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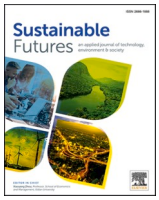

The impact of rural human capital on household energy consumption structure: Evidence from Shaanxi Province in China

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ABSTRACT

The structure of rural household energy consumption is crucial for rural residents' living standards and quality of life, constituting an integral component of energy transition and promoting Chinese-style modernization. Meanwhile, rural human capital is a prerequisite for agricultural and rural modernization. Drawing on survey data from 791 households in Shaanxi Province, this study empirically examines the impact and mechanisms of human capital on the household energy consumption structure with the ordinary least square (OLS) model and instrumental variable (IV) method. The findings indicate that human capital significantly reduces traditional energy consumption while increasing the adoption of transitional and advanced energy. This conclusion remains robust after rigorous testing. Mechanism analysis reveals that human capital facilitates the shift from traditional to transitional and advanced energy by enhancing purchasing power, environmental awareness, and the frequency of energy-saving technology usage within households. Further analysis demonstrates that higher levels of human capital correlate with a greater likelihood of households transitioning from traditional energy to transitional and advanced energy. Particularly, households with a high school education exhibit a significant increase in the consumption of transitional and advanced energy while notably reducing traditional energy consumption. Moreover, compared to low-income households, human capital has a significantly positive effect on increasing the adoption of advanced energy in high-income households. Hence, prioritizing investment in rural education, providing more educational resources, improving school facilities, and implementing incentive policies to emphasize education within households are recommended strategies to enhance rural residents' human capitals. This, in turn, facilitates their adoption of transitional and advanced energy, reducing dependence on traditional energy.

1. Introduction

Since adopting the Paris Agreement in 2015, discussions surrounding energy usage have undergone significant shifts in both governmental and academic spheres, focusing on energy-related activities to achieve global sustainable development transitions [41]. Energy is an indispensable resource in modern society, and household energy consumption constitutes a vital area closely intertwined with daily life, encompassing how households utilize energy to fulfill various needs, including heating, lighting, cooking, and electricity [35]. Rural household energy consumption is a crucial component of China's energy demand [51]. Therefore, understanding the patterns, trends, and influencing factors of rural household energy consumption is essential for energy policies, sustainable development, and environmental protection. From 1980 to 2021, China's per capita energy consumption increased from 60[1, 3, 4] kgs to 478 kgs of standard coal.[1] The household sector constitutes a significant consumer of energy, particularly solid fuels such as loose coal. Compared to cleaner energy like electricity and natural gas, solid fuels have difficulties achieving full combustion, resulting in substantial emissions of pollutants in household energy consumption dominated by solid fuels like loose coal. Furthermore, unlike the power and industrial sectors, pollutants generated by the

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[1] It is derived from CEIC data.

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household sector often undergo no end-of-pipe treatment and are directly emitted into the atmosphere, making the household sector one of the major sources of atmospheric pollutant emissions [28,59].

Accompanying the rapid increase in energy consumption, significant changes have occurred in the energy consumption patterns of rural households in China, although issues of insufficiency and imbalance persist. Structurally, there is a growing diversity in energy consumption choices, and energy use patterns have improved, yet reliance on traditional solid fuels such as firewood and loose coal persists [20]. Spatially, variations in energy usage structures exist among regions [29]. The irrationality of household energy consumption structures exacerbates economic poverty on the one hand [26,27] and poses severe threats to the environment, climate, and residents' health on the other [1,44,57]. Therefore, promoting the transition of rural household energy is not only a crucial proposition for realizing China's energy transition but also an objective necessity for improving residents' living standards, accelerating rural economic development, and narrowing the urban-rural gap. Currently, the level of economic development in rural China remains relatively low. Despite substantial subsidies provided by the government for equipment purchase and energy use, these do not fully cover the energy expenses of rural households. Most families still cannot afford the high energy costs. Moreover, the higher prices of advanced energy exacerbate the difficulty of energy transition. In this predicament, clarifying the objective laws governing the energy consumption structure of rural households in China becomes exceptionally crucial.

Based on the survey results of 791 households in Shaanxi Province (Table 1), households solely consuming traditional energy like firewood account for only 1.39 %. Those consuming firewood, coal, and refined oil constitute 1.77 %, while households consuming firewood, electricity, natural gas, and solar energy represent 72.95 %. Additionally, households consuming coal, refined oil, electricity, natural gas, and solar energy account for 64.85 %, and those consuming all mentioned energy types comprise 53.60 %. Household energy consumption is transitioning from traditional sources like firewood to transitional sources like coal and refined oil, as well as to high-quality sources like electricity, natural gas, and solar energy. Concerning rural residents' energy choices, existing literature has proposed the phenomenon of energy stacking in residents' energy selection behaviors [3,48]. This hypothesis suggests that as social and economic statuses improve, residents' energy choices undergo corresponding changes, leading to the emergence of energy stacking, which can be categorized into three stages. The first stage is the initial stage, characterized by residents primarily using traditional biomass energy such as firewood, straw, and animal manure. The second stage is the transitional stage, where residents abandon traditional biomass energy and shift towards fossil fuels like charcoal, coal, and kerosene. The third stage is the advanced stage, where residents predominantly use modern commercial energy like electricity, natural gas, and liquefied petroleum gas, which exhibit higher energy efficiency and lower costs than previous stages.

Existing research on the influencing factors of household energy consumption structure mainly includes several aspects: geographic location [51], socio-cultural factors [10], household size and composition [60], household economic status [45], energy equipment and technologies used by households [49], individual and household lifestyles and consumption habits [18], energy price fluctuations and increases [24], and government energy policies and regulations [40].

Human capital serves as the engine for long-term economic growth in an economy [38], and education is the primary mode of investment in human capital. The "Opinions on Accelerating the Rural Revitalization through Talent Development" issued by the General Office of the Central Committee of the Communist Party of China and the General Office of the State Council in 2021 emphasized placing the development of rural human capital in a primary position, improving the rural talent work system and mechanisms, strengthening talent revitalization guarantee measures, and making essential arrangements for accelerating the revitalization of rural talents. Rural human capital has always been the intrinsic driving force for rural revitalization [50], and a key strategy for improving farmers' income, coping with demographic challenges and promoting social stability [37]. Theoretically, the enhancement of human capital enables households to adopt clean energy technologies more effectively. It increases their awareness, skills, and resources to play a more active role in the clean energy sector [2,22]. This helps reduce dependence on traditional energy, promotes clean, sustainable energy consumption, and aids in addressing climate change and reducing environmental pollution. In addition, existing studies have explored the important role of rural human capital from the perspectives of health investment, agricultural productivity, and urbanization level. It is found that improving human capital in rural areas can significantly promote agricultural modernization [61] and facilitate the process of urbanization [11]. Although existing research has not explicitly stated that rural human capital can improve household energy consumption structures, logically, there is a specific connection between the two. This is because human capital is the primary means of enhancing the quality, knowledge, and abilities of rural labor, serving as a complement and alternative to productive assets in household production, promoting increased household income, and thus enabling households to afford a broader range of energy consumption options [16]. Therefore, exploring the impact of rural human capital on household energy consumption structures holds significant practical significance.

Therefore, based on the energy stacking hypothesis, this paper will research the energy consumption structure of rural residents in China, examining the impact of rural human capital on residents' energy consumption structure. The aim is to provide a new perspective for research on energy and climate/environmental issues and offer scientific references and bases for formulating energy transition policies. Compared to previous studies, this paper attempts to supplement existing research in the following aspects: Firstly, in terms of research content, this study incorporates rural human capital into the analysis of household energy consumption structures to verify its role in optimizing these structures, thereby providing a new perspective for improving household energy consumption patterns. Secondly, in terms of theoretical mechanisms, this study will focus on analyzing how rural human capital influences household energy consumption structures through payment capacity, environmental awareness, and the frequency of energy-saving technology usage. Lastly, from a research perspective, this study will explore the differences in the impact of various levels of human capital on household energy consumption structures, as well as the role of human capital in influencing the energy consumption structures of households with different income levels, thereby offering a decision-making basis for effectively improving household energy consumption structures.

The rest of the paper is structured as follows: The second section comprises theoretical analysis and research hypotheses. The third

Table 1
Types of household energy consumption.

Only firewood is consumed		Consumption of firewood; Coal, refined oil		Consumption of firewood; Electricity, natural gas, solar		Consumption of coal and refined oil; Electricity, natural gas, solar		Consumption of firewood; Coal, refined oil; Electricity, natural gas, solar	
Number of households	Proportion of total (%)	Number of households	Proportion of total (%)	Number of households	Proportion of total (%)	Number of households	Proportion of total (%)	Number of households	Proportion of total (%)
11	1.39	14	1.77	577	72.95	513	64.85	424	53.60

section covers models, variables, and data. The fourth section entails empirical analysis, and the fifth comprises conclusions and policy implications.

2. Theoretical analysis and research hypotheses

According to the theory of human capital, individuals can enhance their competitiveness and income levels in the labor market by investing in human capital accumulation through education and training [13]. Higher income levels may lead to households being more capable of paying high energy costs or purchasing more efficient energy equipment, affecting household energy consumption levels [17]. This is primarily manifested in the following aspects: Firstly, there is an improvement in education and awareness. On one hand, providing energy consumption education and training enables households to understand the importance of energy conservation and sustainable energy, enhancing the energy management skills of household members, including how to use household appliances and equipment more effectively [33]. On the other hand, promoting energy-saving awareness encourages households to adopt more environmentally friendly energy consumption habits, fostering knowledge of sustainable energy among household members, such as using renewable energy like solar and wind energy [31]. Secondly, there is an enhancement in technological and innovation levels. Through investment in education in technology and innovation fields, household members can better understand emerging energy-saving technologies and are more likely to accept and adopt these technologies. They can develop an understanding of smart home technologies and energy management systems to monitor and manage household energy consumption more effectively [39]. Lastly, there is the role of advocacy and education. High human capital family members have some influence in the community. By sharing knowledge and experience, they can promote energy-efficient and environmentally friendly lifestyles and influence families around them to adopt greener energy consumption patterns [32]. High human capital family members may also become advocates of "green living", spreading information about energy conservation and renewable energy through social media or community activities, thereby driving the improvement of the energy consumption structure of the entire community [53]. Based on this, the following hypotheses are proposed:

H1: Increased human capitals can improve household energy consumption structures.

Furthermore, on the one hand, household members, through higher education, vocational training, and skill development, enhance their employability, thereby gaining access to higher-paying job opportunities, increasing their incomes, and allowing households to invest more funds in energy-efficient home appliances and sustainable energy technologies. Continuous career development and income growth provide households with more financial resources to purchase solar panels, efficient appliances, and energy-saving devices. These typically consume less energy and help reduce energy consumption and associated energy costs, thereby improving household energy consumption structures [58]. On the other hand, individuals with higher levels of education can accumulate wealth through intelligent investment and financial management, thereby enhancing their payment capability. By investing in renewable energy projects or other opportunities in environmental sectors, households can achieve long-term energy cost savings [34]. Additionally, highly educated households can develop long-term energy efficiency improvement plans, gradually reducing energy waste and enhancing household payment capabilities. High-income households are more likely to consider long-term investments because they can pay for them and expect to benefit from them in the coming years. As time progresses, the costs of clean energy technologies gradually decrease while their performance continues to improve [36]. Therefore, high-income households are more likely to keep up with the development of these technologies, making it easier for them to choose clean energy as part of their energy supply. Based on the above analysis, the following research hypotheses are proposed:

H2a: Increased human capitals improve household energy structures by enhancing household payment capability.

Lastly, the Knowledge, Attitude, and Practice (KAP) theory posits that knowledge, attitudes, and practices are interrelated and collectively influence individual behavior [56]. Regarding household energy consumption, household members' knowledge level and attitudes (such as environmental awareness) may influence their cognition and attitudes towards energy use, thereby affecting their actual energy-saving behaviors. Some studies suggest that higher education households are more conscious of adopting energy-saving measures and sustainable lifestyles [31]. Additionally, the Technology Acceptance Model (TAM) suggests that the degree to which people accept new technology depends on their perceptions of its usefulness and ease of use [9]. Therefore, in household energy consumption, household members' knowledge and skill levels regarding energy-saving technology may affect their acceptance of energy-saving equipment and technologies, thus influencing energy consumption behavior. Individuals with higher education levels are more likely to understand the importance of energy conservation and its implementation methods, thus potentially adopting more energy-saving behaviors in household energy consumption. Based on this, the following hypothesis is proposed:

H2b: Increased human capitals improve household energy structures by enhancing environmental awareness.

Human capital encompasses an individual's accumulation of knowledge, skills, health status, and education levels, all of which are crucial for understanding and adopting new technologies [15]. Therefore, enhancing human capitals can promote the frequency of household energy-saving technology usage in multiple ways. On one hand, higher education levels typically make people more receptive to new technologies. Increasing people's knowledge levels helps them better understand the principles and advantages of energy-saving technologies, making them more willing to adopt them [55]. On the other hand, enhancing human capital means people have more skills, including the ability to use and maintain new technologies. This makes household members more adaptable to and capable of using energy-saving technologies, such as solar panels and smart thermostat devices [54]. Additionally, a higher level of human capital implies more attention to health and quality of life. People may be more concerned about environmental issues and willing to adopt technologies that reduce environmental impacts, thus increasing the frequency of household energy-saving technology usage [62]. Therefore, improving human capital involves more factors related to understanding, accepting, and adopting technology, providing favorable conditions for household energy-saving technologies.

H2c: Increased human capitals improve household energy structures by enhancing the frequency of energy-saving technology usage.

3. Models, variables and data

3.1. Models

To examine the influence of human capital on the household energy consumption structure, this study selects household energy consumption structure as the dependent variable, specifically encompassing consumption of traditional energy (firewood and charcoal), transitional energy (coal, refined oil), and advanced energy (electricity, natural gas, solar energy). The core independent variable is human capital. Drawing upon existing research, this study establishes the following econometric

model:

$$htec = \alpha_0 = \alpha_1 hc + \alpha_2 hc^2 + \alpha_3 X + \varepsilon_1 \quad (1)$$

$$tec = \beta_0 + \beta_1 hc + \beta_2 hc^2 + \beta_3 X + \varepsilon_2 \quad (2)$$

$$aec = \gamma_0 + \gamma_1 hc + \gamma_2 hc^2 + \gamma_3 X + \varepsilon_3 \quad (3)$$

In Eqs. (1)-(3), htec, tec, and aec represent household traditional energy consumption, transitional energy consumption, and advanced energy consumption. Where, hc denotes human capital, X represents individual, household, and regional characteristics in the sample and other factors influencing household energy consumption among farmers. ε_1 and ε_3 are random disturbance terms, representing unobservable factors following a standard normal distribution. α_0, β_0 and γ_0 are constant terms, and α_1, $\beta_1, \gamma_1, \alpha_2, \beta_2, \gamma_2, \alpha_3, \beta_3$ and γ_3 are coefficients to be estimated. The models in Eqs. (1)-(3) may suffer from endogeneity issues, such as the causal relationship between human capital and household energy consumption structure among farmers and omitted variables. Therefore, this paper adopts instrumental variables and employs instrumental variable estimation methods to mitigate estimation biases caused by endogeneity issues.

3.2. Variables

3.2.1. Explained variables

Drawing on existing research [52], this study selects household traditional energy consumption (years of firewood and charcoal use), transitional energy consumption (per capita consumption of coal and petroleum products), and advanced energy consumption (per capita consumption of natural gas, electricity, and solar energy) to measure household energy consumption structure.

3.2.2. Key explanatory variable

Following previous literature [39], this paper employs the years of education of the head of household to measure human capital.

3.2.3. Mediating variables

Based on theoretical analysis regarding the influence of human capital on household energy consumption structure, this study selects mediating variables, including household affordability, environmental awareness, and frequency of energy-saving technology usage.[2] Household affordability is measured by income level, while environmental awareness is measured by the willingness and degree of participation in environmental governance.[3]

3.2.4. Control variables

Referring to existing research [58], this paper controls for other factors influencing the energy structure of farmer households, including the age, gender, education level, health status of the household head, household size, per capita net income, per capita expenditure, housing area, and whether the household has village cadres. Variable definitions and descriptive statistics are detailed in Table 2.

3.3. Data

The data used in this study are sourced from a questionnaire survey conducted by the research team in 2023 among corn growers in Shaanxi Province. The research team chose the farmers in Shaanxi province as the research objects for the following reasons: On the one hand, Shaanxi Province is a major energy province in China, with abundant coal, natural gas and wind energy resources, which makes the energy industry one of the pillar industries in the region, and at the same time faces a series of challenges such as environmental pollution and energy efficiency. In recent years, Shaanxi Province has vigorously promoted the development of the energy and chemical industry in the direction of clean and high-end, adopted a series of measures to promote energy transformation, and invested in clean energy, especially wind and solar power generation. In 2021, a total of 6.07 million kW of 55 projects will be included in the guaranteed grid-connected scale of Shaanxi wind power and photovoltaic power generation projects in 2021.[4] On the other hand, human capital is a necessary condition for the modernization of agriculture and rural areas, and factors such as credit constraints in rural areas and urban-biased educational resource allocation policies have widened the gap between urban and rural human capital, especially in Western China. Therefore, this paper takes Shaanxi Province in western China as an example to explore whether rural human capital will affect household energy consumption and its mechanism.

The research team undertook thorough preparations before field investigations, including questionnaire design and modification, expert review, and pre-surveys. The official field survey commenced in May 2023. In the process of sample selection, the research team adopted a multi-stage sampling method in Shaanxi Province, which can be roughly divided into three stages: In the first stage, the research team selected Yulin and Yan'an in northern Shaanxi, and Weinan and Tongchuan in the Guanzhong region as sample cities, considering regional differences and economic development levels. In the second stage, the research team randomly selected two sample counties from each of the four sample cities and then randomly selected two sample townships from each of the eight sample counties. In the third stage, the research team randomly selected two sample villages from each sample township,

Table 2
Summary statistics.

Variable	N	Explanation	Mean	SD
Human capital	791	Education of household head (years)	6.517	3.753
Traditional energy	791	Use of fuelwood (years)	42.93	18.01
Transitional energy	791	Per capita coal consumption (t/year)	0.429	0.507
	791	Per capita refined oil consumption (L/year)	132.3	275.7
Advanced energy	791	Per capita electricity consumption (KWH/year)	612.2	850.3
	791	per capita natural gas consumption (m3 / year)	78.68	246.1
	791	Number of solar energy	0.489	0.556
Houshold characteristics	791	Age of household head (years)	59.49	10.26
	791	Gender of head of household: male=1, female=0	0.942	0.255
	791	Head of household marriage: unmarried =1; married =2; divorce =3; widowed =4	2.069	0.600
	791	Head of household health: incapacity to work =0; difference =1; medium =2; good =3; advantage =4	1.013	0.474
	791	Household size (persons)	3.811	1.889
	791	Per capita net income (Yuan/year)	4192	377.7
	791	Housing area (m2)	124.1	86.86
	791	Whether there are village cadres at home: yes =1; No =0	0.144	0.362
	791	Length of residence in the village (years)	52.36	16.02

[2] Frequency of energy-saving technology usage is represented by "setting the air conditioner to 26°C for environmental protection during hot summers" (never=1, occasionally=2, frequently=3)

[3] Believing villagers should participate in rural habitat environment improvement (strongly disagree=1; strongly agree=5)

[4] Competitive allocation results of wind power and photovoltaic power generation guaranteed grid-connected projects announced by Shaanxi Energy Bureau in 2021.

totaling 32 villages. With the assistance of village cadres, investigators conducted face-to-face questionnaire surveys with 25 households randomly selected from each sample village.

The household receipts obtained from this questionnaire survey include characteristics of household heads, household characteristics, and household energy consumption patterns, with the data year being 2022. A total of 800 questionnaires were completed in this survey. After excluding some missing data and outliers, 791 valid questionnaires were obtained, resulting in an effective questionnaire rate of 98.88 %.

4. Empirical results

4.1. Baseline regression

As previously discussed, this paper posits that improving human capital levels will enhance the household energy consumption structure. To validate this hypothesis further, the paper employs a count model to analyze the issue. A discussion and analysis of this problem aid in clarifying the stage of rural household energy transition in China and deepen understanding of subsequent household energy choices.

According to Table 3, in the linear model, human capital significantly impacts energy consumption structure. Specifically, human capital has a significant positive effect on transitional energy consumption and a significant negative effect on advanced energy consumption. Nonlinear test results indicate that the coefficient of the squared term of human capital on advanced energy consumption is significantly positive, combined with its first-order coefficient being significantly negative, indicating a "U"-shaped trend in household advanced energy consumption concerning the level of human capital.

This "U"-shaped relationship manifests as follows: when human capital levels are low, and there is no external administrative intervention, residents, considering energy costs, tend to choose lower-cost or even cost-free firewood [7]. As human capital levels increase, residents' incomes rise, and they become more concerned about environmental protection and sustainability. Therefore, residents gradually increase their energy-efficient equipment and opt for higher-quality fuels but still need to abandon using poorer-quality energy altogether at this stage [3]. However, when human capital reaches a certain level, residents, considering various factors such as time and health costs, abandon using low-quality energy that require long collection times, have low combustion efficiency, and cause indoor pollution [4]. Thus, improving human capital levels leads households to reduce the use of firewood and increase the use of electricity, natural gas, and other advanced energy. This also indicates that rural residents optimize their household energy structures as human capital levels improve.

In the control variables, gender significantly impacts advanced energy consumption, suggesting that if the household head is female, there is a greater inclination toward choosing advanced energy. The age of the household head has a significant positive impact on traditional energy but no significant impact on transitional and advanced energy, indicating that older household heads tend to use traditional energy. Better health conditions are associated with a greater inclination towards selecting advanced energy. Residents with better health conditions are more likely to focus on environmental and long-term health issues, and energy help reduce environmental pollution, improve air quality, and consequently improve lung and overall health [6]. Variables such as whether the household head is a village cadre, duration of residence, and marital status show no significant differences in energy choices. More extended planting periods lead to a greater tendency to choose traditional energy. This is because households with more extended planting periods have accumulated abundant firewood, thus reducing the need for additional energy purchases, and traditional energy like firewood are cost-saving compared to purchasing other energy [21]. The more significant the household size, the more the inclination towards transitional and advanced energy. Larger housing areas correspond to less use of traditional energy. Larger housing areas typically entail higher energy demands for heating, lighting, and cooking, which traditional energy like firewood cannot adequately meet [42].

Table 3
Baseline regression results.

Variables	Marginal effect		
	Traditional energy (1)	Transitional energy (2)	Advanced energy (3)
Human capital	−1.147*	0.079***	−0.071**
	(0.662)	(0.038)	(0.042)
(Human capital) x (Human capital)	0.040	0.027	0.0020***
	(0.051)	(0.018)	(0.0110)
Gender	5.777	−0.019	−2.217***
	(3.717)	(1.335)	(0.799)
Age	0.350**	0.034	0.012
	(0.144)	(0.052)	(0.031)
Health	0.520	−0.191	0.656***
	(0.676)	(0.243)	(0.145)
Whether village cadre	−2.397	−0.588	0.260
	(2.554)	(0.917)	(0.549)
Length of residence in the village	0.201**	0.069**	0.045**
	(0.085)	(0.031)	(0.018)
Planting years	0.173*	−0.044	0.026
	(0.093)	(0.034)	(0.020)
Marriage	4.173	0.543	0.229
	(1.521)	(0.546)	(0.327)
Family size	−0.528	0.524***	0.371***
	(0.476)	(0.171)	(0.102)
Housing area	−0.022**	0.002	0.002
	(0.010)	(0.004)	(0.002)
Constant	3.871	5.908*	6.091***
	(9.323)	(3.348)	(2.005)
Observations	791	791	791
R-squared	0.144	0.058	0.085

Standard errors in parentheses, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

4.2. Robustness test

The empirical results above indicate that improving human capital significantly enhances household energy consumption structure. This paper attempts two robustness tests to ensure the research findings' credibility further.

4.2.1. Replacement of explained variables

Drawing from existing literature [5], this paper employs the number of energy varieties used to characterize the improvement of household energy consumption structure, thereby replacing the dependent variable for robustness testing. The results of the tests in Table 4 show that higher levels of education are associated with using a greater variety of energy types among farmers. On the one hand, there is an increase in information acquisition and cognitive levels: farmers with higher levels of education are more likely to acquire various information, including different types of energy supply, usage methods, and benefits. They have a deeper understanding of energy and, thus, are more willing to try different energy varieties to meet different needs [43]. On the other hand, individuals with higher levels of education may be more concerned about environmental issues and sustainable development. They may be more willing to try renewable energy such as solar and wind energy to reduce environmental impact. Therefore, they may have a more diversified approach to energy selection [23].

4.2.2. Replacement of explanatory variables

At the individual level, human capital is outwardly manifested by individuals' knowledge, skills, and qualities. Drawing from existing research [8,25], household average years of education and household training expenditures are selected to define human capital, namely

Table 4
Test results of human capital on the number of fuel types.

Variables	Marginal effect (1)
Human capital	0.007**
	(0.025)
(Human capital) x (Human capital)	0.001**
	(0.002)
Gender	0.014
	(0.143)
Age	−0.016***
	(0.005)
Health	0.065***
	(0.026)
Whether village cadre	0.089
	(0.108)
Length of residence in the village	0.005
	(0.004)
Planting years	−0.008***
	0.002
Marriage	0.095**
	(0.045)
Family size	0.047***
	(0.017)
Housing area	−0.000
	(0.000)
Constant	3.101***
	(0.336)
Observations	791
R-squared	0.050

Robust standard errors in parentheses, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

education and training human capital, for robustness testing. Since the variable "training human capital" in the research team is a dummy variable ("whether received agricultural technology education or training": yes=1, no=0), an interaction term between human capital and skills training is used to measure the level of human capital and explore its impact on household energy consumption.

The results of the tests in Table 5 show that after replacing the explanatory variables, the impact of human capital on traditional energy remains significantly negative, is significantly positive for transitional energy with a marginal diminishing effect, and is significantly positive for advanced energy. It is evident that the difference from the baseline regression results is not substantial, indicating that the baseline regression is robust.

4.3. Mechanism test

To further determine how human capital improves household energy structure, this paper examines three aspects: affordability, environmental awareness, and frequency of energy-saving technology usage. The results of the tests in Table 6 indicate that increased human capital significantly enhances farmers' affordability, environmental awareness, and frequency of energy-saving technology usage. Combining the results from Table 7, it is evident that improvements in affordability, environmental awareness, and energy-saving technology usage frequency increase the usage of transitional and advanced energy. Additionally, environmental awareness and the frequency of energy-saving technology usage significantly reduce the usage of traditional energy. The increase in human capital enhances individual competitiveness in the job market, leading to more employment opportunities and higher income levels [16]. Moreover, higher levels of human capital usually imply better education and training, making farmers more likely to understand the importance of environmental issues and sustainable development, thereby enhancing environmental awareness [19]. Finally, higher levels of human capital typically entail more vigorous learning and adaptation abilities, making farmers more likely to understand the benefits of energy-saving technologies and willing to adopt them, encouraging more active usage of energy-saving technologies [46]. Higher-income

Table 5
Test results for alternative explanatory variables.

Variables	Marginal effect		
	Traditional energy (1)	Transitional energy (2)	Advanced energy (3)
(Human capital) x (Skills training)	−0.838**	0.155***	0.033**
	(0.181)	(0.041)	(0.005)
((Human capital) x (Skills training))^2	0.059	0.0519***	0.002
	(0.039)	(0.004)	(0.009)
Gender	6.029	0.07149	−2.208**
	(3.685)	(1.273)	(0.857)
Age	0.497***	0.022	0.029
	(0.108)	(0.040)	(0.022)
Health	0.646	−0.273	0.691***
	(0.667)	(0.240)	(0.143)
Whether village cadre	−2.341	−0.905	0.217
	(2.179)	(0.866)	(0.598)
Length of residence in the village	0.236***	0.049*	0.052***
	(0.073)	(0.028)	(0.016)
Planting years	0.532***	−0.004	−0.047***
	(0.063)	(0.023)	(0.014)
Marriage	4.275***	0.496	0.388
	(1.203)	(0.452)	(0.309)
Family size	−0.541	0.464**	0.363***
	(0.426)	(0.183)	(0.109)
Housing area	−0.021**	0.003	0.001
	(0.012)	(0.002)	(0.007)
Constant	−5.138	1.262	6.662***
	(7.753)	(2.793)	(1.727)
Observations	791	791	791
R-squared	0.134	0.047	0.055

Robust standard errors in parentheses, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 6
Results of mechanism test I.

Variable	Affordability	Environmental awareness	Frequency of energy-saving technology usage
	(1)	(2)	(3)
Human capital	0.158***	0.009**	0.004**
	(0.007)	(0.002)	(0.001)
(Human capital) x (Human capital)	−0.990	0.001*	0.000
	(0.651)	(0.000)	(0.001)
Control variables	yes	yes	yes
Constant	−265.5**	3.503***	2.700***
	(125.1)	(0.459)	(0.255)
Observations	791	791	791
R2	0.011	0.030	0.004

Robust standard errors in parentheses, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

levels enable households to afford relatively expensive but more efficient transitional and advanced energy. Furthermore, with increased environmental awareness and frequency of energy-saving technology adoption, farmers may feel a greater sense of social responsibility and thus be more inclined to choose transitional, advanced energy with lesser environmental impact. Hypothesis H2a-H2c are verified.

4.4. Endogenous treatment: IV estimate

Although human capital significantly improves household energy consumption structure, endogeneity issues may influence this result. Potential endogeneity mainly stems from two aspects: omission variables, such as geographical location, where households in colder regions are more likely to use high-quality energy like electricity, which may lead to biased estimation results. Second is reverse causality, where the

Table 7
Results of mechanism test II.

Variable	Traditional energy (1)	Transitional energy (2)	Advanced energy (3)
Affordability	0.006	0.002***	0.000**
	(0.005)	(0.001)	(0.000)
Environmental awareness	−1.604**	0.748**	0.767***
	(1.070)	(0.338)	(0.204)
Frequency of energy-saving technology usage	−2.627**	2.107***	0.556**
	(1.280)	(0.625)	(0.163)
Control variables	yes	yes	yes
Constant	−7.223	9.693**	4.882
	(11.38)	(4.667)	(3.028)
Observations	791	791	791
R2	0.147	0.078	0.127

Robust standard errors in parentheses, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

cleanliness of household energy usage may have a reverse effect on human capital. Rural households typically have limited budgets, part of which is allocated to purchasing energy such as fuel and electricity. If households need to spend a significant portion of their funds to meet energy needs, they may reduce expenditures in other areas, limiting investments in education or training. Therefore, potential reverse causality may result in biased estimation results.

To address the above endogeneity issues, the paper employs instrumental variable analysis. Drawing from existing literature [12], this paper selects "distance to the nearest primary school" as the instrumental variable for human capital. When households are closer to primary schools, the convenience of attending school increases, making it more likely for individuals to receive education. Thus, the instrumental variable in this paper satisfies the relevance condition. Furthermore, the distance between households and primary schools is unlikely to affect household energy consumption structure directly but may indirectly impact it through the household's human capital. Thus, the instrumental variable in this paper satisfies the exogeneity condition. Therefore, selecting "distance to the nearest primary school" as the instrumental variable is reasonable.

Table 8 reports the results of the two-stage least squares regression. The first-stage regression results indicate that the instrumental variable is significantly positively correlated with the potential endogenous variable at the 1 % level, indicating that the instrumental variable satisfies the relevance condition. The first-stage F-value is 17.66, indicating the absence of weak instrumental variables. The second-stage regression results show that the coefficient direction and significance of energy consumption remain consistent with the baseline regression results, indicating that even after addressing endogeneity issues, human capital still significantly promotes household energy consumption structure, further validating hypothesis 1.

Table 8
Endogenous treatment: Estimation of instrumental variables.

Variable	The first stage	The second stage		
	Human capital (1)	Traditional energy (2)	Transitional energy (3)	Advanced energy (4)
Human capital		−0.183***	0.088***	0.003**
		(0.021)	(0.004)	(0.001)
(Human capital) x (Human capital)		0.103	0.068*	0.001**
		(0.152)	(0.043)	(0.000)
distance to the nearest primary school	0.015***			
	(0.01)			
Control variables	yes	yes	yes	yes
Constant	6.784***	1.746	4.331*	10.255***
	(0.23)	(1.44)	(3.79)	(1.55)
Observations	791	791	791	791
The first stage F	17.66***			
R^2		0.026	0.023	0.017

4.5. Further analysis

To further analyze the impact of human capital on household energy consumption structure, this study, referencing existing literature [14], explores the effects of family members' educational attainment levels on household energy consumption. Specifically, it examines the proportions of individuals with educational levels ranging from primary school or below, junior high school, senior high school (including vocational school), to college or above on household energy consumption. Additionally, considering the differences in education, skills, lifestyles, and resource access among households with different income levels, which may influence their energy needs and choices [47], the paper further investigates the impact of human capital on household energy consumption structure with different family demographic structure and income levels.

4.5.1. Family demographic structure

The results in Table 9 indicate that individuals with primary school education or below significantly increase consumption of traditional and transitional energy. Individuals with junior and senior high school education levels contribute to increased consumption of transitional and advanced energy. At the same time, senior high school education levels also significantly reduce consumption of traditional energy among households. Furthermore, individuals with a college or higher education

Table 9
Estimates of the impact of different education levels of household population on energy consumption structure.

Variable	Marginal effect		
	Traditional energy (1)	Transitional energy (2)	Advanced energy (3)
The proportion of people with primary school education or below	0.262**	0.084**	0.427
	(0.011)	(0.016)	(0.205)
(The proportion of people with primary school education or below)^2	−0.819	−1.459	−1.388
	(0.991)	(2.233)	(1.831)
The proportion of junior high school education	0.78	0.514*	0.544**
	(0.91)	(0.220)	(0.189)
(The proportion of junior high school education)^2	−3.192	0.181**	−3.615
	(10.25)	(0.018)	(2.360)
Proportion of people with high school education (including technical secondary schools)	−3.361***	0.392*	0.255**
	(1.279)	(0.436)	(0.123)
(Proportion of people with high school education (including technical secondary schools))^2	−3.12*	4.749	4.844
	(1.54)	(7.232)	(4.879)
The proportion of people with college degree or above	−3.075	1.446	0.618**
	(6.08)	(4.603)	(0.014)
(The proportion of people with college degree or above)^2	−0.970**	3.322	2.943
	(8.066)	(3.739)	(3.026)
Control variables	yes	yes	yes
Constant	−12.840	−1.863	2.700
	(17.030)	(7.123)	(4.042)
Observations	791	791	791
R2	0.154	0.071	0.100

Robust standard errors in parentheses, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

significantly enhance the consumption of advanced energy. The analysis suggests that households are more inclined to choose transitional and advanced energy as educational levels increase. Moreover, further analysis indicates that the impact of senior high school education on energy consumption structure is most similar to the baseline regression result. Because middle and high school education usually covers basic scientific knowledge and environmental education, it is easier for individuals to understand the importance of environmental issues and the negative environmental impacts of traditional energy sources. This understanding makes them more inclined to choose environmentally friendly transition energy and high-quality energy when choosing energy. This also suggests to policymakers that education may be an important way to promote the energy transition. By strengthening education, especially in relation to the environment and energy, society can be guided towards sustainable development. Therefore, policymakers need to consider improving education levels while ensuring that low-income and low-education populations have access to advanced energy opportunities.

4.5.2. Income levels

Drawing from existing research [30], households with income levels greater than the median income are considered high-income households, while those below the median income are considered low-income households. The results of the tests in Table 10 indicate that for households with different income levels, an increase in human capital significantly suppresses their consumption of traditional energy and increases their consumption of transitional energy. For high-income households, an increase in human capital level also significantly impacts the consumption of advanced energy. This suggests that the significant increase in advanced energy consumption is primarily due to increased human capital among high-income households. High-income households imply stronger affordability, so they can afford more expensive but advanced energy, consistent with the earlier analysis.

5. Conclusion and policy implications

Based on the survey data from 791 households in Shaanxi Province in 2023, this study systematically evaluates the impact of human capital on the energy consumption structure of rural households and its underlying mechanisms. It also explores how different levels of education among household members influence the selection of traditional, transitional, and advanced energy and the differences arising from varying household income levels. The study reveals the following findings: (1) Human capital can significantly reduce traditional energy consumption while increasing the use of transitional and high-quality energy sources. This conclusion remains robust after robustness checks and instrumental variable treatments. Existing literatures mainly focus on the influence of geographical location and socio-cultural factors, household size and economic status, and energy prices and policies on household energy consumption structure. Hence, this paper provides a new perspective for improving the energy consumption structure of farmers. (2) The results of the mechanism analysis indicate that human capital promotes the transition from traditional to transitional and high-quality energy sources by enhancing households' payment capacity, environmental awareness, and frequency of energy-saving technology usage. This suggests that the energy stacking theory applies in rural China, where an increase in household income facilitates the transition and upgrading of energy consumption. (3) Compared to existing literature, this study also finds that the higher the level of education, the more likely rural households are to shift from consuming traditional energy to transitional and high-quality energy sources. In particular, a high school education significantly increases the consumption of transitional and high-quality energy while significantly reducing traditional energy consumption. (4) Compared to low-income households, the effect of human capital on increasing the consumption of high-quality energy is significantly positive for high-income households. Therefore, policymakers need to consider improving education levels while ensuring that low-income and low-education populations have access to advanced energy opportunities.

Based on the above conclusions, this study derives the following policy implications. Firstly, policymakers should enhance investment in educational resources, particularly rural areas, to improve residents' education levels and skill training. This will help increase their purchasing power, environmental awareness, and the frequency of energy-saving technologies, thereby facilitating the transition and upgrading of energy consumption. Secondly, policies should support and promote the adoption of cleaner and more efficient energy sources through subsidies and incentive mechanisms, encouraging households to shift from traditional to transitional and high-quality energy sources, thereby reducing their dependence on conventional energy. Furthermore, given that the effect of human capital on the consumption of high-quality energy is more pronounced in high-income households, policy design should consider the needs of families with different income levels. More support should be provided to low-income households, such as through subsidies or low-interest loans, to help them access and utilize cleaner energy, thereby narrowing the gap in energy consumption transitions between low- and high-income families. Lastly, policies should focus on improving the education levels of rural residents, mainly through the expansion and promotion of high school education. This would not only enhance residents' environmental awareness and purchasing power but also further promote the optimization of energy consumption structures in rural areas.

At the same time, this study has certain limitations. On the one hand, it employs survey data from the research team in 2023 to investigate the impact of non-farm employment on household energy consumption. However, analyzing this issue using multi-period panel data could better address potential endogeneity issues in the model. Therefore, in future research, the research team will consider using tracking data, combining

Table 10
Estimation results of human capital on energy consumption structure of households with different incomes.

Variable	Marginal effect					
	Low-income family			High-income family		
	Traditional energy (1)	Transitional energy (2)	Advanced energy (3)	Traditional energy (4)	Transitional energy (5)	Advanced energy (6)
Human capital	−1.525*	0.089***	0.143	−0.667	0.213**	0.018**
	−0.87	−0.007	−0.173	−1.06	−0.045	−0.003
(Human capital) x (Human capital)	0.063	0.030	0.005	−0.020***	0.040	0.009**
	−0.065	−0.022	−0.013	−0.000	−0.036	−0.001
Control variables	yes	yes	yes	yes	yes	yes
Constant	−7.221	7.602	4.078	10.910	4.900	7.947***
	−14.190	−4.687	−2.829	−12.100	−5.083	−2.884
Observations	791	791	791	791	791	791
R2	0.146	0.074	0.132	0.162	0.084	0.039

Standard errors in parentheses, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

multiple micro databases, and utilizing multi-period panel data further to explore the influencing factors of household energy consumption. On the other hand, due to data availability constraints, this study needs to sufficiently control factors related to household subjective emotions and other characteristics at the subjective level. These factors were not included in the research model due to limitations in data availability, and the further analysis of the main effects needs to be more comprehensive. Hence, in future research, the team plans to integrate questionnaire data with statistical data to comprehensively examine the impact of human capital on household energy consumption structures, enabling a more systematic analysis.

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CRediT authorship contribution statement

Xiuqing Li: Writing – original draft. **Hui Mao:** Writing – original draft. **Lan Fang:** Writing – original draft.

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Data availability

Data will be made available on request.

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