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Sustainable Energy Pathways in Ageing Societies: Heterogeneous Effects of Socioeconomic and Climate Factors

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ABSTRACT

This study investigates how population ageing shapes sustainable energy pathways and introduces a novel multidimensional index to measure sustainable energy performance. The index is constructed using an entropy weighting method and measures progress across the main pillars of SDG7. It captures renewable energy expansion, energy efficiency improvements and clean energy access. Using panel quantile regression in OECD countries, the results show clear heterogeneity. The effect of ageing varies across sustainable energy performance levels and depends on socioeconomic conditions and climate vulnerability. Ageing is associated with stronger sustainable energy outcomes in high-income and climate-resilient, countries, while it constrains sustainable energy performance with high urban pressure. These findings demonstrate that demographic structure interacts with socioeconomic capacity and climate exposure in shaping sustainable energy pathways. Policies that ignore this heterogeneity risk misallocating resources. The results provide a measurement framework and distributional evidence that can support more targeted and context-specific sustainable energy transition strategies.

JEL Classification: Q4, Q54, J1

1 | Introduction

Sustainable energy has become a central policy priority due to its role in combating the global climate crisis. The United Nations Development Program defines sustainable energy as “energy solutions that simultaneously address development issues related to economic growth, environment and social equity” (United Nations Development Programme [UNDP] n.d.). This definition aligns closely with Sustainable Development Goal 7, which aims to ensure access to affordable, reliable, modern, and sustainable energy for all. Much of the existing literature discusses the sustainable energy future by focusing on a single aspect, such as renewable energy shares, energy efficiency or energy consumption (Feng et al. 2022; Li, Ma, and Li 2025; Sui et al. 2024; Umit et al. 2019). This one-dimensional focus limits the assessment of overall performance and weakens the basis for coherent policy design.

Sustainable energy is commonly understood as a broad and multidimensional concept built on three core pillars: energy access, energy efficiency, and renewable energy deployment (United Nations Development Programme [UNDP] n.d.). Each of these contributes to achieving sustainable energy, but none of which individually fully describes sustainable energy. Deployment of renewable energy without improving access can leave parts of the population underserved. Also, efficiency enhancement alone

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does not guarantee a shift away from fossil fuels due to the rebound effect (Wang et al. 2016). Therefore, a comprehensive assessment of sustainable energy requires an approach that integrates all three pillars.

International commitments such as the Paris Agreement place strong pressure on countries to expand renewable energy transition, improve efficiency, enhance accessibility and reduce carbon intensity (Anke and Möst 2021; Feng et al. 2022). Yet, implementing these dimensions together in a coordinated way to achieve sustainable energy remains challenging in practice.

Energy systems are shaped by political, technological, economic, social, and institutional factors, which often interact in complex ways (Pereira et al. 2025). Many countries remain locked into fossil fuel-based systems, creating resistance to structural change and slowing the adoption of clean energy technologies (Ankrah et al. 2025). Also, climate vulnerability increases uncertainty by damaging infrastructure and diverting public resources toward adaptation (Brownbridge and Canagarajah 2024; Porro et al. 2025). Most importantly, demographic structure represents an additional and increasingly important factor shaping sustainable energy outcomes (Wang et al. 2023). Population ageing, in particular, has become a defining feature of demographic change worldwide. By 2050, one in six people globally will be aged 65 or older (UN 2020). This shift has implications for energy demand, investment capacity, public finance, and policy priorities, all of which are central to sustainable energy development.

Population ageing is pronounced in developed economies, where low fertility rates and rising life expectancy have increased the share of older individuals in the population (Lee et al. 2025; Pais-Magalhães et al. 2022). According to United Nations criteria, a country is considered an ageing society when at least 10% of its population is aged 60 or above, or 7% is aged 65 or above (UN, 2019).

The existing literature presents mixed evidence on how ageing affects energy outcomes. Some studies suggest that ageing may constrain energy development by increasing pressure on public budgets, reducing labor supply, and slowing the adoption of new technologies (Sui et al. 2024; Wei et al. 2017; Willis et al. 2011). Others argue that older societies may place greater value on environmental quality, energy security, and long term stability, which could support cleaner energy choice (Lee et al. 2025). The net effect of ageing therefore remains theoretically ambiguous.

Moreover, the impact of population ageing is unlikely to be uniform across countries. Socioeconomic conditions shape how demographic change translates into energy outcomes (Dabirian et al. 2026). Higher income levels can ease financing constraints and support investment in renewable energy and energy efficiency (Ergun and Rivas 2023). Urbanization can promote efficient energy use and facilitate modern energy infrastructure (Fang et al. 2022). Human development and education influence awareness, technology acceptance, and public support for sustainability policies (Opoku et al. 2022; Yao et al. 2020). These factors may strengthen or weaken the effect of ageing on sustainable energy pathways. Climate vulnerability also may condition this relationship through risk spillover effects, where risks spread from one system to another (Işık et al. 2025). Higher climate vulnerability can increase the urgency of sustainable energy adoption by raising the cost of inaction, but it can also strain public resources and weaken investment capacity.

Despite growing interest in the links between ageing and energy outcomes, existing studies remain limited. Most focus on single countries and examine direct effects, without accounting for cross country heterogeneity in income, human development, urbanization, or climate vulnerability (Guang et al. 2025; Lee et al. 2025). As a result, current evidence provides limited guidance on how ageing interacts with broader socioeconomic and environmental conditions to shape sustainable energy pathways.

This study addresses these gaps by examining how population ageing influences sustainable energy outcomes across OECD countries and also accounting for differences in socioeconomic conditions and climate vulnerability. OECD countries provide a suitable setting for this analysis because they exhibit variation in demographic structure, income levels, human development, urbanization, and climate vulnerability, while also offering reliable data and relatively comparable institutional frameworks. Figure 1 illustrates the variation in ageing across OECD countries, showing the share of the population aged 65 and above as a percentage of the total population in 2023. The map highlights the differences, with some countries having relatively young populations while others are highly aged, providing clear visual context for analyzing how ageing may shape sustainable energy pathways under different socioeconomic conditions.

The paper makes three contributions. First, it develops a new sustainable energy index (SEI) based on the entropy-weighting method. The index integrates energy access, energy efficiency, and renewable energy deployment, providing a more comprehensive measure than commonly used single indicators. Second, it moves beyond the assumption of a uniform ageing effect by employing a quantile regression framework to capture heterogeneity across different levels of sustainable energy performance. Third, it embeds demographic structure within a broader socioeconomic and climate context, allowing us to identify when population ageing supports sustainable energy pathways and when it acts as a constraint.

The rest of the paper is structured as follows. Section 2 introduces the theoretical foundation and reviews the related literature. Section 3 outlines the data and methodology. Section 4 presents and discusses the empirical results, while Section 5 concludes.

2 | Theoretical Foundation and Related Literature

2.1 | Theoretical Foundation

This study is based on a sociotechnical transition model by (Alcamo 2015), which explains how energy systems evolve through interactions between natural and built components, such as energy resources and infrastructure, and societal and institutional elements. The model emphasizes that long-term structural forces, or "landscape pressures," guide the direction of these transitions. Demographic ageing acts as one such landscape pressure by influencing consumption, savings, labor

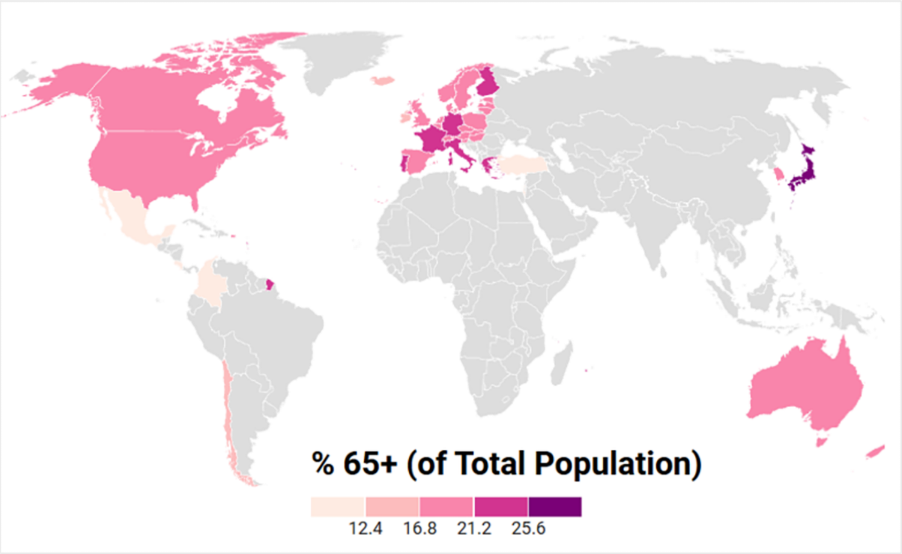


FIGURE 1 | Ageing population in OECD countries in 2023. *Note:* Lighter shades indicate lower levels of Ageing while darker shades indicate higher levels.

supply, and policy priorities (Doerr et al. 2025). Older populations often have stable but fixed incomes, different energy needs, stronger preferences for reliability, and slower adoption of new technologies (Lansley 2005). Ageing also shapes consumption patterns through lifetime reallocation and strategic savings, altering household energy demand and broader economic activity. Because these effects operate simultaneously across households, firms, and institutions, ageing has a wide, system-level influence. Consequently, its impact on sustainable energy cannot be fully understood through isolated indicators, but requires an integrated, system-wide assessment that captures deployment, efficiency, and access.

2.2 | Ageing and Sustainable Energy

Several studies have examined how ageing influences different aspects of energy systems. Most research, however, focuses on single dimensions, such as renewable energy adoption, energy efficiency, or household consumption rather than considering sustainable energy as an integrated system. This fragmented approach has produced mixed findings, for example ageing can improve some outcomes like renewable deployment as suggested by Sui et al. (2024), while hindering others like equitable energy access as suggested by Li, Lu, et al. (2025) and Li, Ma, and Li (2025). This limits the ability to understand the overall effect of ageing and weakens policy design. To clarify these mixed results, it is necessary to review how ageing shapes each dimension of sustainable energy.

Population ageing affects sustainable energy through its three main dimensions. First, it can support renewable energy production by encouraging automation and industrial upgrading. Sui et al. (2024) using data of 212 countries from 2000 to 2021, found a positive impact of ageing on renewable energy development. But also, it often slows renewable adoption at the household level due to habits, information gaps, and financial limits among the elderly (Li, Lu, et al. 2025; Wang et al. 2023; Yagita and Iwafune 2021).

Second, ageing may improve energy efficiency in industry as firms respond to labor shortages, while reducing efficiency at the household level because older people tend to live in inefficient homes and adopt new technologies more slowly. Sheng et al. (2024) argue that population ageing promotes corporate green innovation activities through energy efficiency and waste reduction. In contrast, Shi et al. (2023) using a behavior-based model examined how ageing affects household hourly consumption patterns in Shanghai. The author finds that population ageing not only raises total energy demand but also reshapes hourly consumption patterns, widening the difference between peak and off-peak periods.

Third, ageing worsens energy access and equality (Li, Lu, et al. 2025; Li, Ma, and Li 2025). The authors argue that many elderly people in rural China do not use the internet, which restricts their ability to obtain reliable information. This constraint reduces their exposure to clean energy options and related support programs. Households with a high share of elderly members face greater difficulty using new information channels, especially online platforms. As a result, the gap in access to clean energy information between these households and others continues to grow.

2.3 | Socioeconomic and Environmental Factors as Moderators

The evidence above shows that ageing influences the core dimensions of sustainable energy, but these effects do not occur in isolation. The strength and direction of the relationship depend on the broader socioeconomic and environmental context in which ageing takes place. Differences in income levels, urbanization, and human development shape the ability of households, firms, and

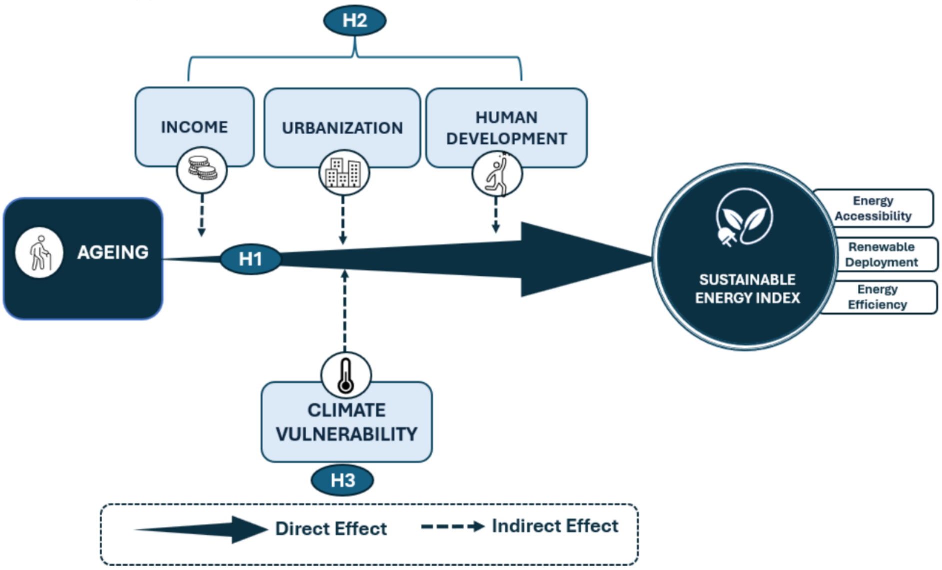


FIGURE 2 | Conceptual framework of the role of ageing on sustainable energy.

governments to adapt to demographic change and invest in modern energy systems (Gelo et al. 2023; Mills and Schleich 2012; Yan 2026). While higher income increases renewable energy investment capacity, urbanization creates scale economies in infrastructure and energy distribution, and education and awareness improve acceptance of new technologies and strengthen policy support. Liu et al. (2025) find that urbanization can indirectly advance the energy transition by increasing rural disposable income, improving infrastructure conditions, and strengthening regional policy provision. Recent multi-criteria evidence shows that European OECD countries differ markedly and persistently in their levels of sustainable development and living standards, with these gaps potentially stemming from structural disparities in income, urbanization, and human capital (Łuczak et al. 2025, 2026).

At the same time, climate vulnerability can alter policy priorities and increase the urgency of energy transition. Recent evidence highlights the role of climate vulnerability in shaping energy outcomes. A study by Zhang et al. (2026) develops a new measure of the resilience of national energy consumption and shows that higher climate vulnerability reduces the capacity of energy systems to absorb shocks and maintain stable consumption patterns. Also, Anton (2026) using a panel of 162 countries, found a positive relationship between climate vulnerability and energy consumption. These findings suggest that climate vulnerable countries face rising energy demand while their energy systems become less resilient to disruptions. This combination increases pressure on energy systems and strengthens the need for policies that enhance resilience and accelerate the energy transition.

2.4 | Synthesis and Hypotheses

The key message that can be drawn from the literature is that the relationship between population ageing and energy variables is a complex, multi-dimensional issue characterized by conflicting findings across different geographic and socio-economic scales. While some research views ageing as a “blessing” that promotes renewable energy at the industrial level, other studies frame it as a “curse” that hinders clean energy adoption and efficiency at the household level. Therefore, the overall impact on the full system remains unclear, especially regarding how it changes under different socioeconomic conditions and levels of climate vulnerability. Our study aims to address this gap as shown in Figure 2 and propose the following hypotheses:

H1. *Population ageing has a significant and heterogeneous effect on sustainable energy outcomes in OECD countries.*

H2. *Socioeconomic conditions, captured by income level, urbanization, and human development, moderate the relationship between population ageing and sustainable energy.*

H3. *Climate vulnerability moderates the relationship between population ageing and sustainable energy.*

3 | Methods and Data

3.1 | Data

This study uses annual panel data for 37 OECD countries covering the period 1995 to 2023. The sample period is determined by data availability (see Table A1). The dependent variable is a composite SEI constructed in this study, which captures three core dimensions of sustainable energy: renewable energy deployment, energy accessibility, and energy efficiency based on UNDP.

The deployment of renewable energy is measured by the share of renewable energy consumption in total final energy consumption (Badeeb and Lean 2026; Bourcet 2020). This measure is the standard SDG7 tracking indicator adopted by the World Bank and the International Energy Agency, giving the index direct comparability with global policy benchmarks. Consumption outcomes are more policy-relevant than capacity measures because they reflect

TABLE 1 | Variables and data sources.

Variable	Symbol	Description	Source
Sustainable energy index	SEI	The index was constructed to capture three key dimensions of sustainable energy performance: renewable energy deployment measured as the share of renewable energy in total energy consumption. Energy efficiency measured as the inverse of energy intensity (GDP per unit of total primary energy consumption). Accessibility to clean energy measured using the share of the population with access to clean fuels and technologies for cooking and heating.	Indicator source: WDI and Our World in Data—
Ageing population	AGE	Population ages 65 and above (% of total population)	WDI
Income	GDPC	GDP per capita (constant 2015 US$)	WDI
Urbanization	URB	Urban population (% of total population)	WDI
Human development	HDI	Human Development Index	ND-GAIN https://gain.nd.edu/our-work/country-index/
Climate vulnerability	CLV	The Index summarizes a country's vulnerability to climate change and other global challenges in combination with its readiness to improve resilience. A higher ND-GAIN score means lower vulnerability and greater readiness	ND-GAIN https://gain.nd.edu/our-work/country-index/

the mix of energy that actually reaches households and firms. Access to clean fuels and technologies is included to reflect the accessibility dimension of sustainable energy, focusing on households' ability to use modern and clean energy sources. Finally, energy intensity is used to represent the efficiency dimension, capturing how effectively energy is used in the production of economic output.

The main explanatory variable is population ageing, measured by the share of the population aged 65 and above in total population. To account for socioeconomic differences across countries, the analysis includes income, urbanization, and human development. Income is measured using real GDP per capita, urbanization is captured by the share of the urban population, and human development is proxied by the Human Development Index. To account for environmental difference, we use climate vulnerability indicator extracted from the ND GAIN index. This index reflects countries' vulnerability and readiness in relation to climate change. All variables, except the climate vulnerability indicator and the human development measure, are obtained from the World Development Indicators database. Climate vulnerability and human development data are sourced from Notre Dame Global Adaptation Initiative. Table 1 reports the definition of each variable and its data source.

3.2 | Models

The main objective of this study is to examine how population ageing influences sustainable energy pathways in OECD countries, taking into account the role of key socioeconomic factors and climate vulnerability. For this, our baseline regression model is constructed as follows:

$$SEI_{it} = \alpha_1 AGE_{it} + \alpha_2 GDPC_{it} + \alpha_3 URB_{it} + \alpha_4 HDI_{it} + \alpha_5 CLV_{it} + \varepsilon_{it} \quad (1)$$

where SEI represents sustainable energy index, GDPC is the natural logarithm of GDP per capita, URB is the natural logarithm of urban population to total population, HDI is human development index, CLV is the climate vulnerability and ε is error term.

To assess how socio-economic conditions and climate vulnerability shape the effect of ageing on sustainable energy, we extend the baseline model by introducing interaction terms between ageing and GDP per capita, urbanization, human development, and climate vulnerability, each entered separately. Accordingly, the conditional effects models are as follows:

3.2.1 | Income

$$\begin{aligned} SEI_{it} = {} & \beta_1 AGE_{it} + \beta_2 GDPC_{it} + \beta_3 URB_{it} + \beta_4 HDI_{it} + \beta_5 CLV_{it} \\ & + \beta_6 (AGExGDPC)_{it} + \varepsilon_{it} \end{aligned} \quad (2)$$

where (*AGExGDPC*) is the interaction term between ageing and income. When β_1 is positive and the interaction term's coefficient β_6 is negative, it means that a slight increase in income subsequently weakens the relationship between ageing and the SEI. While the stronger linkage between ageing and sustainable energy is established in the case of both β_1 and β_6 being positive.

3.2.2 | Urbanization

$$SEI_{it} = \gamma_1 AGE_{it} + \gamma_2 GDPC_{it} + \gamma_3 URB_{it} + \gamma_4 HDI_{it} + \gamma_5 CLV_{it} + \gamma_6 (AGExURB)_{it} + \varepsilon_{it} \tag{3}$$

3.2.3 | Human Development

$$SEI_{it} = \delta_1 AGE_{it} + \delta_2 GDPC_{it} + \delta_3 URB_{it} + \delta_4 HDI_{it} + \delta_5 CLV_{it} + \delta_6 (AGExHDI)_{it} + \varepsilon_{it} \tag{4}$$

3.2.4 | Climate Vulnerability

$$SEI_{it} = \vartheta_1 AGE_{it} + \vartheta_2 GDPC_{it} + \vartheta_3 URB_{it} + \vartheta_4 HDI_{it} + \vartheta_5 CLV_{it} + \vartheta_6 (AGExCLV)_{it} + \varepsilon_{it} \tag{5}$$

4 | Methodology

4.1 | Construction of Sustainable Energy Index

The use of composite indicators is well established in the sustainability and development literature, where single indicators often fail to capture the multidimensional nature of complex phenomena (Mazziotta and Pareto 2013; Greco et al. 2019). Widely used composite measures include the Sustainable Development Goal (SDG) Index, the World Energy Trilemma Index, and the Energy Transition Index, each of which aggregates several dimensions into a single comparable score across countries. These indices rely largely on expert assigned weights or equal weighting, which may not reflect the actual information content of the underlying indicators. The SEI developed in this study differs in two respects. First, it focuses specifically on the three core pillars of sustainable energy defined by the UNDP, namely renewable energy deployment, energy efficiency, and access to clean energy, providing a more targeted measure than broader sustainability indices. Second, it applies an entropy weighting scheme that is fully data driven, so the weight of each dimension reflects its observed variability across countries and years rather than expert judgement. The SEI therefore complements existing composite measures by offering a transparent and reproducible indicator that is specifically designed to track sustainable energy performance.

Building on this conceptual foundation, the study proceeds to operationalize sustainable energy performance through the construction of the SEI using the entropy-weighting method. The procedure is as follows:

Because the indicators differ in units and scales, the raw data are first standardized to remove dimensional effects. We apply min–max normalization, rescaling each indicator using its observed minimum and maximum across all countries and years in the sample. This approach is transparent and preserves relative dispersion within the sample, thereby providing a consistent basis for subsequent index construction (Carrino et al. 2016). Prior to normalization, we also harmonize indicator directionality: positively oriented indicators are retained as is (higher values indicate better transition performance), whereas negatively oriented indicators are reverse-coded to ensure that, after standardization, larger values consistently represent superior sustainable energy outcomes.

Step 1: Min–max normalization.

The standardized value is computed as follows:

$$z_{itj} = \frac{x_{itj} - \min\left(x_{\ldots j}\right)}{\max\left(x_{\ldots j}\right) - \min\left(x_{..j}\right)} \tag{6}$$

where x_{itj} is the original value of indicator j for country i in year t, and $\min\left(x_{\ldots j}\right)$ and $\max\left(x_{\ldots j}\right)$ denote the minimum and maximum of indicator j across all countries and years in the sample.

Step 2: Computing proportional shares.

Next, we compute the proportional share of each observation under indicator j, which reflects the relative contribution of each country–year observation to the total information of that indicator:

$$p_{itj} = \frac{z_{itj}}{\sum_{i=1}^{N} \sum_{t=1}^{T} z_{itj}} \tag{7}$$

Step 3: Information entropy.

We then compute the information entropy of each indicator. Entropy measures the information content (or dispersion) of an indicator:

$$e_j = -k \sum_{i=1}^{N} \sum_{t=1}^{T} p_{itj} \ln\left(p_{itj}\right), k = \frac{1}{\ln(n)} \tag{8}$$

A lower entropy value implies greater dispersion, indicating that the indicator provides more discriminating information and should receive a larger weight. Where n is the number of valid observations (typically $n = N \times T$).

Step 4: Objective weights.

The objective (entropy-based) weight of indicator j is calculated based on its information utility $1 - e_j$:

$$w_j = \frac{1 - e_j}{\sum_{j=1}^{M} \left(1 - e_j\right)} \tag{9}$$

Step 5: Construct the composite SEI.

We construct the composite SEI as a weighted sum of the standardized indicators:

$$SEI_{(it)} = sum_{(j=1)}^{M} w_j z_{(itj)} \tag{10}$$

where $SEI_{(it)}$ denotes the composite sustainable energy performance of country i in year t; $z_{(itj)}$ is the min–max normalized value of dimension j; and w_j is the corresponding entropy-based weight, satisfying $\sum_{j=1}^{3} w_j = 1$. Here, $M = 3$ indicates that the index comprises three dimensions, namely energy accessibility, energy efficiency, and renewable energy deployment. Specifically, energy accessibility captures the availability and affordability of

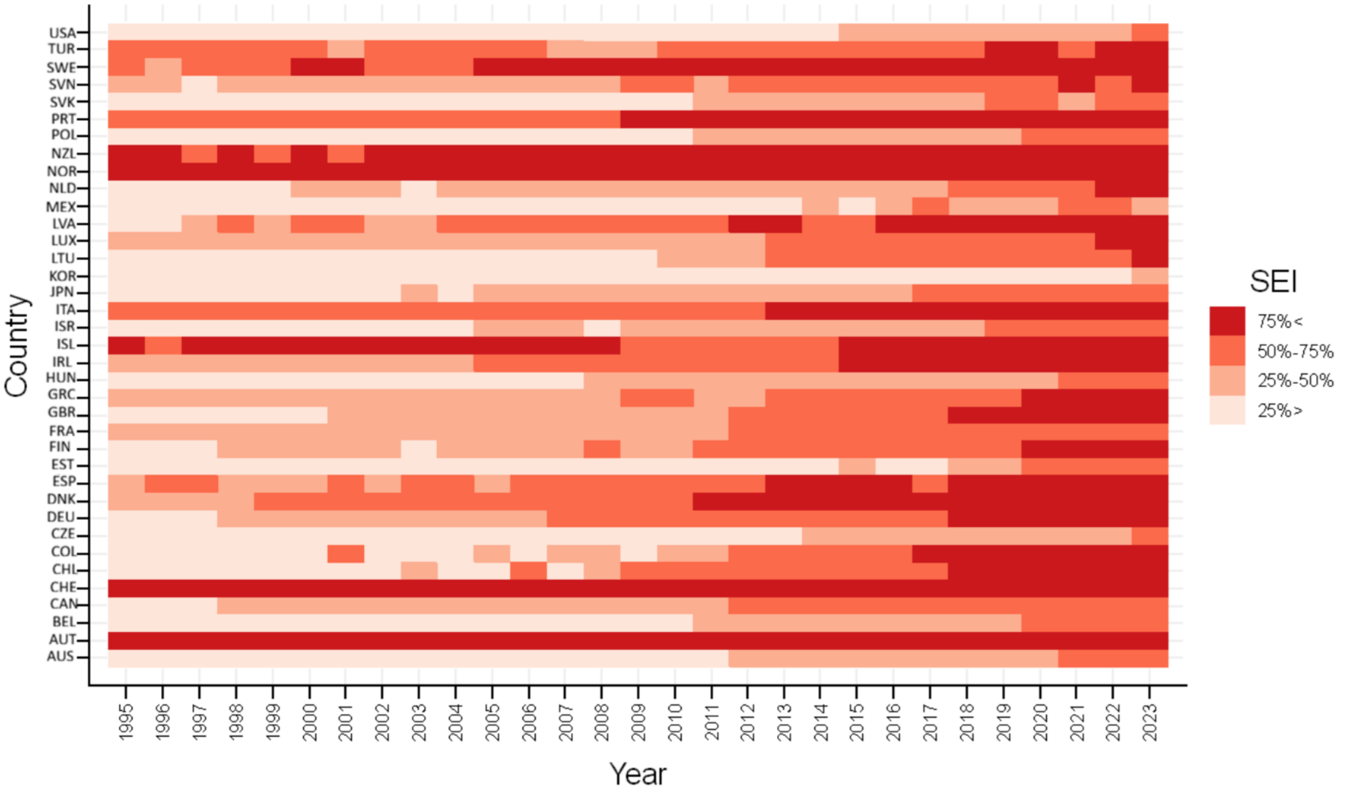


FIGURE 3 | Heatmap of sustainable energy index (SEI) by country and year.

modern energy services; energy efficiency reflects how effectively energy inputs are converted into economic output (e.g., improvements associated with declining energy intensity); and renewable energy deployment measures the scale and penetration of renewable energy within the energy system. By integrating these three dimensions within a unified framework of normalization and entropy-based weighting, the resulting $SEI_{(it)}$ provides a more comprehensive representation of national sustainable energy progress than any single proxy measure.

Figure 3 presents the yearly and country-level distribution of the SEI. The heatmap shows the magnitude of sustainable energy performance, with darker colors representing countries in higher quantiles of the index. The results indicate that countries like Norway (NOR), Denmark (DEN), Switzerland (CHE), and Austria (AUT) consistently rank higher on sustainable energy performance throughout the period, reflecting stronger performance in energy access, efficiency, and overall sustainability. In contrast, Slovak (SVK), Korea (KOR), and the United States (USA) occupy the lowest quantiles.

4.2 | Heterogeneity and Cross-Sectional Dependence

Since the analysis is based on panel data, it is necessary to examine the two key issues: slope heterogeneity and cross section dependence. Countries may share some common features but still differ in their economic structures and policy settings. If these differences are ignored, the estimates may become biased. To address this issue, the slope homogeneity test proposed by (Pesaran and Yamagata 2008) is applied. This test examines whether slope coefficients are the same across countries, with the null hypothesis of homogeneous slopes.

In addition, cross section dependence is tested using the approach developed by Pesaran et al. (2004). In a globalized world, shocks in one country may easily spill over to others. Ignoring this dependence may lead to misleading results. The following equation presents the mathematical form of the test described above, where the null hypothesis assumes cross sectional independence:

$$CD_{Test} = \sqrt{\frac{2T}{N(N-1)}\sum_{i=1}^{N-1}\sum_{k=1+i}^{N} T_{ik}} \tag{11}$$

4.3 | Unit Root and Cointegration Tests

After confirming the presence of slope heterogeneity and cross section dependence, an appropriate panel unit root test is required. This study applies the cross sectional IPS (CIPS) unit root test developed by (Pesaran 2007). This test explicitly accounts for cross section dependence by including the cross sectional averages in the regression. Compared with traditional unit root tests, the CIPS test provides more reliable results when countries are interconnected and when the time dimension is shorter than the cross section dimension.

Once stationarity is confirmed, the long run relationship among the variables is tested using the error correction based panel cointegration test proposed by (Westerlund 2007). This method allows for both heterogeneity and cross section dependence. It tests whether an error correction mechanism exists, with the null hypothesis of no cointegration. The test provides both group and panel statistics, which makes it suitable for heterogeneous panels such as developing countries.

4.4 | Panel Quantile Regression

Panel quantile regression is employed to examine how population ageing affects sustainable energy pathways across countries. Most existing studies rely on conventional OLS estimation, which focuses on the conditional mean of the dependent variable and therefore masks variation across different levels of sustainable energy performance (Lin and Xu 2017). This limitation is important in a cross-country setting, where countries differ substantially in development level, energy structure, and climate vulnerability. The relationship between ageing and sustainable energy is unlikely to be uniform across countries that perform poorly and those that perform strongly in the energy transition. Quantile regression addresses this issue by allowing the estimated coefficients to vary across different points of the conditional distribution of the dependent variable. This makes it possible to capture heterogeneous effects of ageing across countries with low, medium, and high levels of sustainable energy transition. In addition, the quantile regression framework is more robust to heteroscedasticity, outliers, and unobserved heterogeneity, which are common features of macro panel data (Koenker 2005). For these reasons, this study adopts a panel quantile regression approach to examine the impact of ageing, together with income, urbanization, human development, and climate vulnerability, across different quantiles of the SEI. The econometric specification follows the panel quantile framework proposed by Koenker (2005). The econometric model is set out below to address the conditional quantile function of the panel data:

$$Q_{yit}\left(\tau x_{it}\right) = x'_{it}\beta(\tau) + \alpha_i + \varepsilon_{it} \qquad (12)$$

where $Q_{yit}\left(\tau x_{it}\right)$ indicates the τth quantile of the dependent variable; x_{it} denotes the vector of explanatory variables; α_i is the individual effect; τ denotes the quantile; $\beta(\tau)$ represents the regression parameter of the τth quantile, and can be computed through the following formula:

$$\beta(\tau) = argmin \sum_{k=1}^{q} \sum_{t=1}^{T} \sum_{i=1}^{N} (|y_{it} - \alpha_i - x'_{it}\beta\left(\tau|\omega_{it}\right)) \qquad (13)$$

where q denotes the number of quantiles; T stands for the number of years and N for the number of cities; W_{it} is the weight of the ith country in the tth year, which is consistent with the piecewise linear quantile loss function proposed by Koenker and Bassett Jr (1978).

The weight can be defined as follows:

$$\text{if } y_{it} - a_i - x'_{it}\beta(\tau) < 0, \text{then :}$$

$$\omega_{it} = \tau \qquad (14)$$

$$\text{if } y_{it} - a_i - x'_{it}\beta(\tau) > 0, \text{then :}$$

$$\omega_{it} = 1 - \tau \qquad (15)$$

In order to express the relationships between the explanatory variables and the different conditional distributions of the explained variables, we set 25th, 50th, and 75th quantiles. Quantile regression is a key estimation method because it remains consistent and robust, particularly when the error term is heteroskedastic and not normally distributed (Xu and Lin 2016).[1]

5 | Results and Discussion

This section presents empirical results. We first carry out pre-estimation diagnostics. We then examine the relationship between the ageing population, sustainable energy, and the main influencing factors.

5.1 | Pre-Estimation Diagnostics

Table 2 presents the correlation matrix for the key variables. Overall, the variables do not have a strong correlation with each other. Then our analysis continues with descriptive statistics in Table 3. The mean values of the study variables reflect their average levels, while the standard deviations indicate the extent of variation around the mean, highlighting differences across observations. The minimum and maximum values show the range of the data, pointing to substantial heterogeneity among countries. Skewness and kurtosis describe the shape of the distributions. The table shows that AGE, GDPC, URB, and CLV are negatively skewed, while other variables are positively skewed. The significant Jarque-Bera tests indicate that the variables are not normally distributed.

After completing the descriptive statistics, we move on to test slope heterogeneity and cross-sectional dependence on the variables. Table 4 shows the results of the slope heterogeneity test. The test statistics are significant at the 1% level, which means we

TABLE 2 | Correlation matrix.

	SEI	GDPC	URB	HDI	CLV
SEI	1				
GDPC	0.364	1			
URB	0.485	0.471	1		
HDI	0.137	−0.023	0.439	1	
CLV	−0.196	−0.309	−0.445	0.231	1

TABLE 3 | Descriptive statistics.

Variable	SEI	AGE	GDPC	URB	HDI	CLV
Mean	0.1798	2.6743	10.1938	4.3195	0.4555	0.6231
Std. dev.	0.0212	0.3407	0.7363	0.1479	0.0729	0.0781
Min	0.1087	1.4355	8.2858	3.9073	0.3365	0.4140
Max	0.2522	3.3865	11.6300	4.5573	0.6571	0.7832
Skewness	0.5370	−1.3391	−0.4759	−0.7322	0.4291	−0.4743
Kurtosis	4.2139	4.9820	2.4715	2.9353	2.3492	2.7216
Jarque-Bera	60.96	192.79	49.30	63.83	59.76	34.60
Probability	0.000	0.000	0.000	0.000	0.000	0.000

TABLE 4 | Slope heterogeneity.

Test	Statistic
Delta	29.903***
Delta. Adj	34.332***

***$p < 0.01$.

TABLE 5 | Cross-sectional dependence.

Variable	CD-test	p
SEI	120.708***	0.000
AGE	129.947***	0.000
GDPC	120.784***	0.000
URB	61.888***	0.000
HDI	6.859***	0.000
CLV	101.439***	0.000

***$p < 0.01$.

TABLE 6 | Unit root test (CIPS).

Variable	I(0)	I(1)	Level of integration
SEI	−2.844***	—	I(0)
AGE	−1.540	−2.743**	
GDPC	−1.777	−3.657 ***	I(1)
URB	−1.409	−2.658**	I(1)
HDI	−1.667	−3.133 ***	I(1)
CLV	−2.327	−4.901***	I(1)

***$p < 0.01$.
**$p < 0.05$.

reject the null hypothesis of homogeneity. This indicates that the slope coefficients vary across units, confirming the presence of heterogeneity in this study's models.

Table 5 shows the results for cross-sectional dependence. The results are significant at the 1% level. This means the null hypothesis of no cross-sectional independence is rejected, which confirms that the variables display cross-sectional dependence.

The unit root analysis was conducted using (Pesaran 2007) CIPS test, with results presented in Table 6. All variables are significant only after first difference, except for SEI, which is significant at level. The result of unit root test allows us to examine variables' long-run relationships using Westerlund (2007) cointegration test. The results reported in Table 7 reject the null hypothesis of no cointegration. The significant p values confirm a long-term relationship among the variables in our model.

5.2 | Panel Quantile Regression

The parameters of quantile regression models are estimated for the 25th, 50th, and 75th quantiles, allowing for an assessment of the significance of the relationships between individual variables and SEI depending on its prevalence. The analysis proceeds in two steps. The first uses the baseline regression model, reported in Table 8, to test H1 regarding the significance and heterogeneity of the ageing effect across the quantile distribution. The second uses the conditional effects model, reported in Table 9, to test H2 and H3. Columns 1 through 9 examine how socioeconomic conditions, captured by income, urbanization, and human development, moderate the relationship between ageing and sustainable energy, as proposed in H2. Columns 10 through 12 examine whether climate vulnerability moderates this relationship, as proposed in H3.

TABLE 7 | Cointegration test (Westerlund ECM cointegration test).

Variable	Value	Z-value	p
Model 1			
G_t	−2.989	4.724	0.000***
G_a	−9.149	2.04	0.979
P_t	−19.506	6.597	0.000***
P_a	−8.873	0.643	0.26

***$p < 0.01$.

TABLE 8 | Panel quantile regression (baseline model).

Variables	Q25	Q50	Q75
AGE	0.020***	0.012***	0.004*
	(0.002)	(0.003)	(0.002)
GDPC	0.011***	0.012***	0.016***
	(0.001)	(0.002)	(0.002)
URB	−0.025***	−0.023***	−0.024***
	(0.005)	(0.007)	(0.007)
HDI	−0.010	0.051***	0.077***
	(0.010)	(0.015)	(0.013)
CLV	0.032***	0.058***	0.096***
	(0.007)	(0.011)	(0.010)
Constant	0.097***	0.061**	0.030
	(0.017)	(0.025)	(0.022)

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

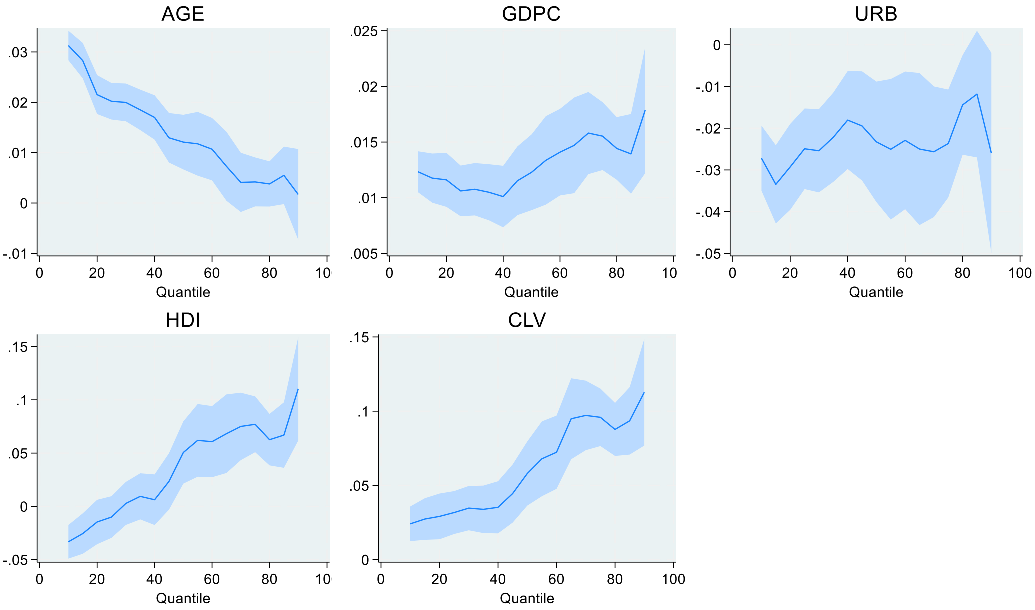
5.2.1 | Baseline Effect

The results from Table 8 show that Population ageing has a positive link with the SEI in all quantiles, supporting our first hypothesis (H1). The effect is strongest in countries at the lower end of sustainable energy and becomes smaller toward the top. A one unit increase in ageing raises the index by 0.020 at Q25, 0.012 at Q50, and 0.004 at Q75. This means older societies tend to support sustainable energy, but the influence fades once countries already have strong sustainable energy policies and systems in place. Older populations tend to support environmental regulation, risk reduction, and stable public investment (Albalate et al. 2023), which can accelerate early transition efforts. This mechanism is also consistent with political economic arguments

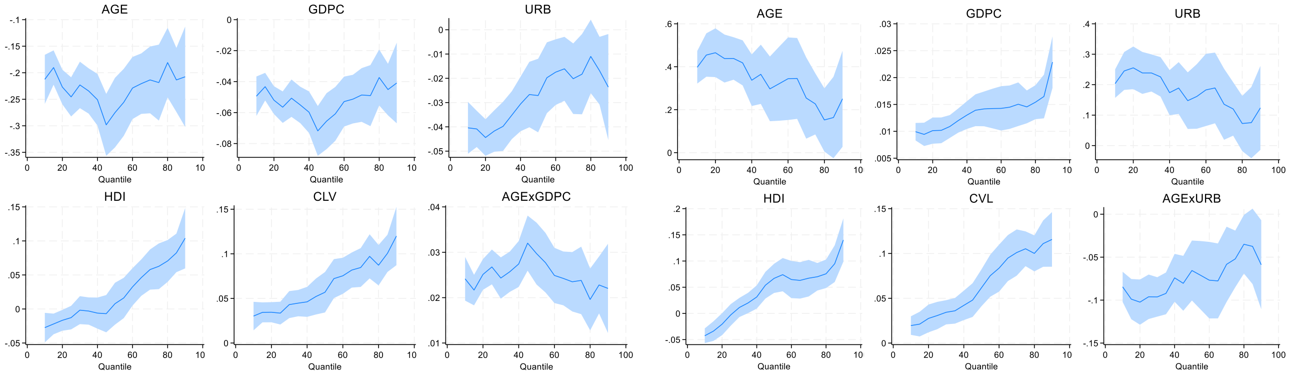
TABLE 9 | Panel quantile regression (interactions models).

Variables	**Income**			**Urbanization**			**Human development**			**Climate vulnerability**		
	Q25	**Q50**	**Q75**	**Q25**	**Q50**	**Q75**	**Q25**	**Q50**	**Q75**	**Q25**	**Q50**	**Q75**
AGE	−0.245***	−0.275***	−0.219***	0.438***	0.297***	0.227***	0.104***	0.120***	0.134***	−0.030***	−0.021	−0.040***
	(0.019)	(0.033)	(0.036)	(0.057)	(0.077)	(0.073)	(0.010)	(0.016)	(0.012)	(0.010)	(0.016)	(0.014)
GDPC	−0.057***	−0.066***	−0.049***	0.010***	0.014***	0.015***	0.013***	0.017***	0.016***	0.012***	0.013***	0.015***
	(0.005)	(0.009)	(0.010)	(0.001)	(0.002)	(0.002)	(0.001)	(0.002)	(0.001)	(0.001)	(0.002)	(0.002)
URB	−0.042***	−0.027***	−0.018**	0.239***	0.147***	0.120***	−0.033***	−0.033***	−0.027***	−0.028***	−0.026***	−0.024***
	(0.004)	(0.008)	(0.008)	(0.035)	(0.047)	(0.045)	(0.005)	(0.008)	(0.006)	(0.005)	(0.008)	(0.007)
HDI	−0.013	0.008	0.063***	−0.003	0.067***	0.070***	0.464***	0.653***	0.772***	−0.003	0.054***	0.068***
	(0.009)	(0.016)	(0.017)	(0.011)	(0.014)	(0.013)	(0.052)	(0.084)	(0.066)	(0.010)	(0.016)	(0.014)
CLV	0.034***	0.057***	0.097***	0.031***	0.062***	0.105***	0.032***	0.057***	0.117***	−0.188***	−0.091	−0.088
	(0.007)	(0.012)	(0.013)	(0.008)	(0.010)	(0.010)	(0.007)	(0.012)	(0.009)	(0.042)	(0.069)	(0.060)
AGExGDPC	0.027***	0.030***	0.024***									
	(0.002)	(0.003)	(0.004)									
AGExURB				−0.096***	−0.066***	−0.052***						
				(0.013)	(0.018)	(0.017)						
AGExHDI							−0.170***	−0.218***	−0.252***			
							(0.019)	(0.031)	(0.024)			
AGExCLV										0.081***	0.054**	0.071***
										(0.016)	(0.026)	(0.023)
Constant	0.831***	0.846***	0.614***	−1.047***	−0.711***	−0.580***	−0.129***	−0.243***	−0.339***	0.230***	0.153***	0.155***
	(0.052)	(0.092)	(0.100)	(0.153)	(0.207)	(0.195)	(0.031)	(0.051)	(0.040)	(0.031)	(0.050)	(0.043)

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

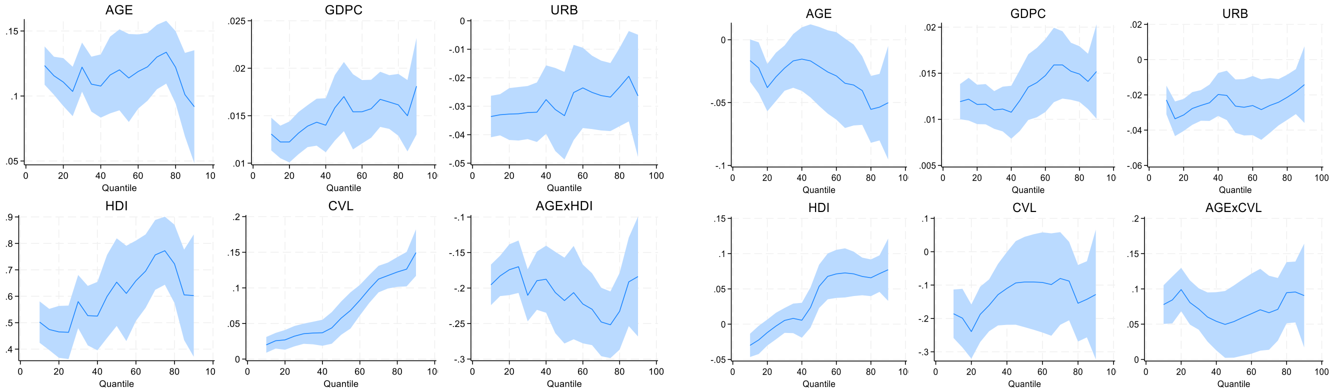


Baseline Model



Income

Urbanization



Human Development

Climate Vulnerability

FIGURE 4 | Graphical depiction of the coefficients.

presented by (Goerres 2007). The author suggests that older individuals show stronger voting participation and more stable voting behaviour, which increases their influence on policy priorities. Their higher exposure to climate risks and stronger voting engagement can increase support for ambitious climate and energy policies. This reinforces the role of ageing as a driver of early-stage progress in sustainable energy. Once countries reach advanced stages, energy systems and policies are already well established, so the additional influence of ageing becomes smaller. These results are partially similar to Sui et al. (2024) who found positive impact of ageing on renewable energy development.

In line with Umit et al. (2019) our results show a positive relationship between income and sustainable energy, which reflects stronger financial and technical capacity for renewable energy, efficiency improvements, and better energy access.

Urbanization shows a negative effect on all quantiles. This result contrast with Yan (2026) who found that urbanization improves household access to modern energy infrastructure in China. Yan's study focuses on a single dimension of sustainable energy, while the present analysis captures a broader measure. Broadly, urbanization increases pressure on energy systems, as cities account for about 75% of global primary energy consumption (UN-Habitat n.d.). Most of this energy is used for transport, buildings, and heating systems. These large, long-lasting systems create what is called carbon lock-in, meaning they are difficult to change quickly (Eitan and Hekkert 2023). As a result, cities continue relying on cars and fossil fuels, which slows the transition to sustainable energy.

Human development is not important at the lower quantile but becomes positive and significant in the middle and upper quantiles. This suggests that education, skills, and better institutions help countries' sustainable energy efforts only after they reach a certain level of capacity. The reason can be attributed to low levels of sustainable energy; countries still face basic structural and financial barriers such as infrastructure gaps, energy dependence, and limited investment capacity. In this stage, improvements in education, health, and living standards do not immediately translate into cleaner or more efficient energy systems because the core energy structure has not yet shifted. Once countries reach moderate levels of sustainable energy, human development starts to matter. Higher education improves skills and awareness, better health supports productivity, and higher living standards increase demand for cleaner energy.

Climate vulnerability shows a positive and significant effect across all quantiles, and the effect grows stronger at higher quantiles. The ND-GAIN climate vulnerability index used here captures both exposure to climate-related risks and countries' readiness to improve resilience. A higher score therefore reflects greater adaptive capacity, not greater threat. The positive coefficient indicates that countries with stronger institutional and adaptive readiness achieve higher sustainable energy outcomes, and this advantage is larger among countries already at advanced stages of energy transition.

Overall, the results show that ageing gives a small but steady push, income and human development shape the ability to deliver progress, urban structures remain a barrier, and climate vulnerability increases the pressure to advance the more sustainable energy status.

5.2.2 | Conditional Effects

This section discusses how socio-economic factors such as income, urbanization, and human development, together with climate vulnerability, interact with ageing in shaping sustainable energy outcomes in OECD countries. These four interaction tests are used to examine our second and third hypotheses, H2 and H3. The results from Table 9 confirm our argument that ageing does not act alone. Its impact depends on the socioeconomic and environmental context.

Specifically, when we added the interaction between ageing and income, the direct effect of ageing becomes negative, while the interaction term is positive across all quantiles, lending support to the income role of H2. This means the marginal effect of ageing increases with income, indicating that ageing is associated with higher sustainable energy levels in wealthier countries. Higher income and stronger pension support can reduce household energy poverty (Gelo et al. 2023), improve access to modern energy, and encourage a shift toward cleaner energy sources. This is important because many older people rely on stable but fixed incomes that limit their ability to afford rising energy costs.

The interaction with urbanization shows a negative and significant pattern across quantiles, while the main effect of ageing remains positive. This means ageing is associated with higher sustainable energy outcomes, but the effect weakens as urbanization rises, which is consistent with the moderation logic of H2. As mentioned before, urban living involves high demand for transport, housing, electricity, and dense infrastructure, creating fixed patterns of energy use that change slowly. As a result, even if older populations support clean energy, their preferences have a smaller marginal impact on overall energy outcome.

Further support for H2 comes from human development. Ageing has a positive main effect, but the interaction with human development is negative across quantiles. This indicates that the influence of ageing diminishes as human development increases. In countries with higher human development, sustainable energy outcomes are shaped more by institutional strength, advanced technologies, and regulatory capacity, which reduces the marginal role of demographic changes.

The interaction with climate vulnerability is positive across quantiles, supporting for H3. The main effect of ageing is negative and significant. This indicates that, at average levels of adaptive capacity, ageing has no independent positive association with sustainable energy. The interaction term is positive across all quantiles, meaning the marginal effect of ageing on sustainable energy increases with adaptive capacity. Countries with stronger institutional and adaptive readiness provide the conditions under which older populations' preferences for stable, low-risk, and clean energy systems translate into measurable policy and investment outcomes. Without that readiness, the demographic effect is either absent or negative.

These results are consistent with recent evidence on structural cross-country differences in sustainable development and living standards in Europe and with the related literature on ageing and environmental outcomes in European OECD countries (Jorge 2025; Łuczak et al. 2025, 2026). More broadly, the findings support the argument that demographic factors interact with socio-economic and institutional conditions rather than operating as isolated determinants of sustainable energy performance.

In sum, the interaction results show a consistent pattern: ageing has a stronger association with sustainable energy in countries with higher income and greater climate vulnerability, and a weaker association in highly urbanized and highly developed contexts. This highlights that the role of ageing depends on the broader socio-economic and environmental setting, and policies aiming to promote sustainable energy should consider these contextual factors. Figure 4 presents the graphical trends of the study variables across all quantiles.

5.2.3 | Robustness Check

For robustness, the study uses an alternative measure of population ageing, the Age dependency ratio, old (% of working-age population). It also applies a different estimation method, the Method of Moments Quantile Regression (MMQR). The results remain consistent with the main findings. This consistency supports the reliability of the baseline results. Details appear in Table A2 and Figure A1.[2]

6 | Conclusion

The paper examines how population ageing shapes sustainable energy pathways in OECD countries. The study builds a multidimensional composite SEI that captures renewable energy deployment, energy efficiency, and access to clean energy. The results show that the influence of ageing depends on the stage of sustainable energy and socio-economic and environmental conditions. Population ageing has a positive effect on sustainable energy across all quantiles, with the strongest impact in countries at lower levels of sustainable energy and a gradually smaller effect as countries move toward higher performance. This indicates that ageing acts as a catalyst in early stages of the transition but faces diminishing effects as energy systems mature.

The analysis also shows that the influence of ageing is shaped by socio-economic and environmental contexts. Interaction results indicate that the positive association between ageing and sustainable energy is stronger in high-income countries, where greater fiscal capacity allows demographic demand to translate into investment, innovation, and technological progress (Acheampong and Opoku 2025). In contrast, the contribution of ageing becomes weaker in highly urbanized and highly human-developed countries, where education, health, institutional strength, and technological capability already play a dominant role in shaping sustainable energy outcomes and leave less room for additional demographic effects.

Environmental conditions also matter. The interaction between ageing and the climate vulnerability index shows that the positive association between ageing and sustainable energy is stronger in countries with higher climate vulnerability scores. The ND-GAIN index used here captures both exposure to climate challenges and countries' capacity to respond. A higher score therefore reflects stronger readiness alongside climate exposure. In countries where this combined score is higher, the preferences of older populations translate more effectively into policy support and investment in sustainable energy. This result indicates that climate conditions amplify the demographic channel rather than simply creating pressure to act.

These findings have clear policy implications. Ageing populations already provide a positive push toward sustainable energy, particularly in countries at early stages of the transition. Policymakers should turn this support into practical policies. Given the sizable costs associated with energy system transitions, ensuring energy remains affordable for people and the older population is a key policy (Demski et al. 2017). Governments should focus on stable electricity supply, protect households from price shocks, expand home insulation and invest in reliable public transport powered by clean energy. These actions match the concerns of older citizens and can gain strong public acceptance. In highly urbanized countries, policymakers should target structural constraints, such as improving transport, upgrading buildings by making them more energy-efficient and environmentally friendly (van Hoof et al. 2025), and strengthen local energy systems so that ageing populations can effectively support sustainable energy.

Finally, where climate vulnerability scores are moderate, the evidence suggests that older populations can support sustainable energy progress, but the enabling conditions must be in place. Policymakers in these countries should strengthen regulatory frameworks, expand green finance, and improve public procurement practices. These investments allow demographic support for sustainable energy to produce measurable outcomes. In countries with already high climate vulnerability scores, structural and technological drivers tend to dominate, and the marginal role of demographic change is smaller. Policy in these settings should focus on sustaining those structural drivers rather than relying primarily on demographic momentum.

The study has a few limitations. First, the consumption-based renewable energy measure may overstate the renewable share for countries that are net importers of electricity, since cross-border electricity trade within OECD countries means that a high renewable consumption share does not necessarily reflect domestic generation capacity. Second, the SEI covers three core dimensions and does not capture grid flexibility, storage capacity, or regulatory quality. As data availability improves, future work can extend the index to incorporate these dimensions. Third, the analysis is restricted to OECD countries. This choice ensures cross-country comparability but limits the external validity of the findings, since demographic pressures and energy system conditions in developing economies differ considerably from those in the OECD context. Fourth, the ageing variable is an aggregate measure and does not account for heterogeneity within older populations in terms of health status, labor market participation, or political engagement. Future research drawing on cohort-level or micro-level data could shed light on the specific channels through which ageing affects sustainable energy.

Author Contributions

Ramez Abubakr Badeeb: conceptualization, investigation, methodology, validation, visualization, software, formal analysis, writing – original draft, writing – review and editing, data curation. **Ziqing Lin:** writing – original draft, visualization, conceptualization.

Disclosure

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Endnotes

[1] All estimations are carried out in Stata 17. The cross-sectional dependence test uses xtcdf; the CIPS unit root test uses xtcips; and the Westerlund cointegration test uses xtwest.

[2] We do not reproduce the whole results of the robustness tests to conserve space; however, the results are available upon request.

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Appendix A

TABLE A1 | List of OECD countries.

Country name	Country code
Australia	AUS
Austria	AUT
Belgium	BEL
Canada	CAN
Chile	CHL
Colombia	COL
Czechia	CZE
Denmark	DNK
Estonia	EST
Finland	FIN
France	FRA
Germany	DEU
Greece	GRC
Hungary	HUN
Iceland	ISL
Ireland	IRL
Israel	ISR
Italy	ITA
Japan	JPN
Korea, Rep.	KOR
Latvia	LVA
Lithuania	LTU
Luxembourg	LUX
Mexico	MEX
Netherlands	NLD
New Zealand	NZL
Norway	NOR
Poland	POL
Portugal	PRT
Slovak Republic	SVK
Slovenia	SVN
Spain	ESP
Sweden	SWE
Switzerland	CHE
Turkey	TUR
United Kingdom	GBR
United States	USA

Appendix B

TABLE A2 | MMQR and graphical depiction of the coefficients.

Variables	Location	Scale	(1) Q25	(2) Q50	(3) Q75
AGED	0.011***	−0.007***	0.017***	0.012***	0.004*
	(0.002)	(0.001)	(0.002)	(0.002)	(0.003)
GDPC	0.014***	0.004***	0.010***	0.013***	0.017***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.002)
URB	−0.019***	−0.006**	−0.013***	−0.018***	−0.024***
	(0.005)	(0.003)	(0.004)	(0.005)	(0.006)
HDI	0.049***	0.052***	0.000	0.039***	0.095***
	(0.010)	(0.006)	(0.009)	(0.010)	(0.014)
CLV	0.061***	0.030***	0.033***	0.056***	0.088***
	(0.008)	(0.005)	(0.007)	(0.007)	(0.010)
CONSTANT	0.030*	−0.019**	0.048***	0.033**	0.013
	(0.015)	(0.009)	(0.014)	(0.015)	(0.020)

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

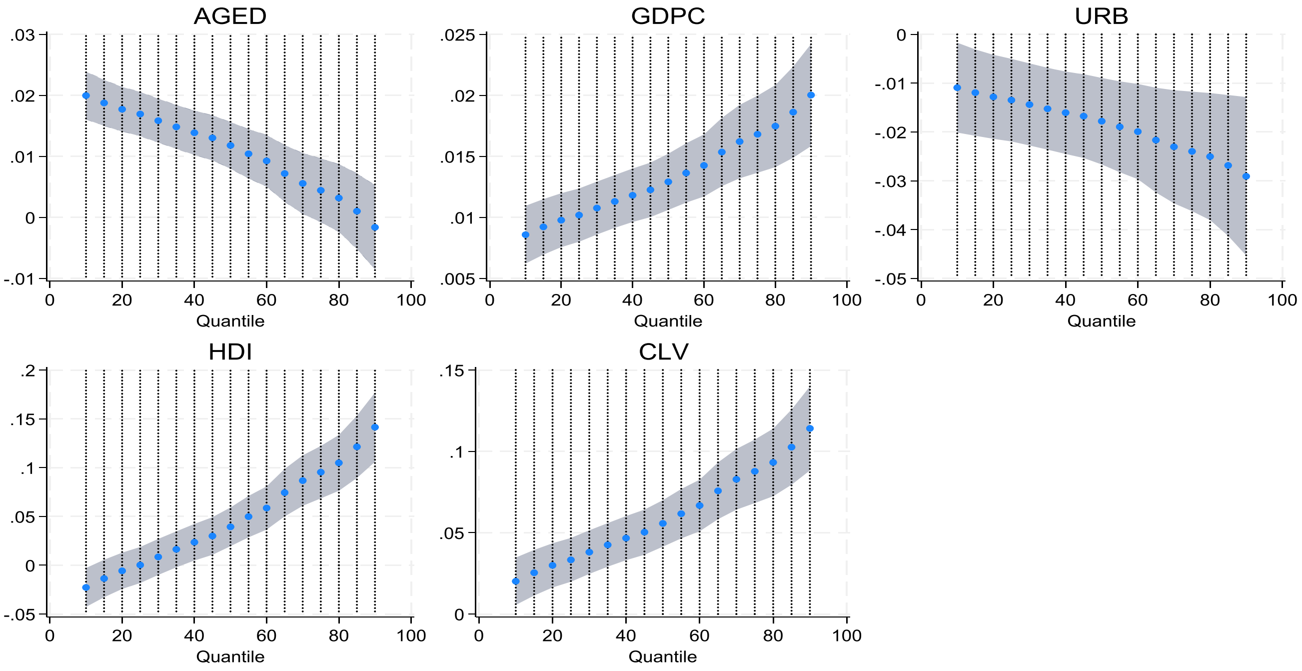

FIGURE A1 | Graphical depiction of the coefficients—MMQR.