



Understanding Justice Perceptions in Rural Renewable Energy Projects: Evidence from Marginalised Communities in India

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Abstract

Renewable energy interventions in marginalised rural communities often face challenges not related to technology but to how fairness, accountability, and institutional behaviour are perceived by local communities. This study examines justice perceptions among marginalised households, focusing on how interactions with project actors — such as non-governmental organisations, government departments, and implementing agencies — shape community evaluations of decentralised renewable energy interventions across five empirically derived dimensions: technical reliability, financial stability, institutional continuity, procedural predictability, and maintenance responsiveness. The study is grounded in qualitative fieldwork conducted across villages in Kerala, where renewable energy projects had been implemented. Insights from interviews and community discussions were used to identify key justice-related concerns experienced by households during project implementation and post-installation phases. Based on these insights, a structured household survey was developed and administered to 270 respondents from the Scheduled Tribe and the Scheduled Caste. To identify the dominant dimensions underlying justice perceptions, Principal Component Analysis (PCA) was employed as an exploratory tool to organise community perceptions into interpretable components. The findings indicate that multiple, interrelated factors shape perceptions of justice. Key factors include the perceived competence of project actors, transparency in decision-making processes, responsiveness to community needs, and a commitment to long-term maintenance and grievance redressal. The study highlights that perceptions of justice in renewable energy projects are primarily shaped by everyday institutional interactions rather than by technical performance alone. By foregrounding community-defined understandings of fairness and responsibility, the findings offer practical insights for improving the design, implementation, and governance of renewable energy interventions in marginalised rural settings. This study contributes to the literature on renewable energy and governance by providing an empirically grounded understanding of justice perceptions and demonstrating the value of combining qualitative insights with exploratory quantitative analysis to capture community perspectives in marginalised contexts.

Keywords: Energy justice, justice perceptions, renewable energy, decentralised energy, marginalised communities

1. Introduction

Decentralised renewable energy systems have become central to rural development strategies across the Global South (Obi et al., 2025), promoted as sustainable alternatives to grid expansion. Community-based renewable energy interventions are expected to deliver reliable, long-term energy services while strengthening local autonomy and resilience (Terrapon-Pfaff et al., 2014). Beyond environmental benefits, such systems promise continuity of lighting, livelihoods, institutional engagement, and infrastructural presence. However, sustainability in decentralised renewable energy cannot be assumed from installation alone. While projects are often framed as durable and self-sustaining, empirical evidence shows that long-term outcomes vary considerably (Hong et al., 2015). Some systems remain stable and embedded within communities. In contrast, others gradually weaken due to institutional disengagement, maintenance gaps, financial fragility, or governance ambiguity (Sitzenfrei & Rauch, 2014). These variations suggest that sustainability is not merely a technical property but a structured condition shaped by governance arrangements, operational ecosystems, and community expectations (Katre & Tozzi, 2018).

In marginalised communities, where prior experiences of institutional withdrawal may shape trust, sustainability carries normative weight. A system that is perceived as unlikely to endure is not simply inefficient—it risks being experienced as unreliable or unjust. Thus, sustainability becomes a practical lens through which communities evaluate the fairness and credibility of development interventions. This study examines how households in Kerala participating in a decentralised renewable energy project experience and evaluate sustainability, and how these evaluative concerns are internally structured within community perception.

1.1 Energy Justice: Theoretical Foundations

Energy justice has emerged as a central framework for evaluating the fairness of energy systems, particularly in contexts where marginalised communities bear disproportionate burdens from energy transitions and infrastructure interventions. The foundational architecture of energy justice scholarship rests on three analytically distinct but practically interrelated tenets: distributive justice, which concerns the equitable allocation of benefits and burdens; procedural justice, which addresses whether decision-making processes are transparent, inclusive, and accountable; and recognition justice, which examines whether communities are acknowledged in their diversity, dignity, and lived experience (Jenkins et al., 2016; McCauley et al., 2013). Heffron and McCauley demonstrate that this triadic framework transcends disciplinary boundaries — operating across law, political science, sociology, and engineering — making it uniquely suited to the evaluation of community-level project experiences where institutional, material, and social dimensions intersect (Heffron & McCauley, 2017). This framework has become the dominant reference point in energy justice scholarship precisely because it connects material outcomes, institutional processes, and social standing within a single evaluative lens.

Sovacool and Dworkin extend this framework by demonstrating its practical applicability across energy access contexts, arguing that justice in energy systems cannot be reduced to supply adequacy but must encompass procedural fairness, restorative accountability, and the protection of community rights throughout the project lifecycle (Sovacool & Dworkin, 2015). Their work is particularly relevant to decentralised energy settings where communities interact directly with project actors and where institutional behaviour shapes everyday experiences of fairness. A systematic review of energy justice in the developing world by Lacey-Barnacle and colleagues confirms that decentralisation, institutional instability, and gendered marginalisation are recurring structural concerns across Global South contexts, reinforcing the

need to examine justice not merely at the policy level but at the community-project interface (Lacey-Barnacle et al., 2020).

In the Indian context specifically, empirical energy justice scholarship has demonstrated that the three tenets are deeply interconnected in practice. Yenneti and Day's analysis of the Charanaka solar park in Gujarat shows how procedural injustice — manifested through weak information disclosure, tokenistic consultation, and the systematic exclusion of pastoralists and lower-status groups — directly produced unequal distributive outcomes (Yenneti & Day, 2015). Pandey and Sharma extend this argument by demonstrating that recognition failures are not peripheral to participation but constitutive of it. Across multiple Indian cases, communities resisted renewable energy interventions when project actors approached them through a deficit lens, ignoring caste, livelihood, local knowledge, and dignity (Pandey & Sharma, 2021). Taken together, this body of work establishes that justice in rural energy projects is not experienced primarily through abstract policy categories but through the quality of everyday interactions with institutions, rules, and service delivery.

1.2 Sustainability in Decentralised Renewable Energy: From Technical Outcomes to Community Experience

The sustainability literature approaches similar questions from a different starting point, examining why decentralised energy systems endure or fail over time. Sustainability in this context extends well beyond technical performance to encompass institutional stability, financial viability, operational capacity, and governance legitimacy (Katre & Tozzi, 2018; Poudel & Parton, 2018). The convergence between justice and sustainability scholarship is increasingly evident: the conditions that determine whether a project survives are precisely the conditions through which communities evaluate whether it is fair.

Technical reliability remains foundational. Evidence from rural India consistently shows that the adequacy and consistency of electricity supply are the strongest predictors of household satisfaction, with duration, voltage stability, and predictability mattering more than formal connection status alone (Aklin et al., 2016; Bhattacharyya, 2013). Graber and colleagues demonstrate that users in Uttar Pradesh placed particular value on reliable evening electricity, suggesting that predictability at socially meaningful times carries greater weight than aggregate supply hours (Graber et al., 2018). This finding points to an important normative dimension: reliability is not merely a technical metric but a signal of whether a project takes community needs seriously.

Financial stability constitutes a distinct but equally significant dimension. Palit and Chaurey establish that long-term sustainability in off-grid systems requires financial arrangements that support not only initial deployment but ongoing maintenance and component replacement (Palit & Chaurey, 2011). In the Indian mini-grid context, Bandi and colleagues identify a structural tension between business viability and household affordability, in which providers under commercial pressure may prioritise higher-capacity users, resulting in fairness concerns for low-income domestic consumers (Bandi et al., 2022). Barnes and Foley further demonstrate that funding mechanisms for maintenance — often left unspecified at project launch — constitute a critical determinant of long-term system continuity (Barnes & Foley, 2004). For marginalised households, uncertainty about future costs is not merely a financial concern but an evaluative signal about the project's credibility and commitment.

Institutional continuity has emerged as one of the most analytically significant determinants of sustainability outcomes. Katre and colleagues, in a systematic study of community-owned mini-grids in India, find that long-run sustainability depends on the interaction of technical, financial, and institutional capacities — all of which are strengthened through early community

engagement, clear role allocation, and locally legitimate governance (Katre et al., 2019). Gollwitzer and colleagues reframe electricity in mini-grids as a common pool resource whose sustainability depends on simple rules, accountable monitoring, low-cost conflict resolution, and clearly defined collective responsibilities (Gollwitzer et al., 2018). Nathan and colleagues document the cost of failing to build these conditions in Odisha, where most surveyed microgrids became dysfunctional. The lone functional case depended on collective action and local maintenance capacity (Nathan et al., 2022). Lockwood and Smits similarly demonstrate that long-term service delivery in decentralised infrastructure requires clarity of post-project responsibility and durable accountability structures (Lockwood & Smits, 2011).

Procedural predictability — the transparency of decision-making, clarity of rules, and accessibility of grievance channels — shapes how communities interpret institutional behaviour over time. Walker and Devine-Wright establish that procedural transparency is central to community legitimacy in renewable energy projects, with exclusion from key decisions functioning as a signal of disrespect and institutional unreliability (Devine-Wright, 2005; Walker & Devine-Wright, 2008). Stritzke and colleagues demonstrate that accountability and responsiveness in energy access governance depend on rule of law and transparency as foundational prerequisites (Stritzke et al., 2021). In contexts where communities have experienced prior institutional withdrawal, procedural unpredictability amplifies distrust and erodes confidence in project longevity.

Maintenance responsiveness constitutes a fifth and analytically distinct dimension. Yadoo and Cruickshank's cross-national study of electrification technologies identifies maintenance failure as a primary pathway to system deterioration in off-grid settings, with local technical capacity and spare parts availability functioning as decisive mediating conditions (Yadoo & Cruickshank, 2012). Katre and colleagues reinforce this finding, showing that even governance-effective mini-grids depend on local operators capable of resolving routine faults before they escalate into political grievances (Katre et al., 2019). Joshi and colleagues demonstrate that community-inclusive solar interventions in Rajasthan, where local assembly and repair services were embedded, generated significantly stronger user confidence and continued engagement (Joshi et al., 2019). Maintenance responsiveness is therefore not merely an operational concern but an everyday demonstration of institutional answerability.

1.3 Community Perceptions: Measurement Gaps and the Missing Construct

Despite the richness of both the justice and sustainability literatures, the field has not yet produced a validated instrument that integrates community perceptions of project-level justice across service quality, financial arrangements, institutional continuity, procedural clarity, and maintenance responsiveness. Existing measurement approaches remain fragmented. Satisfaction scales capture overall appraisals but do not disentangle the justice meanings embedded within them (Aklin et al., 2016). Choice experiment methods reveal service preferences but are limited in their capacity to capture trust, recognition, and governance concerns (Graber et al., 2018; Gunatilake et al., 2012). Service access indices measure adequacy more than fairness (Pelz & Urpelainen, 2020). Fairness-specific designs using factorial survey methods demonstrate that procedural and distributive fairness can be measured independently, but these approaches have not been adapted to rural decentralised energy contexts in India (Liebe & Dobers, 2020).

Bal and colleagues argue that fairness perceptions in energy transition research remain conceptually thin and empirically undermeasured, and that the field lacks the validated constructs necessary to capture how justice is experienced at the community level (Bal et al., 2023). Halder and colleagues, in a systematic review of energy justice in India, confirm that while distributive, procedural, and recognition claims recur consistently across empirical

studies, measurement frameworks capable of capturing their integration at the project level remain absent (Halder et al., 2023). Brisbois similarly notes that governance for decentralised electricity systems must be evaluated through inclusion, transparency, capacity, and adaptability — dimensions that have not yet been synthesised into a community-level perception instrument (Brisbois, 2020).

1.4 Research Gap and Objectives

The literature thus reveals a clear and significant gap. Energy justice scholarship and sustainability research have developed in parallel rather than in dialogue, with justice frameworks operating at normative and policy levels while sustainability studies treat operational dimensions as managerial variables rather than as community fairness concerns. Neither body of work has examined how communities cognitively organise sustainability-related concerns as justice perceptions at the project level, nor has either produced empirically validated constructs capable of capturing this integration (Ankon et al., 2022; van der Horst et al., 2021).

The present study addresses this gap by examining how households in marginalised communities in Kerala evaluate a decentralised renewable energy project across five theoretically grounded and empirically derived dimensions: technical reliability, financial stability, institutional continuity, procedural predictability, and maintenance responsiveness. Drawing on qualitative fieldwork and a structured household survey, the study employs Principal Component Analysis to assess whether these dimensions are empirically distinguishable in community perceptions. By doing so, it provides an empirically grounded understanding of how sustainability expectations underpin perceptions of justice at the project level — a contribution neither the justice nor the sustainability literature has yet to produce.

2. Methodology

2.1 Research Design

This study adopts an exploratory mixed-methods design to examine how justice perceptions are cognitively organised among marginalised rural households participating in decentralised renewable energy interventions. The sequential design moves from a qualitative phase — used to generate context-grounded survey items — to a quantitative phase employing Principal Component Analysis (PCA) to identify the latent perceptual structure underlying community evaluations. The study was conducted in selected villages in Wayanad and Thiruvananthapuram districts of Kerala, where decentralised renewable energy projects had been implemented among Scheduled Tribe (ST) and Scheduled Caste (SC) communities.

2.2 Study Context: The Micro Solar Dome Intervention

The Micro Solar Dome (MSD) is an off-grid solar lighting technology designed to provide clean, affordable illumination to households without reliable grid connectivity. Each unit comprises a solar dome integrated with a charging unit, delivering direct lighting solutions to individual households. The MSD intervention was implemented across selected villages in Kerala, targeting Scheduled Caste (SC) and Scheduled Tribe (ST) communities identified on the basis of their marginalised energy access status, consistent with the national programme's targeting criteria derived from 2011 Census data on SC/ST population concentration. Implementation in the study area commenced in December 2019 and was completed by April 2022, with the intervention remaining operational at the time of this study (Karthik et al., 2024).

2.3 Study Area and Sampling

A total of 321 households were purposively selected across the two study locations, and 270 completed the survey instrument, yielding a response rate of 84.11%. Non-response was

primarily attributable to household unavailability during scheduled field visits. Where the household head was absent, a return visit was made; households that remained uncontactable after two attempts were excluded from the sample. . The achieved sample of 270 respondents yields a subject-to-item ratio of 10.8:1 for the final 25-item instrument, exceeding the commonly cited minimum ratio of 5:1 and approaching the 10:1 ratio recommended for stable factor solutions (Costello & Osborne, 2005; Nunnally, 1978). Missing data were minimal: no respondent had missing responses on more than two items, and listwise deletion was applied, resulting in no reduction from the achieved sample of 270 for the PCA. All 270 cases were retained in the final analysis.

Purposive sampling was appropriate given the study's focus on communities with specific and shared experiences of the intervention, enabling the capture of justice-relevant perceptions grounded in actual project encounters. The sample comprised 206 respondents from Mananthavady (Wayanad district) and 64 from Vellanad (Thiruvananthapuram district). Of the total sample, 76.3% were from Scheduled Tribe households and 23.7% from Scheduled Caste households. The socioeconomic profile of the sample is presented in Table 1.

Table 1. Socioeconomic characteristics of the household head

Demographic Variable	Category	Frequency	Percentage (%)
Gender	Male	168	62.22
	Female	102	37.78
Caste	SC	64	23.70
	ST	206	76.30
Age (in years)	21–30	25	9.26
	31–40	97	35.93
	41–50	82	30.37
	51–60	37	13.70
	Above 60	29	10.74
Location	Mananthavady (Wayanad district)	206	76.30
	Vellanad (Thiruvananthapuram district)	64	23.70

Source: Primary Data

2.4 Instrument Development: Item Generation

Survey items were developed through a two-stage process that integrated a systematic literature review and qualitative fieldwork. In the first stage, existing scholarship on the sustainability of decentralised renewable energy and energy justice was reviewed to identify broad thematic domains relevant to community-level project evaluation. This review informed the conceptual structure of the instrument, establishing key domains including technical reliability, financial stability, institutional continuity, procedural predictability, and maintenance responsiveness.

In the second stage, qualitative fieldwork comprised eight focus group discussions (FGDs) with 6–8 participants each and two individual semi-structured interviews, engaging a total of 54 community members from the study villages. Field notes were taken during all sessions. Data were analysed thematically, with recurring concerns and expressed experiences coded and grouped into emergent categories. Where the literature had identified broad domains, the qualitative phase provided community-grounded language and context-specific concerns that shaped the precise wording of individual items. Survey items were originally developed in English and subsequently translated into Malayalam by a bilingual researcher familiar with the study context, to ensure comprehension across varying literacy levels among respondents

An initial pool of 27 items was generated. Following review for clarity and contextual appropriateness, a pilot administration was conducted with a small group of respondents prior

to full deployment. Items were refined based on comprehension feedback. Two items — pertaining to role clarity and feedback system accessibility — were subsequently removed during PCA due to low communalities, yielding the final 25-item instrument. The item generation process, including literature sources and corresponding qualitative themes, is presented in Table 2.

Table 2. Item Generation — Literature Basis and Field Survey Themes

Item	Item Label	Literature Source	Field Survey
1	Consistency of energy supply	Bhattacharyya (2013); Khalid et al. (2023)	X
2	Resilience under adverse conditions	Bhattacharyya (2013); Chaurey & Kandpal (2010)	X
3	Stability of energy service provision	Chaurey & Kandpal (2010); Pratiwi & Juerges (2022)	✓
4	Adequacy of energy service	Khalid et al. (2023); Bhattacharyya (2013)	✓
5	Durability of installed systems	Chaurey & Kandpal (2010); Bhattacharyya (2013)	✓
6	Affordability of energy costs	Palit & Chaurey (2011); Grant et al. (2025)	✓
7	Transparency of payment arrangements	Ojong et al. (2025); Palit & Chaurey (2011)	✓
8	Availability of maintenance funds	Barnes & Foley (2004); Palit & Chaurey (2011)	X
9	Long-term financial viability	Palit & Chaurey (2011); Barnes & Foley (2004)	✓
10	Affordability of component replacement	Grant et al. (2025); Khalid et al. (2023)	✓
11	Post-project institutional responsibility	Lockwood & Smits (2011); Katre & Tozzi (2018)	✓
12	Commitment of implementing institutions	Katre & Tozzi (2018); Lockwood & Smits (2011)	✓
13	Institutional response to system failures	Lockwood & Smits (2011); Yadoo & Cruickshank (2012)	X
14	Clarity of institutional accountability	Katre & Tozzi (2018); Lockwood & Smits (2011)	X
15	Continuity of institutional presence	Lockwood & Smits (2011); Katre & Tozzi (2018)	✓
16	Transparency of institutional communication	Walker & Devine-Wright (2008); Katre & Tozzi (2018)	✓
17	Clarity of operational rules	Katre & Tozzi (2018); Lockwood & Smits (2011)	✓
18	Clarity of fault reporting procedures	Katre & Tozzi (2018); Yadoo & Cruickshank (2012)	X
19	Transparency of decision-making processes	Walker & Devine-Wright (2008); Sovacool & Dworkin (2015)	✓
20	Accessibility of grievance mechanisms	Sovacool & Dworkin (2015); Walker & Devine-Wright (2008)	✓
21	Availability of operational support	Yadoo & Cruickshank (2012); Pratiwi & Juerges (2022)	✓
22	Timeliness of repair services	Yadoo & Cruickshank (2012); Lockwood & Smits (2011)	✓
23	Accessibility of technical personnel	Yadoo & Cruickshank (2012); Bhattacharyya (2013)	✓
24	Availability of spare components	Yadoo & Cruickshank (2012); Pratiwi & Juerges (2022)	✓
25	Responsiveness to minor technical faults	Pratiwi & Juerges (2022); Yadoo & Cruickshank (2012)	✓

The final instrument comprised 25 perception-based statements measured on a five-point Likert scale (1 = Strongly Disagree to 5 = Strongly Agree), administered via face-to-face interviews to ensure clarity and inclusivity across varying literacy levels.

2.5 Ethical Considerations

The study was conducted in accordance with the institutional guidelines of the Indian Institute of Technology Kharagpur. Participation in the study was entirely voluntary. Respondents were informed of the research purpose and assured that their responses would remain confidential and anonymous. No personally identifiable information was recorded in the dataset. Informed consent was obtained prior to participation, and respondents retained the right to withdraw at any stage without consequence.

2.6 Analytical Strategy

To identify the latent structure underlying justice perceptions, Principal Component Analysis (PCA) was employed. PCA is appropriate when the objective is to reduce a set of correlated variables to a smaller number of interpretable components while preserving as much variance as possible. Given that the study does not impose predefined justice dimensions, PCA enables the empirical identification of how respondents cognitively organise their evaluative concerns about project sustainability. PCA was preferred over common factor analysis (EFA) because the objective is data reduction and empirical organisation of perceptions into interpretable components, rather than estimation of causally underlying latent factors (Fabrigar et al., 1999). Given the exploratory nature of the instrument and the absence of prior validated constructs in this context, PCA is the more appropriate choice. To verify that the five components were empirically independent, an oblique rotation was tested alongside the primary Varimax solution, as recommended for confirming orthogonality assumptions in PCA (Costello & Osborne, 2005).

Prior to extraction, the suitability of the data was assessed using the Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy and Bartlett's Test of Sphericity. A KMO value exceeding 0.60 and a statistically significant Bartlett's test confirm that the correlation matrix is appropriate for dimensionality reduction. Components were extracted using the principal component method, with retention decisions guided by eigenvalues greater than one and the interpretability of the resulting structure.

Varimax orthogonal rotation was applied to enhance the clarity of component interpretation, yielding a solution in which each item loads strongly on a single component with minimal cross-loadings. Items with factor loadings above 0.40 were considered substantively significant. Following extraction, component labels were assigned inductively based on the conceptual commonality of items within each component.

Internal consistency reliability was assessed for each component using both Cronbach's alpha (α) and McDonald's omega (Ω). Cronbach's alpha assumes tau-equivalence among items — that each item contributes equally to the latent construct — while McDonald's omega relaxes this assumption and is considered a more robust estimator when item loadings vary (McDonald, 1999; Hayes & Coutts, 2020). Reporting both coefficients allows for a more complete picture of internal consistency. Values above 0.70 are considered acceptable and above 0.80 indicate good to excellent reliability (Nunnally, 1978).

The structural stability of the five-component solution was assessed using a split-sample validation procedure. The full sample ($N = 270$) was randomly divided into two equal subsamples ($n = 135$ each), and PCA with Varimax rotation was performed independently on each subsample. Consistency of factor composition, loading ranges, and variance explained across both subsamples was examined to evaluate whether the identified structure was replicable beyond the full-sample solution.

To minimise interviewer bias, field investigators were briefed on neutral administration of survey items and trained to avoid leading prompts. Social desirability bias was addressed through guaranteed anonymity and voluntary participation. To assess potential common method bias — a concern inherent to single-source, self-report survey designs — Harman's single factor test was conducted. An unrotated PCA solution was examined to determine whether a single dominant factor accounted for most of the variance. The first unrotated factor accounted for 17.671% of the total variance, well below the 50% threshold, suggesting that common method bias is not a significant concern in this study.

3. Results and Discussion

3.1 Data Suitability and PCA Outcomes

Prior to the main analysis, descriptive statistics for all 25 items are presented in Table 3. Item means ranged from 3.31 to 4.16 and standard deviations from 0.94 to 1.21, indicating adequate response variance across all items.

Table 3. Item-Level Descriptive Statistics

Item Code	Item Label	Mean	SD
TR1	Consistency of energy supply	4.16	1.123
TR2	Resilience under adverse conditions	3.81	1.111
TR3	Stability of energy service provision	3.73	1.160
TR4	Adequacy of energy service	3.85	1.211
TR5	Durability of installed systems	3.92	1.077
FS1	Affordability of energy costs	4.08	1.094
FS2	Transparency of payment arrangements	4.16	1.092
FS3	Availability of maintenance funds	4.03	1.082
FS4	Long-term financial viability	3.99	1.047
FS5	Affordability of component replacement	3.97	1.022
IC1	Post-project institutional responsibility	3.99	0.937
IC2	Commitment of implementing institutions	4.04	0.997
IC3	Institutional response to system failures	4.07	1.001
IC4	Clarity of institutional accountability	3.56	1.029
IC5	Continuity of institutional presence	4.07	1.102
PP1	Transparency of institutional communication	4.09	0.981
PP2	Clarity of operational rules	4.01	1.047
PP3	Clarity of fault reporting procedures	3.95	0.972
PP4	Transparency of decision-making processes	3.79	1.127
PP5	Accessibility of grievance mechanisms	3.69	1.103
MR1	Availability of operational support	3.48	1.103
MR2	Timeliness of repair services	3.31	0.978
MR3	Accessibility of technical personnel	3.93	1.031
MR4	Availability of spare components	3.58	0.971
MR5	Responsiveness to minor technical faults	3.46	1.037

Source: Primary data

The suitability of the data for Principal Component Analysis was assessed using the Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy and Bartlett's Test of Sphericity. The KMO value of 0.837 exceeds the recommended threshold of 0.60, confirming that the inter-item correlations are sufficiently patterned for dimensionality reduction. Bartlett's Test of Sphericity was statistically significant ($\chi^2 = 3929.686$, $df = 300$, $p < 0.001$), confirming that the correlation matrix is not an identity matrix and that the variables share sufficient common variance to warrant PCA. These results are presented in Table 4.

Table 4. KMO and Bartlett's Test of Sphericity

Test	Value
Kaiser-Meyer-Olkin (KMO) Measure	0.837
Bartlett's Test	3929.686
df	300
Sig. (p-value)	0.000

Source: Calculated from primary data

3.2 Component Extraction and Variance Explained

PCA yielded a five-component solution accounting for 69.997% of total variance, indicating that the identified structure captures the dominant organising principles within community justice perceptions. The eigenvalues, percentage of variance explained per component, and cumulative variance are presented in Table 5. All five components recorded eigenvalues greater than one, satisfying the Kaiser criterion for component retention. The retention decision was further confirmed by examining the scree plot and the interpretability of the resulting structure.

Table 5. Total Variance Explained

Component	Factor Name	Eigenvalue	% Variance	Cumulative %
1	Technical Reliability	4.418	15.956	15.956
2	Financial Stability	3.856	14.467	30.422
3	Institutional Continuity	3.448	14.184	44.606
4	Procedural Predictability	3.040	13.002	57.608
5	Maintenance Responsiveness	2.738	12.389	69.997

Extraction Method: Principal Component Analysis

Source: Calculated from primary data

3.3 Inter-Construct Correlations

An oblique rotation was tested alongside the primary Varimax solution to verify the independence of the five components, as recommended for confirming orthogonality assumptions in PCA (Costello & Osborne, 2005). The resulting inter-construct correlation matrix is presented in Table 6. All correlations among the five components were negligible (range: $-.135$ to $.121$), confirming that the components do not overlap and that Varimax orthogonal rotation was the appropriate choice, as in Table 6.

Table 6. Inter-Construct Correlation Matrix

Component	1	2	3	4	5
Technical Reliability	1.000	-.056	-.035	-.135	.121
Financial Stability	-.056	1.000	.059	-.053	-.033
Institutional Continuity	-.035	.059	1.000	-.021	.035
Procedural Predictability	-.135	-.053	-.021	1.000	.001
Maintenance Responsiveness	.121	-.033	.035	.001	1.000

Note. 1 = Technical Reliability; 2 = Financial Stability; 3 = Institutional Continuity; 4 = Procedural Predictability; 5 = Maintenance Responsiveness.

Source: calculated from Primary data

3.3 Communalities

Communality values for all 25 items are presented in Table 7. Extraction communalities ranged from 0.532 (MR4 — Availability of spare components) to 0.807 (FS5 — Affordability of component replacement), indicating that the five-component solution accounts for a substantial proportion of variance in each item. All communalities exceed the commonly recommended threshold of 0.50, indicating that no item is underrepresented in the extracted structure

Table 7. Communalities

Item code	Item Label	Extraction
TR1	Consistency of energy supply	0.661
TR2	Resilience under adverse conditions	0.773
TR3	Stability of energy service provision	0.757
TR4	Adequacy of energy service	0.744
TR5	Durability of installed systems	0.634
FS1	Affordability of energy costs	0.798
FS2	Transparency of payment arrangements	0.773
FS3	Availability of maintenance funds	0.796
FS4	Long-term financial viability	0.794
FS5	Affordability of component replacement	0.807
IC1	Post-project institutional responsibility	0.548
IC2	Commitment of implementing institutions	0.713
IC3	Institutional response to system failures	0.738
IC4	Clarity of institutional accountability	0.640
IC5	Continuity of institutional presence	0.600
PP1	Transparency of institutional communication	0.705
PP2	Clarity of operational rules	0.710
PP3	Clarity of fault reporting procedures	0.744
PP4	Transparency of decision-making processes	0.736
PP5	Accessibility of grievance mechanisms	0.722
MR1	Availability of operational support	0.630
MR2	Timeliness of repair services	0.699
MR3	Accessibility of technical personnel	0.650
MR4	Availability of spare components	0.532
MR5	Responsiveness to minor technical faults	0.594

Extraction Method: Principal Component Analysis

3.4 Component Matrix and Reliability

Varimax orthogonal rotation was applied to maximise the interpretability of the component structure. The rotation converged in five iterations, producing a clean solution in which each item loaded strongly on a single component with no substantive cross-loadings. All factor loadings exceeded 0.70, well above the 0.40 threshold for substantive significance. The rotated component matrix and Cronbach's alpha values for each component are presented in Table 8.

Table 8. Component Matrix

Factor	Item Code	Item Label	1	2	3	4	5	α	Ω
Technical Reliability	TR1	Consistency of energy supply	0.808					0.895	0.896
	TR2	Resilience under adverse conditions	0.876						
	TR3	Stability of energy service provision	0.864						
	TR4	Adequacy of energy service	0.859						
	TR5	Durability of installed systems	0.779						
Financial stability	FS1	Affordability of energy costs		0.89				0.934	0.934
	FS2	Transparency of payment arrangements		0.874					
	FS3	Availability of maintenance funds		0.888					
	FS4	Long-term financial viability		0.883					

	FS5	Affordability of component replacement		0.885					
Institutional Continuity	IC1	Post-project institutional responsibility			0.737			0.860	0.861
	IC2	Commitment of implementing institutions			0.841				
	IC3	Institutional response to system failures			0.856				
	IC4	Clarity of institutional accountability			0.789				
	IC5	Continuity of institutional presence			0.768				
Procedural Predictability	PP1	Transparency of institutional communication				0.834		0.910	0.902
	PP2	Clarity of operational rules				0.839			
	PP3	Clarity of fault reporting procedures				0.856			
	PP4	Transparency of decision-making processes				0.846			
	PP5	Accessibility of grievance mechanisms				0.857			
Maintenance Responsiveness	MR1	Availability of operational support					0.785	0.842	0.840
	MR2	Timeliness of repair services					0.83		
	MR3	Accessibility of technical personnel					0.804		
	MR4	Availability of spare components					0.724		
	MR5	Responsiveness to minor technical faults					0.767		

Extraction Method: Principal Component Analysis

Source: Calculated from primary data

All five components demonstrated good to excellent internal consistency across both reliability estimators. Cronbach's alpha ranged from 0.842 (Maintenance Responsiveness) to 0.934 (Financial Stability), and McDonald's omega ranged from 0.840 (Maintenance Responsiveness) to 0.934 (Financial Stability), all exceeding the 0.80 threshold for good reliability (Nunnally, 1978). The near-identical α and Ω values across all five components indicate that the tau-equivalence assumption holds well within this instrument, confirming that alpha does not inflate reliability estimates and that the observed consistency is robust across both metrics (McDonald, 1999; Hayes & Coutts, 2020).

3.5 Split-Sample Validation

To evaluate the replicability of the five-component structure, PCA with Varimax rotation was conducted independently on two randomly drawn equal subsamples ($n = 135$ each). In both subsamples, a five-component solution emerged, with all eigenvalues exceeding 1.0, explaining 70.48% and 69.69% of the total variance, respectively — closely approximating the 69.997% explained in the full-sample solution. Factor compositions were highly consistent across subsamples, with items loading strongly on their designated constructs and no substantive cross-loadings observed. Minor variations in component ordering across subsamples were noted but did not affect construct composition. Loading ranges per construct across both subsamples are presented in Table 9.

Table 9. Split-Sample Loading Ranges

Component	Split 1 Loading Range	Split 2 Loading Range
1	.880 – .902	.854 – .867
2	.807 – .866	.723 – .885
3	.804 – .863	.839 – .883
4	.744 – .881	.706 – .828
5	.603 – .814	.772 – .830

Note: Loading ranges derived from Varimax-rotated PCA conducted independently on each subsample ($n = 135$ each).

The convergence of factor structures across independent subsamples provides preliminary evidence of structural replicability within this dataset. Notably, the lower bound of the Maintenance Responsiveness loading range in Split 1 (.603) was comparatively modest relative to other constructs, suggesting that one item within this dimension exhibits slightly less stable cross-sample performance. This finding warrants closer examination in future Confirmatory Factor Analysis work. While CFA on an independent external sample would constitute a stronger test of construct validity, the split-sample consistency supports the robustness of the five-component perceptual architecture identified in the full-sample solution.

3.6 Parallel Analysis

Parallel analysis was additionally conducted using SPSS syntax (O'Connor, 2000) with 1,000 randomly generated datasets and the 95th percentile as the retention criterion (Horn, 1965). The eigenvalues for all five components substantially exceeded their corresponding 95th-percentile random-data thresholds (real eigenvalues: 4.418, 3.856, 3.448, 3.040, and 2.738; random thresholds: 1.691, 1.568, 1.491, 1.421, and 1.363, respectively), while the sixth component eigenvalue (0.758) fell well below its random threshold (1.307), independently confirming retention of five components.

3.7 Discussion

PCA yielded a five-component solution revealing a highly differentiated perceptual structure underlying justice evaluations among households participating in the decentralised renewable energy project. The statistical clarity of the solution — characterised by strong factor loadings, absence of cross-loadings, and high internal consistency — indicates that respondents do not evaluate project justice as a diffuse or undifferentiated judgement. Rather, justice perceptions are cognitively organised into five empirically distinct evaluative domains.

Technical Reliability emerged as the first component, capturing perceptions of supply consistency, resilience under adverse conditions, energy adequacy, and system durability. This finding aligns with established decentralised energy scholarship, which consistently identifies technical reliability as foundational to long-term sustainability and community trust (Bhattacharyya, 2013; Aklin et al., 2016). Critically, the empirical separation of this dimension indicates that households evaluate technical continuity independently from institutional and financial considerations. In this context, system durability functions not merely as a performance attribute but as a visible signal of project credibility. Technical breakdowns are interpreted not only as operational failures but also as potential indicators of deeper institutional instability, connecting distributive justice concerns—the adequacy of what households receive—to the everyday performance of the energy system (Jenkins et al., 2016).

Financial Stability emerged as the second and analytically independent component, encompassing affordability of costs, clarity of payment arrangements, availability of maintenance funds, and long-term financial viability. Although financial planning is widely

recognised as a structural determinant of renewable energy sustainability (Palit & Chaurey, 2011; Barnes & Foley, 2004), its emergence as a distinct perceptual cluster indicates that households cognitively isolate economic continuity from institutional trust. Even when institutional responsibility is perceived positively, uncertainty about replacement cycles or cost transparency may generate scepticism about the overall project's durability. This finding resonates with Bandi and colleagues, who identify an inherent tension between provider viability and household affordability in rural mini-grids, with fairness consequences when cost structures are unclear or unpredictable (Bandi et al., 2022).

Institutional Continuity emerged as the third component, capturing expectations that implementing organisations remain responsible beyond the installation phase. The clustering of items relating to post-project responsibility, institutional commitment, crisis response, accountability clarity, and assurance against abandonment indicates that respondents treat institutional endurance as a core evaluative criterion. In semi-withdrawn governance arrangements — where institutions reduce direct involvement while retaining symbolic association — this concern becomes particularly salient. Lockwood and Smits establish that long-term service delivery in decentralised infrastructure requires durable accountability structures beyond project rollout (Lockwood & Smits, 2011). The present study extends this insight by demonstrating that communities differentiate institutional continuity as a perceptual domain distinct from both procedural clarity and maintenance responsiveness. This distinction carries important implications for recognition justice: sustained institutional presence is interpreted by communities as an acknowledgement of their worth and a signal that the project regards them as ongoing partners rather than passive beneficiaries (Jenkins et al., 2016; Pandey & Sharma, 2021).

Procedural Predictability emerged as the fourth component, encompassing transparency in communication, clarity of operational rules, fault-reporting procedures, transparency in decision-making, and accessibility of grievance mechanisms. Its separation from Institutional Continuity indicates that respondents distinguish between the existence of responsibility and its clarity in enactment. Institutions may remain nominally present yet fail to communicate how decisions are made, how faults should be reported, or how complaints are addressed — all of which independently erode sustainability perceptions. Walker and Devine-Wright establish that procedural transparency is central to community legitimacy in renewable energy projects (Walker & Devine-Wright, 2008), and Sovacool and Dworkin demonstrate that procedural justice encompasses the right of communities to participate in and understand decisions that affect their energy access (Sovacool & Dworkin, 2015). The present findings confirm that procedural predictability operates as an autonomous justice domain at the project level, reinforcing governance stability as an independent pillar of perceived fairness.

Maintenance Responsiveness emerged as the fifth component, reflecting the operational support ecosystem encompassing technician accessibility, repair timeliness, spare parts availability, and responsiveness to minor faults. Yadoo and Cruickshank identify maintenance failure as a primary pathway to system deterioration in off-grid settings (Yadoo & Cruickshank, 2012). The distinct clustering of these items suggests that operational responsiveness is perceived separately from technical durability: a system may be technically robust yet perceived as vulnerable if repair networks are weak. Katre and colleagues demonstrate that even governance-effective mini-grids depend on local operators capable of resolving routine faults before they escalate (Katre et al., 2019). Maintenance responsiveness thus functions as a practical bridge between technology and governance — an everyday demonstration of whether institutions remain answerable to community needs and align with interactional justice principles (Jenkins et al., 2016).

Taken together, the five-component structure reveals that justice perception in decentralised renewable energy projects operates as a layered continuity architecture. Households differentiate among technical stability, financial security, institutional endurance, procedural clarity, and operational support as analytically distinct but experientially interrelated domains. The clarity of separation among these dimensions suggests that justice is not experienced as a singular affective response but as a structured cognitive assessment spanning multiple aspects of project governance and service delivery.

This multidimensional structure has important implications for energy justice theory. Rather than mapping directly onto the canonical distributive-procedural-recognition triad, community justice perceptions appear to be organised through continuity-based signals embedded across the five domains. Technical reliability and financial stability reflect distributive concerns — what communities receive and at what cost. Procedural predictability reflects procedural concerns — how decisions are made and how grievances are handled. Institutional continuity and maintenance responsiveness reflect recognition concerns — whether communities are regarded as partners deserving of sustained engagement and responsive care. The five dimensions thus constitute an empirically grounded elaboration of the energy justice framework as experienced at the project level in marginalised communities.

4. Conclusion

This study examined how marginalised rural households participating in the Micro Solar Dome intervention in Kerala cognitively organise justice-relevant evaluations of a decentralised renewable energy project. Drawing on qualitative fieldwork and a structured household survey, Principal Component Analysis identified five empirically distinct dimensions underlying community perceptions: Technical Reliability, Financial Stability, Institutional Continuity, Procedural Predictability, and Maintenance Responsiveness.

The findings demonstrate that justice perception in decentralised renewable energy contexts is not a singular or undifferentiated construct. Households differentiate technical stability from financial security, institutional endurance from procedural clarity, and operational responsiveness from system durability — treating each as a distinct evaluative domain through which the fairness and credibility of the intervention are assessed. This multidimensional structure constitutes what the study terms a layered continuity architecture: a cognitive framework through which communities evaluate whether a project is likely to remain technically sound, financially viable, institutionally accountable, procedurally transparent, and operationally responsive over time.

The study makes two principal contributions to existing scholarship. First, it demonstrates that the canonical energy justice framework — organised around distributive, procedural, and recognition tenets (Jenkins et al., 2016; Sovacool & Dworkin, 2015) — finds empirical expression at the project level through continuity-based evaluative concerns rather than through abstract justice categories. Technical Reliability and Financial Stability reflect distributive concerns about what communities receive and the costs involved. Procedural Predictability reflects procedural concerns about transparency, rule clarity, and grievance accessibility. Institutional Continuity and Maintenance Responsiveness reflect recognition concerns about whether communities are regarded as ongoing partners deserving of sustained institutional engagement. Second, the study addresses a gap identified in the literature: while justice and sustainability scholarship have developed in parallel, neither has produced an empirically validated construct capturing how communities integrate sustainability expectations and justice perceptions at the project level. The five-component structure presented here constitutes a first step toward such a construct.

Several limitations should be acknowledged. The use of purposive sampling, while appropriate for capturing project-specific experiences, limits statistical generalisability because participants were selected based on specific institutional exposure rather than a random population distribution. The findings reflect the perceptual structure of marginalised ST and SC communities within specific intervention contexts in Kerala and should not be extrapolated without caution. The study does not include outcome measures — such as overall satisfaction or project acceptance — that would permit regression or structural equation modelling to examine how the five dimensions predict evaluative outcomes. Future research should address this gap by incorporating outcome variables and testing the predictive validity of the identified structure. Confirmatory Factor Analysis across independent samples would further strengthen confidence in the structural stability of the five dimensions. Cross-regional and cross-technological comparisons would allow examination of whether this perceptual architecture generalises beyond the MSD intervention and the Kerala context. Specifically, Confirmatory Factor Analysis (CFA) on an independent external sample and testing predictive validity against outcome variables such as household satisfaction and project acceptance are identified as the immediate next steps in validating this instrument.

For policy and practice, the findings suggest that sustainability in decentralised renewable energy interventions must be monitored and managed across all five dimensions simultaneously. Technical performance audits alone are insufficient. Lifecycle financial planning with transparent cost communication, durable accountability structures that clarify post-project institutional responsibility, governance mechanisms that ensure procedural clarity and grievance accessibility, and locally embedded maintenance ecosystems are each necessary — and independently evaluated — conditions for community confidence in project continuity. Where any one layer weakens, broader perceptions of institutional legitimacy and project fairness may erode. These insights are particularly relevant for interventions targeting marginalised communities in semi-withdrawn governance arrangements, where the period following project closure presents the greatest risk of trust breakdown and sustainability failure.

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APPENDIX

Factor	Full Item Statement
Financial Stability	The costs of using this energy system are affordable for our household.
	Funds are available to cover future maintenance of this system.
	The cost of replacing components in the future is affordable.
	The financial arrangements for this system are viable in the long term.
	The payment arrangements for this system are transparent and clearly communicated.
Procedural Predictability	There is a clear procedure for reporting faults with this system.
	The processes by which decisions about this project are made are transparent.
	There is an accessible mechanism for raising grievances about this system.
	The operational rules governing this system are clearly defined.
	Communication from the institutions managing this system is transparent and open.
Institutional Continuity	The institutions involved in this project remain committed to its long-term success.
	The responsible institution responds effectively when serious system failures occur.
	There is clarity about which institution is ultimately accountable for this system.
	The implementing organisation continues to take responsibility for this project after installation.
	The institutions involved in this project maintain a continuous presence in our community.
Technical Reliability	The energy provided by this system is stable and consistent over time.
	This system continues to perform reliably even under adverse conditions.
	The energy supplied by this system is adequate for our household needs.
	The installed system is technically robust and built to last.
	This system provides a consistent energy supply throughout the year.
Maintenance Responsiveness	Repair services for this system are provided promptly.
	Technically qualified personnel are accessible when problems arise.
	Operational support for this system is available when required.
	Minor technical issues with this system receive prompt attention.
	Spare components for this system are available when needed.