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Sustainable supply chain practices as catalyst for energy poverty alleviation in developing countries: a necessary condition analysis

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Abstract
Energy poverty remains a critical obstacle to socioeconomic progress in developing countries, affecting over 733 million people globally. This study investigates how sustainable supply chain practices serve as catalysts for alleviating energy poverty, focusing on efficient logistics, local sourcing, community engagement, regular maintenance, and training programs. Employing Necessary Condition Analysis (NCA), the research identifies indispensable supply chain conditions for successful renewable energy deployment. The findings reveal that efficient logistics and community engagement have the most significant impact, requiring minimum thresholds to ensure energy access effectiveness. Though moderate in effect size, local sourcing and training programs are equally essential for long-term sustainability. Regular maintenance emerged as a critical factor, underscoring the importance of ongoing support. The study integrates Necessary Condition Theory, Energy Justice Framework, and Socio-Technical Systems Theory to demonstrate that these practices must be complementary rather than substitutive. The results provide actionable insights for managers and policymakers, advocating targeted investments in supply chain resilience and local capacity building. By offering an understanding of the interplay between supply chain management and energy access, this research advances theoretical and practical frameworks for tackling energy poverty. Future studies should explore these dynamics across different sectors to generalise the findings further.

Keywords Energy poverty alleviation · Necessary condition analysis · Developing countries · Supply chain resilience · Socio-technical systems · Community engagement · Sustainable supply chain practices

1 Introduction

Energy poverty remains one of the most pressing challenges facing developing countries, where approximately 733 million people still lack access to electricity, and nearly 2.4 billion rely on traditional biomass for cooking and heating [26]. Energy poverty significantly impedes socioeconomic development, contributing to poor health outcomes, limited educational opportunities, and reduced economic productivity [50]. Addressing energy poverty is essential to achieving several United Nations Sustainable Development Goals (SDGs), particularly SDG 7, which calls for universal access to affordable, reliable, sustainable, and modern energy by 2030. However, the complexity of energy poverty extends beyond energy access alone, as it intertwines with supply chain inefficiencies and sustainability

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challenges, especially in rural communities where conventional energy supply chains are often fragmented, unreliable, and unsustainable [22].

Nigeria, despite being Africa's largest economy, exemplifies the complex challenges of energy poverty that affect a substantial portion of its population [6, 59]. The country's energy infrastructure struggles to meet the needs of its inhabitants, with limited access to grid electricity and frequent power interruptions [2, 6]. This stark reality exists despite Nigeria's abundant energy resources, including significant oil reserves, natural gas, and renewable energy potential [18, 37, 38]. The disconnect between Nigeria's energy resource wealth and widespread energy poverty underscores the critical need for sustainable supply chain practices that can bridge this gap [39]. Particularly in rural areas, where a significant portion of the population lacks reliable access to modern energy services [13], the implementation of sustainable supply chain practices could potentially transform energy accessibility, affordability, and reliability. The Nigerian government's commitment to achieving universal energy access aligns with the Sustainable Development Goals [55], making the country an ideal case study for examining how sustainable practices can catalyse energy poverty alleviation in developing nations [36].

While much of the existing literature on energy poverty emphasises technological, financial, and policy barriers, the role of supply chain management in ensuring effective and sustainable energy delivery remains underexplored. Supply chain practices are crucial in successfully deploying renewable energy technologies, yet they are frequently overlooked in the energy poverty discourse [34]. Research has shown that supply chains for renewable energy systems in developing countries are plagued by logistical challenges, lack of infrastructure, high costs, and inadequate local capacity for maintenance and repairs, leading to suboptimal energy outcomes [46]. Sustainable supply chain practices, such as local sourcing of materials, community engagement in the distribution process, and efficient inventory management, ensure that renewable energy technologies reach the most underserved communities effectively and sustainably [34]. However, a significant knowledge gap exists concerning the specific supply chain conditions necessary to support the sustainable adoption of renewable energy solutions in energy-poor areas in Nigeria.

The significance of this study lies in its focus on sustainable supply chain practices as a catalyst for alleviating energy poverty. While much of the existing literature on energy poverty emphasises technological, financial, and policy barriers, the role of supply chain management in ensuring effective and sustainable energy delivery remains underexplored. Supply chain practices, such as local sourcing, community engagement, efficient logistics, regular maintenance, and training programmes, are critical for the successful deployment and maintenance of renewable energy systems [34, 42]. By investigating these practices, this study aims to address a critical gap in the energy poverty discourse and provide actionable insights for designing more resilient supply chain models.

This research is motivated by the practical challenges associated with energy supply chains in energy-poor regions. Fragmented logistics, high transportation costs, lack of local capacity, and inadequate community involvement often lead to suboptimal energy outcomes [34]. For instance, renewable energy projects in rural areas frequently suffer delays or failures due to the absence of robust supply chains that can adapt to local conditions. These challenges necessitate a deeper understanding of the specific supply chain practices that are indispensable for improving energy access.

To address these gaps, this study is guided by the following research questions:

- Are specific sustainable supply chain practices necessary for alleviating energy poverty?
- What are the minimum levels of these practices required for effective energy provision?
- How do factors like local sourcing, efficient logistics, and community involvement impact the success of renewable energy projects?

This research employs a quantitative survey methodology and integrates Necessary Condition Analysis (NCA) with the Energy Justice Framework and Socio-Technical Systems Theory. NCA is used to identify the indispensable supply chain conditions required for energy poverty alleviation, while the Energy Justice Framework provides a critical lens to evaluate equity, fairness, and inclusivity in energy access. Socio-Technical Systems Theory complements this by offering insights into the integration of social and technical factors, emphasising the interplay between technological innovations and community realities. By combining these approaches, the study offers a comprehensive framework for examining the structural, social, and contextual requirements of energy access.

This study's contributions are both theoretical and practical. Theoretically, the research advances the understanding of sustainable supply chains by demonstrating the necessity of specific practices, such as efficient logistics and community engagement, for energy poverty alleviation. Practically, the findings provide actionable recommendations for managers and policymakers, advocating targeted investments in supply chain resilience, local capacity building, and community-driven approaches to energy access. The study also supports the global goal of reducing energy poverty and achieving sustainable development in underserved regions.

This paper is organised as follows: The next section provides a review of the relevant literature, discussing the theoretical and empirical foundations of sustainable supply chain practices and their role in addressing energy poverty. The methodology section describes the research design, data collection, and analytical techniques employed in this study. The results section presents key findings, followed by a discussion of their implications for theory and practice. Finally, the conclusion highlights the study's contributions, limitations, and potential directions for future research.

2 Literature review

2.1 Theoretical foundation

Various theoretical frameworks have been extensively applied to examine the intersection of energy poverty and supply chain management. However, the predominant theories—Resource-Based View (RBV), Institutional Theory, Complex Adaptive Systems Theory, and Transition Theory—demonstrate significant limitations in explaining the fundamental conditions necessary for sustainable energy access and poverty alleviation in developing countries. While these theories offer valuable insights into specific supply chain dynamics, they fail to capture the essential prerequisites for effective interventions. RBV, a widely used framework, explains how firms leverage unique capabilities for competitive advantage [5, 31]. In energy poverty contexts, RBV suggests that firms with superior resource configurations—such as local knowledge networks and adaptive technical capabilities—achieve better outcomes [53]. However, RBV's firm-centric focus overlooks broader structural constraints, including inadequate infrastructure, policy inefficiencies, and socioeconomic disparities, often outweigh firm-level advantages in determining intervention success [53].

Institutional Theory has examined how regulatory environments, cultural norms, and social expectations shape supply chain practices [9, 33]. While useful for understanding regional variations in adoption, it does not establish the fundamental conditions for sustained energy access. Institutional pressures may drive compliance but do not inherently ensure effectiveness. Furthermore, the theory does not differentiate between necessary and sufficient conditions, limiting its utility for policy formulation [33]. Similarly, Complex Adaptive Systems Theory highlights the dynamic nature of energy supply chains, emphasising adaptability to environmental, social, and technical conditions [25, 57]. While the theory underscores resilience and flexibility, it lacks predictive precision and does not specify the essential factors required for success. Its descriptive nature limits its applicability in deriving actionable policy recommendations [57]. Also, Transition Theory, frequently employed to study energy system transformations, provides insights into long-term shifts and their implications for supply chain management [3]. However, it remains overly broad and descriptive, offering little specificity in identifying the immediate, practical interventions needed for energy poverty alleviation. Its primary focus on systemic evolution over time makes it less effective for addressing short-term supply chain challenges [3].

To address these theoretical limitations, this study adopts a structured approach integrating Necessary Condition Theory (NCT), the Energy Justice Framework, and Socio-Technical Systems Theory. These frameworks collectively provide a rigorous foundation for understanding supply chain practices in energy poverty alleviation. NCT serves as the primary theoretical foundation due to its capacity to distinguish between essential and merely associated factors [10]. Unlike traditional correlation-based approaches, which identify general relationships, NCT establishes conditions that must be present for a desired outcome [19]. It defines absolute constraints—factors without which energy poverty alleviation is impossible—rather than simply highlighting contributory elements [10, 20]. For instance, while efficient last-mile distribution and inventory management are necessary for sustained energy access, they are insufficient to eliminate energy poverty [22, 50]. The absence of these conditions precludes success, whereas their presence alone does not guarantee it, highlighting the necessity of complementary factors [1, 34, 53]. A critical advantage of NCT is its ability to impose a "ceiling effect," whereby no additional factors can compensate for the absence of a necessary condition [19]. This provides a methodological edge over traditional regression models and Qualitative Comparative Analysis (QCA), which primarily assess correlations and sufficient configurations [35]. While QCA can identify necessary conditions, its analytical scope is narrower than NCA's ability to quantify the minimum levels required for each factor. Traditional multilevel mixed-effects regression models, such as those used by Ozdemir and Koukoufikis [40] in examining EU energy poverty, assess relative variable influence but do not determine which conditions are indispensable. In contrast, NCT allows for the precise identification of "must-have" elements in energy supply chain management [41].

The Energy Justice Framework complements NCT by addressing the distributive, procedural, and recognition dimensions of energy access [48]. Existing theories inadequately consider justice and equity in energy transitions. RBV prioritises firm-level advantages; Institutional Theory emphasises institutional conformity and Complex Adaptive Systems Theory focuses on system resilience—all while neglecting inclusivity concerns. Energy poverty disproportionately affects marginalised populations, yet many supply chain interventions fail to incorporate justice-oriented principles. Recent applications of the Energy Justice Framework extend to spatial justice and energy democracy, emphasising equitable energy distribution and participatory decision-making [44]. Without these considerations, even technically sound supply chain solutions risk perpetuating structural inequalities.

Socio-Technical Systems Theory completes the theoretical foundation by integrating technological and social dimensions of energy supply chains [54]. Unlike prior theories that treat technical and social factors separately, this framework emphasises their interdependence. Effective energy poverty alleviation requires not only technical innovation but also community acceptance and institutional alignment [3]. Many energy initiatives fail due to misalignment between technological solutions and socio-economic realities. This theory is particularly relevant in analysing how supply chains facilitate systemic change while ensuring social stability [3].

Together, these three frameworks—NCT, the Energy Justice Framework, and Socio-Technical Systems Theory—offer a more robust and targeted theoretical foundation than previous models. NCT identifies the essential prerequisites, the Energy Justice Framework ensures equity considerations, and the Socio-Technical Systems Theory bridges technical and social dimensions. This integrated approach enables a comprehensive understanding of the constraints and enablers of supply chain effectiveness in energy poverty alleviation. Furthermore, this study addresses a critical methodological gap. While traditional approaches—such as regression models, QCA, and system dynamics—have been used to analyse supply chain practices in energy poverty contexts, they often fail to establish the necessary conditions for success. This study employs Necessary Condition Analysis (NCA) for its unique capacity to identify the minimum factors required for effective energy poverty alleviation. Unlike QCA, which focuses on sufficient configurations, NCA isolates indispensable conditions, providing clearer policy implications. As Ragin [41] notes, while QCA can assess necessary conditions, its approach lacks the precision of NCA's threshold-based analysis. This methodological choice strengthens the study's contribution to policy and practice by pinpointing the "must-have" elements for energy poverty interventions.

2.2 Energy poverty and supply chains in developing countries

Energy poverty affects over 733 million people globally, extending beyond lack of access to include challenges related to affordability, reliability, and quality [50]. This is a critical challenge given that reliable and affordable energy is fundamental to economic development, education, and public health [22, 58]. In sub-Saharan Africa, many rural households rely on traditional biomass, with limited access to modern energy systems, exacerbating socio-economic disparities [26]. Nigeria exemplifies the paradox of energy poverty amid resource abundance, with over 85 million people—approximately 43% of the population—lacking reliable electricity despite the country's status as Africa's largest economy [58]. This challenge is particularly acute in rural areas, where frequent outages, inadequate infrastructure, and unreliable supply hinder economic and social development [6]. Beyond accessibility, affordability remains a significant issue, with prohibitive electricity costs burdening households and irregular supply undermining business productivity [2]. Fragmented supply chains, particularly in the renewable energy sector, exacerbate these challenges through logistical inefficiencies, limited technical expertise, and inadequate maintenance infrastructure [34]. Nigeria's vast geography further complicates distribution, particularly in remote communities [39]. Despite significant oil, gas, and renewable energy potential, the persistent gap between availability and accessibility underscores the necessity of efficient supply chain strategies to bridge this divide [18, 38].

Prior research highlights the potential of decentralised renewable energy solutions to mitigate these challenges by reducing reliance on biomass and fostering local economic development [34, 43, 58]. However, addressing energy poverty requires a systemic understanding of its underlying barriers, including financial constraints, inadequate infrastructure, and fragmented supply chains [34, 43, 50]. The Energy Justice Framework provides critical insights into the socio-political dynamics of energy access, emphasising equitable distribution and community participation [48]. Additionally, behavioural and cultural factors influence adoption, as demonstrated in rural Kenya and India, where alignment with local customs and proactive community engagement facilitated higher adoption rates and long-term sustainability [34, 43, 50].

Jones and Reyes [28] identify three key themes relevant to energy poverty research: definitions and metrics, the efficacy of energy assistance programs, and energy transition and justice. The first theme underscores the need for a comprehensive assessment of energy access affordability, reliability, and quality. This study contributes by examining how sustainable supply chain practices address these metrics, offering practical solutions for underserved regions. The second theme, concerning energy assistance programs, aligns with the study's focus on operational mechanisms such as efficient logistics, local sourcing, and community engagement—critical to the success of renewable energy initiatives [8, 45]. The third theme, energy transition and justice, provides an equity-centred lens to ensure inclusive access to renewable energy. Through the Energy Justice Framework, this research highlights supply chain contributions to distributive and procedural justice, addressing systemic inequities in energy access.

Existing research predominantly focuses on technological advancements or policy interventions while overlooking the operational mechanisms crucial for their implementation. Sustainable supply chain practices—local sourcing, efficient logistics, and community involvement—are essential to bridging this gap. Decentralised supply chains mitigate logistical challenges in remote areas, while community engagement fosters local ownership and project sustainability [34, 43]. This study builds upon these insights, positioning supply chain efficiency as a fundamental element in energy poverty alleviation.

Theoretical frameworks such as Energy Justice and Socio-Technical Systems further underscore the importance of equitable and resilient energy systems. These perspectives inform supply chain strategies that ensure technological feasibility and embed social equity, making them indispensable for addressing the complexities of energy poverty.

2.3 Sustainable supply chain practices and energy accessibility

Sustainable supply chain management (SSCM) integrates environmental, social, and economic considerations into supply chain operations to promote long-term sustainability [34, 43]. In renewable energy projects, SSCM encompasses practices such as local sourcing, decentralised logistics, and community engagement, which are crucial for effective deployment and long-term sustainability. However, despite their recognised importance, significant challenges persist in implementation, particularly in aligning these practices with local conditions [34, 43].

Local sourcing is frequently promoted to enhance supply chain resilience and support local economies by reducing dependence on costly imports [34, 43]. This strategy also mitigates risks from international supply chain disruptions and high transportation costs. However, it is often undermined by the limited availability and poor quality of local materials, which can compromise the efficiency and reliability of renewable energy systems. Despite the recognised benefits of local sourcing, the literature largely neglects the critical need for capacity-building initiatives to enable local industries to meet technical standards.

Efficient logistics are equally pivotal for reducing delays and ensuring timely delivery of renewable energy technologies, particularly in remote areas. Decentralised warehousing and improved transportation networks can significantly enhance supply chain performance [21]. However, these improvements demand substantial investment and robust stakeholder coordination, challenges that the literature frequently overlooks, assuming their feasibility without addressing associated financial and organisational constraints.

Engaging local suppliers is essential for fostering adaptive supply chains and building local expertise. However, this requires more than transactional relationships; it necessitates sustained investment in training and development to help local suppliers meet technical standards [60]. Although cited as a best practice, the literature offers limited insight into the mechanisms for systematically developing and maintaining such supplier relationships over time.

Community involvement is widely recognised as critical for ensuring renewable energy projects' relevance, acceptance, and sustainability [8, 45]. However, participatory frameworks are often absent, and power imbalances and a lack of inclusionary practices frequently undermine community engagement initiatives. While many studies advocate for greater community involvement, they rarely provide practical, equitable and effective implementation strategies.

Environmental sustainability is a key component of SSCM, emphasising carbon footprint reduction and the promotion of renewable resources. However, the literature often highlights tensions between environmental objectives and economic realities, particularly in developing countries where cost pressures frequently override sustainability goals [12]. Addressing this conflict requires innovative approaches to balance environmental and economic priorities, a gap that remains inadequately addressed in current research.

Supply chain reliability and adaptability are critical for ensuring energy systems meet the needs of underserved rural areas [34, 43]. However, achieving such adaptability demands additional investment and complex coordination, challenges that the literature acknowledges but fails to address with concrete solutions. Poor inventory management and component shortages further exacerbate disruptions, underscoring the need for robust planning and inventory control strategies, which remain underexplored in existing research.

Maintenance and repair processes are widely recognised as crucial for preventing the degradation of renewable energy systems. Despite their importance, many projects suffer from inadequate maintenance protocols, primarily due to funding constraints, insufficient technical capacity, and weak organisational support [43]. The literature frequently highlights these issues but offers limited practical solutions, particularly in resource-constrained settings.

Cost-effectiveness is central to ensuring the affordability of renewable energy technologies in low-income regions. However, the pursuit of lower costs often results in quality compromises, leading to frequent system failures and reduced operational efficiency [34]. Although studies emphasise the importance of balancing cost management with quality control, they often underestimate the complexities of achieving this balance within real-world constraints.

While the literature advocates for integrating sustainable supply chain practices in renewable energy projects, it falls short in providing actionable solutions for aligning these practices with local needs and operational challenges. A strategic approach to SSCM—balancing cost, efficiency, environmental sustainability, and community engagement—is essential for overcoming these barriers. However, current research offers limited practical pathways for achieving this balance, highlighting the need for more focused, context-specific approaches to sustainable supply chain management in the renewable energy sector.

2.4 Community integration in supply chain management

Community involvement is pivotal for enhancing the sustainability and effectiveness of renewable energy projects, aligning supply chain operations with local needs and fostering a sense of ownership [45]. Effective community engagement, particularly during planning and implementation, ensures that projects address specific local challenges and constraints [7]. However, despite widespread acknowledgement of these benefits, implementation often remains superficial, with community participation limited to tokenistic consultation and minimal influence over decision-making processes [29]. This disconnect between theoretical ideals and practical outcomes frequently results in misalignment between project objectives and local expectations.

Structured community feedback mechanisms are essential for creating adaptive and responsive supply chains [27]. Such mechanisms enable the refinement of operations and alignment with evolving local needs. However, existing literature highlights a significant gap: feedback processes are often poorly structured, with collected inputs rarely informing decision-making [49]. This one-way information flow undermines the potential benefits of community contributions. Addressing this issue requires embedding participatory feedback loops within supply chain frameworks to ensure that community input translates into actionable improvements.

Capacity-building initiatives, particularly through local training programs, are critical for ensuring the long-term sustainability of renewable energy projects. Such programs empower community members by enhancing their technical capabilities for system operation and maintenance, reducing dependency on external support [29]. Despite their importance, investment in comprehensive training remains limited, resulting in skill gaps that compromise project longevity. This shortfall reflects a broader issue in supply chain management, where immediate deployment is often prioritised over sustained community empowerment.

Active community participation in system maintenance is integral to project sustainability. However, the literature reveals that such involvement is often sporadic and poorly coordinated, leading to inconsistent maintenance practices and a reliance on external support [49]. Structured participation frameworks are necessary to standardise maintenance efforts and strengthen community autonomy. Additionally, local leadership is crucial in bridging the gap between supply chain operators and the community, fostering trust and cooperation. Effective engagement with community leaders requires more than symbolic gestures; it demands meaningful partnerships that value local knowledge and include leaders in substantive decision-making processes [27]. Yet, many projects reduce leadership involvement to ceremonial roles, undermining their potential impact.

Employing local community members within supply chains offers dual benefits: it supports local economic development and enhances the supply chain's adaptability to local conditions [7]. However, this practice remains inconsistently applied, with many projects favouring external labour perceived as more skilled or reliable. This preference limits local economic benefits and overlooks opportunities to develop a skilled local workforce capable of supporting project sustainability.

Community ownership of renewable energy systems represents the highest level of integration, driving long-term sustainability through local stewardship. Ownership fosters a sense of responsibility and ensures systems are maintained and utilised effectively. However, transitioning from externally managed to community-owned systems presents significant challenges, including technical skill deficits, resource constraints, and the absence of supportive governance structures [49].

Current approaches often fail to provide the robust frameworks needed to facilitate genuine community ownership, resulting in superficial engagement rather than substantive local control.

While the literature strongly advocates integrating community involvement within renewable energy supply chains, practical implementation remains limited by tokenistic practices, insufficient capacity-building, and fragmented feedback mechanisms. Addressing these gaps requires a shift towards participatory frameworks that embed community input into decision-making, comprehensive training programs that empower local actors, and structured pathways to community ownership. Achieving these outcomes will necessitate more than superficial engagement; it will require a commitment to genuine partnerships that leverage local knowledge and foster sustainable community leadership.

2.5 Gaps in the literature

The existing body of literature on sustainable supply chain practices in the context of energy poverty alleviation reveals significant gaps that limit its practical application and theoretical development. A major issue is the lack of empirical analysis quantifying the minimum thresholds of practices such as efficient logistics, local sourcing, community engagement, and training. While these practices are widely recognized as critical, their indispensability in achieving effective energy poverty alleviation remains poorly defined [22].

Additionally, much of the research emphasizes correlations and sufficiency in supply chain practices rather than identifying non-negotiable, necessary conditions. The absence of such analyses leaves a gap in understanding the critical prerequisites for success, making it difficult for policymakers and practitioners to prioritize interventions effectively [10, 19]. Although the Energy Justice Framework and Socio-Technical Systems Theory provide valuable insights into equity and the integration of technical and social systems, their application often remains theoretical. There is limited research on how these frameworks can be operationalised to ensure inclusivity, equitable distribution of benefits, and seamless integration of technical and social realities in supply chain operations [3, 48].

Moreover, despite being a frequently cited factor in achieving energy access, community engagement is often implemented superficially. Many studies fail to provide structured and actionable models for fostering meaningful community involvement throughout the supply chain process, from planning to maintenance [50, 7]. Similarly, while integrating local talent and resources is widely recommended, there is insufficient exploration of systematic approaches to build local capacity and align practices with technical standards [34].

Another critical gap lies in addressing the trade-offs between environmental, economic, and social priorities in sustainable supply chain management. While cost-effectiveness is vital, achieving this without compromising material quality, logistical robustness, and sustained community engagement remains a significant challenge, particularly in resource-constrained settings [22, 43]. The literature rarely offers strategies for balancing these competing objectives.

Methodologically, the dominant reliance on traditional approaches, such as correlation-based analyses and regression models, further limits progress. These methods primarily reveal correlations between variables and their relative impact on outcomes but are incapable of determining necessary conditions. This limitation creates a methodological void in identifying non-negotiable prerequisites for energy poverty alleviation [10, 19]. Approaches like QCA can explore sufficient conditions but often fall short of fully identifying and quantifying individual necessary conditions [35]. In contrast, NCA provides a more suitable methodological framework by identifying "must-have" conditions and their minimum thresholds. However, NCA remains underutilized in the field of sustainable supply chain management and energy poverty [10]. Furthermore, there is a lack of cross-contextual studies that account for diverse socioeconomic and infrastructural conditions in developing countries, restricting the generalizability of findings [22].

To address these gaps, this study employs NCA to identify and quantify critical supply chain practices for energy poverty alleviation. By integrating NCA with equity-focused frameworks like the Energy Justice Framework [48] and Socio-Technical Systems Theory [3], it seeks to provide actionable insights. This approach bridges theoretical perspectives and practical applications, offering solutions adaptable to diverse regional contexts and addressing the complex interplay of social, technical, and environmental factors in sustainable energy access.

3 Methodology

This study employs a quantitative survey approach to investigate the role of sustainable supply chain practices in alleviating energy poverty in developing countries. The methodology ensures rigour, reliability, and validity, leveraging established frameworks and analytical techniques to generate novel insights into the necessary conditions for energy poverty alleviation.

3.1 Research design and data collection

A structured questionnaire, designed using a 5-point Likert scale, was adapted from validated studies [12, 34, 43], to collect data from key stakeholders, including supply chain managers, energy providers, and community leaders involved in energy supply chains. The survey targeted participants from Nigeria, focusing on regions severely affected by energy poverty, to ensure the findings reflect the operational realities of supply chains in these contexts. Participants were selected through purposive sampling, ensuring representation from diverse stakeholder groups. The survey was administered online and in person using Qualtrics to maximise accessibility and response diversity. To ensure data quality, the survey included two attention-check questions placed in different sections, and responses failing these checks were excluded [30]. Additionally, responses with missing values were removed [23], and rapid or straight-line responses were excluded [16].

3.2 Necessary condition analysis (NCA)

Data analysis was conducted using Necessary Condition Analysis (NCA), a technique uniquely suited to identifying critical conditions that must be present for successful outcomes [10]. Unlike correlation-based methods, NCA focuses on "must-have" conditions that constrain outcomes when absent, providing a robust framework for identifying indispensable supply chain practices. The study employed two NCA techniques: ceiling envelopment with a free disposal hull (CE-FDH) and ceiling regression with a free disposal hull (CR-FDH). The CR-FDH technique was prioritised for its greater accuracy, suitability for parametric data, and lower sensitivity to outliers [10, 47]. Descriptive and inferential statistics, including regression analysis, complemented the NCA to comprehensively understand the relationships between supply chain practices and energy access outcomes.

3.3 Ethical considerations

The study adhered to stringent ethical guidelines throughout the research process. Ethical approval was obtained from the University of Cumbria ethics committee, and informed consent was secured from all participants. Data confidentiality was rigorously maintained, and participants were assured of the anonymity of their responses. A pilot test was conducted to refine the survey instrument, and Cronbach's alpha was calculated to assess reliability, with all constructs achieving values above the acceptable threshold of 0.7. Expert reviews further validated the questionnaire to ensure alignment with key concepts of sustainable supply chain management and community engagement, enhancing the credibility of the findings [19].

3.4 Survey participants' characteristics

The survey targeted stakeholders directly involved in energy supply chains from regions significantly affected by energy poverty. A total of 1923 responses were collected, of which 1872 met the inclusion criteria for analysis. The sample size was deemed sufficient based on Cohen's (1992) statistical criteria for hypothesis testing. Participants represented three primary categories: supply chain managers (45%), energy providers (35%), and community leaders (20%). This distribution ensured diverse perspectives, capturing insights into logistical operations, technical and financial aspects of energy distribution, and local community needs. Approximately 60% of participants held advanced degrees (master's or doctoral qualifications) in relevant fields such as engineering, supply chain management, and energy studies, while 30% held bachelor's degrees and 10% had vocational training or certifications. This combination of professional roles and educational qualifications underscores the participants' capacity to provide informed perspectives on supply chain practices.

3.5 Measures and instrumentation

The structured questionnaire addressed key constructs related to sustainable supply chain practices, community integration, and their impact on energy poverty alleviation. The first section focused on sustainable supply chain practices, including logistics efficiency, local sourcing, community engagement, regular maintenance, and cost-effectiveness. These measures were adapted from established multi-item scales [22, 34, 43, 60], and validated using exploratory factor analysis (EFA) and confirmatory factor analysis (CFA). Factor loadings exceeded 0.7, demonstrating strong internal consistency and reliability [24]. The second section assessed community integration, emphasising stakeholder feedback incorporation, alignment of supply chain practices with community needs, and capacity-building programs such as training. These items were adapted from Eklund et al. [11] and Choi and Hong [7] and validated through factor analysis. High factor loadings and strong discriminant validity confirmed the construct's robustness. The third section explored perceptions of renewable energy systems and their effectiveness, focusing on reliability, affordability, and overall performance. These measures, adapted from Gonzalez-Salazar et al. [22] and Abu-Ebid and Selby [1], demonstrated strong convergent validity, with average variance extracted (AVE) values exceeding the recommended threshold of 0.5 [15]. The final section employed the NCA framework to evaluate critical supply chain conditions, such as efficient logistics, local sourcing, and community engagement, to determine their necessity for successful energy deployment. Cronbach's alpha values for these measures ranged from 0.718 to 0.925, meeting the acceptable threshold of 0.7 and demonstrating robust internal consistency [4].

3.6 Analysis strategy

The analysis framework models sustainable supply chain practices as necessary but not sufficient conditions for alleviating energy poverty. NCA was employed to identify and quantify these necessary conditions using two primary techniques: CE-FDH and CR-FDH [10, 51, 52]. The dependent variable, energy poverty alleviation, was operationalised through metrics measuring access, reliability, and affordability of renewable energy systems. Independent variables included efficient logistics, local sourcing, community engagement, regular maintenance, and training programs.

Data preparation involved standardising responses to ensure consistency and compatibility with NCA requirements. Ceiling lines were constructed using the NCA package in R, with CE-FDH estimating a piecewise linear ceiling line and CR-FDH providing a continuous ceiling line robust to outliers. Effect sizes were calculated to determine the extent to which each variable constrained energy poverty alleviation, with variables exhibiting effect sizes greater than zero deemed necessary. Bottleneck analysis identified specific thresholds for each necessary condition, clarifying the minimum levels required for successful energy deployment.

Cross-validation and sensitivity analysis were conducted to ensure the reliability and robustness of the findings. These validation processes confirmed that the identified necessary conditions were consistent across various scenarios, reinforcing their criticality for achieving energy poverty alleviation.

4 Results

This study evaluated ten sustainable supply chain practices to identify the conditions necessary for alleviating energy poverty. Using NCA, five practices emerged as the most critical: efficient logistics, local sourcing, community engagement, regular maintenance, and training programs. These practices demonstrated strong effect sizes and high ceiling accuracy values, confirming their indispensability. The remaining five practices—inventory management, supplier partnerships, demand forecasting, technology adoption, and environmental sustainability—exhibited lower effect sizes and were not deemed necessary as standalone conditions. However, their complementary roles are acknowledged and included in Appendix A.

4.1 Effect size and significance testing

The analysis calculated effect sizes (d) for all ten supply chain practices and assessed their statistical significance to confirm their necessity [10]. A condition was deemed necessary if it satisfied three criteria: theoretical justification, an effect size (d) greater than zero, and a p-value less than 0.05. These criteria ensured rigorous validation of each condition's criticality for achieving energy poverty alleviation. Table 1 summarises the effect sizes, ceiling accuracy, and ceiling zones for the five critical practices using Ceiling Envelopment with Free Disposal Hull (CE-FDH) and Ceiling Regression with Free Disposal Hull (CR-FDH) techniques. CE-FDH constructs a piecewise linear ceiling line, while CR-FDH generates a continuous regression-based ceiling line, offering a smoother and more robust representation of thresholds [10]. The discussion focuses on the CR-FDH results, which align closely with those from CE-FDH.

The findings indicate that Efficient logistics demonstrates a large effect size with CE-FDH (d = 0.321) and CR-FDH (d = 0.335), indicating its strong necessity for sustainable supply chain performance. The high ceiling accuracy (94.6% for CE-FDH and 97.6% for CR-FDH) further confirms its critical role. A ceiling zone (10.448% for CE-FDH and 15.229% for CR-FDH) suggests that while efficient logistics is a necessary condition, additional factors may be required to achieve optimal performance. Local sourcing exhibits medium effect sizes (d = 0.234 for CE-FDH and d = 0.223 for CR-FDH), highlighting its moderate necessity. The high ceiling accuracy (95.8% for CE-FDH and 97.0% for CR-FDH) underscores its importance, though the absence of a ceiling zone for CR-FDH suggests that local sourcing alone may not be sufficient for achieving top-tier performance. Community engagement shows a large effect size (d = 0.355 for CE-FDH and d = 0.326 for CR-FDH), indicating its necessity for sustainable supply chains. The high ceiling accuracy (94.6% for CE-FDH and 97.6% for CR-FDH) and the presence of a ceiling zone for CE-FDH (8.774%) suggest that while community engagement is critical, complementary practices may be needed to maximize its impact. Regular maintenance demonstrates medium to large effect sizes (d = 0.258 for CE-FDH and d = 0.218 for CR-FDH). The 100% ceiling accuracy for CE-FDH highlights its necessity, while the presence of a ceiling zone (16.667% for CE-FDH and 7.276% for CR-FDH) indicates that additional factors may enhance its effectiveness. Training programs exhibit large effect sizes (d = 0.285 for CE-FDH and d = 0.252 for CR-FDH), emphasizing their necessity for sustainable supply chain performance. The 100% ceiling accuracy for CE-FDH and the presence of a ceiling zone (18.286% for CE-FDH) suggest that training programs are a critical but not standalone condition for achieving optimal outcomes.

4.2 Necessary condition analysis

Figure 1 illustrates the NCA scatter plots depicting the relationships between energy poverty alleviation and key sustainable supply chain practices: efficient logistics, local sourcing, community engagement, regular maintenance, and training programs. The empty spaces in the upper-left corners of each plot indicate the presence of necessary conditions for alleviating energy poverty. Three ceiling lines are shown: ordinary least squares (OLS), ceiling envelopment with a free

Table 1 NCA results for critical sustainable supply chain practices

Sustainable supply chain practice	Technique	% of observations covered	Mean	Maximum	Effect size (d)	p-value	Ceiling accuracy (%)	Ceiling zone (%)
Efficient logistics	CE-FDH	100	4.979	15.528	0.321	0.000	94.6	10.448
	CR-FDH	89.2	5.197	15.528	0.335	0.000	97.6	15.229
Local sourcing	CE-FDH	100	4.152	17.744	0.234	0.000	95.8	4.211
	CR-FDH	95.8	3.959	17.744	0.223	0.000	97.0	0.000
Community engagement	CE-FDH	100	0.355	22.884	0.355	0.000	94.6	8.774
	CR-FDH	94.6	0.326	22.884	0.326	0.000	97.6	0.000
Regular maintenance	CE-FDH	100	5.343	20.716	0.258	0.000	100.0	16.667
	CR-FDH	97.6	4.511	20.716	0.218	0.011	97.0	7.276
Training programs	CE-FDH	100	5.690	19.933	0.285	0.000	100.0	18.286
	CR-FDH	97.0	5.032	19.933	0.252	0.000	97.6	0.000

Effect Size (d) Interpretation: Small effect ($0 < d < 0.1$), Medium effect ($0.1 \le d < 0.3$), Large effect ($0.3 \le d < 0.5$), Very large effect ($d \ge 0.5$). Source: Author's Analysis Based on Survey Data

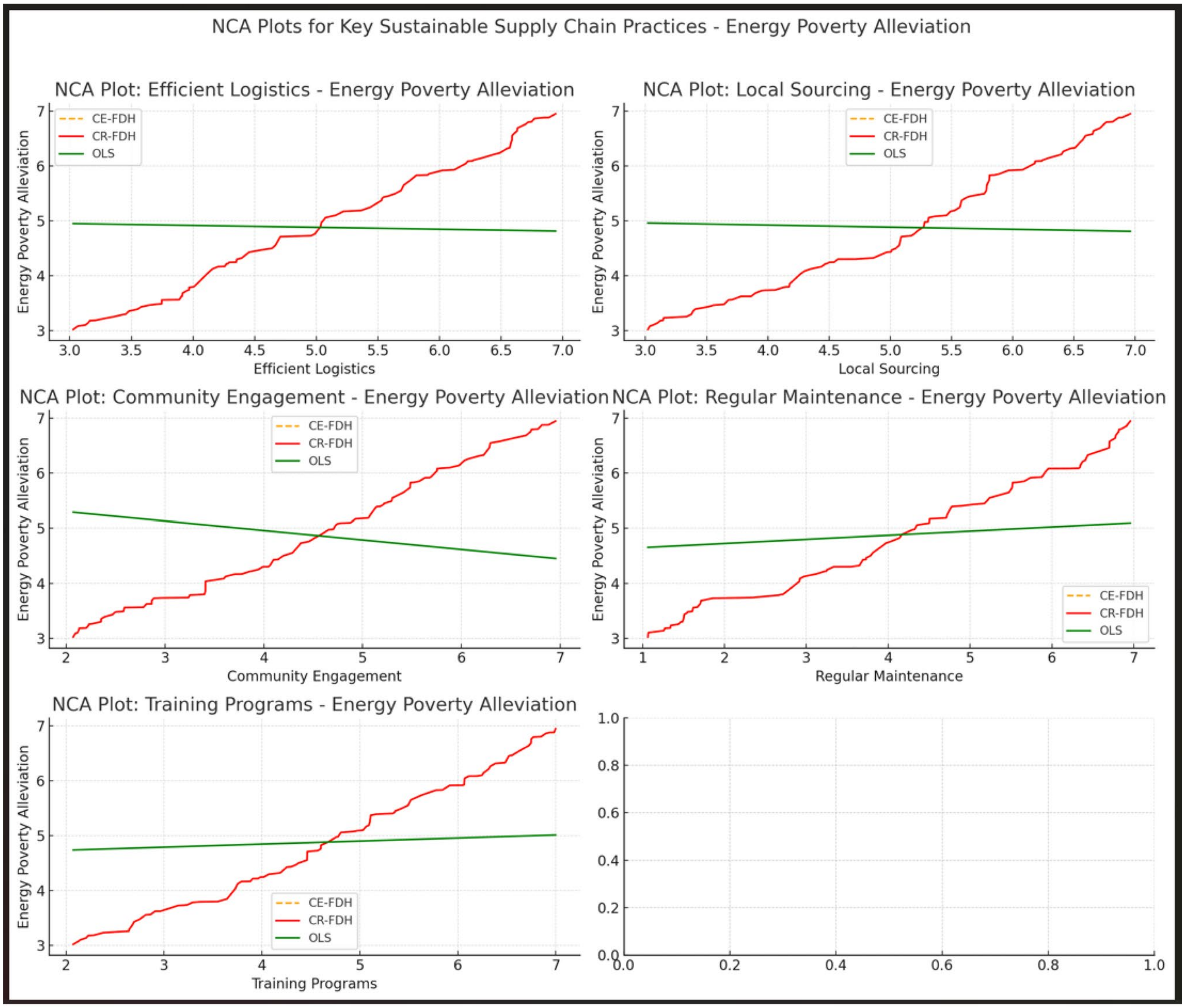

Fig. 1 Necessary condition analysis plots for key supply chain practices

disposal hull (CE-FDH), and ceiling regression with a free disposal hull (CR-FDH). The CE-FDH line is piecewise linear, while the CR-FDH line is continuous. This study prioritises the CR-FDH technique due to its greater accuracy, appropriateness for parametric data, and lower sensitivity to outliers [10, 47].

The ceiling accuracy, or the percentage of observations above the line, ranges from 94.6 to 97.6%, supporting the robustness of these necessary conditions. The ceiling zones span from 0.326 to 5.690, while the ceiling scopes range from 17.744 to 22.884. Effect sizes, obtained by dividing the ceiling zone by the scope, range between 0.218 and 0.355. Following Dul's [10] guidelines, the effect sizes for local sourcing (d = 0.223), regular maintenance (d = 0.218), and training programs (d = 0.252) are categorised as medium. In contrast, efficient logistics (d = 0.326) and community engagement (d = 0.335) are considered large. From 0.000 to 15.229, condition inefficiencies indicate that 100% execution of some practices is not essential for maximum energy poverty alleviation. For instance, Fig. 1a demonstrates that a minimum threshold of community engagement is necessary for significant energy poverty alleviation, with an effect size of 0.335, indicating a large impact. Bottleneck analysis shows that a community engagement score of at least 63.3% is required. However, while necessary, this level alone does not guarantee high alleviation; achieving it only makes high alleviation possible, not certain.

The necessity of each practice was assessed using NCA across five dimensions. Figure 1a–e confirm that efficient logistics, local sourcing, community engagement, regular maintenance, and training programs are indispensable. The effect sizes align as follows: local sourcing (d = 0.223), efficient logistics (d = 0.326), regular maintenance

Table 2 Bottleneck levels (in percentages) using CR-FDH analysis

Energy poverty alleviation (%)	Efficient logistics	Local sourcing	Community engagement	Regular maintenance	Training programs
0	NN	NN	NN	NN	NN
10	NN	NN	NN	NN	NN
20	NN	NN	NN	NN	NN
30	10.2	NN	NN	NN	NN
40	22.8	NN	NN	NN	NN
50	33.5	NN	18.3	NN	11.4
60	43.7	6.2	35.8	18.9	31.2
70	54.5	26.5	52.9	38.2	50.8
80	65.7	46.1	70.4	57.3	71.6
90	76.3	66.7	87.5	76.1	90.7
100	85.9	85.3	NA	94.5	NA

Source: Author's Analysis Based on CR-FDH Method (NN = not necessary)

(d = 0.218), training programs (d = 0.252), and community engagement (d = 0.335). Table 2 outlines minimum thresholds: 6.2 for local sourcing, 10.2 for efficient logistics, 18.9 for regular maintenance, 11.4 for training programs, and 18.3 for community engagement. These thresholds are necessary but insufficient for fully achieving energy poverty alleviation, reinforcing the study's overarching framework.

4.3 Bottleneck analysis

Bottleneck analysis identified the minimum thresholds for the five key practices necessary to achieve varying levels of energy poverty alleviation. For example, efficient logistics required thresholds of 10.2% for medium alleviation (30–80%) and 85.9% for very high alleviation (90–100%). Similarly, community engagement needed thresholds of 8.7% for medium alleviation and 87.5% for very high alleviation. These results illustrate the increasing importance of these practices as energy access goals become more ambitious.

The results of the NCA using the CR-FDH method are presented in Table 2, which details the minimum levels of essential sustainable supply chain practices required to achieve specific outcomes in energy poverty alleviation. This bottleneck analysis expresses these levels as percentages of the observed range, where 0% represents the lowest and 100% the highest observed values [10, 52]. The analysis confirms that each supply chain practice—efficient logistics, local sourcing, community engagement, regular maintenance, and training programs—demonstrates varying degrees of necessity for achieving effective energy poverty alleviation.

Following the effect size assessment, a comprehensive bottleneck analysis was performed (Table 2). The table specifies the minimum values each practice needs to support different alleviation levels. For medium-to-high alleviation (30%–80%), efficient logistics must be at least 10.2%. Local sourcing becomes necessary at higher levels, requiring a minimum of 6.2% for 60% alleviation. At 50–80% alleviation, community engagement must be at least 18.3%, while regular maintenance and training programs need to be at least 17.4% and 11.4%, respectively, for 60–80% alleviation.

For very high levels of energy poverty alleviation (90–100%), efficient logistics must reach 85.9%, while local sourcing, community engagement, regular maintenance, and training programs should not be lower than 66.7%, 87.5%, 76.1%, and 90.7%, respectively. Table 2 illustrates these thresholds, categorising alleviation levels into three bands: low (0–25%), medium (25–75%), and high (> 75%). The findings indicate that no practice is essential at low alleviation levels, but all practices are critical at medium and high levels. For instance, achieving 40% alleviation necessitates a minimum of 22.8% efficiency in efficient logistics. These findings align with the frameworks of Dul [10] and Shahjehan and Qureshi [47], highlighting the strategic importance of targeted investments in supply chain practices to foster impactful and sustainable energy solutions in developing regions.

5 Discussion

This study addresses three fundamental questions about sustainable supply chain practices in energy poverty alleviation, examining necessary conditions, implementation thresholds, and impact factors in developing contexts [10, 19]. While our analysis focuses primarily on renewable energy systems, it's important to acknowledge that traditional energy sources, such as diesel generators, can provide immediate relief in areas with acute energy poverty due to their established infrastructure and rapid deployment capabilities. However, these sources come with significant trade-offs, including environmental degradation and public health risks from emissions [50]. This study's findings should, therefore, be considered within the broader context of energy choices and their implications.

Drawing on the Energy Justice Framework [48] and Socio-Technical Systems Theory [3], our perception-based methodology captures stakeholder insights on supply chain practices and their perceived importance. While this approach provides valuable perspectives, it limits our ability to validate theoretical assumptions with empirical data from specific energy projects. The NCA identified five essential practices, with efficient logistics emerging as the most critical factor, demonstrating the highest effect size (d = 0.335) and ceiling accuracy of 97.6%. This finding strongly supports Gonzalez-Salazar et al.'s [22] and Masood et al.'s [34] emphasis on logistical efficiency's fundamental role in energy access, particularly in remote regions where distribution challenges often impede successful implementation [59, 6].

This study contributes to two key themes in the energy poverty literature: "energy transition and justice" and "efficacy of assistance programs" [28]. Identifying critical supply chain practices advances the understanding of how operational mechanisms can facilitate equitable energy access. The emphasis on community engagement and local sourcing addresses distributive and procedural justice, ensuring that energy solutions benefit marginalised populations and reflect their needs. Additionally, the findings on logistics and maintenance underscore the operational resilience required for effective assistance programs, particularly in regions with challenging infrastructure and socio-economic conditions.

Community engagement is closely followed in importance with an effect size of d = 0.326, validating Abu-Ebid and Selby's [1] and Romero-Lankao et al.'s [45] assertions that participatory approaches are essential for project sustainability. This aligns with previous studies emphasising community involvement in energy transitions [8, 29]. The analysis also revealed moderate but significant effect sizes for local sourcing (d = 0.223), regular maintenance (d = 0.218), and training programs (d = 0.252), confirming these as necessary conditions rather than merely beneficial factors. These findings support Masood et al.'s [34] research on supply chain resilience, Reshard et al.'s [43] work on sustainable practices in developing contexts, and Zhang et al.'s [60] emphasis on capacity building through local engagement.

5.1 Implementation thresholds and practice requirements

The bottleneck analysis provided crucial insights into implementation thresholds, aligning with methodological approaches suggested by Dul [10] and Vis and Dul [56] for identifying necessary conditions. The analysis revealed that different levels of energy poverty alleviation require varying degrees of practice implementation, supporting findings from recent energy poverty studies [28, 40]. For medium-level alleviation (30–80%), efficient logistics requires a minimum threshold of 10.2%, while community engagement needs at least 18.3%, consistent with findings from previous supply chain studies [21, 46]. These requirements increase substantially for very high alleviation (90–100%), with efficient logistics demanding 85.9% implementation and community engagement requiring 87.5%. Similar patterns emerge for other practices, with local sourcing requiring 66.7%, regular maintenance 76.1%, and training programs 90.7% for high-level alleviation. These thresholds provide concrete benchmarks for practitioners and policymakers, supporting Sovacool et al.'s [50] emphasis on structured implementation protocols and aligning with recent research on energy assistance program efficacy [53, 57].

5.2 The role of key supply chain factors

5.2.1 Logistics and distribution effectiveness

The high effect size of efficient logistics (d = 0.335) demonstrates its crucial role as a fundamental prerequisite for successful energy access initiatives, supporting findings from recent studies on energy supply chains in developing countries [22, 34]. This finding is particularly relevant in remote areas where logistical challenges often present significant barriers to energy provision [2, 6]. The analysis reveals that logistical efficiency serves as a foundation upon which other supply chain practices build, aligning with research on supply chain integration [17, 32] and supporting the successful deployment and maintenance of energy systems in challenging contexts [36, 39]. Strategies such as decentralised warehousing, improved transportation networks, and streamlined distribution processes are essential to overcome these challenges, although they require significant investment and stakeholder coordination.

While showing a moderate but important effect size, local sourcing reinforces the argument that leveraging local materials and resources can reduce costs and increase supply chain resilience. This aligns with Masood et al. [34] and Reshard et al. [43], who emphasise the importance of local sourcing in enhancing the adaptability of supply chains and mitigating risks associated with international material procurement. However, the study also acknowledges that the quality and availability of local materials often fall short of technical standards. Capacity-building initiatives targeting local industries, as highlighted by Zhang et al. [60], are crucial to improving material quality and ensuring alignment with the requirements of renewable energy systems.

5.2.2 Community engagement and participation

Community engagement demonstrated a strong effect size (d = 0.326), emphasizing its critical role in ensuring project sustainability. This finding aligns with Romero-Lankao et al.'s [45] research on stakeholder participation and supports Devine-Wright and Devine-Wright's [8] emphasis on community-based energy service provision. The results validate Abu-Ebid and Selby's [1] assertions about participatory approaches and Kalkbrenner and Roosen's [29] findings on community acceptance of renewable energy projects. The analysis reveals that meaningful community engagement enhances both project legitimacy and long-term sustainability through local ownership and active participation [27, 49]. Moreover, community feedback and inclusion in decision-making processes enhance the social legitimacy of energy systems, creating a foundation for equitable and inclusive energy access.

However, achieving meaningful community engagement requires addressing structural barriers such as power imbalances and limited participatory frameworks. As Romero-Lankao et al. [45] highlight, genuine engagement must go beyond tokenism, ensuring that communities have substantial influence over project planning, implementation, and maintenance.

5.2.3 Local sourcing and supply chain resilience

Local sourcing's moderate effect size (d = 0.223) highlights its essential role in building supply chain resilience. While not showing as strong an effect as logistics or community engagement, its importance grows with higher levels of energy poverty alleviation, supporting Zhang et al.'s [60] emphasis on capacity-building initiatives. This finding aligns with recent research on supply chain sustainability in developing economies [34, 42] and studies on local value creation in energy projects [46, 53]. The analysis reveals that local sourcing becomes increasingly critical as projects aim for higher impact, particularly in contexts where international supply chains may prove unreliable or cost-prohibitive [57].

5.2.4 Regular maintenance and technical support

Regular maintenance emerged as a necessary condition with a moderate effect size (d = 0.218), emphasizing the importance of ongoing technical support in maintaining energy system functionality. This finding supports Sovacool et al.'s [50] research on maintenance protocols and aligns with studies highlighting the critical role of technical support in renewable energy sustainability [7, 21]. The analysis reveals that structured maintenance frameworks, supported by adequate funding and technical expertise, are essential for preventing system degradation and ensuring long-term reliability [12, 33].

5.2.5 Training programs and capacity building

Training programs demonstrated a significant effect size (d = 0.252), underlining their importance in building local capacity for system management. This finding supports research on skill development in energy projects [60] and aligns with studies on community empowerment in renewable energy initiatives [1, 45]. The analysis shows that comprehensive training initiatives, when tailored to local contexts, not only enhance operational capabilities but also reduce dependence on external support [27, 29]. This factor becomes particularly critical at higher levels of energy poverty alleviation, where sustained local management capability is essential for long-term success [53, 57].

The interconnected nature of these five factors suggests that successful energy poverty alleviation requires an integrated approach. Each factor demonstrates varying levels of necessity at different stages of implementation, supporting recent theoretical frameworks on sustainable energy transitions [3] and energy justice [48]. The findings indicate that while individual factors are necessary, their effectiveness is maximized when implemented as part of a comprehensive strategy that considers local contexts, community needs, and long-term sustainability requirements [28, 40].

5.2.6 Advancing energy justice and supply chain sustainability

These findings contribute significantly to our understanding of energy justice and supply chain resilience. The high effect sizes of community engagement and training programs support both procedural and distributive justice, ensuring that energy access initiatives not only reach communities but also build lasting capacity for system management. The necessity of local sourcing and efficient logistics underscores the importance of building resilient supply chains that can withstand local challenges while supporting regional economic development.

6 Conclusion

This study demonstrates the critical role of sustainable supply chain practices in alleviating energy poverty, employing Necessary Condition Analysis (NCA) to identify five indispensable practices: efficient logistics ($d = 0.335$), local sourcing ($d = 0.223$), community engagement ($d = 0.326$), regular maintenance ($d = 0.218$), and training programs ($d = 0.252$). These findings underscore the necessity of integrating these practices to build resilient energy supply chains capable of addressing energy poverty comprehensively in Nigeria. The analysis further reveals critical thresholds for achieving high levels of energy poverty alleviation, with very high levels (90–100%) requiring minimum thresholds of 85.9% for efficient logistics and 87.5% for community engagement, offering actionable benchmarks for practitioners [10, 34]. Efficient logistics ensure timely energy delivery, local sourcing enhances cost-effectiveness and resilience, community engagement fosters ownership and acceptance, regular maintenance guarantees system longevity, and training programs build local capacity for sustainable management. Collectively, these findings highlight the interdependence of logistical, social, and technical factors in energy poverty alleviation, reinforcing the need for an integrated approach.

This study contributes significantly to the energy poverty discourse by empirically validating the necessity of these practices and their thresholds, advancing the theoretical understanding of how operational mechanisms drive equitable and effective energy delivery. Integrating Necessary Condition Theory with the Energy Justice Framework provides a robust foundation for understanding the interplay between supply chain practices and energy access outcomes [10, 48]. The findings also address key themes in the literature, such as "energy transition and justice" and the "efficacy of assistance programs," emphasising the importance of distributive and procedural justice in ensuring inclusive energy solutions for marginalised populations [28].

While the study focuses on renewable energy as a sustainable solution, it acknowledges the potential role of traditional energy sources, such as diesel generators, in addressing immediate energy needs in acute poverty contexts. However, these sources have significant trade-offs, including environmental degradation and public health risks [50]. Policymakers should, therefore, adopt transitional strategies that integrate traditional energy sources to meet urgent needs while laying the groundwork for a sustainable shift to renewable energy, balancing immediate energy access with long-term sustainability goals.

6.1 Theoretical and practical implications

Theoretically, this research advances the understanding of supply chain management in energy poverty contexts by empirically validating the necessity of the identified practices and their complementary roles. It demonstrates that integrated approaches yield better energy outcomes, particularly in resource-constrained settings like Nigeria [22]. Practically, the findings provide actionable insights for managers and policymakers. Managers should prioritise resource allocation toward improving logistics efficiency, fostering meaningful community engagement, and developing robust training programs. Policymakers must focus on creating enabling environments for local sourcing and enhancing logistics infrastructure, particularly in rural areas where energy poverty is most acute. A balanced approach addressing all identified practices is essential to maximise the impact of renewable energy initiatives.

6.2 Limitations

While this study's methodology is robust, some limitations must be acknowledged. First, the reliance on a single respondent per organisation may introduce response bias, as individual perspectives may not fully capture the complexities of organisational supply chain challenges. Future studies should consider multiple respondents per organisation to provide an in-depth understanding. Second, the focus on Nigeria, while contextually significant, limits the generalizability of the findings to other developing countries with differing infrastructural, governance, and cultural dynamics. Expanding the geographic scope in future research would enhance the external validity of the results. Third, the use of self-reported data introduces the potential for response biases, such as social desirability or recall biases, which may affect the accuracy of the findings. Additionally, while professional roles and educational qualifications were used as proxies for expertise, these measures may not fully capture the multifaceted and context-dependent nature of expertise required for complex supply chain management. Expertise is influenced by experiential, contextual, and interdisciplinary factors, which were beyond the scope of this study's measures. Finally, the study's cross-sectional design precludes insights into the long-term sustainability and effectiveness of the identified supply chain practices. Longitudinal studies are needed to assess how these practices evolve over time and their enduring impact on energy poverty alleviation. Moreover, emphasising renewable energy supply chains may overlook other potential strategies for addressing energy poverty, such as hybrid energy systems or transitional energy solutions. Future research should explore these alternative approaches to provide a more comprehensive understanding of energy poverty alleviation strategies.

6.3 Future directions

Future research should delve deeper into the interplay between supply chain practices and external factors, including policy frameworks, cultural dynamics, and economic conditions. By broadening the scope to encompass other sectors and regions, scholars can enhance the generalizability of the findings and provide a more comprehensive understanding of sustainable energy solutions. Additionally, longitudinal studies are necessary to evaluate the long-term sustainability and effectiveness of interventions over time. Further investigations should also address specific areas of interest. For instance, integrating traditional and renewable energy sources could provide a balanced approach to meeting both immediate energy needs and long-term sustainability goals. Exploring the role of governance and cultural influences on supply chain effectiveness would yield valuable insights into how contextual factors shape outcomes. Moreover, examining the potential of digital technologies and innovative financing mechanisms could uncover new ways to improve the efficiency and resilience of energy supply chains. Future research should incorporate empirical analyses of specific energy projects to refine practical applications and offer real-world validation of the proposed practices. Investigating regional variations in energy poverty dynamics and supply chain challenges would provide nuanced, context-specific insights, enabling tailored strategies that address the unique needs of diverse communities.

Author contributions Augustine Okeke and Ifeanyi Onyemere contributed to the manuscript through Conceptualization, Methodology, Investigation, Data Curation, Formal Analysis, Visualization, Validation, and Writing—including the Original Draft and Review and Editing. The authors have reviewed and approved the final version of the manuscript and accept accountability for all aspects of the work, ensuring that any questions regarding its accuracy or integrity are properly investigated and resolved.

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Data availability The datasets generated by the survey research during and/or analysed during the current study are available in the Mendeley Data repository https://doi.org/10.17632/fgxw3b8j5d.1. These are also available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate All procedures performed in this study involving human participants were approved by the Ethics committee and in accordance with the ethical standards of the University of Cumbria and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

Consent for publication The authors affirm that human research participants provided informed consent for publication of the images in Figures and Tables used in this article.

Competing interests The authors declare no competing interests.

Appendix

Appendix A

Comprehensive questionnaire for the study

This questionnaire is designed to collect data on sustainable supply chain practices, community integration, and their impact on energy poverty alleviation through renewable energy systems in developing countries. The questions are structured in a 5-point Likert scale format ranging from "1 = Strongly Disagree" to "5 = Strongly Agree." The questionnaire items have been adapted from established scales and previous studies to ensure validity and reliability. Each section includes items that align with the study's objectives and theoretical framework.

Section A: demographic information

1. **Gender:**
   - o Male
   - o Female
   - o Other

2. **Age group:**
   - o 18-24
   - o 25-34
   - o 35-44
   - o 45-54
   - o 55 and above

3. **Role in the supply chain:**
   - o Community Member
   - o Energy Provider
   - o Supply Chain Manager
   - o Policymaker
   - o Other (please specify)

4. **Years of experience in energy sector:**
   - o Less than 1 year
   - o 1-3 years
   - o 4-6 years

- o 7-10 years
- o More than 10 years

Section B: sustainable supply chain practices

This section is adapted from Fontes et al. [14] on sustainable supply chain management in renewable energy and Reshad et al., [42] on supply chain barriers in developing countries.

1. Our supply chain prioritises the use of locally sourced materials.
2. We have efficient logistics systems in place that reduce delays in delivering renewable energy technologies.
3. Our supply chain actively engages with local suppliers to build capacity.
4. We have established processes for regular maintenance and repair of renewable energy systems.
5. Environmental sustainability is a key consideration in our supply chain decisions.
6. Our supply chain operations are cost-effective without compromising on quality.
7. We actively involve community stakeholders in supply chain decisions.
8. Our supply chain practices enhance the reliability of energy systems in rural areas.
9. The supply chain is adaptable to changes in local conditions and needs.
10. There is a clear strategy for managing the supply of renewable energy components.

Section C: community integration in supply chain management

This section is adapted from Eklund et al. [11] on the role of the community in supply chains and Choi and Hong [7] on supply network structures.

1. The community is involved in the planning and implementation of energy projects.
2. Community feedback is regularly sought and incorporated into supply chain processes.
3. Our supply chain operations are well-aligned with local community needs.
4. Community training programs are provided to build local capacity in managing renewable energy systems.
5. Community members are aware of and actively participate in maintaining the energy systems.
6. The supply chain has strong support from local community leaders.
7. Community engagement has improved the sustainability of our energy projects.
8. Local community members are employed within the supply chain.
9. There is a strong partnership between the supply chain operators and the community.
10. The community takes ownership of the renewable energy systems provided.

Section D: perceptions of renewable energy systems and supply chain effectiveness

This section is adapted from Gonzalez-Salazar et al. [22] on renewable energy supply chain optimisation and Abu-Ebid and Selby [1] on supply chain constraints.

1. The current supply chain effectively meets the energy needs of the community.
2. Renewable energy systems provided are reliable and function as expected.
3. There are minimal disruptions in the supply of renewable energy components.
4. The supply chain is responsive to maintenance and repair needs of energy systems.
5. The renewable energy systems are cost-effective in the long term.
6. The supply chain is transparent about costs and operational challenges.
7. There are clear communication channels between the supply chain and the community.
8. The supply chain has successfully reduced energy poverty in our area.
9. Renewable energy systems are easy to use and maintain for local communities.
10. The overall performance of the supply chain meets community expectations.

Section E: critical supply chain conditions (necessary condition analysis)

This section is adapted based on the principles of Necessary Condition Analysis (NCA) from Dul [10] and Goertz and Mahoney [19] on identifying necessary conditions.

1. Efficient logistics are essential for the success of renewable energy projects.

2. Local sourcing of materials is critical for reducing energy costs.
3. Community engagement is necessary for the sustainability of energy systems.
4. Regular maintenance is a must-have for the long-term functioning of energy technologies.
5. Adequate training programs are essential for local management of energy systems.
6. A transparent supply chain is necessary to build trust with the community.
7. Cost-effective supply chain practices are crucial to making energy systems affordable.
8. Reliable supply of components is necessary for uninterrupted energy access.
9. Decentralised supply chains are more effective than centralised ones in rural contexts.
10. Strong partnerships between supply chain operators and communities are critical.

Section F: policy and practical recommendations
This section is adapted to align with the study's objective of providing actionable insights for stakeholders.

1. Policymakers should support local sourcing in supply chains to enhance energy access.
2. Training programs for community members should be prioritised in energy projects.
3. Supply chains should be decentralised to better address rural energy needs.
4. Financial incentives for sustainable supply chain practices would improve renewable energy deployment.
5. Community engagement should be a mandatory component of energy supply chains.
6. Supply chain transparency should be enforced through policy measures.
7. There should be greater investment in logistics to improve supply chain efficiency.
8. Collaboration between NGOs, businesses, and communities can enhance supply chain effectiveness.
9. Regular assessments of supply chain performance are necessary for continuous improvement.
10. Policies should support the development of local maintenance capabilities for energy systems.

Appendix B

Analysis of additional sustainable supply chain practices

The table below provides detailed insights into the remaining five supply chain practices that were analyzed but found to have lower effect sizes and were not deemed necessary as standalone conditions. Their complementary roles in supporting overall supply chain functionality are acknowledged.

Sustainable supply chain practice	Description	Observed effect size (d)	p-value	Complementary role
Inventory management	Practices ensuring adequate stock levels and timely replenishment of renewable energy components	0.089	0.086	Supports uninterrupted supply chain operations and reduces delays in deployment of energy technologies
Supplier partnerships	Collaborative relationships with suppliers to ensure quality and reliability of materials	0.072	0.102	Enhances material availability and reduces risks in the supply chain
Demand forecasting	Use of predictive models to estimate future energy needs and supply chain adjustments	0.054	0.115	Improves planning accuracy and prevents under or over-supply in renewable energy systems
Technology adoption	Integration of advanced tools and systems to optimize supply chain performance	0.081	0.078	Improves logistics efficiency and reduces operational costs
Environmental sustainability	Adoption of eco-friendly practices to minimize the carbon footprint of supply chain activities	0.065	0.098	Promotes alignment with sustainability goals and enhances community acceptance

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