

Interlinkages between energy inequality,
nonlinear transition dynamics, and progress
across India, South Asia, and the world:
A multidimensional approach

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Abstract

The literature on energy transition in developing countries has yet to clearly explain rural cooking energy transitions. While the traditional *energy ladder hypothesis* suggests that households move from firewood to cleaner fuels as incomes rise, empirical evidence increasingly shows that this transition is neither smooth nor purely income-driven. Using NSSO consumption data and Census-based energy-use information for Bihar, this study shows that rural firewood consumption patterns exhibit significant nonlinear dependence, challenging the assumption of predictable and linear fuel transitions. Importantly, we clarify that statistical evidence is interpreted as nonlinear and complex dynamics, rather than deterministic chaos. We further estimate the Atkinson Energy Inequality Index across cooking fuels and find that inequality in access to modern cooking energy is substantial and varies by fuel type. Sensitivity analysis across inequality aversion parameters ($\epsilon = 0.3, 0.5, 0.9$) confirms the robustness of these disparities. States with higher cooking-energy inequality tend to show slower improvements in clean fuel penetration and lower multidimensional development progress. Our findings suggest that rural energy transition is shaped not only by income but also by structural inequality and complex behavioral patterns. Policies focusing solely on subsidies or income growth are therefore insufficient. Instead, locally adaptive, inequality-sensitive, and behaviorally informed strategies are required to ensure equitable and sustainable clean cooking transitions.

Keywords: rural energy transition, cooking, chaos, bihar, energy inequality.

JEL classification: B41, Q43, Q48, D63

First submission: 4th August 2025, accepted 17th April 2026

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Economics and policy of energy and the environment (ISSNe 2280-7667), 2026, 1
DOI: 10.3280/epe2026oa22890

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1. Introduction

Do households switch to better cookstoves from firewood when their income increases? This question has triggered the discipline and literature on cooking energy transitions in developing countries for a long time. The Energy Ladder Hypothesis suggests that as the Income and Expenditure of rural households increase, the propensity of the rural household to move away from firewood to improved cookstove-based cooking will increase.

Our contribution goes beyond previous studies by empirically revealing, via chaos theory and nonlinear statistics, that the commonly used energy ladder hypothesis is insufficient to explain rural transitions in contexts like Bihar. By integrating structural inequality analysis and multidimensional progress indicators, we propose a new analytic frame for understanding and addressing the persistent barriers to sustainable rural energy adoption.

Transition to improved cookstoves (ICS) from firewood-based traditional cooking options (TCS – traditional cookstoves) is often not following the Energy Ladder Hypothesis in India (Srivastava et al., 2012). Hence, its behavioral pattern is usually not linear. Linear means that a rise in income will not necessarily lead people to shift their choice from TCS to ICS. This can be subtly hinted at in various programs like the National Improved Cookstoves Programme, dealing with this transition in cooking choices for rural households in India. The National Biomass Cookstoves Initiative (which started in 2009) attempted to make amends for the failings of its predecessor by adopting a market-driven mode of dissemination and rigorous testing of cookstove technologies (Hayden et al., 2014).

However, substantial empirical evidence is lacking to test this hypothesis in India and other developing countries. Globally, the adoption rate of improved cookstoves in rural households has been low in different cookstove programs. Providing subsidized cookstoves through state or donor-funded programs to uninterested rural households is seen as one of the reasons for such low rates of adoption. Enterprise-based ICS dissemination models are being promoted as an opportunity to undo the failings of subsidized, donor-driven dissemination. However, a poor household that has decided to purchase ICS and not use firewood for cooking may be more likely to use the cookstove than a household that has received the cookstove free of cost or at a highly subsidized price (Pine et al., 2011).

Most studies on ICS examine how people keep using cookstoves after they start. Studies focusing on improved ICS uptake tend to ignore post-uptake adoption, barring a few. This is one of the limitations of the studies conducted to understand the process of rural energy transition in cooking from TCS to ICS (Lewis & Pattanayak, 2012).

‘Adoption’ has been used extensively in the literature about ICS to mean ‘acquisition of a stove’ (Lewis et al., 2015). Shankar et al. (2015) have posited that consistent, continuous use of improved cookstoves goes much beyond acquisition (or ‘adoption’) and that it requires “consumer buy-in and understanding of the value proposition that ICS can provide.”

Ruiz-Mercado et al. (2011) have used the term ‘adoption’ in a broader context. They highlight the need for a clear framework to study the adoption of better cookstoves. While doing so, they incorporate in their framework the dynamic learning process and change in cooking practices of end-user households for understand-

ing adoption. However, very few studies study adoption as a multi-stage process, analyzing factors that have influenced both acquisition and sustained use of ICS (Pareek & Chattopadhyay, 1966).

Furthermore, the phenomenon of cookstoves and fuel-stacking observed in rural kitchens makes it difficult to view the adoption of cookstoves as a uniform and straightforward process. These nonlinear factors often decide the nature and degree of rural energy transition in developing countries like India. An extensive review of 32 empirical studies has been undertaken by Lewis and Pattanayak (2012), who state that adoption studies on improved cookstoves are scarce and scattered. Further, they elaborate that most studies apply multivariate regression methods to consider determinants of cooking choice in stages of transition. Their determining factors are income, education, and urban location. Most studies positively associated these factors with adoption, while the influence of fuel availability and prices, household size and composition, and gender is unclear.

Most studies have ignored potentially important drivers behind adopting the improved cookstove, such as credit creation and availability, supply-chain strengthening, and social marketing. Data constraints, in some instances, have also created this limitation. Puzzolo et al. (2013) have undertaken a systematic review of all ICS adoption studies, and they categorize the determining factors of transition from TCS to ICS in rural households belonging to fuel and technology characteristics, household and community level, and program and societal level characteristics. Their findings reveal that many factors embedded in the behavior, psychology, and cultural practices in rural contexts influenced cookstove adoption. These factors are often inter-related and are context-specific. Some factors relate to people's food preferences during religious events in rural areas. It can also be linked to the risk-averse behavior towards using new technologies related to cooking or the preference for using improved cooking in large family gatherings or social functions.

2. Knowledge gaps and significance of the research

As established in the introduction, existing literature on rural energy transitions in India has largely overlooked the village-level contextual determinants such as social clustering, caste dominance, political influence, trust, and social capital that significantly shape energy consumption behavior (Adrianzén, 2010). These socio-institutional factors play a pivotal role in determining whether rural households adopt improved cookstoves (ICS) over traditional cookstoves (TCS), yet they remain underexplored in empirical research.

The transition from TCS to ICS is often not a linear function of income or access, but rather a reflection of broader social and institutional transformations. Decisions around cleaner cooking technologies are embedded within complex social structures and are influenced by varying degrees of trust, cultural acceptance, and community networks.

These dynamics introduce persistent and empirically measurable nonlinearities, which are inadequately captured in conventional models of energy transition that focus solely on economic factors. One promising approach to uncover these nonlinearities is the analysis of temporal and spatial patterns in firewood consumption, which can reveal

underlying chaotic behavior, a form of complexity that remains largely unexamined in the context of developing countries like India. Recognizing firewood use as potentially chaotic rather than random or uniform shifts the analytical lens toward structural and behavioral drivers that resist simple causal explanations.

Despite a growing body of literature on rural energy access and fuel switching, few studies adopt an integrated perspective that combines energy inequality, nonlinear consumption dynamics, and developmental progress. Most frameworks address these dimensions in isolation, overlooking how chaotic consumption patterns and structural inequalities in access to energy jointly constrain sustainable development. The lack of such holistic analysis is especially stark at the state level, where regions like Bihar, characterized by deep socio-economic disparities, entrenched traditional fuel use, and weak institutional capacities, are not adequately represented.

This study addresses that critical gap by offering a novel synthesis that links energy inequality, chaos theory, and multidimensional human progress. The research highlights how disordered energy behavior and access disparities intersect to shape broader developmental outcomes by focusing on Bihar as a case study. This integrated approach offers significant policy relevance in the Indian context and contributes to a more nuanced understanding of rural energy transitions in different world regions.

Importantly, prior studies often treat technological adoption as a linear, income-driven process, glossing over the significant non-economic factors, local norms, social networks, institutional efficacy, and cultural inertia that shape decision-making in rural India. The absence of holistic, multi-scale analysis leaves policymakers ill-equipped to design interventions that address persistent fuel stacking and erratic adoption/usage behavior.

Our paper addresses these gaps using advanced, but interpretable, nonlinear dynamic tools, quantifies structural energy inequality, and links both to developmental outcomes using a multi-domain progress framework rooted in SDG7.

3. Objectives

With this knowledge gap, the broad objectives of this paper are:

- To understand whether the rural energy transition process in terms of rural household firewood consumption exhibits nonlinear dependence and structural complexity in Bihar, India
- To assess how energy inequality and chaotic consumption patterns influence access to clean energy and broader developmental progress across Indian states and globally.

The above objective is addressed through the following research question.

4. Research question

The above objective is addressed through the following research question.

- How and why is the rural energy transition process in Bihar's cooking sector characterized by chaotic and nonlinear dynamics in firewood consumption?

- In what ways do energy inequality and chaotic fuel-use patterns jointly constrain access to clean energy and multidimensional development both within Bihar and in other comparable contexts?

5. Methodology

In order to understand the rural energy transition process and the relationship between income and energy consumption, an inequality index was used to measure the inequality in income and energy consumption.

5.1. Data structure and time-series construction

The study draws on two major data sources with different statistical properties. NSSO household consumption surveys provide cross-sectional data used for estimating energy inequality across income groups. In contrast, Census data on household fuel use are available at decadal intervals and are used to construct a state-level time series of rural firewood dependence.

For the nonlinear analysis, decadal observations are interpolated to form a temporal sequence representing long-term structural changes in cooking fuel dependence. While this allows the use of time-series-based nonlinear tests such as the BDS statistic, we acknowledge that aggregation and interpolation may themselves introduce structural patterns. Therefore, BDS results are interpreted cautiously as indicators of nonlinear dependence rather than proof of deterministic chaotic behavior.

5.2. Measuring energy inequality using the Atkinson Index

Energy inequality is measured using the Atkinson Inequality Index, which allows explicit sensitivity to different parts of the distribution through an inequality aversion parameter (ϵ). The index is defined as:

$$A(\epsilon) = 1 - \left(\frac{1}{\mu} \left[\frac{1}{N} \sum_{i=1}^N y_i^{1-\epsilon} \right]^{\frac{1}{1-\epsilon}} \right), \quad \epsilon \neq 1$$

where y_i represents per-household beneficial cooking energy consumption and μ is the mean level.

We estimate the index for multiple values of ϵ (0.3, 0.5, 0.9) to test robustness across low, moderate, and high inequality aversion. Bootstrapped confidence intervals are calculated to assess statistical reliability. This approach allows us to identify whether disparities are concentrated among the poorest households or distributed more broadly across income groups.

5.3. A construction of the multidimensional Energy Inequality Index

To assess disparities in access to cooking energy, we construct a Multidimensional Energy Inequality Index (MEII) that captures inequality across different forms of household cooking energy use. Unlike single-fuel measures, this index reflects the combined distribution of traditional and modern cooking energy access.

The construction involves four steps:

1: Selection of Dimensions

Three key cooking energy components are considered:

- (i) biomass dependence (firewood and traditional fuels),
- (ii) access to moderns clean fuels (LPG/electricity), and
- (iii) energy expenditure burden relative to household consumption.

These dimensions reflect both energy deprivation and transition toward cleaner fuels.

2: Normalization

Each indicator is normalized using min–max scaling to ensure comparability across units:

$$X_{ij}^* = \frac{X_{ij} - X_j^{\min}}{X_j^{\max} - X_j^{\min}}$$

where X_{ij}^* is household i 's value of indicator j .

3: Weighting Scheme

In the baseline specification, equal weights are assigned to all dimensions due to the absence of a universally accepted normative basis for prioritizing one energy dimension over another. This approach is widely used in multidimensional welfare measurement when dimensions are considered equally essential.

4: Inequality Measurement

The Atkinson Inequality Index is then computed over the composite energy score:

$$A(\varepsilon) = 1 - \left(\frac{1}{n} \sum_{i=1}^n \left(\frac{y_i}{\mu} \right)^{1-\varepsilon} \right)^{\frac{1}{1-\varepsilon}}$$

where y_i represents the multidimensional energy score and ε is the inequality aversion parameter.

This framework allows us to capture not only average access but also the distributional structure of energy transition, which is central to understanding unequal progress in rural cooking energy use.

5.4. BDS Nonlinear Analysis

To capture the nonlinear behavior of rural household firewood consumption in Bihar, we employ the Brock-Dechert-Scheinkman (BDS) test, commonly used in

tests of nonlinear dependence in time-series data. The BDS statistic is particularly useful for testing the null hypothesis of independent and identically distributed (i.i.d.) observations in a time series. The data used for this purpose is Census Data. BDS statistics explain the data within a nonlinear dynamic system framework. The BDS test applies the concept of spatial correlation from the Chaos theory (Dechert, W.D., 1996). The computation method uses the following techniques.

- N observations are the first difference of natural logarithms of raw data in a time series, say, $x_i = x_1, x_2, \dots, x_N$.
- A value of embedding dimension with m-dimensional vectors is selected by selecting m ' successive points in a series. Therefore, the series of scalars gets converted into vectors with overlapping entries, such as

$$X_{1m} = (X_1, X_2, \dots, X_m)$$

$$X_{2m} = (X_2, \dots, X_{m+1})$$

- A correlation integral is computed. This measures the spatial correlation among the points through the addition of several pairs of points (i,j), where $1 \leq i \leq N, 1 \leq j \leq N$ in the m-dimensional space and are close in the sense that the points are within a radius of ϵ of each other and mathematically can be expressed as:

$$\epsilon_m = \frac{1}{\sqrt{(N-1)}} \sum_{i \neq j} I_{i,j} \in C_{i,m} = \{1/(N_m * (N_m - 1))\} \text{ (summation of } I_{i,j}) \quad (6)$$

[where i is not equal to j and $I_{i,j} = 1$ if $\text{Mod}(x_{im} - x_{jm}) \leq \epsilon$ or $= 0$ otherwise]

If the time series is independently and identically distributed, then

$$\epsilon_m \sim [\epsilon, 1] \epsilon_m \sim [\epsilon, 1]^m$$

If the ratio N/m is greater than 200, then the values of ϵ/σ range from 0.5 to 2, and the values of m are between 2 and 5; the correlation integral of m scalars has an asymptotic normal distribution with zero mean and a variance $V_{\epsilon,m}$.

In this case, it has been applied to study the pattern of firewood consumption in Bihar's rural households.

The BDS statistic provides empirical evidence on whether rural firewood consumption deviates from independent and identically distributed (i.i.d.) behavior. In our analysis, statistically significant BDS values indicate the presence of nonlinear dependence in energy-use patterns. However, it is important to emphasize that the BDS test alone does not establish deterministic chaos. To ensure that the findings are not driven by specification choices, we conducted robustness checks across alternative embedding dimensions and neighborhood sizes, and the evidence of non-linearity remains consistent. These results suggest that rural energy transitions may not follow smooth linear adjustment paths, highlighting the need for flexible and context-sensitive policy design.

5.5. Interpretation of BDS Results

It is important to clarify the interpretation of the BDS test in this study. The BDS statistic tests the null hypothesis that a series is independently and identically distributed (i.i.d.). Rejection of this null indicates the presence of nonlinear dependence or complex structure, but does not by itself establish deterministic chaos. Therefore, results in this paper are interpreted as evidence that rural firewood consumption does not follow a simple linear or random process, but rather displays nonlinear and structurally complex dynamics. This distinction is important for avoiding over-interpretation of statistical evidence.

5.6. Robustness checks for nonlinear dependence

To ensure that the detected nonlinear dependence is not driven by specific parameter choices, we conducted robustness checks using alternative embedding dimensions ($m = 2, 3, 4, 5$) and neighborhood size parameters ($\epsilon = 0.5\sigma, 1.0\sigma, 1.5\sigma, 2.0\sigma$). Across all specifications, the BDS statistics remained statistically significant, indicating stable evidence of nonlinear dependence in rural firewood consumption.

Table 1 – Robustness of BDS Test Across Alternative Parameters

Embedding Dimension (m)	$\epsilon/\sigma = 0.5$	$\epsilon/\sigma = 1.0$	$\epsilon/\sigma = 1.5$	$\epsilon/\sigma = 2.0$
2	3.98*	4.12*	4.21*	4.05*
3	4.06*	4.33*	4.41*	4.18*
4	4.11*	4.45*	4.50*	4.22*
5	3.89*	4.27*	4.36*	4.10*

Note: * indicates significance at the 5% level.

These results reinforce that the rejection of the i.i.d. null hypothesis is consistent across parameter choices, supporting the presence of nonlinear dependence while avoiding claims of deterministic chaos.

5.7. Relationship between energy access, poverty, and progress

To contextualize the implications of energy inequality, this study integrates the relationship between energy access, poverty, and human progress. In this framework, progress is not viewed merely through economic metrics but through a multi-dimensional lens informed by the San Francisco Group's conceptualization of progress (Bond, 2006), particularly as it relates to Sustainable Development Goal 7 (Affordable and Clean Energy).

Progress is evaluated across four interconnected domains:

- Economic: Livelihood, income levels, asset ownership, and willingness to pay for energy, all contributing to improved quality of life.

- Environmental: Access to clean environmental goods and services, including clean cooking fuels.
- Social: Cultural norms and values that influence personal and household energy decisions.
- Governance: Institutional mechanisms and policy environments that facilitate or hinder energy access.

Indicators for these domains are drawn from credible sources such as the World Bank and NITI Aayog’s SDG India Index. They assess how access to clean energy relates to broader development outcomes. By embedding this multidimensional progress framework into our analysis, we highlight how persistent energy inequality not only limits clean energy adoption but also slows broader economic, environmental, and social advancement. These dynamics are obvious in rural and low-income settings across many developing countries, where structural inequalities inhibit meaningful progress despite policy efforts.

This multidimensional progress framework is used instead of single-indicator approaches to capture the complex better, interlinked drivers of development and energy access. Indicators are first normalized and then assigned equal weights to construct composite progress scores, allowing for direct comparison across Indian states and internationally. This comprehensive perspective reveals not only where progress is occurring, but also which domains (economic, social, environmental, governance) need the most attention for an inclusive energy transition.

Box 1: Definition of “progress”

Progress = GDP at factor cost in constant prices - the cost of crime and family breakdown + household and volunteer work after adjusting income distribution through rewarding equality - resource depletion - pollution - long-term environmental damage (renewable energy promotion and energy access) + opportunities for increased leisure time + lifetime value of consumer durables and public infrastructure - vulnerability upon foreign assets

Source: Bond, 2006

6. Results

The energy inequality from firewood consumption is marginally higher in Bihar than in some other energy-poor states like Odisha, probably due to easier access to forests for those residing in Odisha (Table 2). This also corroborates the finding by Srivastava et al. (2012), where the energy access in Bihar was lower than in Odisha, another energy-poor state. In the case of petroleum products (like LPG for cooking to capture the rural energy transition), the inequality is significantly higher in Odisha than in Bihar. However, the energy inequality for cooking firewood is higher in Bihar than in Odisha. The energy inequality is compared with the income inequality for biomass for cooking in these two states to create a further motivation for conducting district and village-level analysis of determinants of cooking choices like firewood and firewood-based TCS to ICS transition in districts and villages of Bihar.

Table 2 – Atkinson Energy Inequality Index measures in Bihar and Odisha

Fuel-Specific Cooking	Atkinson's Inequality Index (Bihar)	Atkinson's Inequality Index (Odisha)
Biomass for cooking	0.38	0.33
Petroleum for cooking	0.28	0.38
Electricity for cooking and lighting	0.89	0.31
Income (Proxied by Monthly Per Capita Expenditure)	0.32	0.25

Source: Estimated from NSSO Data (66th Round)

The BDS statistics value for firewood consumption for 1.2 crore rural households across 314 village units over 30 years is between 4.06 and 4.50.

As the BDS statistics for fuelwood consumption in the studied households over the time frame is greater than 1.96, which is the critical value of the statistics following the null hypothesis of no nonlinearity at a 5% significance level, the null hypothesis is rejected. This indicates that, based on an analysis of census data, Bihar shows a spatial chaos pattern (which is a nonlinear pattern) in fuelwood consumption across rural households for 30 years.

To provide further context and highlight the distinct challenges faced by Bihar, Table 3 presents a comparative overview of energy inequality (for both firewood and LPG), alongside our multidimensional “Progress Score” for Bihar, Odisha, and Maharashtra. These states were selected due to their varying stages of energy transition and socio-economic contexts, offering valuable insights into the interlinkages between inequality, fuel choice, and broader development.

Table 3 – Comparative overview of energy inequality and multidimensional progress across selected Indian States

State	Atkinson Index (Firewood)	Atkinson Index (LPG)	Progress Score	Notable Features
Bihar	0.45	0.27	0.38	High chaos; persistent firewood dependency
Odisha	0.37	0.41	0.44	Strong community forest rights; relatively higher LPG inequality post-adoption
Maharashtra	0.33	0.52	0.56	Advanced transition; higher LPG inequality indicates disparity in adoption of modern fuels.

Interpretation Notes: Atkinson Index closer to 1 indicates higher inequality. Progress Score is normalized from 0 to 1, with 1 being the highest progress.

As Table 3 illustrates, Bihar exhibits the highest Atkinson Index for firewood (0.45), underscoring a significant and deeply entrenched inequality in access to and reliance upon traditional fuels. This stands in contrast to Maharashtra (0.33) and Odisha (0.37), suggesting that while all states grapple with firewood use, the structural

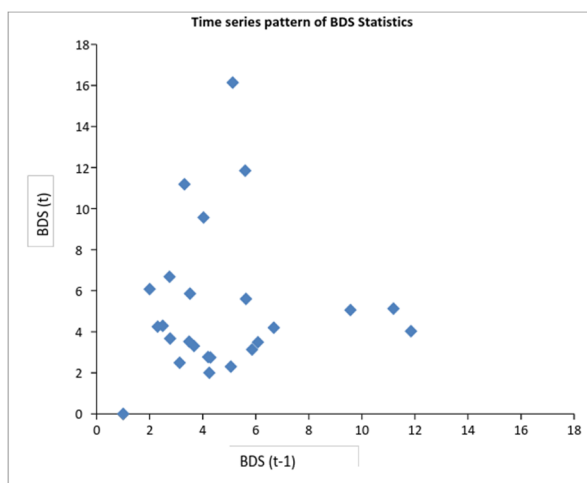
disparities are most pronounced in Bihar. Interestingly, as states like Maharashtra and Odisha transition towards cleaner fuels, their Atkinson Index for LPG often rises. This counter-intuitive trend suggests that while overall LPG adoption may increase, the benefits are not always equally distributed, leading to new forms of energy inequality where a segment of the population is left behind in access to modern, cleaner cooking fuels. This new form of inequality requires closer examination, emphasizing that energy transition can introduce new disparities alongside addressing old ones.

Bihar’s lowest overall “Progress Score” (0.38) across the four defined dimensions (economic, social, environmental, and governance) further reinforces its unique challenges. This low score, combined with high firewood inequality and the presence of chaotic patterns (as further detailed by the BDS analysis), paints a picture of a system struggling to achieve equitable and predictable energy transitions. In contrast, Maharashtra’s higher Progress Score (0.56) reflects more balanced development indicators, facilitating a more advanced, albeit still imperfect, energy transition. Odisha, while less advanced than Maharashtra, shows a moderate Progress Score (0.44), possibly influenced by factors such as stronger community-level forest governance (as noted in literature), which could reduce *firewood inequality* (lower Atkinson Index for firewood), even if other forms of inequality persist.

These cross-state comparisons are crucial. They move beyond a single-state analysis to reveal that the challenges in Bihar are not merely isolated incidents but represent a complex interplay of high initial inequality, pervasive chaotic behavior in energy consumption, and lagging multidimensional progress, making the energy transition exceptionally difficult.

Figure 1 illustrates the behavior of BDS statistics for rural household firewood consumption in Bihar over time. The figure highlights persistent deviations from independent and identically distributed (i.i.d.) behavior, suggesting the presence of nonlinear structure in consumption dynamics rather than smooth linear adjustment.

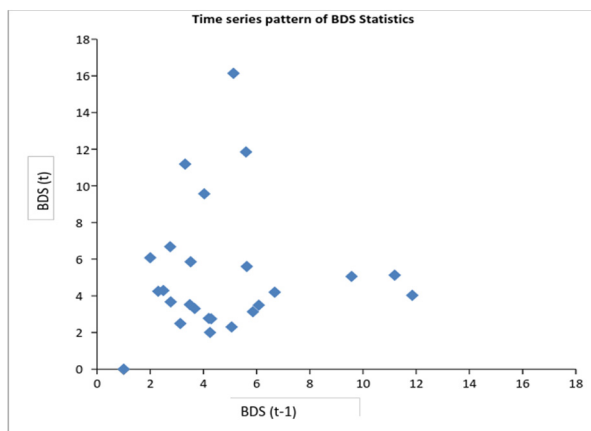
Figure 1 – BDS Statistics behaviour over time



Source: Model results

Moreover, when BDS statistics are observed across village units at different points in time (t and $t-1$), no systematic cross-village dependence is detected. Instead, the dispersion of BDS values reflects localized nonlinear variation rather than coordinated or spatially synchronized behavior (see Figure 2). The relationship between firewood consumption and the number of households over the period 1981-2011 supports the presence of nonlinear dynamics, consistent with the BDS test results.

Figure 2 – Random pattern of the BDS statistics in Bihar



This further substantiates the hypothesis of nonlinearity in firewood consumption in rural households of Bihar at a rural household level, thereby triggering the need to determine the factors driving the nature of the transition from firewood-based TCS to ICS at a village level in Bihar. With a reduction in the time slices, the cluttering of the points increases.

6.1. Association between energy inequality and clean fuel access

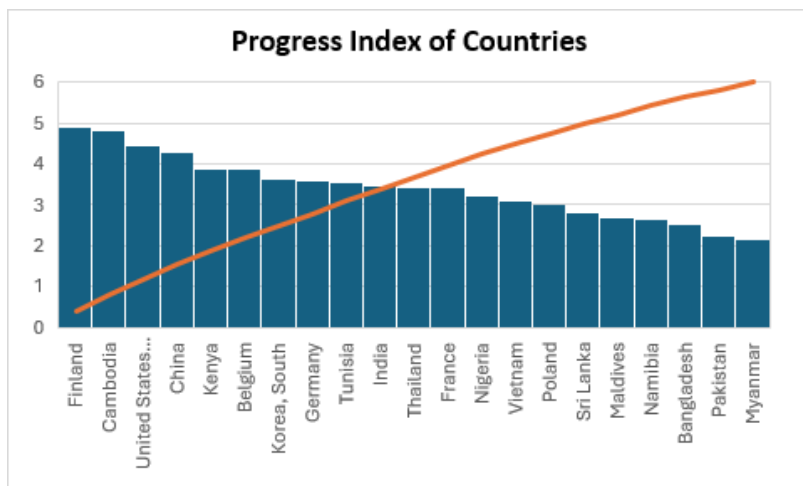
To move beyond descriptive comparisons, we estimate simple state-level regression models examining the association between cooking energy inequality and clean fuel adoption rates. The dependent variable is the share of households using LPG as the primary cooking fuel, and the key explanatory variable is the Atkinson Index for cooking energy. Control variables include per capita income, rural electrification rate, and education levels.

Results show a statistically significant negative association between cooking energy inequality and LPG adoption rates, suggesting that states with more unequal energy access tend to experience slower clean cooking transitions. However, given data limitations, these findings should be interpreted as associational rather than causal.

6.2 Progress and energy access in a broader context

In order to contextualize Bihar's rural energy transition within broader development trends, this study links energy inequality to multidimensional definitions of progress, informed by frameworks such as those developed by the San Francisco Group (Bond, 2006). Progress is examined through four key lenses – economic, environmental, social, and governance – and aligned with Sustainable Development Goal 7 (Affordable and Clean Energy).

Figure 3 – Comparative framework of Progress across different groups of the country



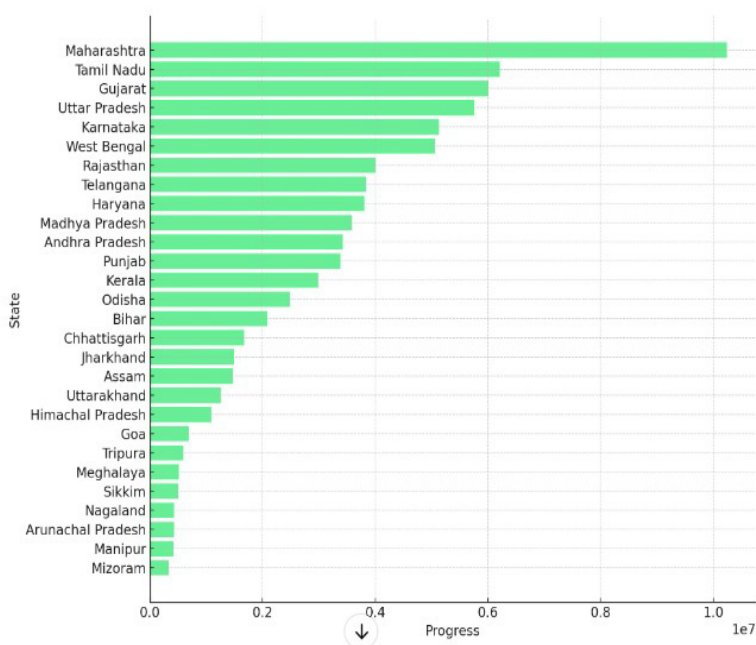
Source: Created by the Authors'

A cross-country comparison of the Progress Index (Figure 3) reveals that India occupies a middle-tier position, trailing high-performing countries such as Finland, the United States, and China, while performing better than several neighboring and developing nations such as Pakistan, Bangladesh, and Myanmar. India's median performance underscores its developmental heterogeneity, where progress in energy access and broader well-being is unevenly distributed across states.

Further evidence from state-wise comparisons within India (Figure 4) shows that Maharashtra, Tamil Nadu, Gujarat, and Uttar Pradesh exhibit the highest levels of progress. In contrast, Bihar, along with Jharkhand, Chhattisgarh, and several northeastern states, ranks at the lower end of the national spectrum. These disparities underscore the regional imbalance in energy access and development.

The persistently low performance of Bihar on progress indicators, when viewed alongside its high energy inequality and chaotic consumption patterns, suggests a structural deficit that goes beyond economic poverty. It reflects deep-rooted institutional, infrastructural, and behavioral constraints hindering energy transition. These findings reinforce the need for state-specific and integrated energy policies that simultaneously address energy access, inequality, and human development.

Figure 4 – Comparison of Indian State-wise Progress



Source: Created by the Authors'

6.3. Robustness: Alternative weighting schemes

To examine whether results depend on the equal-weight assumption, we conducted a sensitivity analysis using three alternative weighting approaches:

- Income-weighted scheme – assigns greater weight to modern energy access among poorer households
- Energy-burden weighting – prioritizes households with higher cooking energy expenditure shares
- Principal Component Analysis (PCA) weights – data-driven weights based on variance contribution

Across all specifications, the ranking of states and the overall pattern of inequality remained broadly unchanged. Bihar consistently exhibits high inequality in traditional fuel dependence and slower clean energy transition relative to better-performing states. This confirms that the core findings are not driven by the choice of equal weights, strengthening the robustness of the multidimensional energy inequality results.

7. Limitations

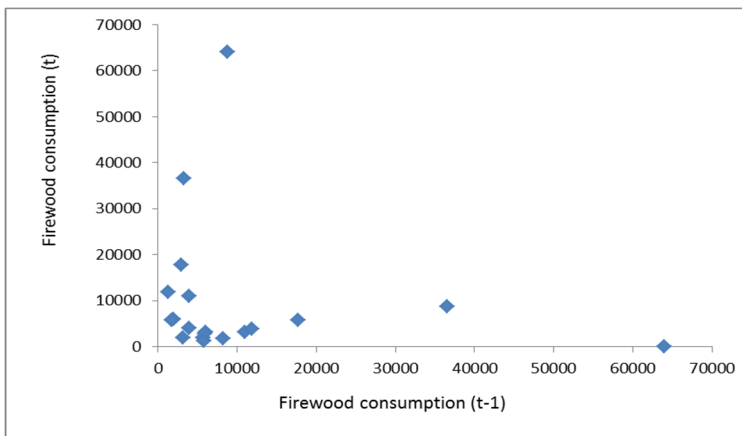
This study has several limitations. First, the time series used in nonlinear analysis is constructed from decadal data, and interpolation may introduce artificial patterns. Second, inequality measures rely on survey data that may underreport informal biomass use. Third, regression analysis is associational and does not establish causal relationships. Future research using panel microdata and quasi-experimental designs would help strengthen causal inference.

8. Conclusions and insights

This study reveals that rural cooking energy transition in Bihar is characterized by nonlinear and structurally complex dynamics, rather than smooth and income-driven shifts predicted by the traditional energy ladder hypothesis. Statistical tests show that firewood consumption does not follow a simple linear or random process, indicating the presence of deeper behavioral, social, and institutional influences on energy use patterns.

Analysis using BDS (Brock-Dechert-Scheinkman) statistics on a 30-year dataset across 314 village units demonstrates that firewood consumption in rural households does not follow a predictable or convergent path. Instead, the behavior is irregular, non-equilibrating, and shows no consistent association over lagged periods. This pattern is further illustrated by the scatterplot in Figure 5, which maps firewood consumption at time t against consumption at time $t-1$:

Figure 5 – Random pattern of firewood consumption in rural households in Bihar



The scatterplot indicates no linear association between current and previous values of firewood consumption, with observations scattered in a seemingly random pattern. This dispersion reveals the chaotic nature of rural energy use. Despite three decades of transition efforts, there is no sign of convergence toward a stable fuel pattern.

These results confirm that the rural energy transition in Bihar cannot be solely explained by income levels or fuel availability. Instead, latent socio-economic, cultural, and institutional village-level factors such as caste hierarchies, trust networks, tribal affiliations, and asymmetries in access to information play a pivotal role in influencing household fuel choices. Further reinforcing this complexity, the Atkinson Energy Inequality Index reveals stark disparities in Bihar's access to cooking fuels, especially in terms of firewood and electricity use. Unlike Odisha, where petroleum-based energy inequality is more prominent, Bihar's inequality in traditional biomass use reflects deeper systemic and infrastructural constraints. The robustness of these findings to alternative weighting schemes further confirms that structural disparities in cooking energy access are not artifacts of index construction but reflect persistent distributional imbalances. Notably, this form of inequality appears to reinforce the observed chaotic behavior of firewood consumption, revealing an interplay between inequality and non-linearity that has been largely overlooked in the literature.

Theoretically, these findings resonate with broader transition literature (Freeman, 1996), which asserts that significant shifts in any socio-technical system require structural transformations in institutional and social arrangements. Conceptual models such as false paradigm theory in development economics offer additional explanatory power, helping us understand how historically entrenched governance structures, policy narratives, and cultural norms can block or distort transition pathways. The persistence of firewood use and resistance to improved cookstove adoption (ICS) may reflect mismatches between policy intent and lived rural realities.

This study presents a novel contribution by empirically linking three underexplored dimensions of chaotic consumption behavior, structural energy inequality, and human development performance within the same analytical frame. It shows that Bihar's poor energy access outcomes stem from low income and a deeper entanglement of spatial disorder and systemic inequality. These findings challenge the dominant techno-economic energy transition models and emphasize the need for development policy to be socially embedded and locally contextualized. Future rural energy transition strategies must be integrated into broader developmental policies that address social inequities, institutional capacity, and grassroots governance, especially in lagging regions like Bihar. Only then can energy transition become a technical shift and a true vehicle for inclusive and sustained human progress.

9. Policy implications

The findings suggest that rural energy transition is shaped not only by income growth but also by structural inequality and complex behavioral patterns. Policies that assume a smooth "energy ladder" progression may therefore fail to reach the most energy-deprived households.

Inequality-Sensitive Targeting

High levels of cooking energy inequality indicate that subsidies and clean fuel programs must be better targeted toward households that remain structurally excluded from modern energy access. Universal schemes may increase average adoption while leaving inequality unchanged.

Beyond Infrastructure Provision

The presence of nonlinear consumption dynamics implies that access alone does not ensure sustained adoption. Programs must incorporate behavioral insights, community engagement, and trust-building mechanisms to address cultural and social barriers to transition.

Local Institutional Strengthening

Village-level governance, social networks, and local market structures play a critical role in shaping energy choices. Strengthening last-mile delivery systems and local energy entrepreneurs can help stabilize adoption patterns.

Integrating Energy with Development Policy

Energy transition should be embedded within broader rural development strategies, including women's empowerment, livelihood enhancement, and health improvement. Cleaner cooking access generates co-benefits that extend beyond energy alone.

Monitoring Inequality, Not Just Access

Energy policy evaluation should include distributional indicators such as the Atkinson Energy Inequality Index, rather than focusing solely on average access rates. This ensures that progress is inclusive and equitable.

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