areas of the Loess Plateau)	Rural areas in ecol. fragile areas of arid desert areas of Northwest China = 1, other = 0	0.29	0.455	0	1	1.520
	Rural areas in ecol. fragile areas of the Qinghai-Tibet Plateau = 1, other = 0	0.28	0.449	0	1	1.745

households in the five northwestern provinces in 2020 (i.e., approximately 1000 yuan/year, see Table 3), this paper sets the growth rate of per capita annual household income to five levels, i.e., 1000, 2000, 3000, 4000, and 5000 yuan/year. Then, we analyze the impact of income growth on decision-making of rural households regarding clean energy use according to their clean energy use decisions at different levels of income growth, and analyze the situation in the next five years according to the current income growth trend.

Regarding energy subsidy growth rate, according to the 2020 China coal governance report, the current coal-to-electricity[1] and coal-to-gas[2] subsidies range from 600 to 2400 yuan per household; therefore, the five-level subsidies were set at 600, 1000, 1500, 2000, and 2400 yuan.

3. Control variables

To eliminate interference in the measurement model of the influencing factors, we also set up the control variables of personal and family characteristics, which may affect the decision-making of rural households regarding clean energy use. Following [16], the member who was most familiar with family finances was selected as the family representative. In rural families, these persons may be the main decision-makers, and their characteristics determine the family decision-making.

Individual characteristics included the genders, ages, and education levels of the respondents; family characteristics included the family size, income type, and annual income. In addition, the heterogeneity in the sample was controlled by including these variables in the regression specification.

[1] "Coal to electricity" refers to the replacement of traditional coal-fuelled boilers with electricity-based heating boilers, replacing ordinary coal boilers with electric boilers.

[2] "Coal to gas" refers to the use of natural gas (including conventional natural gas, unconventional natural gas, coal gas, etc.) in residential life, industrial production and power generation to replace coal, which is less efficient in energy use and produces more polluting emissions.

4. Dummy variables

To control for the potential effects of factors such as time and region during the research process, this study included dummy variables. First, considering that the survey spanned two years, time dummy variables were added to control the potential impact of time factors, using 2021 as the reference year. Additionally, given the variations in policy support for coal-to-electricity and coal-to-gas conversions across different ecol. fragile areas, regional dummy variables were included in the analysis, with the Loess Plateau ecol. fragile area selected as the reference. The definitions, assignments, and descriptive statistics for all variables are shown in Table 4.

Methods

Logistic regression model

The decision regarding clean energy use in households is a multi-discrete variable and it is unsuitable for use in a traditional OLS regression as an estimation method. A logistic regression model is typically used when the dependent variable is discrete [16, 46]. From a microscopic perspective, we used the household as the basic unit to construct a regression model and analyze how households transition from traditional solid energy to a specific clean energy. The model can be expressed as follows:

$$Y_{ijl} = \beta_{j0} + \beta_{j1}x_{ijl} + \beta_{j2}x_{j2} + \cdots + \beta_{jk}x_{jk} + \varepsilon_{ijl}, j = 0, \ldots, M, \quad (1)$$

where Y_{ijl} indicates that the ith respondent chooses energy j when the income (subsidy) increases to the l-level, x_{ijl} represents the ith respondent's income (subsidy) growth rate at the l-level, $x_{j2}...x_{jk}$ represents the factors affecting the utility, such as income level and age, β represent the corresponding coefficient, and k is the total number of independent variables. Certain factors may be excluded from the equation and some cannot be measured accurately; therefore, we added the error term ε_{ijl} to capture this uncertainty [75].

To help readers understand the results more intuitively, we calculated the probability change after each change in x, choosing the probability of using clean energy as the dependent variable. The model is expressed as follows:

$$P\left(Y_{ijl} = m\right) = \frac{exp(\beta_{m0}+\beta_{m1}x_{iml}+\beta_{m2}x_{m2}+\cdots+\beta_{mk}x_{mk})}{\sum_{j=0}^{M} exp\left(\beta_{j0}+\beta_{j1}x_{ijl}+\beta_{j2}x_{j2}+\cdots+\beta_{jk}x_{jk}\right)}, m = 0, \ldots, M. \quad (2)$$

In a multiple regression model, changes in x affect the probabilities of each outcome, and these probabilities are constrained by summation to 1; thus, it is a system with M equations but only $M-1$ independent unknowns. To solve this problem, we standardized the $\beta_{0k}=0$, k = 1, ..., k. Subsequently, we changed Eq. (2) into the following:

$$P\left(Y_{ijl} = m\right) = \frac{exp(\beta_{m0}+\beta_{m1}x_{iml}+\beta_{m2}x_{m2}+\cdots+\beta_{mk}x_{mk})}{1+\sum_{j=1}^{M} exp\left(\beta_{j0}+\beta_{j1}x_{ijl}+\beta_{j2}x_{j2}+\cdots+\beta_{jk}x_{jk}\right)}, m = 1, \ldots, M \quad (3)$$

$$P\left(Y_{ijl} = 0\right) = \frac{1}{1+\sum_{j=1}^{M} exp\left(\beta_{j0}+\beta_{j1}x_{ijl}+\beta_{j2}x_{j2}+\cdots+\beta_{jk}x_{jk}\right)}. \quad (4)$$

Therefore, the estimated coefficients reported in the table below represent the effect of one unit change in the corresponding independent variable on the probability that households choose clean energy.

Threshold regression model

In reality, both the income and subsidy growths are limited. How much can an increase in income or subsidy affect the decision-making of rural households regarding clean energy use? Determining this threshold is conducive to a more reasonable formulation of clean energy promotion policies. To this end, we adopted the threshold regression model proposed by Hansen [67] and further constructed a regression model with income (subsidy) growth rate as the threshold variable to determine this "turning point". The basic form of the threshold regression model is

$$Y_{it} = \mu_i + \theta_1{}' x_{it} + \varepsilon_{it}, (q_{it} < \gamma), \quad (5a)$$

$$Y_{it} = \mu_i + \theta_2{}' x_{it} + \varepsilon_{it}, (q_{it} > \gamma), \quad (5b)$$

where Y_{it} represents whether rural households use clean energy for cooking, heating, and producing hot water, q_{it} represents the threshold variable, and γ is the threshold to be estimated. Equation (5) can be written as:

$$Y_{it} = \mu_i + \theta_1{}' x_{it} \times I(q_{it} \leq \gamma) + \theta_2{}' x_{it} \times I(q_{it} > \gamma) + \varepsilon_{it}, \quad (6)$$

where ε_{it} obeys an independent homogeneous distribution and I is the indicator function. The threshold estimation principle is based on minimizing the sum of squared residuals (SSR) as a condition to determine the threshold value. Equation (6) can effectively identify the difference between the decision coefficient of clean energy use below and above the threshold, thereby overcoming the bias of subjectively setting structural mutation points. For detailed steps, see [67].

Results

Effect of energy affordability on decision-making regarding clean energy use in rural households

Four models were established based on different classifications and functions of the independent variables. Model I included only income growth, thereby exploring the impact of income growth on clean energy choices. Model III included only subsidy growth, thereby

Table 5 Logistic model regression results on decision-making regarding clean energy use for cooking

Variable	Model I		Model II		Model III		Model IV	
	B	EXP (B)	B	EXP (B)	B	EXP (B)	B	EXP (B)
Income growth	0.066*** (0.002)	1.068	0.069*** (0.002)	1.071				
Subsidy growth					0.156*** (0.005)	1.169	0.163*** (0.005)	1.177
Gender			− 0.074 (0.065)	0.929			− 0.107 (0.067)	0.899
Age			− 0.185*** (0.053)	0.831			− 0.127** (0.055)	0.881
Education			0.257*** (0.079)	1.294			0.202** (0.082)	1.223
Family size			− 0.042* (0.022)	0.959			0.017 (0.022)	1.017
Income type			0.322*** (0.044)	1.380			0.249*** (0.045)	1.283
Income-level			0.331*** (0.037)	1.392			0.351*** (0.038)	1.421
Time dummy variables (2021 as reference)								
Year-2022	− 0.955*** (0.104)	0.385	− 0.882*** (0.111)	0.414	− 1.078*** (0.112)	0.340	− 1.059*** (0.119)	0.347
Area dummy variables (with reference to rural areas in the ecologically fragile region of the Loess Plateau)								
Rural Northwest Arid Desert Ecologically Vulnerable Area	1.439*** (0.086)	4.215	1.428*** (0.091)	4.170	1.412*** (0.091)	4.102	1.457*** (0.096)	4.294
Rural areas in the ecologically fragile region of the Tibetan Plateau	− 1.647*** (0.080)	0.193	− 1.875*** (0.093)	0.153	− 1.296*** (0.080)	0.274	− 1.505*** (0.093)	0.222
Cox and Snell R^2	0.315		0.341		0.304		0.327	
Nagelkerke R^2	0.430		0.464		0.424		0.456	

*, * *, * * * indicate the 10, 5, and 1% significance levels, respectively; standard errors are in parentheses. The unit of income and subsidy growth is 100 yuan, and the estimated coefficient in the report represents the impact of an increase of 100 yuan in income and subsidies on the probability of households opting for clean energy

exploring the impact of subsidy growth on clean energy choices. Models II and IV combined individual and household characteristic variables with income growth and subsidy growth, respectively, thereby exploring how the addition of control variables affects the choice of clean energy. The Cox and Snell R2 and Nagelkerke R2 values in Tables 5, 6, and 7 show that the fits of Models II and IV are better than those of Models I and III.

This study collectively referred to electricity, gas, and solar energy as clean energy and used a logistic regression model to verify the role of energy affordability in this transition. The regression results showed that energy affordability is a key variable affecting the decision-making of rural households in ecol. fragile areas of Northwest China regarding clean energy use; it is significant at the 1% level and has a positive effect. Higher income and subsidy growth imply more affordable energy; therefore, households are more likely to opt for energy that is more expensive and accessible. The results of regressions of models II and IV also showed that the estimated coefficients remain positive and significant at the 1% level, indicating that income and subsidy growth effects on decision-making regarding clean energy use do exist. However, there are differences in the degree of influence of different types of use. Overall, H1 and H2 were confirmed.

(1) *Decision-making regarding clean energy usage for cooking.* Table 5 shows that for every 100 yuan increase in income and subsidies, the probabilities of rural households opting for clean energy for cooking increased by 7.1% and 17.7%, respectively. The incentive effect of subsidy growth on rural households' decision-making regarding clean energy use for cooking was stronger than that of income growth, indicating that the promotion of clean energy for cooking is more dependent on government subsidies than on the active adoption of income growth in ecol. fragile areas of Northwest China.

(2) *Decision-making regarding clean energy use for heating.* The regression results demonstrated that the effect of subsidy growth is stronger than that of income growth. For every 100 yuan increase in subsidies, the probability of rural households choosing clean energy for heating increased by 16.9%, while a 100 yuan increase in income led to a 6.0% increase in the probability of choosing clean energy for heating. These findings are consistent with the results of clean energy adoption decisions for cooking. However, considering the current status (see Fig. 4), the degree of clean energy use for cooking is significantly

Table 6 Logistic model regression results in decision-making regarding clean energy use for heating

Variable	Model I		Model II		Model III		Model IV	
	B	EXP (B)	B	EXP (B)	B	EXP (B)	B	EXP (B)
Income growth	0.055*** (0.002)	1.057	0.058*** (0.002)	1.060				
Subsidy growth					0.145*** (0.005)	1.156	0.156*** (0.005)	1.169
Gender			0.135** (0.068)	1.144			0.065 (0.066)	1.067
Age			− 0.097* (0.055)	0.907			− 0.092* (0.053)	0.912
Education			− 0.147** (0.073)	0.864			− 0.067 (0.071)	0.936
Family size			− 0.005 (0.022)	0.995			0.036 (0.022)	1.037
Income type			0.137*** (0.047)	1.146			0.166*** (0.045)	1.181
Income-level			0.530*** (0.039)	1.699			0.587*** (0.038)	1.799
Time dummy variables (2021 as reference)								
Year-2022	− 2.362*** (0.101)	0.094	− 2.415*** (0.109)	0.089	2.510*** (0.106)	0.081	− 2.633*** (0.115)	0.072
Area dummy variables (with reference to rural areas in the ecologically fragile region of the Loess Plateau)								
Rural Northwest Arid Desert Ecologically Vulnerable Area	0.783*** (0.081)	2.187	0.769*** (0.086)	2.158	0.769*** (0.080)	2.158	0.811*** (0.086)	2.251
Rural areas in the ecologically fragile region of the Tibetan Plateau	− 0.695*** (0.098)	0.499	− 1.181*** (0.113)	0.307	− 0.270*** (0.086)	0.763	− 0.728*** (0.101)	0.483
Cox and Snell R^2	0.225		0.257		0.266		0.308	
Nagelkerke R^2	0.329		0.375		0.371		0.430	

*, * *, * * * indicate the 10, 5, and 1% significance levels, respectively; standard errors are in parentheses. The unit of income and subsidy growth is 100 yuan, and the estimated coefficient in the report represents the impact of an increase of 100 yuan in income and subsidies on the probability of households opting for clean energy

better than that for heating. Therefore, the degree to which energy affordability affects decision-making regarding clean energy use for cooking is significantly higher than that for heating. This phenomenon may be related to the high cost of immature clean heating; therefore, attention should be paid to the development and popularization of clean energy in rural ecol. fragile areas of Northwest China.

(3) *Decision-making regarding clean energy use for hot water production.* Compared with cooking and heating, when income and subsidies increase, the probability of opting for clean energy to produce hot water increases slightly. Specifically, for every 100 yuan increase in income and subsidies, the probability of rural households opting for clean energy for producing hot water increases by 4.5% and 12.0%, respectively, which also shows that the boosting effect of subsidy growth is stronger, with the reason being related to the current high proportion of clean energy use for producing hot water in ecol. fragile areas of Northwest China (see Fig. 4).

During field research, rural households in ecol. fragile areas of Northwest China were found to have different preferences for different types of clean energy. Therefore, we tested the income and subsidy growth effects of the transition from traditional solid energy to specific clean energy to facilitate the formulation of targeted clean energy promotion measures. A multivariate logistic regression model was used to analyze the transition from traditional solid energy to electricity, gas, and solar energy (Tables 8 and 9).

(1) *Decision-making regarding clean energy usage for cooking.* Similar to the results of the transition from traditional solid energy to clean energy, energy affordability remains an important factor. For every 100 yuan increase in income, the probability of rural households opting for electricity as the main energy source for cooking increased by 7.9%, while the probability of opting for gas increased by only 5.0%. The overall impact of subsidy growth was stronger than that of income growth. for every 100 yuan increase in subsidies, the probability of rural households opting for electricity as the main energy source for cooking increased by 19.6%, while the probability of opting for gas increased by 12.5%.

(2) *Decision-making regarding clean energy use for heating.* The effects of income and subsidy growth also resulted in a higher probability of rural households opting for electricity as their main energy source for heating (7.4 and 20.3%, respectively) than for gas (3.2 and 9.6%, respectively). This is mainly because gas is still less

Table 7 Logistic model regression results for decision-making regarding clean energy use for producing hot water

Variable	Model I		Model II		Model III		Model IV	
	B	EXP (B)	B	EXP (B)	B	EXP (B)	B	EXP (B)
Income growth	0.042*** (0.002)	1.043	0.044*** (0.002)	1.045				
Subsidy growth					0.109*** (0.004)	1.115	0.113*** (0.004)	1.120
Gender			− 0.018 (0.064)	0.982			− 0.104 (0.068)	0.901
Age			− 0.011 (0.053)	0.989			0.106* (0.056)	1.112
Education			0.191** (0.080)	1.211			0.189** (0.085)	1.208
Family size			0.025 (0.022)	1.025			0.067*** (0.024)	1.069
Income type			0.393*** (0.043)	1.481			0.343*** (0.046)	1.409
Income-level			0.191*** (0.035)	1.211			0.274*** (0.037)	1.316
Time dummy variables (2021 as reference)								
Year-2022	− 0.634*** (0.122)	0.531	− 0.455*** (0.128)	0.635	− 0.585*** (0.131)	0.557	0.420*** (0.138)	0.657
Area dummy variables (with reference to rural areas in the ecologically fragile region of the Loess Plateau)								
Rural Northwest Arid Desert Ecologically Vulnerable Area	0.096 (0.085)	1.100	0.063 (0.089)	1.065	− 0.037 (0.090)	0.964	− 0.039 (0.095)	0.961
Rural areas in the ecologically fragile region of the Tibetan Plateau	− 1.609*** (0.078)	0.200	− 1.632*** (0.089)	0.196	− 1.537*** (0.083)	0.215	− 1.595*** (0.095)	0.203
Cox and Snell R^2	0.175		0.196		0.174		0.197	
Nagelkerke R^2	0.254		0.285		0.264		0.299	

*, * *, * * * indicate the 10, 5, and 1% significance levels, respectively; standard errors are in parentheses. The unit of income and subsidy growth is 100 yuan, and the estimated coefficient in the report represents the impact of an increase of 100 yuan in income and subsidies on the probability of households opting for clean energy

popular in rural areas of ecol. fragile areas of Northwest China compared to electricity, and, with rising incomes and subsidies, rural households tend to opt for more familiar electricity as their main energy source. However, regarding income growth, the increase in the probability of rural households opting for electricity as the main energy source for heating was 2.31 times as high as that for gas (7.4% vs. 3.2%), while the difference between electricity and gas for cooking (7.9% vs. 5.0%) was smaller. The same holds for subsidy growth. This shows that rural households in ecol. fragile areas of Northwest China are more accepting of gas for cooking than for heating.

(3) *Decision-making regarding clean energy use for hot water production.* The main energy source for hot water is solar energy, which is widely used in ecol. fragile areas of Northwest China. However, the regression results showed that the increase in the probability of rural households opting for solar energy to produce hot water is the lowest with income and subsidy growth. Specifically, for every 100 yuan increase in income (subsidy), the probability of rural households opting for solar energy as the main energy source to produce hot water increased by only 3.7% (9.9%) and the probability of opting for electricity and gas increased by 5.3% (14.0%) and 5.5% (13.4%), respectively. The reason for the low probability of the added value of decision-making regarding clean energy use for producing hot water is that the proportion of existing rural households using solar energy to produce hot water is already high.

Estimation of energy affordability thresholds for rural households opting for clean energy

The threshold regression results revealed the thresholds of energy affordability that cause changes in clean energy use decisions, and found differences in the thresholds for different types of use. Overall, the minimum income growth thresholds for the decision-making changes regarding using clean energy for cooking, heating, and hot water were 2000, 3000, and 2000 yuan, respectively. Based on the above-mentioned income growth rate and the current annual income growth trend of rural households in the northwest, the decision-making of rural households in ecol. fragile areas in Northwest China regarding using clean energy for cooking and producing hot water will change significantly after at least two years. The time for the transformation of heating and energy use may be relatively lagging, and the smallest turning point is three years after. The same phenomenon exists for the subsidy growth threshold. If the subsidy provided by the

Table 8 Impact of income growth on decision-making regarding specific energies for different types of use

Variable	Cooking				Heating				Producing hot water					
	T to E		T to G		T to E		T to G		T to E		T to G		T to S	
	B	EXP (B)	B	EXP (B)	B	EXP (B)	B	EXP (B)	B	EXP (B)	B	EXP (B)	B	EXP (B)
Income growth	0.076*** (0.002)	1.079	0.049*** (0.003)	1.050	0.071*** (0.003)	1.074	0.032*** (0.003)	1.032	0.052*** (0.002)	1.053	0.054*** (0.006)	1.055	0.036*** (0.002)	1.037
Gender	− 0.084 (0.070)	0.919	− 0.051 (0.087)	0.951	0.166** (0.078)	1.180	0.074 (0.110)	1.077	− 0.007 (0.072)	0.993	0.320* (0.190)	1.377	− 0.044 (0.070)	0.957
Age	− 0.166*** (0.057)	0.847	− 0.190*** (0.071)	0.827	− 0.091 (0.062)	0.913	− 0.075 (0.092)	0.928	− 0.074 (0.059)	0.929	0.007 (0.151)	1.007	0.056 (0.058)	1.058
Education	0.347*** (0.083)	1.415	0.043 (0.102)	1.044	0.100 (0.080)	1.105	− 0.745*** (0.142)	0.475	0.162* (0.089)	1.176	0.066 (0.209)	1.069	0.222*** (0.085)	1.249
Family size	− 0.008 (0.023)	0.992	− 0.119*** (0.029)	0.887	− 0.019 (0.025)	0.981	0.026 (0.037)	1.027	0.034 (0.024)	1.034	0.066 (0.060)	1.068	0.018 (0.024)	1.019
Income type	0.242*** (0.048)	1.274	0.465*** (0.059)	1.593	− 0.004 (0.055)	0.996	0.420*** (0.077)	1.522	0.253*** (0.049)	1.288	0.403*** (0.128)	1.496	0.508*** (0.047)	1.663
Income-level	0.284*** (0.039)	1.328	0.479*** (0.052)	1.614	0.607*** (0.044)	1.836	0.394*** (0.064)	1.484	0.157*** (0.040)	1.171	0.218** (0.107)	1.244	0.226*** (0.039)	1.253
Time dummy variable	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled
Area dummy variables	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled
Cox and Snell R^2	0.545				0.364				0.275					
Nagelkerke R^2	0.615				0.475				0.304					

*, * *, * * * indicate the 10, 5, and 1% significance levels, respectively; standard errors are in parentheses. The unit of income growth is 100 yuan, and the estimated coefficient in the report represents the impact of an income increase of 100 yuan on the probability of households opting for clean energy. T: traditional solid energy; E: electricity; G: gas; S: solar energy

Table 9 Impact of subsidy growth on decision-making regarding specific energies for different types of use

Variable	Cooking				Heating				Producing hot water					
	T to E		T to G		T to E		T to G		T to E		T to G		T to S	
	B	EXP (B)	B	EXP (B)	B	EXP (B)	B	EXP (B)	B	EXP (B)	B	EXP (B)	B	EXP (B)
Subsidy growth	0.179*** (0.005)	1.196	0.118*** (0.006)	1.125	0.185*** (0.006)	1.203	0.092*** (0.007)	1.096	0.131*** (0.005)	1.140	0.126*** (0.013)	1.134	0.094*** (0.005)	1.099
Gender	− 0.086 (0.072)	0.918	− 0.157* (0.089)	0.854	0.085 (0.074)	1.089	0.019 (0.108)	1.020	− 0.124* (0.075)	0.884	0.271 (0.203)	1.312	− 0.101 (0.074)	0.904
Age	− 0.117** (0.059)	0.890	− 0.112 (0.072)	0.894	− 0.077 (0.060)	0.926	− 0.102 (0.090)	0.903	0.063 (0.062)	1.065	0.200 (0.164)	1.221	0.159*** (0.061)	1.172
Education	0.267*** (0.086)	1.306	0.045 (0.103)	1.046	0.168** (0.077)	1.182	− 0.728*** (0.138)	0.483	0.166* (0.093)	1.181	− 0.054 (0.230)	0.947	0.222** (0.090)	1.248
Family size	0.057** (0.024)	1.058	− 0.076** (0.030)	0.927	0.036 (0.024)	1.037	0.027 (0.037)	1.028	0.082*** (0.026)	1.085	0.128** (0.064)	1.136	0.054** (0.026)	1.056
Income type	0.153*** (0.049)	1.166	0.439*** (0.060)	1.551	0.060 (0.051)	1.061	0.398*** (0.075)	1.489	0.184*** (0.051)	1.202	0.361*** (0.136)	1.434	0.483*** (0.050)	1.620
Income-level	0.314*** (0.040)	1.369	0.485*** (0.052)	1.624	0.651*** (0.042)	1.917	0.458*** (0.064)	1.581	0.261*** (0.041)	1.298	0.391*** (0.113)	1.478	0.289*** (0.041)	1.336
Time dummy variable	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled
Area dummy variables	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled
Cox and Snell R^2	0.542				0.418				0.292					
Nagelkerke R^2	0.613				0.523				0.325					

*, * *, * * * indicate the 10, 5, and 1% significance levels, respectively; standard errors are in parentheses. The unit of subsidy increase is 100 yuan, and the estimated coefficient in the report indicates the impact of a subsidy increase of 100 yuan on the probability of households opting for clean energy. T: traditional solid energy; E: electricity; G: gas; S: solar energy

Table 10 Threshold model regression results

Variable		Cooking		Heating				Producing hot water	
Income	Threshold	2000		3000		4000		2000	
		≤ 2000	> 2000	≤ 3000	4000		5000	≤ 2000	> 2000
	Coefficient	0.459*** (0.007)	0.792*** (0.133)	0.162*** (0.006)	0.362*** (0.123)		0.568*** (0.123)	0.623*** (0.007)	0.840*** (0.128)
Subsidy	Threshold	1000		1500		2000		1000	
		≤ 1000	> 1000	≤ 1500	2000		2400	≤ 1000	> 1000
	Coefficient	0.493*** (0.006)	0.860*** (0.007)	0.187*** (0.006)	0.500*** (0.013)		0.702*** (0.013)	0.649*** (0.006)	0.892*** (0.006)

*, * *, * * * indicate the 10, 5, and 1% significance levels, respectively; standard errors are in parentheses

government increases by 1,000 yuan per year, rural households will generally opt for using clean energy for cooking and hot water. However, for switching to using clean energy for heating, the turning point of the subsidy growth is increased to 1,500 yuan per year.

In addition, the decision-making coefficients regarding using clean energy for heating are substantially smaller than those for cooking and producing hot water after the first turning point regardless of income or subsidy growth (Table 10); therefore, we focus on the larger thresholds for decision-making regarding using clean energy for heating. When the subsidy increased by 2400 yuan per year for coal-to-electricity and coal-to-gas conversions, the decision-making coefficient regarding using clean energy for heating can reach 0.702, which is barely close to those for the other types of use. In terms of income, even if that increases to 5000 yuan, the coefficient for heating is still far lower than those for other types of use, which shows that a longer time is required for the popularization of clean energy for heating in rural households in ecol. fragile areas in the northwest. This may be because of the large and prolonged energy consumption required for heating, which requires higher energy affordability. Moreover, the northwestern region is cold in winter, and energy there is used primarily for heating; this particularity cannot be ignored. Therefore, it is necessary to promote efficient clean energy equipment and provide appropriate subsidies in stages.

Heterogeneity analysis of the impact of energy affordability on the decision-making of rural households regarding clean energy use

The results of the sample characteristics revealed significant differences in energy usage decisions among rural households in different ecol. fragile areas. This phenomenon is related to the individual and household characteristics of respondents in different regions. From the regression results in Tables 5, 6, and 7, it can be observed that factors such as age, education level, income level, income sources, and region had a significant impact on the clean energy usage decisions of rural households in ecol. fragile areas of Northwest China. To further refine the impact of energy affordability on the decision-making of rural households in ecol. fragile areas of Northwest China regarding clean energy use, we examined the heterogeneity of the impact among rural households of different ages, educational levels, income levels, income types, and ecology types.

Heterogeneity analysis of different types of respondents

1. Heterogeneity analysis of respondents in different age groups

Age has a significant impact on the daily decision-making and habits of rural residents [44]. Due to the influence of cognition and traditional ideas, older residents are less likely to understand and accept clean energy operating rules than young and middle-aged residents. Following [46], respondents aged 60 and above were defined as elderly, while others were defined as young and middle-aged. The regression results are presented in Table 11. Although the effect of energy affordability was positively significant in both groups, the extent of the effect of energy affordability on decision-making regarding clean energy use in cooking and heating was stronger for young and middle-aged decision-makers. Specifically, the coefficient of per capita annual income growth had a greater impact on clean energy usage decisions for cooking and heating among middle-aged and young decision-makers (0.072 and 0.061, respectively) than among elderly decision-makers (0.063 and 0.053, respectively).

The effects of the government energy subsidies on both groups were largely consistent. However, for the decision to use clean energy for hot water, the increase in government energy subsidies had a greater effect on elderly decision-makers. In addition, the influence of the energy payment ability on the decision to use clean energy for hot water between the elderly and non-elderly groups was reduced at higher per capita annual incomes. This may be because clean energy for hot water is relatively

Table 11 Heterogeneity of individual characteristics in the impact of energy affordability on decision-making regarding clean energy use

Variable	Young and middle-aged group			Elderly group			Low education group			High education group		
	Cooking	**Heating**	**Hot water**	**Cooking**	**Heating**	**Hot water**	**Cooking**	**Heating**	**Hot water**	**Cooking**	**Heating**	**Hot water**
Income growth	0.072*** (0.003)	0.061*** (0.003)	0.044*** (0.002)	0.063*** (0.004)	0.053*** (0.004)	0.044*** (0.004)	0.069*** (0.002)	0.057*** (0.002)	0.044*** (0.002)	0.074*** (0.007)	0.068*** (0.006)	0.043*** (0.006)
Subsidy growth	0.171*** (0.006)	0.161*** (0.006)	0.114*** (0.005)	0.148*** (0.009)	0.147*** (0.009)	0.115*** (0.009)	0.164*** (0.005)	0.153*** (0.005)	0.113*** (0.005)	0.170*** (0.015)	0.184*** (0.013)	0.121*** (0.015)
Control variables	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled
Dummy variable	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled
Observations	4956			1752			5760			948		

*, * *, * * * indicate that 10, 5, and 1% significance levels, respectively; standard errors are in parentheses. The unit of income and subsidy growths is 100 yuan, and the estimated coefficient in the report represents the impact of 100 yuan increase in income and subsidies on the probability of households opting for clean energy

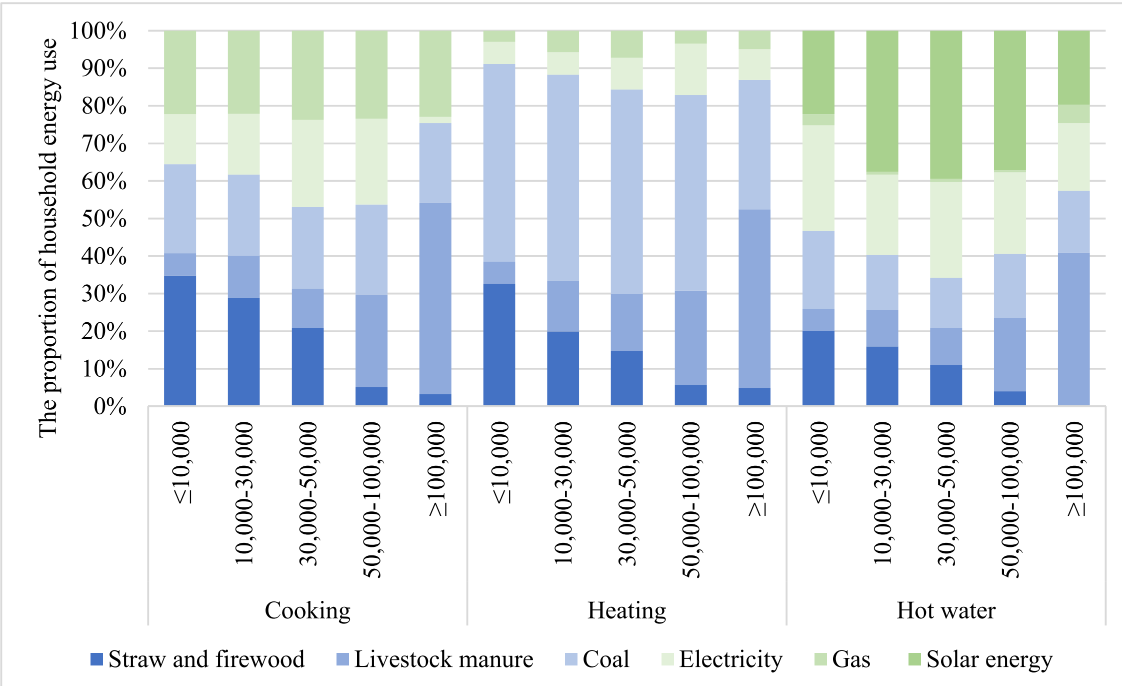

Fig. 5 Decision-making regarding energy use of rural households at different income levels

common in rural areas of ecol. fragile areas of Northwest China. However, elderly decision-makers have a greater demand for hot water than middle-aged and young decision-makers. Therefore, they are more likely to accept the use of clean energy for hot water when there is an increase in government energy subsidies, whereas middle-aged and young decision-makers can choose not to use hot water as a substitute.

2. Heterogeneity analysis of respondents with different educational levels

Since the educational level of rural residents in ecol. fragile areas of Northwest China is relatively low (i.e., mostly junior high school and below), we collectively referred to the groups that have received high school education and above as the high education group. The regression results showed that energy affordability played a greater role in the high education group than in the low education group (only junior high school education and below). Taking the cooking clean energy usage decision as an example, the coefficients of per capita annual income and subsidy growth had a higher impact on decision-making regarding the use of clean energy for cooking among individuals with higher educational attainment (0.074 and 0.170) compared to those with lower educational attainment (0.069 and 0.164). This is likely because the more educated the respondents, the more they recognize the importance of clean energy use and the more willing they are to use clean energy when it becomes more affordable. However, as per capita annual income increased, the difference in the coefficients of decision-making regarding the use of clean energy for hot water decreased. This may be attributed to the widespread adoption of solar energy in hot water production.

Heterogeneity analysis of different income characteristics

1. Heterogeneity analysis of households with different income levels

As clean energy is a commodity and its use requires payment, there may be differences in decision-making regarding clean energy use between households of different income levels. Figure 5 shows the relationship between the income levels of rural households in the ecol. fragile areas of Northwest China and their decisions to use clean energy for different purposes. As the income level increases, rural households in ecol. fragile areas of Northwest China are more likely to choose clean energy; however, when the income level exceeds 100,000 RMB, this trend is not applicable.

Based on this, we analyzed the impact of energy affordability among groups with different income levels (Table 12). For rural households with lower income levels, the improvement in energy affordability had little

Table 12 Income-level heterogeneity in the impact of energy affordability on decision-making regarding clean energy use

Variable	≤ 10,000			10,000–30,000			30,000–50,000			50,000–100,000			≥ 100,000		
	Cooking	**Heating**	**Hot water**	**Cooking**	**Heating**	**Hot water**	**Cooking**	**Heating**	**Hot water**	**Cooking**	**Heating**	**Hot water**	**Cooking**	**Heating**	**Hot water**
Income growth	0.057*** (0.006)	0.050*** (0.007)	0.040*** (0.005)	0.064*** (0.003)	0.055*** (0.004)	0.042*** (0.003)	0.077*** (0.004)	0.061*** (0.004)	0.043*** (0.004)	0.091*** (0.007)	0.069*** (0.006)	0.054*** (0.005)	0.106*** (0.013)	0.073*** (0.011)	0.063*** (0.009)
Subsidy growth	0.142*** (0.013)	0.152*** (0.016)	0.098*** (0.012)	0.160*** (0.008)	0.147*** (0.008)	0.113*** (0.007)	0.163*** (0.009)	0.156*** (0.008)	0.108*** (0.008)	0.211*** (0.016)	0.175*** (0.012)	0.127*** (0.012)	0.242*** (0.027)	0.229*** (0.025)	0.206*** (0.026)
Control variables	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled
Dummy variable	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled
Observations	810			2412			2070			1050			366		

*, * *, * * * indicate the 10, 5, and 1% significance levels, respectively; standard errors are in parentheses. The unit of income and subsidy growths is 100 yuan, and the estimated coefficient in the report represents the impact of 100 yuan increase in income and subsidies on the probability of households opting for clean energy

effect on their decision-making regarding clean energy use, whereas, for rural households with higher income levels, the improvement in energy affordability had a greater effect on their decision-making regarding clean energy use. For rural households with an income level above 100,000 yuan, the coefficients of per capita annual income and subsidy increase had a substantial impact on decision-making regarding the use of clean energy for cooking. Specifically, the coefficients were 0.106 and 0.242, respectively. Therefore, if appropriate subsidies are provided for high-income groups, they may choose to use clean energy, while for low-income groups, additional subsidies are necessary; however, government subsidies are limited. Therefore, raising the incomes of rural households in ecol. fragile areas of Northwest China should be a priority.

2. Heterogeneity analysis of households of different income types

Income type is an important factor affecting the consumption decisions of rural households and inevitably affects their use of clean energy [76]. Table 13 shows that, in cooking and heating activities, the affordability of energy had the smallest impact coefficient on clean energy usage decision-making for non-farming rural households. This suggests that non-farming rural households are relatively less influenced by the affordability of energy and may be more constrained by other factors. However, a different phenomenon was observed for hot water usage. The coefficients of per capita annual income and subsidy increase on decision-making regarding the use of clean energy for cooking in non-farming rural households were 0.049 and 0.117, respectively, which were higher than the coefficients for farming rural households (0.038 and 0.103). This may be because clean energy from hot water is more prevalent, convenient, and advanced in rural areas. Therefore, non-farming rural households that are more knowledgeable about clean energy are willing to transition when they have sufficient energy affordability. These factors limit the relatively weak influence of energy affordability on cooking and heating activities.

Heterogeneity analysis of different ecologically fragile areas

As there are significant differences in the energy use behavior of rural households in different types of ecol. fragile areas (see Fig. 4), we further discussed the impact of energy affordability in different ecol. fragile areas on the decision-making of rural households' clean energy use. From the regression results in Table 14, it can be seen that in the ecol. fragile areas of the Qinghai-Tibet Plateau, where clean energy usage rates are the lowest and high-income pastoralists are predominant, the promotion effect of energy affordability is much higher than in the other two types of ecol. fragile areas. For example, in decision-making regarding the use of clean energy for cooking, the coefficient of per capita annual income growth in the ecol. fragile areas of the Qinghai-Tibet Plateau was 0.127, which was significantly higher than the coefficients in the Loess Plateau and northwest arid desert (0.055 and 0.047, respectively). The main reason for this difference is that the proportion of rural households at the high-income level in ecol. fragile areas of the Qinghai-Tibet Plateau is far higher than those in the other regions (see Table 14). While households can accept clean energy with higher costs with appropriate subsidies, the difference is also related to the high proportion of purely agricultural rural households in the Qinghai-Tibet Plateau.

These results imply that the effects of energy affordability on rural households were not uniform. In general, it should start with highly educated, young, and middle-aged decision-makers, as well as high-income and purely

Table 13 Income type heterogeneity in the impact of energy affordability on decision-making regarding clean energy use

Variable	Purely agricultural			Part-time agricultural			Non-agricultural		
	Cooking	Heating	Hot water	Cooking	Heating	Hot water	Cooking	Heating	Hot water
Income growth	0.073*** (0.004)	0.065*** (0.005)	0.038*** (0.003)	0.072*** (0.004)	0.069*** (0.004)	0.050*** (0.003)	0.064*** (0.004)	0.048*** (0.003)	0.049*** (0.004)
Subsidy growth	0.177*** (0.009)	0.173*** (0.010)	0.103*** (0.007)	0.160*** (0.008)	0.173*** (0.008)	0.129*** (0.008)	0.159*** (0.010)	0.135*** (0.007)	0.117*** (0.010)
Control variables	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled
Dummy variable	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled
Observations	2016			2538			2154		

*, * *, * * * indicate the 10, 5, and 1% significance levels, respectively; standard errors are in parentheses. The unit of income and subsidy growth is 100 yuan, and the estimated coefficient in the report represents the impact of 100 yuan increase in income and subsidies on the probability of households opting for clean energy

Table 14 Spatial heterogeneity in the impact of energy affordability on decision-making regarding clean energy use

Variable	Areas in the Loess Plateau			Arid desert areas in Northwest China			Areas in the Qinghai-Tibet Plateau		
	Cooking	Heating	Hot water	Cooking	Heating	Hot water	Cooking	Heating	Hot water
Income growth	0.055*** (0.003)	0.064*** (0.003)	0.043*** (0.003)	0.047*** (0.004)	0.041*** (0.003)	0.030*** (0.004)	0.127*** (0.006)	0.110*** (0.008)	0.055*** (0.003)
Subsidy growth	0.127*** (0.006)	0.164*** (0.008)	0.112*** (0.008)	0.120*** (0.010)	0.111*** (0.007)	0.077*** (0.008)	0.277*** (0.012)	0.267*** (0.015)	0.142*** (0.007)
Control variables	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled
Dummy variable	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled
Observations	2868			1956			1884		

*, * *, * * * indicate the 10, 5, and 1% significance levels, respectively; standard errors are in parentheses. The unit of income and subsidy growth is 100 yuan, and the estimated coefficient in the report represents the impact of 100 yuan increase in income and subsidies on the probability of households opting for clean energy

agricultural rural households, to maximize the effect of improving the energy affordability and utilization rate of clean energy in rural areas. Specifically, for ecol. fragile areas of the Loess Plateau and the northwest arid desert with low income levels, income levels should be improved to promote the popularization of clean energy in these areas. For ecol. fragile areas of the Qinghai-Tibet Plateau, where high-income residents and purely agricultural rural households are the majority, it is important to implement subsidy policies and improve the popularity and convenience of clean energy. Thus, H3 was confirmed.

Robustness tests

To ensure the robustness of the above results, we conducted robustness tests on the estimated results by replacing explanatory variables, sample selection, and endogeneity discussion. First, we analyzed the relationship between decision-making regarding clean energy use and energy affordability for cooking, heating, and producing hot water; the regression results can be the results of substituting the explained variables with one another. In the above results, the relationship between energy affordability and decision-making for clean energy use was positive and significant, indicating that the baseline estimation results are robust.

Second, elderly (i.e., over 60 years old) residents are often unable to engage in many agricultural production and operation activities, as well as energy collection activities, because of their reduced fitness, cognition, and learning ability [43]. However, 30.49% of respondents were over 60 years old. To prevent possible bias in the results caused by elderly respondents, we excluded respondents over 60 years old from the sample and used the subsample regression method to test model robustness. The results are presented in Table 11. Energy affordability still had a significant positive impact on the decision-making of rural households regarding clean energy use, which shows that the benchmark regression results are robust.

For endogeneity issues, the impact of energy affordability may lead to spurious correlations due to omitted variables, sample self-selection, and so on. The problem of omitted variables was mitigated by controlling for individual, household, and other relevant variables that influence decision-making regarding clean energy use in the model-setting process. For the sample self-selection problem, there was no self-selection in the estimation of energy affordability because income growth and government energy subsidies were based on relevant reports and were not related to rural household preferences.

Discussion

Energy affordability is an important factor influencing rural households' decisions on clean energy use

The results of sample characterization indicate that rural households in the ecol. fragile areas of Northwest China still use traditional solid energy sources, such as coal and firewood, as their main energy sources, particularly for heating in winter [39, 55]. This energy consumption pattern is related to the relatively lagging economic development and weak energy affordability of rural households in the ecol. fragile areas of Northwest China [16]. Consistent with previous research, this study examined the impact of energy affordability on the decision-making of rural households regarding clean energy use, thereby logistic regression results confirming that those with higher energy affordability are more likely to use clean energy [16, 77].

Notably, this study analyzed the role of energy affordability based on two dimensions of endogenous variables (i.e., per capita annual household income) and external inputs (i.e., government energy subsidies), both of which confirmed the energy ladder theory with improving

Table 15 Baseline regression results

Variable	Regression 1	Regression 2	Regression 3	Regression 4
Income growth	0.025*** (0.001)	0.025*** (0.001)		
Subsidy growth			0.063*** (0.001)	0.063*** (0.001)
Gender		− 0.073*** (0.023)		− 0.081*** (0.022)
Age		0.073*** (0.019)		0.086*** (0.018)
Education		0.149*** (0.026)		0.124*** (0.025)
Family size		0.008 (0.007)		0.023*** (0.007)
Income type		0.357*** (0.015)		0.305*** (0.014)
Income-level		0.011 (0.012)		0.060*** (0.012)
R^2	0.163	0.243	0.233	0.299

*, * *, * * * indicate the 10, 5, and 1% significance levels, respectively; standard errors are in parentheses

economic conditions, the increasing preference for modern clean energy such as electricity and gas, and the positive effects of higher subsidies proposed by Feng et al. [78]. By comparing their impacts, we determined that subsidies had a greater effect than income, which shows that promoting the use of clean energy in rural households by only increasing the income level will be slow and that the provision of subsidies to improve energy affordability in rural households can accelerate the pace of transformation. However, in addition to income and subsidies, other factors, such as energy prices, determine energy affordability. Therefore, in the future, we will supplement this study and compare it with existing research. During the variable selection process, this study faced limitations in terms of the research conditions. Because of these constraints, macro-level data such as per capita annual income growth and subsidy data were chosen for the analysis. However, these data may not fully capture the true impacts of household income growth and subsidy increases on clean energy use. Therefore, in future research, it is essential to enhance the collection of actual income and subsidy data for rural households and enrich the survey questionnaire data.

Differences in the effect of energy affordability on decisions to use clean energy for different uses

The results showed that energy affordability had a weaker effect on decision-making regarding the use of clean energy for heating than for cooking and that income and subsidy growth thresholds that induced changes in decision-making regarding clean energy use for heating were substantially higher than those for cooking and hot water production. As income and subsidies increase, energy transitions for cooking and producing hot water can occur spontaneously, whereas energy transitions for heating become more difficult. There were differences in the impact of energy affordability on decision-making regarding clean energy for different types. As energy affordability increased, rural households tended to use electricity and solar energy. The results showed that rural households were more accepting of gas for cooking than for heating. These differences indicate that in future research, we should further quantify various factors to explore their role in decision-making regarding clean energy for different types of use, and then make targeted recommendations.

In addition, the decision-making regarding clean energy use in rural households can be analyzed in terms of how much clean energy is used and the representation of clean energy. The findings of the sample characteristics align with those of previous research [46, 79], indicating that the energy sources utilized for cooking, heating, and hot water activities in rural households vary. This suggests that household energy usage tends to be more diverse than it is uniform. Therefore, we explored the relationship between the ability to pay for energy and the amount of clean energy used using the amount of clean energy as the dependent variable. The results of the baseline regression are shown in Table 15. It can be seen that there is a significant positive effect of the ability to pay for energy on the amount of clean energy used and this result remains significant after the inclusion of control variables, which indicates a significant relationship between the ability to pay for energy and the amount of clean energy available. Therefore, future research could consider analyzing rural households' decision-making regarding clean energy use from the perspective of the quantity of clean energy used to make the findings richer.

Impact of energy affordability on clean energy use decisions is non-uniform

Regarding the heterogeneity of the impact of energy affordability, the research findings indicate that the influence of energy affordability on the decision-making process of clean energy use in rural households in ecol. fragile areas of Northwest China is uneven. Consistent with previous studies [42, 80], this study found that the education level and age of decision-makers, as well as differences in household income level and income sources, play a moderating role in the impact of energy affordability on the decision-making of clean energy use in rural households in the ecol. fragile areas. Owing to the differences in the aforementioned characteristics among rural households in different types of ecol. fragile areas, energy choices also vary when energy affordability improves. Therefore, it is necessary to leverage the role of energy affordability from different perspectives for rural households in ecol. fragile areas.

However, when considering the heterogeneity of the impact of energy affordability on decision-making regarding clean energy use in rural households, this study only discussed regional differences in the influence of energy affordability from the perspective of different types of ecol. fragile areas, overlooking the heterogeneity within villages. However, different villages have variations in decision-making among rural households owing to external factors such as energy policies and promotional efforts [78, 81]. Therefore, in future research, it is essential to delve into more regions and select villages of different types to thoroughly explore heterogeneity among regions.

Conclusions

Conclusions

Ecol. fragile areas of Northwest China are generally rich in clean energy resources; however, achieving an energy transition remains a challenge. Energy affordability is an important factor affecting the decision-making of rural households in ecol. fragile areas of Northwest China. Using microsurvey data from rural households in ecol. fragile areas of Northwest China, this study constructed a household-level database of energy use and empirically tested the relationship between energy affordability and rural household decision-making regarding clean energy use. The main conclusions are as follows:

First, energy affordability had a significant positive effect on the decision-making of rural households in the ecol. fragile areas of Northwest China regarding clean energy for various types of use, in which the impact of energy affordability on the decision-making regarding using clean energy for cooking was significantly greater than that for heating. Moreover, for cooking, heating, and hot water production, the incentive effect of subsidy growth on rural households' decision-making regarding clean energy use was greater than that of income growth.

Second, in decision-making regarding the use of clean energy for cooking and heating, the affordability of energy increased and the probability of rural households opting for more familiar electricity as the main energy source was greater than that for gas as the main source. However, rural households were more likely to use gas for cooking than for heating. In decision-making regarding the use of clean energy to produce hot water, there was a small difference between the probability added values of electricity and gas.

Third, the income and subsidy growth thresholds for decision-making changes regarding the use of clean energy for cooking and producing hot water will be smaller than those for heating. Energy transition can occur spontaneously with an increase in income and subsidies, whereas energy transition for heating is more difficult. Even with 2400 yuan per year increases in coal-to-electricity and coal-to-gas conversion subsidies, the decision-making coefficient of using clean energy for heating barely approached that of other types of use. In addition, even with a 5000 yuan increase in income, the coefficient for heating remained far lower than those for other types of use and it would take more than five years to popularize the use of clean energy for heating in rural households in ecol. fragile areas of Northwest China.

Fourth, the impact of energy affordability on decision-making regarding clean energy use by rural households in the ecol. fragile areas of Northwest China was heterogeneous. Rural households in different ecol. fragile areas should better play the role of energy affordability from different perspectives. Ecol. fragile areas of the Loess Plateau and the northwest arid desert with low income levels should first aim to improve income levels. In ecol. fragile areas of the Qinghai-Tibet Plateau, where the income level is high and rural households are purely agricultural, it is important to implement subsidy policies and improve rural households' understanding of clean energy.

Finally, although this study obtained valuable research results, there were limitations owing to its subjective nature and the research conditions. Therefore, it is necessary to improve the results in subsequent studies. (1) In addition to income factors, the determinants of energy affordability may include various aspects such as energy prices and types of energy supply. Therefore, in future research, it is necessary to further quantify the effects of other influencing factors and discuss their impacts on clean energy use decisions categorized by usage and type. These findings should be compared with existing research results to provide targeted recommendations. (2) Macrolevel data may not fully capture the true impact of household income growth and subsidy increases on clean energy use. In future research, the collection of actual income and subsidy data for rural households should be enhanced. Additionally, expanding the analysis of clean energy use decisions in rural households beyond the choice of clean energy source to include the quantity of clean energy used could provide a more comprehensive understanding. Therefore, considering the perspective of clean energy usage will enrich the findings of this study. (3) This study discussed regional disparities in energy affordability from the perspective of different types of ecol. fragile areas. However, different villages may make different decisions due to variations in energy policies, promotional efforts, and other external environmental factors. Therefore, in future research, it is necessary to visit more regions and select villages of different types to explore the heterogeneity among regions in greater depth.

Policy implications

These findings have important policy implications, revealing the need to adapt clean energy promotion measures to the needs of rural households in the ecol. fragile areas of Northwest China.

First, energy affordability greatly influences the clean energy use decisions of rural households in the ecol. fragile areas of Northwest China, which hinders the promotion of clean energy. Thus, it is crucial to realize that financial resources should be directed to the rural areas in the economically backward ecol. fragile areas of the Northwest. At the same time, as the impact of energy affordability on the clean energy use decisions of rural households in ecologically fragile zones of Northwest China varies across different uses and types of clean energy, energy subsidies should be differentiated by type and period and compensation policies for clean energy should be designed considering time and place.

Second, income is a major indicator of energy affordability and plays an important role in decision-making regarding clean energy use by rural households in the ecol. fragile areas of Northwest China. Considering that agriculture and animal husbandry are the main economic structures of rural, ecol. fragile areas of Northwest China, increased employment opportunities for rural residents should be provided by expanding the scale of planting and breeding and the agricultural and animal husbandry industry chain, thus increasing rural household income.

Third, young and middle-aged people, people with higher education, and rural households with mainly non-farming jobs had a higher level of awareness of clean energy and were more accepting of the use of clean energy. Therefore, there should be increased efforts to publicize and popularize clean energy and activities on environmental protection and the use of clean energy should be organized to increase awareness among rural residents.

Fourth, clean energy technologies, such as solar water heating, have been widely implemented in Northwest China because of their convenience and low cost. Indeed, rural households are increasingly attracted to clean energy sources. However, clean energy technology for heating is still immature and costly; thus, the use of traditional solid energy in heating activities is still widespread. Therefore, attention should be given to the development of energy technologies to promote the maturity of clean energy and improve the accessibility of clean energy applications.

Supplementary Information

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Additional file 1. Survey.

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Author contributions
LL: conceptualization, investigation, methodology, writing—review and editing, reviewing, funding acquisition. HS: investigation, data curation, software, writing—original draft and preparation, writing—review and editing. MD: investigation, writing—review and editing. YZ: investigation. XL: investigation.

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Availability of data and materials
The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
All authors agree to the publication of this manuscript.

Competing interests
The authors declare that they have no competing interests.

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