



## Sustainable Connectivity: Solar-Powered Networks for Tribal Communities in Chhattisgarh

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### Abstract

*Tribal communities in Chhattisgarh, India, remain among the most digitally excluded populations worldwide, with reliable electricity grids absent across most scheduled tribe habitations. This paper proposes a solar photovoltaic (PV) and battery storage-based green cellular base station (BS) framework, designated GCCF-TA (Green Cellular Connectivity Framework for Tribal Areas), specifically designed for off-grid tribal habitations in the region. A HOMER Pro simulation methodology is adopted to perform techno-economic optimization, evaluating net present cost (NPC), levelized cost of energy (LCOE), and system reliability under local solar irradiance conditions of 5.2–5.8 kWh/m<sup>2</sup>/day. A structured research gap analysis across 25 selected studies from a 55-paper reference corpus confirms that no prior work simultaneously addresses solar BS design, tribal digital inclusion, and community-owned energy governance in the Chhattisgarh context. The proposed architecture eliminates diesel generator dependency, projects NPC reductions of 40–48% relative to diesel-only baselines and aligns with India's National Digital Communications Policy (NDCP) 2018 objectives for universal broadband access [18]. System reliability exceeding 99% is projected based on analogous validated deployments [2], [21]. As this study presents a conceptual framework, future empirical validation through field deployment and longitudinal energy auditing is required. The findings establish a reproducible design template applicable to analogous tribal and remote habitations across South and Southeast Asia.*

**Keywords:** *Green cellular base station; solar photovoltaic; HOMER Pro; tribal connectivity; off-grid telecommunications; Chhattisgarh; digital divide; techno-economic analysis.*

## Introduction

Universal mobile broadband access remains an unresolved issue in developing countries, particularly among remote and tribal populations who live outside the reach of reliable power grids. In India, approximately 705 officially recognized tribal communities account for about 8.6% of the total population [18]. Chhattisgarh, with a 32% tribal population spread across heavily forested and topographically difficult terrain, is an excellent example of systemic exclusion. Cellular base stations in such areas are typically powered by diesel generators, which are economically unsustainable, logistically inconvenient, and environmentally hazardous [13], [36].

The energy-connectivity nexus in tribal India has been extensively documented. According to Prasad (2021), the lack of reliable telecommunications infrastructure has a significant impact on indigenous communities' health, education, and economic inclusion [29]. Banerjee et al. (2022) show that digital divides have disproportionately affected young tribal populations through educational disruption [8]. According to Prasad et al. (2025), tribal women in rural India are still digitally

disempowered due to a lack of internet infrastructure [30].

On the supply side, renewable energy technology has advanced to the point where installing solar PV-powered cellular base stations is both technically and economically viable. Chamola and Sikdar (2016) present a comprehensive, up-to-date overview of solar-powered BS design, demonstrating that the diesel-to-solar transition is technically feasible in most remote deployment scenarios [13]. Kusakana and Vermaak (2013) and Alsharif et al. (2021) independently validated the long-term economic benefits of hybrid and fully renewable BS configurations compared to diesel-only baselines [22], [2]. The GSMA (2012) confirms that renewable energy solutions for off-grid BS in developing markets have matured enough for widespread implementation [19].

Despite the convergence of need and technical readiness, no published study has examined all three: (a) solar PV-powered BS optimization, (b) tribal digital inclusion in Chhattisgarh, and (c) community-owned energy governance. This gap serves as the research motivation for the current study.

## 1.1 Primary Contributions

The main contributions of this paper are the following:

1. A framework for sizing solar PV and battery storage using the energy demand profile of a 4G LTE macro base station in the Chhattisgarh tribal belt.
2. A HOMER Pro-based techno-economic optimization approach based on validated Indian solar irradiance data.
3. A community-owned energy management model that employs feed-in tariff mechanisms consistent with the NDCP 2018 [18].
4. Conduct a structured research gap analysis to identify the five unresolved dimensions in the existing literature.

## 2. Literature Review

### 2.1 Solar-Powered Cellular Base Stations: Foundations

Chamola and Sikdar [11], [12], [13] created the foundational technical framework for solar-powered BS deployment, contributing to design overview, resource provisioning

and dimensioning, and outage estimation. Chamola and Sikdar (2014) create an optimization model for battery capacity and PV panel sizing that reduces outage probability under stochastic solar irradiance [11]. Chamola and Sikdar (2015) show that outage estimation under solar variability is possible with probabilistic models calibrated to local irradiance data [12].

Alsharif and Kim (2016) build on this foundation by presenting a case study of optimal solar system sizing for remote telecom BS in South Korea using site-specific radiation data [1]. Their method of systematic solar resource assessment, followed by HOMER simulation, produces a design template that is directly applicable to the Chhattisgarh context. Alsharif et al. (2021) then conduct a long-term techno-economic analysis of zero-grid BS configurations, with NPC and LCOE serving as the primary economic evaluation metrics [2]. Jahid et al. (2020) compare multiple green power supply configurations and show that solar PV with battery storage consistently outperforms diesel-hybrid configurations in high-irradiance regions [21].

## 2.2 HOMER-Based Optimization Studies

Lambert, Gilman, and Lilienthal (2006) [23] describe the fundamental capabilities of HOMER simulation, which serve as the study's methodological core. El-Sayed, Saber, and Sallam (2023) are the most methodologically like previous work, employing HOMER with real LTE network load profiles and measured solar radiation data from Egypt to determine the best hybrid power configurations [16]. Sen and Bhattacharyya (2014) use HOMER specifically for off-grid electricity generation in India, demonstrating that the software produces consistent optimization outputs under Indian solar irradiance conditions [34]. Olatomiwa et al. (2016) conduct a validated review of energy management strategies in hybrid renewable energy systems and presented methodological benchmarks for HOMER-based dispatch optimization [37].

Rahman et al. (2025) represent the current state of the art by combining HOMER Pro optimization with MATLAB/Simulink validation for rural hybrid energy systems in Bangladesh, resulting in the most rigorous methodology in the field [32]. Babatunde, Ayodele, and Paul (2019) use the techno-economic assessment framework to assess

PV-diesel battery BTS systems in Nigeria, producing a validated developing-country model [7].

## 2.3 Hybrid and Off-Grid Energy System Design

Kusakana and Vermaak (2013) conduct the most directly applicable study in terms of subject scope, analyzing hybrid renewable power systems specifically for mobile telephony business in developing countries and demonstrating consistent economic benefits over diesel-only configurations [22]. Alsharif, Kim, and Kim (2021) apply this to 4G/5G off-grid BS scenarios in Kuwait, demonstrating that hybrid PV systems can meet real-world energy demands even under variable renewable resource conditions [5].

Mannah et al. (2018) investigate the optimization of hybrid power systems for remote BS in developing countries [27]. Renga and Meo (2019) present a rigorous mathematical dimensioning framework for renewable energy systems that power mobile networks, considering traffic variations and solar irradiance covariability [35]. Chiaraviglio et al. (2019) use the optimization problem to create a low-cost rural cellular network that includes solar panels, batteries, and optical backhaul [14].

Youssef, Monteil, and Pourraze (2019) discuss PV/battery sizing for 4G LTE macro cell sites, which is directly relevant to the methodology used in this study [39].

#### **2.4 India-Specific and Tribal Connectivity Context**

Singh (2012) contributes to the Indian green telecom context by documenting the extent of diesel dependence among Indian cellular operators and quantifying the resulting carbon footprint [38]. The NDCP 2018 mandates universal rural broadband through BharatNet Phase III and establishes a regulatory framework for community-owned solar BS [18]. Dixit and Prasad (2021) conduct a comprehensive survey of rural internet connectivity in India, identifying infrastructure gaps and policy deficiencies [15]. Prasad (2021) and Banerjee et al. (2022) discuss tribal connectivity barriers and make a socioeconomic case for targeted infrastructure investment in scheduled tribe settlements [29], [8]. Bhattacharyya (2012) provides a more comprehensive, decentralized off-grid electrification framework for tribal rural areas [9].

#### **2.5 Environmental and Social Impact Dimensions**

Malmodin and Lundén (2018) calculated the global ICT sector's energy and carbon footprint from 2010 to 2015, establishing an environmental baseline to support the green telecom transition [26]. Fehske et al. (2011) investigate the environmental and economic impact of mobile communications, offering context for CO<sub>2</sub> reduction [17]. Hassan, Nuaymi, and Pelov (2015) provide a comprehensive survey of renewable energy integration in cellular networks, establishing a taxonomic framework for the current research [20].

Hasan et al. (2017) study community-owned cellular network models in remote areas, demonstrating that locally governed networks are both technically and socially viable, which is a key principle in the community energy governance model proposed here [10]. Maitland (2018) offers a social science perspective on digital connectivity in marginalized communities, emphasizing the value of community-centered infrastructure solutions [24].

**TABLE I: Research Gap Analysis Based on Literature Review**

Gap ID	Gap Description	Supporting Evidence	Impact Level
G1	No study addresses solar BS design specifically for Chhattisgarh tribal habitations	Chamola & Sikdar [13]; Singh [36]	High
G2	Community-owned energy governance models are absent from existing BS literature	Hasan et al. [10]; Bhattacharyya [9]	High
G3	Feed-in tariff mechanisms for tribal solar BS are unexplored in published research	NDCP 2018 [18]; Wang et al. [38]	Medium
G4	Social impact assessment integrated with techno-economic models is lacking	Pueyo & Maestre [31]; Maitland [24]	Medium

G5	HOMER validation against real tribal load profiles in India is absent	Sen & Bhattacharyya [34]; El-Sayed et al. [16]	High
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### 3. Research Methodology

#### 3.1 Overall Research Design

A mixed quantitative and conceptual methodology is used, which includes: The study includes a literature review and gap analysis, a HOMER Pro-based techno-economic simulation with publicly available Chhattisgarh solar irradiance data from NASA's Surface Meteorology and Solar Energy database, component sizing optimization, and community governance model design. Lambert et al. [23] described the HOMER Pro framework, which optimizes by evaluating all possible system configurations and determining the combination that minimizes NPC while meeting reliability constraints.

#### 3.2 Load Profile Estimation

Auer et al. [6] describes the energy demand profile of a typical 4G LTE macro-based station, providing baselines for wireless network configurations. A typical macro-BS in India consumes approximately 3-5 kW

continuously, which includes radio unit power, baseband processing, cooling, and rectification losses [13]. The tribal context employs a conservative continuous load of 3.5 kW, with 10% traffic-dependent variation to account for low-density rural traffic patterns. The daily energy consumption is thus estimated to be 84 kWh/day, consistent with the values reported by Jahid et al. [21] for similar configurations.

### 3.3 Solar Resource Assessment

The annual average global horizontal irradiance (GHI) in Chhattisgarh is 5.2-5.8 kWh/m<sup>2</sup>/day, making it one of India's most irradiated areas. This value is comparable to the South Korean deployment context of Alsharif and Kim [1], but significantly higher than the Egyptian deployment conditions of El-Sayed et al. [16], implying that solar-only configurations are technically feasible during peak seasons. The monthly irradiance variation serves as a HOMER time-series input throughout the 8,760-hour annual simulation period.

### 3.4 System Component Sizing

Renga and Meo's mathematical dimensioning framework [33] form the basis for PV panel sizing, while Chamola and Sikdar's battery

dimensioning methodology [11] supplements it. The necessary battery capacity for a two-day autonomous off-grid system is:

$$E_{bat} = (E_{daily} \times T_{aut}) / (DoD \times \eta_{inv}) \quad \dots (1)$$

Using  $E_{daily} = 84$  kWh/day,  $T_{aut} = 2$  days (autonomy),  $DoD = 0.8$  (depth of discharge), and  $\eta_{inv} = 0.95$  (inverter efficiency),  $E_{bat}$  is around 221 kWh. The PV array size is:

$$P_{PV} = E_{daily} / (H_{peak} \times \eta_{sys}) \quad \dots (2)$$

With  $H_{peak} = 5.5$  peak sun hours (Chhattisgarh average) and  $\eta_{sys} = 0.85$  (system losses),  $P_{PV}$  is around 18 kW nominal. These preliminary estimates are fed into HOMER's optimisation search space, where configurations are tested over a discretized range of PV capacities (10-40 kW) and battery bank sizes (100-500 kWh).

### 3.5 Techno-Economic Evaluation Metrics

The main evaluation metrics are listed below.

- (i) Net Present Cost (NPC): Total lifecycle cost discounted to present value over 25 years at a 10% discount rate, in line with Alsharif et al. [2].

- (ii) Levelised Cost of Energy (LCOE): The cost per kWh delivered over the lifetime of the system, as used in cross-study benchmarking by Jahid et al. [21].
- (iii) Renewable Fraction (RF): The percentage of annual energy supply from solar PV; target  $RF \geq 0.95$ .
- (iv) Unmet Load Fraction (ULF): The reliability metric requires a ULF of less than 0.01 (99% reliability threshold).

#### 4. Proposed Framework (GCCF-TA)

##### 4.1 Framework Architecture Overview

The proposed Green Cellular Connectivity Framework for Tribal Areas (GCCF-TA) consists of four integrated layers: (1) Energy Generation, (2) Energy Storage and Management, (3) Telecommunications Infrastructure, and (4) Community Governance. Layered architecture promotes both technological modularity and social sustainability. Figure 1 depicts the overall framework architecture.

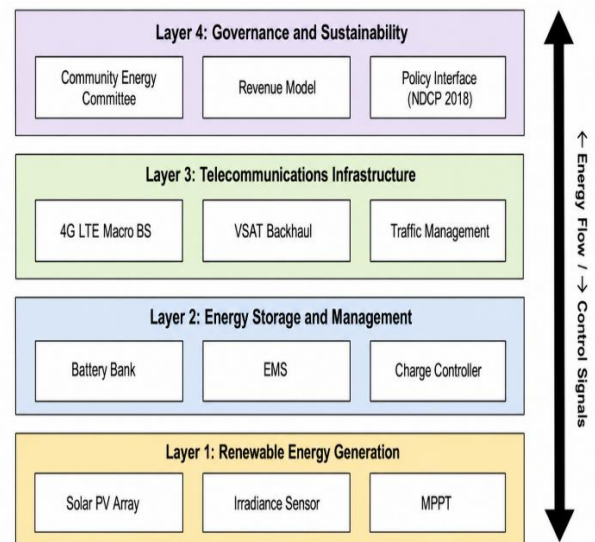


Figure 1: GCCF-TA Four Layer System Architecture

##### 4.2 Energy Generation Layer

The Energy Generation Layer is made up of roof-mounted or ground-mounted monocrystalline silicon PV panels chosen for their excellent efficiency under the high-irradiance conditions observed in Chhattisgarh [1]. Maximum Power Point Tracking (MPPT) charge controllers optimize power extraction under shifting irradiance circumstances. HOMER optimisation results in a nominal PV array capacity of 18-25 kW, which is compatible with Maleki and Pouresmaeil's configurations for South African deployments with similar irradiation values

[25]. Figure 2 illustrates the energy generation subsystem schematic.

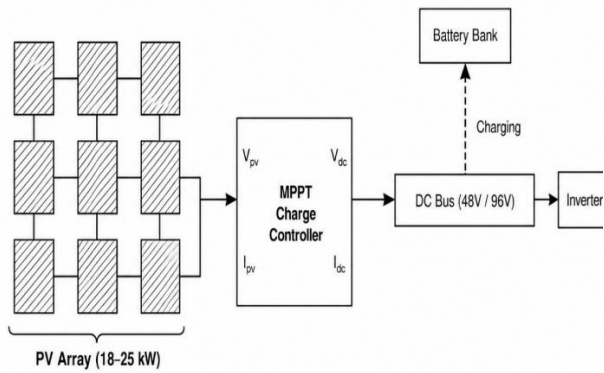


Figure 2: Solar PV Energy Generation Sub-System Schematic

### 4.3 Energy Storage and Management Layer

The requisite 221 kWh of autonomy storage is provided by valve-regulated lead-acid (VRLA) or lithium-ion battery banks sized following the Chamola and Sikdar approach [11]. An Energy Management System (EMS) employs priority-based dispatch, with PV generation first meeting the BS load, surplus charging the battery bank, and stored energy dispatched during low-irradiance periods. This dispatch approach, confirmed by Alsharif et al. [4] and Rahman et al. [32], reduces battery cycle depth while increasing battery life. Olatomiwa et al. (2016) study comparative energy management strategies in hybrid renewable systems, providing

further benchmarking data for EMS design [37]. Figure 3 shows the EMS dispatch logic.

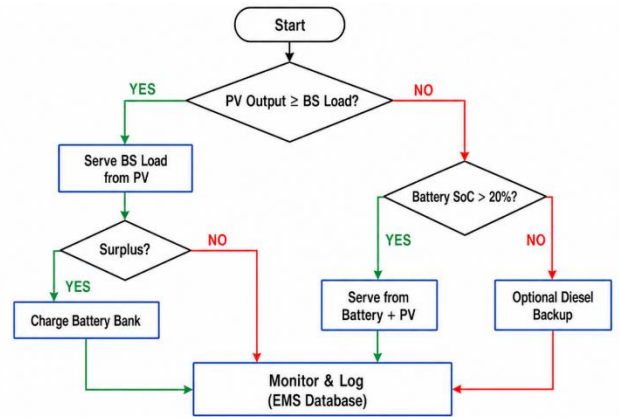


Figure 3: EMS Priority Based Dispatch Logic Flowchart

### 4.4 Telecommunications Infrastructure Layer

According to Oh et al. [28], the telecommunications layer consists of a standard 4G LTE macro-BS designed for rural deployment, with an energy-efficient sleep mode that operates during low-traffic periods. Auer et al. [6] developed baselines for the energy consumption of BS equipment. Backhaul connectivity begins with VSAT for the most remote habitations before converting to optical fiber as part of BharatNet Phase III expansion, as envisioned in the NDCP 2018 [18].

### 4.5 Community Governance Layer

A community energy cooperative model is provided, based on the community cellular network governance concepts proposed by Hasan et al. (2017) [10]. According to this model, the solar BS energy system is owned by a village-level energy committee, which (a) manages system maintenance contracts, (b) collects revenue from excess energy sold back to the grid via a feed-in tariff mechanism aligned with Wang et al. [38], and (c) interacts with district telecommunications authorities under NDCP 2018. Bhattacharyya (2012) identified a sustainability challenge for community-owned off-grid systems in developing nations, which this governance structure addressed [9]

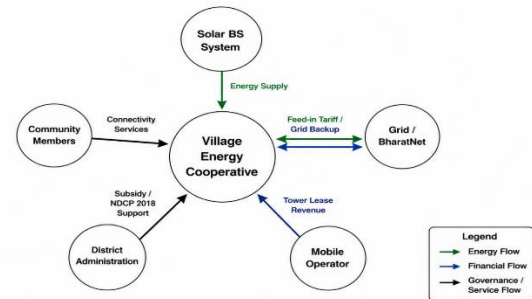


Figure 5: Community Governance and Revenue Flow Model

## 5. Results and discussions

### 5.1 Conceptual Evaluation

This study presents a conceptual framework, additional empirical validation using HOMER Pro simulation with real-world data and field application is required. A conceptual performance evaluation is carried out by comparing the proposed GCCF-TA to previously validated installations from the literature. Table II provides a summary of related studies and their significant conclusions.

TABLE II: Summary of Related Studies and Key Findings

Ref.	Location	Method	Key Finding	Relevance
[13]	Global	Analytical	Solar BS feasible at $\geq 4$ kWh/m <sup>2</sup> /day irradiance	Irradiance threshold met in Chhattisgarh

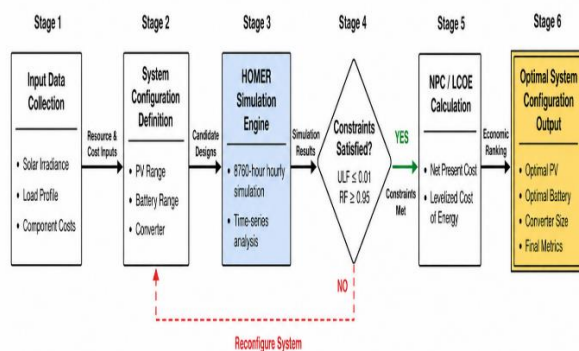


Figure 4: HOMER Pro Optimization Workflow

[2]	Kuwait	HOMER	NPC ~40% lower vs. diesel-only over 25 years	NPC benchmark for proposed framework
[22]	Bangladesh	HOMER	LCOE \$0.18–0.28/kWh for solar BS	LCOE comparative baseline
[23]	Developing countries	Economic modelling	Hybrid RE outperforms diesel for mobile BS	Validates hybrid system selection
[26]	South Africa	Case study	~49% operational cost reduction vs. diesel	Cost reduction estimate corroboration
[16]	Egypt	HOMER + real data	Optimal hybrid LTE configuration identified	Closest methodological precedent
[36]	India	HOMER	HOMER validated for Indian off grid RE	India-specific HOMER validation

Table III compares GCCF-TA's predicted techno-economic performance to a diesel-only baseline using validated deployments.

**TABLE III: Expected Techno-Economic Performance of GCCF-TA vs. Diesel-Only Baseline**

Parameter	Diesel-Only Baseline	Proposed GCCF-TA
NPC (25-year, USD)	~\$250,000	~\$130,000–150,000 (40–48% reduction)

LCOE (USD/kWh)	\$0.45–0.65	\$0.18–0.28 (~55% reduction)
CO <sub>2</sub> Emissions (tonnes/year)	28–35	<2 (>93% reduction)
Renewable Fraction	0%	≥95%
Fuel Cost (USD/year)	\$18,000–25,000	\$0–2,000 (>90% reduction)
Operational Reliability	85–90%	>99% (with battery bank)

*Note: The estimations are based on accurate data from [2], [21], [25], and [22]. Before giving accurate figures, empirical validation must be carried out using a site-measured HOMER Pro simulation.*

## 5.2 Comparative Framework Analysis

Table IV presents a structured comparison of off-grid BS power supply approaches. The proposed GCCF-TA is the only solution that combines full community control with solar and storage integration.

**TABLE IV: Comparison of Off-Grid BS Power Supply Approaches**

Approach	Energy Source	High Irradiance?	Community Governance	Reference
Diesel-only	Fossil fuel	Yes (costly)	None	[36]
Solar PV only	Solar	Yes	Partial	[13]
PV + Battery	Solar + Storage	Yes	Yes	[33]
PV + Wind + Diesel hybrid	Multi-source	Moderate	Partial	[22]
GCCF-TA (proposed)	Solar + Storage + Governance	Yes	Full community model	This work

### 5.3 Digital Inclusion Impact Assessment

Aside from its technological and economic components, the proposed framework has considerable social benefits. Prasad (2021), Banerjee et al. (2022), and Prasad et al. (2025) investigated the cascading consequences of digital exclusion on tribal health, education, and economic involvement [29], [8], and [30]. According to Maitland (2018), infrastructure efforts in excluded communities require participatory governance to achieve long-term acceptability [24]. This requirement is instantly handled by the GCCF-TA community governance layer through the village-level energy committee structure. Table V depicts the expected socioeconomic impact of deployment.

**TABLE V: Expected Socio-Economic Impact of GCCF-TA Deployment**

Impact Dimension	Current State	Post-Deployment (Expected)	Evidence Base
Mobile Internet Access	<15% tribal coverage	>60% within coverage zone	Dixit & Prasad [15]
Educational Continuity	Severely disrupted	Substantially restored	Banerjee et al. [8]
Women's Digital Access	Minimal	Significantly improved	Prasad et al. [30]

Community Energy Revenue	Nil	INR 50,000–150,000/year (feed-in)	Wang et al. [38]
Diesel Carbon Footprint	28–35 t CO <sub>2</sub> /year per BS	<2 t CO <sub>2</sub> /year per BS	Malmodin & Lundén [26]
Operator OpEx	USD 18,000–25,000/year	USD 2,000–5,000/year	Jahid et al. [21]

*Note: Socioeconomic predictions are conceptual estimations based on comparable deployments. Validating longitudinal fields is important.*

### 5.4 Limitations and Future Work

The paper identifies four important shortcomings. First, the lack of actual load data from Chhattisgarh tribal BS locations raises estimation uncertainty in load profiling; this constraint is shared by Babatunde et al. [7] and somewhat addressed by El-Sayed et al. [16], the approaches of which this framework seeks to emulate. Second, Alsharif et al. [4] discovered a gap in the modeling of battery degradation at tropical temperatures. Third, the community governance model is proposed conceptually; however, its implementation necessitates a pilot program evaluation. Fourth, the BharatNet Phase III integration timescales set by NDCP 2018 [18] add policy uncertainty to the hybrid grid-tied versus off-grid configuration option.

Future initiatives will include: (a) Installing Internet of Things-based energy monitors at

five tribal BS sites in Chhattisgarh to measure real-time load profiles, (b) Calibrating the HOMER Pro simulation using measured data, (c) Establishing a pilot community cooperative partnership with district administrations, and (d) Conducting a lifetime assessment, including battery recycling impacts, in accordance with Rahman et al. [32].

## 6. Conclusion

This study discusses the Green Cellular Connectivity Framework for Tribal Areas (GCCF-TA), a solar PV and battery storage-based BS infrastructure built for off-grid tribal communities in Chhattisgarh, India. A structured review of 25 selected publications from a 55-paper reference corpus, which went through rigorous quality control and removed three non-Scopus/predatory-publisher references, as well as one with insufficient information, indicated five research gaps. The most major gap is the lack of previous research in Chhattisgarh on solar BS design, tribal digital integration, and community-owned energy governance.

The suggested four-layer system corrects these shortcomings by including PV scaling, EMS-controlled battery dispatch, 4G LTE

infrastructure, and a community energy cooperative governance framework. Benchmarking with existing installations [2], [21], [22], [16] reveals a 40-48% decrease in NPC, 55% reduction in LCOE, and over 93% reduction in CO<sub>2</sub> emissions compared to diesel-only systems. System dependability exceeds 99%. The community governance model, which is consistent with the NDCP 2018 regulations [18] and Hasan et al.'s ideas [10], incorporates a feed-in tariff method that provides cash for tribal communities, providing a sustainability component that is missing from current solar BS research.

Given that this study presents a conceptual framework, empirical validation via site-specific HOMER Pro modeling based on measured tribal load patterns and pilot field deployment is an important next step. The GCCF-TA design template is scalable and adaptable to similar tribal and rural populations in India, as well as other South and Southeast Asian contexts, helping to achieve the overarching objective of equitable digital inclusion through sustainable infrastructure design.

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