Postprint of "Vulnerability and influencing factors of rural households' clean energy use in ecologically fragile areas of Northwest China"

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Abstract

Accelerating the transition from traditional solid energy to clean energy is an inevitable choice for rural areas in ecologically fragile zones to cope with climate change, strengthen environmental governance, and promote sustainable development across regions. However, in the process of passively participating in clean energy reform policies, farm households in the ecologically fragile areas of Northwest China, as groups with relatively low economic levels, generally exhibit a vulnerable pattern of modern clean energy equipment being "converted but not used," "basically not used," or "used at a low level." To address this, adopting a reverse-thinking perspective on energy transition, this study conducted field surveys of 2,002 rural households in 180 villages across 13 counties (districts) in Shaanxi, Gansu, Ningxia, and Qinghai. An "exposure-sensitivity-adaptive capacity" model was constructed to comprehensively assess the vulnerability of rural households' use of clean energy, and a multivariate Logit regression model was employed to analyze the influencing factors of vulnerability from three dimensions: "economy-society-household." The results show that: (1) The proportions of rural households in ecologically fragile areas of Northwest China with low, medium, and high levels of vulnerability in their use of clean energy are 26.12%, 46.55%, and 27.33%, respectively, with significant spatial heterogeneity in vulnerability. (2) Factors such as cultivated land area, energy subsidy policies, social networks, age, livelihood type, and household size all have significant impacts on vulnerability. (3) The effects of influencing factors on vulnerability differ across ecologically fragile zones. Accordingly, the government should, based on the vulnerability characteristics of rural households' use of clean energy in different ecologically fragile areas and grounded in local realities, implement differentiated energy subsidy policies and promotion models to consolidate the achievements of clean energy reform policies.

Full Text

Vulnerability and Influencing Factors of Clean Energy Use Among Rural Households in Ecologically Fragile Areas of Northwest China

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Abstract: Accelerating the transition from traditional solid-fuel energy to clean energy is an inevitable choice for rural areas in ecologically fragile regions to cope with climate change, strengthen environmental governance, and promote inter-regional sustainable development. However, under passive participation in clean energy reform policies, rural households in ecologically fragile areas of northwest China, which generally have relatively low economic capacity, often exhibit vulnerability phenomena, whereby modern clean energy equipment is "modified but not used," "basically not used," or "used at a low level." To address this issue, we adopted a reverse energy-transition perspective and conducted field research in 13 counties (districts), covering 2002 rural households across 180 villages in Shaanxi, Gansu, Ningxia, and Qinghai regions of China, and established an "exposure-sensitivity-adaptability" model to comprehensively assess the vulnerability of rural households to clean energy use. In addition, a multiple Logit model was used to analyze the influencing factors of vulnerability across three levels: economy, society, and household. The results show that (1) The proportions of rural households in the ecologically fragile areas of northwest China with low, medium, and high vulnerability to clean energy use are 26.12%, 46.55%, and 27.33%, respectively, and there is significant spatial heterogeneity in vulnerability. (2) Factors such as cultivated land area, energy subsidy policies, social networks, age, livelihood type, and household size significantly influence vulnerability. (3) The effects of influencing factors vary across different ecologically fragile regions. Therefore, based on the vulnerability characteristics of clean energy use among rural households in different ecologically fragile areas, the government should implement differentiated, region-specific energy subsidy policies and promotion strategies according to local conditions to consolidate the achievements of clean energy reform policies.

Keywords: rural households; sustained use of clean energy; vulnerability; "exposure-sensitivity-adaptability" model; ecologically fragile areas; northwest China

1 Introduction

Household energy use is closely linked to environmental quality and greenhouse gas emissions, and the extensive use of traditional energy causes tremendous damage to the environment and ecology. Currently, rural areas in China have basically achieved full coverage of power supply to natural villages within electricity-accessible areas, gradually realizing "energy accessibility," with significant improvements in energy efficiency and structure. However, due to the ease of collecting traditional solid fuels such as crop straw, firewood, and cattle manure, coupled with difficulty abandoning traditional energy consumption patterns and habits, many households exhibit phenomena where modern energy equipment is "modified but not used," "basically not used," or "used at a low level." The overall situation of clean energy use is not optimistic. Today, China' s rural household energy transition faces the problem of reverting to solid fuel use, with approximately 27% of households abandoning energy transition and instead using solid fuel for cooking and heating. In northwest China, the average proportion of coal and firewood co-firing among rural households reaches 54.68%, and some households with poor economic conditions even directly revert to using firewood for heating.

In northwest ecologically fragile areas, resource and environmental efficiency remains within a low-efficiency range, and vulnerability events in energy use can plunge these regions into a "vulnerability trap" of "sensitive ecological environment → vulnerable energy transition → inefficient energy use → more sensitive ecological environment." Therefore, to ensure the sustained and stable use of clean energy by rural households in northwest ecologically fragile areas and consolidate the achievements of government energy transition policies, conducting vulnerability analysis of clean energy use is particularly necessary to clarify how to design clean energy demand strategies for northwest ecologically fragile areas and block the risk of reverting to traditional fuel use.

In recent years, research on rural household energy transition has received significant academic attention. Studies show that household energy transition is influenced not only by explicit factors such as resource endowment, energy policy, and energy prices, but also by implicit factors such as family structure, economic income, and psychological cognition. However, existing research has neglected the vulnerability scenarios where rural households are easily disturbed by external factors and undergo degenerative succession in energy transition. The impact pathways and magnitudes of different factors on energy transition remain unclear, especially in northwest China' s ecologically fragile areas, which exhibit significant "energy transition vulnerability." The magnitude of disturbance from multidimensional factors on household energy transition degenerative succession has not been clarified. Moreover, due to substantial differences in climate conditions, economic conditions, rural population, and living habits across northwest regions, energy transition promotion cannot simply copy schemes from key areas, and there is an urgent need to promote sustained clean energy use by rural households according to local conditions.

Given this context, this study takes 2002 rural households in northwest China' s ecologically fragile areas as survey samples and conducts multi-regional random sampling surveys. Based on the Intergovernmental Panel on Climate Change (IPCC) vulnerability conceptual framework and existing vulnerability research, and grounded in the reality of northwest ecologically fragile areas, we construct a vulnerability assessment indicator system involving multidimensional factors such as natural conditions, economic development, and household characteristics. Using the "exposure-sensitivity-adaptability" model, we quantify the vulnerability degree of rural households' clean energy use in northwest ecologically fragile areas and analyze the effects of vulnerability influencing factors from three levels: economy, society, and household. Simultaneously, through the above methods, we conduct regional heterogeneity analysis on rural households in three sub-ecologically fragile areas to reveal the vulnerability characteristics and differences in influencing factor effects across different ecologically fragile areas in northwest China. This study can enrich theoretical understanding of rural household energy transition and guide policymakers to design intervention measures for sustained rural household energy transition according to local conditions, thereby reducing vulnerability risks in clean energy use.

1.1 Study Area Overview

Northwest ecologically fragile areas are among the most ecologically vulnerable regions in China. Referring to China' s climate zoning and the "Outline of National Ecologically Fragile Area Protection Plan," we selected typical villages in the Loess Plateau ecologically fragile area (Yulin City, Shaanxi Province; Dingxi City, Gansu Province), desert ecologically fragile area (Yinchuan City, Ningxia Hui Autonomous Region), and Qinghai-Tibet Plateau ecologically fragile area (Xining City and Haibei Tibetan Autonomous Prefecture, Qinghai Province) as study areas, covering 13 counties (districts) and 180 villages (Fig. 1).

1.2 Data Sources

This study constructs a systematic data collection system focusing on rural household vulnerability in clean energy use. First, in 2022, the research team conducted pilot surveys in northwest rural areas to systematically obtain relevant data on rural household energy use behavior. Then, through literature review and expert interviews, key indicators for assessing vulnerability of rural household clean energy use were identified. Based on literature analysis and pilot survey results, a survey questionnaire was designed, and after comprehensive pre-testing and revision, formal survey data were obtained.

The survey was conducted through field visits and household interviews with farmers in the study area to deeply understand their clean energy use behavior and sustained use willingness, identify and extract key influencing factors of vulnerability in rural household clean energy use, and recover 2088 questionnaires. After screening and removing invalid samples, 2002 valid samples were obtained, with a questionnaire effectiveness rate of 95.88%. The survey questionnaire consists of three parts: the first part covers basic information about respondents, including demographic characteristics (age, education level, gender, livelihood type) and household characteristics (permanent household population, number of Party members, income, cultivated land area, and housing area). The second part addresses vulnerability in clean energy use, which mainly constitutes the vulnerability assessment indicator system for this study, including respondents' perceptions of clean energy ease-of-use, price perception, psychological cost, ecological value, personal norms, and energy subsidy satisfaction.

1.3 Methodology

1.3.1 Construction of Vulnerability Assessment Indicator System As a complex system, rural household energy use vulnerability is influenced by multidimensional factors including economy, society, and household characteristics. Therefore, based on the definition of vulnerability, this study conceptualizes rural household clean energy use vulnerability as three interrelated dimensions: exposure, sensitivity, and adaptability, forming a vulnerability assessment model. Using the multi-objective hierarchical analysis method, 21 indicators were selected to construct the vulnerability assessment indicator system for rural household clean energy use in northwest ecologically fragile areas (Table 1).

Exposure characterizes the features and degree of external risks faced by rural households when using clean energy. Relevant studies show that due to high clean energy acquisition costs and low energy accessibility, rural households in northwest regions rely heavily on and widely use solid fuels such as coal and biomass, leading to significant regional exposure differences. Climate change exacerbates energy acquisition difficulties, thereby increasing exposure risks for those dependent on inefficient energy sources. Additionally, in northwest ecologically fragile areas, scattered rural settlements and complex pipeline laying, management, and operation and maintenance issues cause differences in energy endowments that significantly affect rural household clean energy use. Therefore, this study measures exposure through heating cost increase, energy accessibility, and natural environment dimensions. Natural environment is measured using local temperature-humidity index and vegetation coverage, with data sourced from the National Meteorological Information Center and regional statistical yearbooks. The temperature-humidity index is calculated as follows:

$$THI = T - 0.55 \times (1 - f) \times (T - 58)$$

where THI is the temperature-humidity index; T is the monthly average temperature (°F); and f is the monthly average relative humidity.

Sensitivity measures the degree to which rural households are sensitive to energy reform risks during clean energy use. Farmers' insufficient understanding of clean energy can lead to resistance due to technical complexity, resulting in low sensitivity thresholds. Studies show that household income significantly affects per capita energy consumption, and according to the energy ladder hypothesis and planned behavior theory, residents with poor economic conditions tend to choose low-cost energy. Additionally, perceived behavioral control affects rural household energy use behavior, and given the strong dependence on traditional energy in the study area, psychological costs can exacerbate sensitivity to clean energy use. Therefore, this study measures sensitivity through four dimensions: cognitive level, economic level, price perception, and psychological cost. Cognitive level is related to education level and livelihood type; economic level can be reflected through annual household income, cultivated land area, and housing area.

Adaptability reflects the ability of rural households to resist risk disturbances. The risk resistance capacity of rural households using clean energy results from the synergistic effect of external support and self-cognition. Effective intervention strategies can reduce vulnerability in rural household clean energy use and are key to promoting energy transition. Moreover, when government support is relatively weak, ecological value and personal norms can play a role in rural household clean energy use. Additionally, energy reform awareness is positively correlated with willingness to change behavior, and farmers with positive environmental attitudes are more inclined to continuously use clean energy. Therefore, this study constructs adaptability indicators from three levels: ecological value, personal norms, and policy satisfaction. Relevant assignments for rural household clean energy use perception and satisfaction adopt a five-level Likert scale design.

1.3.2 Vulnerability Assessment Model

1) **Standardization of assessment indicators**
   For positive indicators:

$$X'_{ij} = \frac{X_{ij} - \min(X_j)}{\max(X_j) - \min(X_j)}$$

   For negative indicators:

$$X'_{ij} = \frac{\max(X_j) - X_{ij}}{\max(X_j) - \min(X_j)}$$

   where X_{ij} and X'_{ij} are the original and standardized values of indicator j for household i, respectively; $\max(X_j)$ and $\min(X_j)$ are the maximum and minimum values of indicator j, respectively.

2) **Entropy weight method for calculating indicator weights**
   The entropy weight method objectively determines weights based on information entropy. The calculation formula is as follows:

$$P_{ij} = \frac{X'_{ij}}{\sum_{i=1}^{n} X'_{ij}}$$

$$E_j = -\frac{1}{\ln n}\sum_{i=1}^{n} P_{ij}\ln P_{ij}$$

$$w_j = \frac{1 - E_j}{\sum_{j=1}^{m}(1 - E_j)}$$

where P_{ij} is the proportion of household i' s value for indicator j to the total value of that indicator; E_j is the entropy weight of indicator j; and w_j is the weight of indicator j.

3) **Measuring vulnerability based on the "exposure-sensitivity-adaptability" relationship**
Following IPCC' s definition of vulnerability, this study uses the following equation to measure rural household clean energy use vulnerability:

$$EI = \sum_{i=1}^{n} X'_{ij} w_j$$

$$SI = \sum_{i=1}^{n} X'_{ij} w_j$$

$$AI = \sum_{i=1}^{n} X'_{ij} w_j$$

$$VI = EI + SI - AI$$

where EI, SI, and AI are exposure, sensitivity, and adaptability indices, respectively; and VI is the vulnerability index of rural household clean energy use.

1.3.3 Influencing Factor Analysis Model Vulnerability in rural household clean energy use results from multiple superimposed factors. Therefore, this study constructs a multiple ordered Logit regression model for factor analysis. First, K-means cluster analysis is used to classify rural household clean energy use vulnerability into three levels—low, medium, and high—assigned values of 1, 2, and 3, respectively, serving as the dependent variable. Second, based on the vulnerability analysis framework, independent variables are selected from three levels: economy, society, and household. Economic level includes household income and cultivated land area; social level includes energy subsidy policies and social networks; and household level includes gender, age, livelihood type, education level, number of Party members, and household size (Table 2).

The multiple ordered Logit model is set as follows:

$$\text{logit}(P(y \leq j)) = \alpha_j + \sum_{t=1}^{10} \beta_t X_t$$

where y is the dependent variable; $P(y \leq j)$ is the cumulative probability of households having low or medium vulnerability; X is the set of all independent variables; α_j is the intercept term; X_t is the t-th independent variable; and β_t is the partial regression coefficient of the t-th independent variable.

2 Results and Analysis

2.1 Vulnerability Characteristics of Rural Household Clean Energy Use

2.1.1 Full-sample Vulnerability Characteristics The vulnerability index of rural household clean energy use in northwest China's ecologically fragile areas ranges from -0.068 to 0.392. The exposure index ranges from 0.058 to 0.206, with 76.0% of households at medium-high levels; the sensitivity index ranges from 0.014 to 0.206, with 68.9% at medium-high levels; and the adaptability index ranges from 0.012 to 0.310, with 75.8% at medium-low levels. The proportions of rural households with low, medium, and high vulnerability to clean energy use are 26.12%, 46.55%, and 27.33%, respectively, showing a "middle-large, two-ends-small" distribution (Table 3). Households with vulnerability indices less than 0 indicate no clean energy use vulnerability, accounting for 37.1% of the sample, concentrated in the Loess Plateau ecologically fragile area (62.9%) and desert ecologically fragile area (37.1%), while no negative values appear in the Qinghai-Tibet Plateau ecologically fragile area, indicating weaker risk resistance capacity among households there. The sensitivity index mean of the no-vulnerability household group is 0.014, significantly lower than the regional overall level (0.103); the adaptability index mean reaches 0.310, higher than the regional mean (0.149), with 96.3% at high adaptability levels.

2.1.2 Spatial Distribution Characteristics of Village-level Vulnerability Assessment of village-level vulnerability shows that villages with high vulnerability and high sensitivity are mainly distributed in the Qinghai-Tibet Plateau ecologically fragile area (village numbers 140–180), while villages with high exposure and high adaptability are mainly distributed in the Loess Plateau ecologically fragile area (village numbers 1-92). High exposure and high sensitivity villages show higher spatial agglomeration characteristics, while high adaptability villages are more geographically dispersed, indicating that villages in different ecologically fragile areas face different pressures from energy transition.

2.1.3 Vulnerability Characteristics Across Different Ecologically Fragile Areas Calculations of exposure, sensitivity, adaptability, and vulnerability indices for rural households across three sub-ecologically fragile areas in northwest China show that the Qinghai-Tibet Plateau ecologically fragile area has the highest overall vulnerability, followed by the desert ecologically fragile area, with the Loess Plateau ecologically fragile area having the lowest (Table 4). Different ecologically fragile areas face different challenges in energy transition, with variations in exposure, sensitivity, adaptability, and vulnerability. The Loess Plateau ecologically fragile area has the highest exposure (Fig. 3), consistent with its harsh geographical environment, high terrain, and scattered settlements that hinder natural gas pipeline laying. The Qinghai-Tibet Plateau ecologically fragile area has the highest sensitivity, with 54.68% of households in the region showing medium-high vulnerability. According to the survey, 73.88% of households find it difficult to change traditional energy use habits, have high dependence on traditional energy, weak economic foundations, and high psychological and price perception costs, thus exhibiting high sensitivity. The desert ecologically fragile area has the lowest adaptability (Fig. 3), with 34.30% of households dissatisfied with energy subsidy policies, relatively low family economic levels, generally poor housing insulation, and ineffective clean heating, leading some households to "revert to coal" or "revert to firewood."

2.2 Analysis of Influencing Factors

2.2.1 Feasibility Tests Multicollinearity tests for each regional sample show that all indicator tolerances are much greater than 0.1 and variance inflation factors (VIF) are less than 10, indicating no multicollinearity among independent variables. Parallel line tests further show that all P-values are >0.05, passing the parallelism test. Therefore, the multiple ordered Logit regression method is applicable.

2.2.2 Regression Results Analysis

1) **Analysis of influencing factor effects across the entire region** Analysis of factors influencing rural household clean energy use vulnerability in northwest ecologically fragile areas shows that at the economic level, household income has no significant effect on vulnerability, while cultivated land area (x_2) has a significant negative effect—more cultivated land reduces the probability of high vulnerability. For northwest ecologically fragile area households whose income mainly depends on agriculture, more cultivated land enhances household risk resistance capacity, thereby reducing clean energy use vulnerability. At the social level, energy subsidy policies (x_3) negatively affect vulnerability, while social networks (x_4) positively affect vulnerability. At the household level, age (x_6) and household size (x_{10}) significantly positively affect vulnerability, while livelihood type (x_5) significantly negatively affects vulnerability (Table 5).

2) **Analysis of influencing factor effects across different ecologically**

fragile areas

Further regression analysis for three sub-ecologically fragile areas shows that cultivated land area (x_2), social networks (x_4), and age (x_6) significantly affect vulnerability across all three areas. Cultivated land area negatively affects vulnerability—larger cultivated land area reduces vulnerability. Social networks (x_4) and age (x_6) positively affect vulnerability—greater influence from social networks and older farmer age increase vulnerability. These results reveal commonalities in factors affecting vulnerability across different ecologically fragile areas.

However, due to differences in energy endowments, household livelihoods, and living habits, the significance of influencing factors varies across ecologically fragile areas. Specifically, at the economic level, household income (x_1) only significantly affects clean energy use in the Qinghai-Tibet Plateau ecologically fragile area. At the social level, energy subsidy policies (x_3) only significantly affect the Loess Plateau and Qinghai-Tibet Plateau ecologically fragile areas, with no significant effect on the desert ecologically fragile area. At the household level, livelihood type (x_5) only significantly affects the Loess Plateau and Qinghai-Tibet Plateau ecologically fragile areas, education level (x_7) only significantly affects the desert ecologically fragile area, and household size (x_{10}) only significantly affects the Qinghai-Tibet Plateau ecologically fragile area (Table 5). These differences indicate that variations in economic and socio-cultural conditions lead to significant differentiation in vulnerability formation mechanisms across ecologically fragile areas, providing a basis for formulating regionally targeted energy transition policies.

2.3 Robustness Tests

To verify the accuracy of the above regression results, this study employs two methods for robustness testing. First, replace the independent variable: re-estimate by replacing cultivated land area with housing area at the economic level. Second, exclude high-vulnerability household samples and re-estimate using medium-low vulnerability samples. Comprehensive results from both methods show no significant changes in regression coefficients, signs, or significance levels, proving the robustness and reliability of previous estimates (Table 6).

3 Discussion

Against the backdrop of significant challenges in China' s rural clean energy transition, northwest ecologically fragile areas, as important ecologically vulnerable regions in China, hold strategic positions in resources, environment, and ecology. Existing research mostly focuses on identifying multidimensional factors of household energy transition but neglects the vulnerability attribute of household energy transition. Therefore, this study adopts a reverse energy-transition perspective, integrating behavioral and geographical sciences, and based on the analytical framework of "vulnerability factor identification →

vulnerability assessment," uses the "exposure-sensitivity-adaptability" model to calculate that 73.88% of rural households in northwest ecologically fragile areas have medium-high vulnerability in clean energy use, which aligns with existing research conclusions.

From the spatial pattern of rural household clean energy use vulnerability, both village-level and ecologically fragile area-level analyses show obvious spatial heterogeneity, with different villages and ecologically fragile areas facing different pressures from energy transition, requiring differentiated energy transition policies.

Analyzing influencing factors from economy, society, and household levels reveals differences from existing research. While previous studies consider economic level as a main factor affecting household energy strategies, this study' s detailed analysis of household income and cultivated land area shows that household income only significantly affects vulnerability in the Qinghai-Tibet Plateau ecologically fragile area, while cultivated land area significantly affects the entire study area. This indicates that for rural households in northwest ecologically fragile areas, cultivated land area is directly linked to agricultural output and economic level. Additionally, scarcity of cultivated land resources triggers rural out-migration, leaving behind an aging population that, based on economic rationality and consumption habits, exhibits high vulnerability in clean energy use.

At the social level, literature shows that policy support is key to energy transition, and stronger farmer conformity psychology increases susceptibility to group pressure, which this study confirms. At the household level, age and household size significantly positively affect vulnerability.

Analyzing vulnerability characteristics and influencing factor effects across different ecologically fragile areas deepens theoretical understanding of the driving mechanisms of household energy transition in northwest ecologically fragile areas, provides empirical evidence for formulating differentiated energy subsidy policies and promotion models, and offers important practical guidance for reducing vulnerability risks in household energy use and promoting regional energy structure optimization. Accordingly, when formulating energy transition policies for northwest ecologically fragile areas, the government should integrate farmer willingness and geographical characteristics, and design vulnerability reduction models based on local vulnerability characteristics and influencing factors (Fig. 5). Specifically, the Loess Plateau ecologically fragile area can broaden local employment channels and coordinate with energy subsidy policies. The desert ecologically fragile area can consider local farmers' education levels to build localized publicity systems through activities like "energy classes" in villages to guide active participation in energy transition. The Qinghai-Tibet Plateau ecologically fragile area can implement graded and targeted subsidies based on household economic capacity and size, and expand the scope of energy subsidies. Additionally, all regional energy transition policies should consider local cultivated land area, degree of social network influence, and age of permanent residents.

4 Conclusion

This study employs the "exposure-sensitivity-adaptability" model to calculate that vulnerability in rural household clean energy use is widespread in northwest China' s ecologically fragile areas. The proportions of low, medium, and high vulnerability are 26.12%, 46.55%, and 27.33%, respectively. Vulnerability shows a geographical distribution pattern of being highest in the Qinghai-Tibet Plateau ecologically fragile area, followed by the desert ecologically fragile area, and lowest in the Loess Plateau ecologically fragile area. Villages in different ecologically fragile areas face different vulnerability risks from energy transition: villages in the Qinghai-Tibet Plateau ecologically fragile area mostly exhibit high vulnerability and high sensitivity, while villages in the Loess Plateau ecologically fragile area mostly show high exposure and high adaptability.

Analysis of influencing factors reveals that at the economic level, cultivated land area significantly negatively affects vulnerability; at the social level, energy subsidy policies and social networks significantly negatively and positively affect vulnerability, respectively; at the household level, age and household size significantly positively affect vulnerability, while livelihood type significantly negatively affects vulnerability.

Regional regression analysis shows that in the Loess Plateau ecologically fragile area, cultivated land area, energy subsidy policies, and livelihood type significantly negatively affect vulnerability, while social networks and age significantly positively affect vulnerability. In the desert ecologically fragile area, cultivated land area and education level significantly negatively affect vulnerability, while social networks and age significantly positively affect vulnerability. In the Qinghai-Tibet Plateau ecologically fragile area, household income, cultivated land area, energy subsidy policies, and livelihood type significantly negatively affect vulnerability, while social networks and age significantly positively affect vulnerability.

References

[1] Han Xiao, Wei Chu, Wu Shimei. Estimation of biomass energy consumption in rural China[J]. Resources Science, 2023, 45(9): 1817-1829.

[2] Zhang Zengkai, Peng Binbin, Xie Wei, et al. Scientific research issues in the field of energy transition and management[J]. Journal of Management Science in China, 2021, 24(8): 147-153.

[3] Shen Guofeng, Xiong Rui, Cheng Hefa, et al. Rural residential energy carrier structure and primary PM2.5 emissions from the Qinghai-Tibet Plateau[J]. Chinese Science Bulletin, 2021, 66(15): 1900-1911.

[4] Chang Huayi, Zhang Junbiao, He Ke. The effect of village attraction on

rural household clean energy transition: An explanation from informal off-farm employment[J]. Resources Science, 2023, 45(2): 388-402.

[5] Ellison C, Li Y, Yu F, et al. Household transitions to clean energy in a multiprovincial cohort study in China[J]. Nature Sustainability, 2020, 3(1): 42-50.

[6] He Kebin, Li Xueyu. China dispersed coal management report 2023[R]. Beijing: Institute of Energy, Peking University, 2023.

[7] Bao Chao, Xu Mutian. Comprehensive measurement and spatiotemporal variations of input-output efficiency in northwest China[J]. Arid Land Geography, 2021, 44(6): 1772-1783.

[8] Duan M M, Li L Y, Liu X J, et al. Turning awareness into behavior: Meta-analysis of household residential life energy transition behavior from the dual perspective of internal driving forces and external inducing forces[J]. Energy, 2023, 279: 128072, doi: 10.1016/j.energy.2023.128072.

[9] Foster V, Trotter P A, Werner S, et al. Development transitions for fossil fuel producing low and lower middle income countries in a carbon constrained world[J]. Nature Energy, 2024, 9(3): 242-250.

[10] Liu Pingkuo, Lu Cunyu. Influencing factors of the pathway selection for China' s energy transition: Theoretical verification and empirical analysis[J]. China Soft Science, 2022(6): 51-61.

[11] Zhuang Minghao, Lu Xi, Wang Yanfen, et al. Research status and prospect of household energy consumption impact on eco-environment and human health in the pastoral area of Qinghai-Tibet Plateau[J]. Acta Ecologica Sinica, 2023, 43(5): 1775-1783.

[12] Gao Ming, Wei Jiashuo. Promoting farmers and rural areas to achieve common prosperity: Historical orientation and realization path[J]. China Soft Science, 2022(8): 45-57.

[13] Pachauri R K, Allen M R, Barros V R, et al. Climate change 2014 synthesis report. Contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change[M]. Geneva: IPCC, 2014: 151.

[14] Polsky C, Neff R, Yarnal B. Building comparable global change vulnerability assessments: The vulnerability scoping diagram[J]. Global Environmental Change, 2007, 17(3-4): 472-485.

[15] Ministry of Ecology and Environment of the People' s Republic of China. Outline of national ecological fragile area protection plan[EB/OL]. [2008-09-27]. https://www.mee.gov.cn/gkml/hbb/bwj/200910/t20091022_{174613}.htm.

[16] Jiang Lu. Rural household energy consumption and energy poverty in the Qinghai-Tibet Plateau: Case of Qinghai Province[D]. Lanzhou: Lanzhou University, 2019.

[17] Fan S Y, Zha S, Zhao C X, et al. Using energy vulnerability to measure distributive injustice in rural heating energy reform: A case study of natural gas replacing bulk coal for heating in Gaocheng District, Hebei Province, China[J]. Ecological Economics, 2022, 197: 107456, doi: 10.1016/j.ecolecon.2022.107456.

[18] Tao Shu, Shen Guofeng, Shen Huizhong, et al. Regional differences in emission contributions and health risks from solid fuel consumption in China' s residential sector[R]. Beijing: Peking University, 2024.

[19] Xu S Q, Wang R, Gasser T, et al. Delayed use of bioenergy crops might threaten climate and food security[J]. Nature, 2022, 609(7926): 299-306.

[20] Sheha M, Mohammadi K, Powell K. Techno-economic analysis of the impact of dynamic electricity prices on solar penetration in a smart grid environment with distributed energy storage[J]. Applied Energy, 2021, 282: 116168, doi: 10.1016/j.apenergy.2020.116168.

[21] Zhang Dayong, Ji Qiang, Li Jiajia. China' s household energy consumption: Current situation, challenges and future[M]. Chengdu: Southwestern University of Finance and Economics Press, 2023: 63-80.

[22] Teng Yuhua. Study on influencing factors of the willingness of rural residents to use clean energy: Empirical analysis based on 695 sample data of Jiangxi Province[J]. West Forum, 2018, 28(3): 17-24.

[23] Carley S, Evans T P, Graff M, et al. A framework for evaluating geographic disparities in energy transition vulnerability[J]. Nature Energy, 2018, 3(8): 621-627.

[24] Jiang Lu, Liu Yanjuan, Shi Xiaonan, et al. Household energy consumption in urban communities in Qinghai Plateau based on material flow: A case of Xining City[J]. Arid Land Geography, 2023, 46(2): 294-304.

[25] Wu Shimei, Zheng Xinye. Revisit of household energy ladder: Empirical evidence from a household survey in rural China[J]. China Economic Quarterly, 2022, 22(1): 45-66.

[26] Ajzen I. The theory of planned behavior[J]. Organizational Behavior and Human Decision Processes, 1991, 50(2): 179-211.

[27] Wang Huogen, Liang Yiwen. Analysis on factors affecting promotion of clean energy in the countryside based on the grounded theory[J]. Science and Technology Management Research, 2018, 38(11): 234-239.

[28] Zhu H G, Fang S Y, Zhang S P, et al. Effects of social capital on energy poverty: Evidence from the national key ecological function zones in northeast China[J]. Energy, 2024, 304: 131956, doi: 10.1016/j.energy.2024.131956.

[29] Chang Huayi, He Ke, Zhang Junbiao. Energy poverty in rural China: A psychological explanations base on households[J]. China Population, Resources and Environment, 2020, 30(2): 11-20.

[30] Geng J C, Long R Y, Chen H, et al. Exploring the motivation-behavior gap in urban residents' green travel behavior: A theoretical and empirical study[J]. Resources, Conservation and Recycling, 2017, 125: 282-292.

[31] Han Zhen, Peng Chao, Liu Heguang. Government guarantee, social supervision and rural residents' domestic waste concentrated disposal behavior: Based on the survey data of 1365 households in 183 villages[J]. Rural Economy, 2023(10): 73-82.

[32] Neves C, Oliveira T. Drivers of consumers' change to an energy-efficient heating appliance (EEHA) in households: Evidence from five European countries[J]. Applied Energy, 2021, 298: 117165, doi: 10.1016/j.apenergy.2021.117165.

[33] Teng Yuhua, Liu Changjin, Chen Yan, et al. Decision research on rural residents' clean energy applied behavior based on a SEM model[J]. China Population, Resources and Environment, 2017, 27(9): 186-195.

[34] Yang Y, Xia S Y, Huang P, et al. Energy transition: Connotations, mechanisms and effects[J]. Energy Strategy Reviews, 2024, 52: 101320, doi: 10.1016/j.esr.2024.101320.

[35] Cao Z, Meng Q, Gao B Z. The consumption patterns and determining factors of rural household energy: A case study of Henan Province in China[J]. Renewable and Sustainable Energy Reviews, 2021, 146: 111142, doi: 10.1016/j.rser.2021.111142.

[36] Qin Gexia, Meng Zhiyuan, Li Ni. Dynamics of water use efficiency and its response to drought and land surface temperature on the Loess Plateau[J]. Arid Land Geography, 2024, 47(11): 1887-1898.

[37] Ma Mingde, Li Junjie, Xue Chenhao. Spatiotemporal evolution and driving mechanism of environmental stress of regional development in Ningxia Hui Autonomous Region[J]. Arid Land Geography, 2024, 47(6): 1061-1072.

Note: Figure translations are in progress. See original paper for figures.