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The Impact of Population Aging on Regional Energy Consumption Structure: A Perspective on Environmental Regulation

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Abstract. China is faced with both challenges of global climate shifts and population aging, so energy consumption structure transformation towards cleanliness has become the first key issue if our country wants to achieve sustainable development. The paper utilizes a decade of provincial data (2012-2021) to explore how an aging populace reconfigures energy usage under different levels of environmental governance. Based on fixed effect and threshold estimations, the following results can be obtained: 1) The emergence of a large elderly population acts as an inhibitor of coal reliance and can expedite the adjustment to green energy; 2) Environmental regulation has one threshold in the impact on the energy consumption structure of population aging, and with the continuous improvement of the environmental regulation level, the positive effects of population aging are enhanced; 3) There is a clear spatial divide: The promoting effect in the eastern region is the largest. This study offers reference for promoting the development of sustainable development and differentiated environmental regulation policies in the context of aging and promoting the low-carbon transformation of the energy structure.

Keywords: Population Aging, Energy Consumption, Environmental Regulation, Threshold Model

1. Introduction

The proportion of the elderly population in our country is increasing year by year, and the problem of population aging has become prominent. The Party and the state attach great importance to and actively respond to this issue. Since 2019, a number of strategic planning policies have been introduced. In the draft of the "Fifteen-Five-Year" outline of the 14th National People's Congress of the Communist Party of China in 2026, it is emphasized that "the national strategy of actively responding to population aging should be further implemented, and the policy mechanism for the coordinated development of elderly care services and industries should be improved." The effective alleviation of the problem of aging is related to the well-being of the people. Energy consumption not only concerns China's energy security and consumption structure, but also has a profound impact on China's green and low-carbon development and environmental quality. China has taken a number of measures to address challenges in the energy sector, promoting the clean transformation of

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agricultural structure. The changes in population structure are greatly influencing China's energy consumption structure, and environmental regulation is a key policy tool for controlling pollution emissions, playing an irreplaceable role in promoting the transformation of the energy structure. Therefore, this paper intends to study the influence relationship among population aging, energy consumption, and environmental regulation and conduct an empirical analysis, in order to provide references for policy formulation and subsequent research.

2. Literature review

2.1. Research on population aging and energy consumption structure

Current research indicates that the nexus between demographic aging and energy consumption patterns is multifaceted, mediated by a triad of determinants: consumer behavior, labor dynamics, and technological progression, but the academic community has not yet reached a unified conclusion on the direction of this impact.

Some literature indicates that population aging would impede the clean-up and upgrading of the energy consumption structure. At the micro-behavioral level, elderly cohorts are typically associated with rigid consumption paradigms and a lower willingness to accept new green technologies. Especially in rural areas, the elderly population is more sensitive to economic conditions and usage inertia and they are more likely to stick to conventional energy sources, such as coal and biomass fuels, which postpones the process of popularizing clean energy [1]. From a macro perspective, aging will cause a decrease in the supply of social labor force and overall economic vitality, and further result in a reduction in the investment in social labor force renewal and green technology research and development, which will impede the transformation of the energy structure [2]. Conversely, more and more evidences have indicated that demographic changes to an older society would promote a clean energy pivot. The elderly group has higher expectations on living quality and living environment and they are more inclined to accept stable and clean energy types. In household thermal regulation and illumination sectors, families with senior members have shown an increased preference for stable and low-emission sources, such as electricity and natural gas [3]. The study results of Chen and Hu [4] revealed that the consumption preferences and environmental protection awareness of the elderly population would drive family energy consumption towards a low-carbon and efficient direction, which would further promote the optimization of the overall energy structure.

Combining these conflicting views, recent literature indicates that the impact is conditional and it is not unified but will be situated in certain conditions such as localized economic maturity, natural resource endowment, and prevailing regulation. Zhang's study discovered that in economically backward and energy infrastructure poor areas, aging would promote more traditional energy [5].

2.2. Research on the role of environmental regulation in energy consumption structure

The consensus of many academics is that, whatever types of environmental regulations are concerned, they play as important levers to shift energy consumption matrices to de-carbonized and sustainable directions. It is also demonstrated that both rigid administrative order and market incentive-based environmental regulation are conducive to advance energy structure clean-up: different from Zhao et al. [6], strict environmental target constraints will compel enterprises and local governments to increase investment in clean energy and accelerate low carbon transition of energy consumption structure, while Liu and Jiang [7] have verified the inverse relationship between regulatory strictness and carbon dependency in theory; as for market incentive-based regulation, Xu

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and Sun [8] analyzed China carbon emission trading pilot and found that carbon market motivates reallocation of energy factors through price signals and increases the share of clean energy consumption substantially; moreover, environmental regulation can also regulate the relationship between population aging and energy consumption structure through multiple links. In terms of mechanism analysis, environmental regulation exerts impacts on energy consumption patterns through below three aspects. One is that environmental regulation increases the cost of fossil fuel and compels energy users to choose clean energy as alternatives. The second is that environmental regulation motivates enterprises to innovate green technologies and improves supply and efficiency of clean energy. The third is that environmental regulation sends clear signals to the market and motivates private capitals to enter renewable energy fields. According to Gao et al [9]., different types of environmental regulatory tools will exert different regulatory effects on energy consumption structures through regulating corporate energy costs and preferences differently.

3. Theoretical model and research hypotheses

Population aging, as the core feature of population structure change, profoundly influences regional energy consumption patterns by altering individual consumption preferences and resource allocation methods. Based on consumption preference and life cycle theory, the elderly group's demand for health significantly increases, and they pay more attention to the living environment. Thus, they tend towards low-carbon and clean consumption methods, thereby further promoting the upgrading of consumption structure. Therefore, Hypothesis 1 is proposed.

H1: The deepening aging of the regional population facilitates the transition to a cleaner energy mix.

However, the impact of aging on the energy structure is not an isolated phenomenon. The Porter Hypothesis [10] states that reasonable environmental regulations can innovation to reduce pollution. Only when the policy intensity accumulates to a certain extent will the behavior of market entities undergo a substantive change, and the policy effect will show a marginal increasing tendency. In this article, when the environmental regulation intensity is low, the slight adjustments taken by enterprises and households are not sufficient to change the energy consumption structure. Only when the environmental regulation intensity crosses a specific threshold will the promoting effect be significantly strengthened. Therefore, Hypothesis 2 is proposed.

H2: When environmental regulations reach a certain intensity, they will drive the impact of population aging on the transition to a cleaner energy structure to exhibit a nonlinear characteristic with increasing marginal effects.

The nexus between demographic maturation and the evolutionary trajectory of energy infrastructure is a spatially variegated phenomenon. Based on the resource-based theory, different regions have different resource bases, and the government's attention to resource allocation and population structure, economic conditions, etc. also varies. Therefore, the degree of energy structure transformation varies greatly. Overall, the eastern regions, which have better resource endowments, higher economic levels and higher population quality, have better energy structure transformation. Therefore, Hypothesis 3 is proposed.

H3: The impact of regional population aging on promoting the clean energy transition exhibits regional heterogeneity.

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4. Model setting and description of variables

4.1. Research design

To examine the impact of population aging on regional energy consumption patterns, this study establishes a fixed-effects model as the benchmark regression framework, with the following specifications:

$$EC_{it} = \alpha_0 + \alpha_1 Old_{it} + \beta X_{it} + \lambda_i + \varepsilon_{it} \tag{1}$$

Here, i means provinces, and t represents years. EC_{it} is dependent variable, representing regional energy consumption structure; Old_{it} is the independent variable, indicating population aging degree; X_{it} is the control variable; λ_i denotes provincial fixed effects and ε_{it} is the random error term.

To further investigate how population aging affects energy consumption patterns under varying environmental regulation intensities (ER), we developed a threshold effect model incorporating environmental regulation as a threshold variable, as shown in Equation (2). Here, I(•) is an indicator function with values of 1 or 0, while γ represents the environmental regulation threshold to be estimated.

$$\begin{aligned} EC_{it} = {} & \alpha_0 + \alpha_1 Old_{it} {*} I\left(ER \le \gamma_1\right) + \alpha_2 Old_{it} {*} I\left(\gamma_1 < ER \le \gamma_2\right) \\ & + \alpha_3 Old_{it} {*} I\left(ER > \gamma_2\right) + \beta X_{it} + \lambda_i + \varepsilon_{it} \end{aligned} \tag{2}$$

4.2. Variable selection

The dependent variable is Energy Consumption Structure (EC), measured by the proportion of coal consumption in total energy consumption. The core explanatory variable is Population Aging (Old), measured by the ratio of individuals aged 65 and above to the working-age population (15-64 years). Threshold variable environmental regulation (ER) is calculated by the frequency of environmental protection-related terms in municipal government work reports as an indicator of environmental regulation intensity. Control variables in this paper include economic development level (PGDP, logarithm of each province's GDP), highway mileage (inf, measured in 10,000 kilometers), and household consumption structure (CCR, energy consumption for living purposes).

4.3. Data source and descriptive statistics

The empirical base of this study was built by the methodical organization of authoritative multi-dimensional datasets. The main indicators came from the data released by the National Bureau of Statistics. In particular, population data was collected from the China Population and Employment Statistical Yearbook. Energy and environmental indicators were from the China Energy Statistical Yearbook. Other data from the China Statistical Yearbook, China Price Statistical Yearbook, and China Science and Technology Statistical Yearbook were also often used. Table 1 shows the basic statistical information of all operational variables.

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Table 1. Descriptive statistics of variables (N=300)

Variable	Mean	Std. Dev.	Min	Max
EC	0.373	0.146	0.007	0.687
old	15.415	4.036	8.750	26.700
PGDP	9.868	0.882	7.332	11.734
CCR	3.870	1.967	1.616	11.292
inf	15.690	8.366	1.254	40.539
ER	77.580	28.449	6.000	159.000

5. Analysis of empirical results

5.1. Benchmark regression

The baseline regression outcomes detailing how demographic aging shifts energy utilization patterns are chronicled in Table 2, with control variables introduced sequentially. Without including any control variables, population aging (old) was significant at the 1% level and had a negative correlation, which might be related to the fact that the elderly prefer stable and safe clean energy, thus reducing the share of coal consumption. When the control variable of economic development level is increased, the significance level becomes 10%. After adding the control variables of industrial structure (CCR) and highway mileage (inf), the aging coefficient remained stable at -0.005 and maintained at the 5% significance level, and Hypothesis 1 holds.

Table 2. Baseline regression results (N=300)

VARIABLES	(1)	(2)	(3)	(4)
old	-0.014***	-0.005*	-0.005**	-0.005**
	(0.002)	(0.002)	(0.002)	(0.002)
PGDP		-0.137***	-0.163***	-0.133**
		(0.030)	(0.026)	(0.003)
CCR			0.029***	0.028**
			(0.010)	(0.008)
inf				-0.007**
				(0.003)
Constant	0.588***	1.794***	1.947***	1.754***
	(0.024)	(0.269)	(0.222)	(0.234)
Province Fixed	Yes			
R^2	0.551	0.672	0.719	0.734

Note: Robust standard errors are in parentheses; ***, **, and * denote significance levels of 1%, 5%, and 10%, respectively, as in the table below.

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5.2. Robustness and endogeneity test analysis

This study uses three robustness testing methods to support the reliability of our conclusions: (1) Drop the special year of 2020 to reduce the bias caused by the impact of the pandemic. (2) Narrow the scope of sample by omitting Beijing, Shanghai, Tianjin and Chongqing since there are considerable differences in both population and economy between the four municipalities in China and other provinces. (3) Tail-trim all relevant variables at 5% and 95% quantiles to solve possible outliers in the baseline regression process. As shown in columns (1)-(3) of Table 3, the aging coefficient is always negative and significantly statistical, which shows the reliability of this study. It is believed that instrumental variables could reduce the estimation bias induced by endogeneity. In this study, we use the first lag term of population aging as an instrumental variable in regression analysis since it shows high correlation with dependent variable but is not correlated with current energy consumption. It is predicted that the validity of instrumental variable approach works in Column (4) of Table 3, which can be prove by the significant IV coefficient. More importantly, Kleibergen-Paap rk Wald F-statistic achieves robust value of 286.582, which is far more than the critical values. Then see the second stage results in Column (5), the core negative relationship is still statistically significant at 1% level. Therefore, it can be concluded that even considering the possible endogeneity, the primary empirical conclusions of this study are still valid.

Table 3. Robustness and endogeneity test results

VARIABLES	(1)	(2)	(3)	(4)	(5)
	Excluding year 2020	Exclude municipalities directly under central control	Winsorizing	Instrumental variable method	
old	-0.004*	-0.006**	-0.005**		-0.007***
	(0.002)	(0.002)	(0.002)		(0.002)
L.old				0.844***	
				(0.050)	
Controls Province Fixed	Yes				
Constant	1.799***	1.708***	1.502***	-24.205***	1.227***
	(0.243)	(0.257)	(0.253)	(5.863)	(0.194)
Kleibergen-Paap rk Wald F statistic				286.582	
R^2	0.727	0.725	0.654	0.931	0.967
N	270	260	300	270	270

5.3. Threshold effect analysis

Then, the threshold presence of model (2) was tested. The data presented in Tables 4 and 5 are the critical points of energy consumption behavior in different degrees of demographic aging. From the viewpoint of statistics, environmental regulation is a one-threshold variable because the statistic of double and triple thresholds cannot pass the significance test. What is more interesting is that population aging has more restrictive effects on energy consumption structure when the regulatory intensity becomes higher. When the value of regulatory threshold exceeds 77, the impact coefficient rises from 0.0046 to 0.0054. The marginal effect is enhanced more, and Hypothesis 2 is validated.

Table 4. Threshold effect test

Threshold Variable	Threshold Number	Threshold Value	F-value	P-value	BS	Crit10	Crit5	Crit1
ER	Single	77	9.400	0.093	300	9.132	10.960	14.564

Table 5. Threshold regression results

Core Variable	Threshold Value	$\mathrm{I}\,(ER \leq \gamma_1)$	$\mathrm{I}\,(ER > \gamma_1)$
Old	77	-0.0046***(0.001)	-0.0054***(0.001)

5.4. Heterogeneity analysis

Due to the different development levels of the regions, there exists significant heterogeneity on population structure and energy consumption structure in different regions. This paper follows the previous method of dividing regions in China [11] and divides 30 provincial administrative regions into eastern, central, and western regions and then does regression analysis in each region in Table 6. For eastern region, coefficient of population aging is -0.004, and it has passed the 10% significance test. For the central and western regions, the degree of population aging is still negatively correlated with the energy consumption structure, but it is not significant. Hypothesis 3 holds. Thus, for the eastern, central, and western regions, population aging all have negative impacts, especially in the eastern region. This may be related to the fact that in economically developed regions, the elderly have a stronger awareness of protecting the environment, pay more attention to green and low-carbon issues, and are more inclined to use clean energy.

Table 6. Heterogeneity analysis

	(1)	(2)	(3)
VARIABLES	East	Center	West
old	-0.004*(0.002)	-0.007(0.005)	-0.003(0.003)
Controls		Yes	
Constant	1.448***(0.376)	1.801**(0.659)	2.063***(0.295)
Province Fixed		Yes	
N	110	80	110
R^2	0.730	0.755	0.769

6. Conclusion and recommendation

6.1. Conclusion

Based on a panel dataset consisting of 30 provincial-level divisions from 2012 to 2021, this paper explores the relationships between demographic transition and energy consumption structure under

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the background of environmental governance from the perspective of fixed-effect and threshold modeling. And the main conclusions are as follows: First, population aging greatly drives the clean transformation of energy consumption structure. Second, the cross-effect relationship between these two variables is mediated by environmental regulation, and the threshold effect of environmental regulation is single-threshold. Third, the above effects do not present a uniform spatial distribution. Only in the eastern region, the geographic distribution of the inhibitory effect of aging on the proportion of coal consumption is significantly negative.

6.2. Recommendation

First, population aging is a promoting factor for clean energy structure transformation. When the government formulates policies, it should also take into account the consumption preference of old people, and prompt enterprises to produce more clean energy products that meet the consumption habits of old people. Second, local governments should further strengthen the environmental governance. This paper suggests that the government can try to establish a regular environmental information release mechanism to enhance the actual intensity and sustainability of environmental regulations. Third, strengthen regional cooperation and give full play to the role of optimizing the allocation of regional resource endowment. In the inland provinces of central and western corridors, it is urgently needed to quickly promote the construction of modern power grids and sustainable fuel systems.

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