

Does Renewable Share Enhance Energy Sufficiency: An Empirical Analysis of Panel Threshold based on 65 countries

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Abstract

The green energy development can serve a dual purpose of achieving economic as well as environmental sustainability. However, increasing its share can have non-linear impact on energy sufficiency. This study uses the data over globe by using threshold methodology, explores renewable share impact on energy sufficiency. The findings present an evidence for presence of non-linear relations. The result provide evidence for single threshold model. The magnitude of the threshold level turns to be 3.9% with positive effect above this level. The result imply that fragmented investment in renewable energy is unable to improve energy sufficiency. Therefore renewable share must be beyond a threshold. Further, the positive effect above threshold indicates enhancing energy sustainability to renewable share in energy mix.

Key words: Threshold panel regression, energy sustainability, renewable energy share

1. Introduction

The energy sufficiency and renewable energy has been key element of the environmental and energy policy both. The objective of renewable energy is de-carbonization by fossil fuel replacement. However the energy sufficiency focus on decline in energy demand and to align it with environmental and social welfare (Burke, 2020; Jørgensen et al., 2022).

Enhancing the energy from solar and wind sources in energy mix paves a path to decarbonisation and sustained economic growth (Khan et al., 2022; Santosh et al., 2024). A large number of studies have highlighted efficiency of investment in renewable energy with diminishing impact on climate, designing it a critical strategy to sustainability. The modification of the energy mix by enhancing renewable share can make to move toward carbon neutrality (Yuan et al., 2022a, b). Encouraging cleaner and sustained energy is inevitable for declining the GHG emission level, playing an important role for CO₂ emission (Akram et al., 2020). By enhancing renewable energy share in energy mix can directly decline reliance on carbon intensive sources which move economy closer to low carbon levels (Hassan et al., 2022). The renewable share enhancement can be a strategic move toward sustainable future (A. Chen et al., 2023; Huang and Zhai, 2021).

Energy sufficiency offers feasible ways to decline demand and enhance renewable energy share. The studies argue that decline in energy demand can enhance renewable share to 100% as well (Wiese et al., 2024). However, the nature of relation between energy sufficiency and renewable share is not linear. It is reasonable effect of renewable energy share on sufficiency can exhibit non-linear relationships possibly defined by certain threshold levels. Recent research indicates that renewable energy investment effect becomes significant after certain threshold levels (Chang et al., 2025). Further the effect of renewable energy consumption on SDG are non-linear, with positive relations evident after certain threshold level of renewable (Radulescu et al., 2025). This proposes a non-linear impact of renewable energy share on energy sufficiency, therefore an insightful examination is necessary for exploring the critical juncture.

The study aims to evaluate the threshold effect of renewable energy share on energy sufficiency. This paper will explore the threshold level of renewable energy share in total energy mix that is sufficient to handle the energy demand for the economies. Estimation of threshold renewable energy for energy sufficiency is significant on many grounds. It can help to transfer fully to renewable resources, further it can help us to achieve carbon neutrality targets. 2nd the global energy mix requires a critical amount of renewable energy to achieve climate related targets. 3rd a certain threshold of renewable share can significantly decline the reliance on fossils fuel energy and can enhance the energy security. Above all it will support sustainable development goal 7 which focuses on access to affordable and clean energy.

By detecting the level at which the influence of renewable energy share on energy sufficiency changes, this exploration will provide valuable insights into their complex relationship. Focusing these thresholds is crucial for policymakers and planners. This can help to design more effective and cohesive strategies, optimizing investments in renewable energy and maximizing the societal benefits of energy sufficiency for the transition to sustainable energy system.

The rest of the paper is organized as the chapter two discusses the literature related to issue. The chapter three discusses the methodology followed by the results and discussion. The last chapter concludes the analysis.

2. Literature Review

2.1. Estimating the Threshold Effect of Renewable Energy on Energy Sufficiency

The transition to sustainable energy system requires an aggregate approach. The approach should extend beyond replacing the traditional sources of energy and incorporate the sufficiency element as well. This review present dynamics of relationship between renewable energy share and energy sufficiency.

2.1.1. Energy Sufficiency: A Strategy for De-carbonization

Energy sufficiency is a demand related strategy that aims to decline energy demand. This strategy can ease the encumbrance on supply systems of energy and can facilitate a smoother switch to renewable energy. The energy efficiency in contrast focuses on doing more with less energy. The sufficiency emphasizes on consuming less energy while sustaining well-being (Wiese et al., 2024). The research reveals that a 50% decline in energy demand in Europe is attainable by 2050 by different sufficiency measures. However, this decline will enhance renewable energy share to 100% (Wiese et al., 2024). Therefore, energy sufficiency is highlighted as fundamental strategy for penetration of renewable energy share in energy mix. Further the demand side management comprising sufficiency outperform than supply side management and enhances energy resilience as well as sustainability (Bento et al., 2024).

2.1.2. The Interplay of Renewable Energy Deployment and Demand Management

The growth of renewable energy i.e. wind and solar has shown an effect on de-carbonization (Al-Shetwi et al., 2024). However, the variability of their nature poses challenges for grid stability and therefore, demands flexibility in energy systems (Göke et al., 2023). This integral inconsistency magnifies the prominence of demand-side management strategies, which support with the principles of energy sufficiency. The industrial demand, has substantial role in the promotion of renewable energy in power systems by regulating balance in demand and supply (Li et al., 2023). Further, research indicate that flexibility in electricity demand for heating, transport, and industry can support the integration of instable renewables and lessen the need for extensive storage and backup plants (Göke et al., 2023). The correlation between decline in final energy demand and higher shares of renewables suggest that sufficiency efforts can contribute to a cleaner energy (Scott et al., 2021).

2.1.3. Evidence and Implications of Threshold Effects

The research on threshold renewable share on energy sufficiency is an emerging field. However, the existing studies can offer insights into potential non-linear dynamics. The study by Radulescu et al., 2025 argued for negative relation between renewable adoption and progress in SDG turned positive after certain threshold. This recommends for nonlinear impact for unlocking the potential of renewable energy. Further (Chang et al., 2025) explored the threshold effects of renewable investment on energy efficiency. The result argued for rebound effect at lower renewable investment while beyond certain threshold the gains in energy efficiency becomes effective in declining the fossil fuel consumption.

The presence of the threshold effect can be emphasized owing to cost related to renewable energy adoption. (Brizga et al., 2022) suggest that planning and cost magnitude can be a challenge for enhancing the renewable energy. These contemplation emphasizes for non-linear impacts of renewable energy on energy sufficiency of economies.

3. Summary and Gap

The previous literature has linked the threshold levels of renewable to SDG progress i.e. Radulescu et al., 2025. Further, Chang et al., 2025 explored the effects of renewable investment on energy

efficiency. However, the studies linking the non-linear dynamics of renewable energy share to energy efficiency are scarce. The threshold modelling uses strictly balanced panel therefore the data availability has restricted the inclusion of the economies for issue.

3.1. Empirical Model

The existence of non-linear relationship of renewable energy share on energy sufficiency of the economies can be defined by certain threshold levels. The threshold model has significance as compare to conventional non-linear models. It offers variety of linkages for sign and available magnitude, addressing the heterogeneity issue. Therefore following Chang et al., 2025 empirical model has been specified. Assuming fixed effect the threshold regression technique by Hansen 1999 the model can be written as

$$ESR_{it} = \begin{cases} \mu_t + \beta_1 X_{it} + \alpha x_{it} + \epsilon_{it}, & \text{if } RESH_{it} \leq \tau \\ \mu_t + \beta_2 X_{it} + \alpha x_{it} + \epsilon_{it}, & \text{if } RESH_{it} \geq \tau \end{cases} \quad 3.1$$

$$\alpha = (\alpha_1, \alpha_2, \alpha_3) = x_{it}(gdp, pop, gdps) \quad 3.2$$

- Y_{it} : Dependent variable (e.g., Energy Sufficiency ratio).
- X_{it} : Independent variables.
- τ : Threshold value.

where ESR_{it} is the response variable; $RESH$ is the independent and threshold variable. x_{it} is set of a controlled variable which affect ESR . “ μ_i is the fixed effect; the value of the threshold is γ ; β_1 and β_2 variable coefficient; $\alpha = (\alpha_1, \alpha_2, \alpha_3)'$ are the estimated coefficient of the control variables. ϵ_{it} is the error term having zero mean and finite variance. Hansen 1999 framework analyses the non-linear and regime dependent relationship in panel data. It extends the traditional panel model to provide the varying slope parameters across different regimes split by threshold level of the variable rather heterogeneity in intercepts. Further Hansen introduced bootstrap resampling methodology to evaluate significance of the threshold effects.

Equation (3.1 and 3.2) is rearranged in the following regression format;

$$ESR_{it} = \mu_{it} + \beta_1 RESH_{it} \cdot I(RESH \leq \gamma) + \beta_2 RESH_{it} \cdot I(RESH \geq \gamma) + \epsilon_{it} \quad 3.3$$

Thus, the method is suitable for analysing threshold effects in different regimes and detecting the turning points”. The panel threshold approach has no prerequisite for the nonlinearity equation.

The analysis outcomes explore that renewable energy share has a significant threshold effect on energy sufficiency in different regimes.

3.2. Data and Methodology

The study estimates the threshold effects of renewable energy share for energy sufficiency. On the basis of data availability a sample of 65 countries have been taken to estimate the effects. The panel is comprised of the economies forming balanced panel out of the globe.

Table 1: Data and variable Description

Variable	Nomination	Units	Source
Total energy consumption	TEC	QBTU	International Energy Agency
Total energy consumption from renewables and other		QBTU	
Total energy production	tep	QBTU	
Total energy production from renewables and other	tepr	QBTU	
Total population	pop	Million	WDI
GDP (current US\$)	gdp	\$	
Renewable energy share=TEPR/TEP	<i>RESH</i>		Author construction
Energy sufficiency ratio=TEC/TEP	<i>ESR</i>		Author construction

4. Results and Discussion

Table 1 demonstrates the summary statistics of variables. The mean of all series is positive. The value of skewedness indicate that variables are skewed to the right except for GDP and population. The kurtosis value indicate that variables are leptokurtic except gdp which is platykurtic. The skewness value indicates that energy sufficiency ratio and renewable share are both positively skewed, while gdp and population are negatively skewed.

Table 2: Descriptive Statistics

Variables	Obs	Mean	Std. Dev.	Min	Max	p1	p99	Skew.	Kurt.
Esr	1885	2.058	3.382	.056	88.263	.117	9.289	14.031	316.44
resh	1885	.637	1.024	.007	9	.011	5.397	3.964	23.395
lgdp	1885	25.782	2.083	19.487	30.953	20.664	30.318	-.341	2.8
lpop	1885	17.129	1.516	12.971	21.087	13.229	21.026	-.102	3.584

The table 3 show the correlation coefficient value between the variables. The value of correlation coefficient lies from .17 to .66 that depicts the sufficient variation to explore the estimates. Further the value of the correlation coefficient are appearing positive and negative for certain variables.

Table 3: Matrix of Correlations

Variables	(1)	(2)	(3)	(4)	(5)	(6)
(1) esr	1.000					
(2) resh	0.173	1.000				
(3) lgdp	0.250	-0.367	1.000			
(4) lpop	0.132	-0.273	0.665	1.000		
(5) tep	-0.100	-0.197	0.430	0.432	1.000	
(6) tepr	0.139	0.048	0.360	0.340	0.675	1.000

The table 4 shows the estimation results estimated by fixed effect and random effects. The Hausmann result indicates the suitability of the fixed effects for the sample. The renewable energy share is having positive and significant for the countries. The estimates depicts that unit increase in renewable energy can enhance the sufficiency of energy by 0.8 units. The lgdp (depicting gdp with log) coefficient is negative while gdps stands for the square of the gdp coefficient is positive.

Table 4: Regression Results

Fixed Effects Estimates			Random Effects Estimates	
	Coef.	St.Err.	Coef.	St.Err.
<i>esr</i>				
<i>resh</i>	.796***	.077	.818***	.076
<i>lgdp</i>	-3.752***	1.399	-3.914***	1.091
<i>gdps</i>	.083***	.027	.086***	.021
<i>lpop</i>	-.947	.811	-.015	.156
<i>Constant</i>	59.08***	17.724	45.162***	13.787
<i>Number of obs</i>	1885		1885	
<i>F – test / Chi – square</i>	31.298(0.000)		155.050(0.000)	

Table 5: Hausman (1978) specification test

	Coef.
Chi-square test value	9.79
P-value	.044

The table 6 indicates the results from threshold regression technique. The table 6 has been divided into three panel. The 1st panel reports the threshold value while panel b reports the estimates while last panel indicates the regime effect. By taking a look into estimates we can infer that renewable energy share divides the data in different regimes based on threshold value. The model has been estimated by using three different levels. The results are providing evidence that 3.9% of renewable share is that changes the relationships of the renewable energy to energy sufficiency of these economies. The significance of single threshold provide evidence of non-linear relationship between renewable share and energy sufficiency. Further data supports single structural break indicating one regime change.

The threshold level has been estimated the F stat of the single threshold is greater than 1% of its critical value. The single threshold value is 3.9. The single value indicates that 3.9% of renewable share is turning point for its change in relation to energy sufficiency. At value of 3.9% the renewable share the up gradation of infrastructure can be effective in catering the energy demand for the economies. This threshold further indicates for the impactful intervention, this threshold should be considered. The significance of the 1st threshold indicates the presence of single threshold effect. It validates the two regimes i.e. regime 1(below threshold) and regime 2 (above threshold). The coefficient of below threshold is -1.14 that is RESH value below 3.9% a 1% increase in renewable share is declining energy sufficiency by 1.14 units.

Table 6: Threshold Model Estimates

model	Threshold	Lower	Upper
Th-1	3.977	3.774	4.167
Th-21	3.977	3.774	4.167
Th-22	1.000	0.931	1.008
Th-3	0.025	0.023	0.026

Threshold effect test (bootstrap = 10000 10000 10000):

Threshold	RSS	MSE	Fstat	Prob	Crit10	Crit5	Crit1
Single	13200.000	7.118	70.180	0.017	30.486	40.357	81.516

Double	12900.00 0	6.945	46.400	0.119	52.207	108.385	322.425
Triple	12700.00 0	6.828	31.750	0.500	251.775	334.319	457.369

Panel B Estimates Dependent variable esr1

	Coefficient	Std. err.	t	[95% conf interval]	
lgdp	-2.273**	1.356	-1.680	-4.933	0.387
gdps	0.054***	0.026	2.080	0.003	0.105
lpop	-1.014	0.781	-1.300	-2.546	0.517
_cons	40.171***	17.176	2.340	6.483	73.858

Panel C

_cat#c.res					
0 = Below threshold	-1.14***	21.396	-5.370	-156.843	-72.918
1 = Above Threshold	4.037***	0.398	10.140	3.256	4.817

F test that all $u_i=0$: $F(64, 1813) = 8.61$ $\text{Prob} > F = 0.0000$

The effect of control variables have been reported in panel b of table 5. The coefficient of gdp is negative on energy sufficiency. The negative value implies that increase in gdp declines the energy sufficiency. This can be attributed to the early stage growth effect. The square of i.e. gdps has been used to check the impact of further increase of gdp on energy sufficiency. The square coefficient turns to be positive that is further increases in gdp makes the economies affluent in energy production. The positive coefficient indicates the advance stage growth effect. The higher gdp enhances the use of efficient technology, diversification of energy system to renewable therefore, enhancing the energy sufficiency. The increase in the population decreases the energy sufficiency. The negative coefficient asserts the demand pressure effect of higher population.

The last panel of the table 5 points that the dividing point. If threshold value is 3.9 the estimates coefficient is significant. Presenting an evidence that if the renewable energy is less than 3.9 this point it will affect the energy sufficiency is negative. The statistical significance of single threshold divides the sample into two regimes i.e. the observation with $\text{resh} \leq 3.9$ and observation with $\text{resh} >$

3.9. Since the tests for a second and third threshold are statistically insignificant, the single-threshold specification is retained.

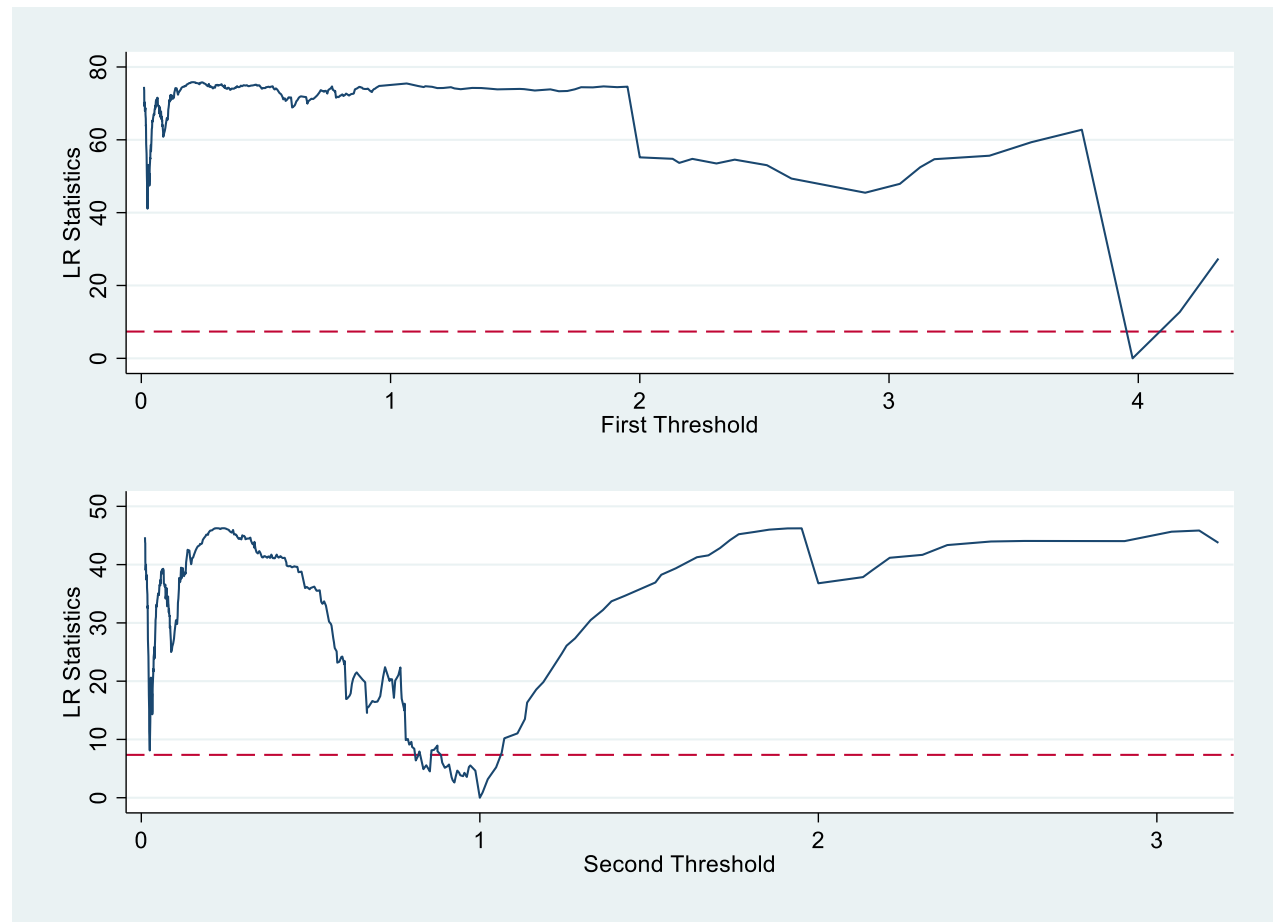


Figure 1

The figure 1 plots the threshold value and LR statistic. The x-axis reports the threshold values for renewable energy share. The v shaped pattern of segment of LR indicates best fit of threshold modelling to the data. The dip of the LR on the dotted line indicates presence of evidence for significant threshold effects. The dips of the LR are at multiple points in 2nd threshold graph indicates that there are multiple threshold. The estimated threshold value is the value of the threshold variable when LR is equal to zero (Figure 2) and the 95% confidence interval is the value interval of the corresponding threshold variable when the LR value is below the dotted line (Wang and Wang, 2020).

5. Conclusion

The energy sufficiency and renewable energy has been key element of the environmental and energy policy both. However, their association has not been explored explicitly. The study used the data over globe by using threshold methodology and explored renewable share impact on energy sufficiency. The findings present an evidence for presence of non-linear relations. The result provide evidence for single threshold model. The magnitude of the threshold level turns to be 3.9% with positive effect above this level. The results reveal the presence of a single threshold therefore providing evidence of two regimes. The threshold is 3.9, indicating that the effect of renewable energy on energy sufficiency differs across regimes.

The value of renewable lesser than threshold indicates that its contribution to energy sufficiency is limited. The weaker effect can be attributed to constraints related to infrastructure and integration challenges related to energy system. However, as renewable energy surpasses the threshold level, its impact becomes significantly stronger. The positive coefficient suggests that after reaching a critical value, renewable energy plays a more effective role in improving energy availability, declining dependence on conventional energy sources, and enhancing overall system resilience. The findings provides an evidence for existence of a nonlinear and regime-dependent relationship. That implies that benefits can be enhanced with renewable energy surpassing a certain threshold.

6. Policy Implications

The empirical findings offer important policy insights:

- The significance of the threshold effects suggest that the policymakers should recognize that a fragmented investments in renewable energy might not deliver meaningful improvements in energy sufficiency. For enhancing energy sufficiency the renewable energy share must beyond a threshold level that appear as 3.9% for the sample of economies.
- The slower expansion of renewable share can trap the economies in low- effect regime. Therefore they must adopt accelerated renewable energy strategies to surpass the threshold rapidly.
- The weaker effect below the threshold suggests the presence of structural barriers. The infrastructural investment for enhancing renewable energy share are necessary for renewable

contribution to energy sufficiency. Further supportive policies in form of subsidies and concessional financing to overcome the initial lumpy cost for renewable adoption can speed up way to energy sufficiency.

- Above all the positive effect of above threshold on sufficiency indicates energy sustainability and energy security of renewable share. Therefore renewable energy policies can be initiated not only to obtain environmental sustainability but also the component of energy security strategy.

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Appendix

Table A1 Country Name
Argentina, Australia, Austria, Bangladesh, Belgium, Bhutan, Bolivia, Brazil, Bulgaria, Cameroon, Canada, Chile, China, Colombia, Cotedoire, Denmark, Ecuador, Egypt, Eswatini, France, Gabon, Germany, Ghana, Greece, Guatemala, Hungary, India, Indonesia, Iran, Iraq, Ireland, Italy, Japan, Malaysia, Morocco, Nepal, Netherlands, New-Zealand, Nigeria, Norway, Pakistan, Papua new guinea, Peru, Philippines, Poland, Romania, Russia, South Africa, Spain, Sweden, Syria, Tajikistan, Tanzania, Thailand, Turkiye, United kingdom, United States, Vietnam, Zambia, Zimbabwe