A Decentralised Renewable Energy Framework for Effective Energy Access in Low-Income Housing in South Africa

Huda Elhussein Sidahmed Elhussein[1*], *M M Mostafa* Almadani[1], *Thokozani* Shongwe[1], *Ali* Hasan[2] and *Clinton* Aigbavboa[3]

[1]Department of Electrical and Electronic Engineering Science, University of Johannesburg, Johannesburg, South Africa.
[2]Department of Engineering Technology, Drexel University, Philadelphia, United States of America.
[3]Department of Construction Management, University of Johannesburg, Johannesburg, South Africa

Abstract. Energy poverty in South Africa is increasingly characterised not solely by the presence of a grid connection but also by the reliability, affordability, and productive utility of electricity. This paper reconceptualises the study as a review-based framework for decentralised renewable energy systems in low-income housing. A structured narrative review was conducted by examining recent policy documents, energy access reports, and peer-reviewed studies on solar photovoltaic systems, battery energy storage, mini-grids, embedded generation, community energy models, and financing mechanisms pertinent to South Africa and comparable Sub-Saharan African contexts. The synthesis indicates that decentralised renewable energy systems can augment grid electrification in scenarios where load shedding, weak distribution networks, high connection costs, and household affordability constraints impede effective energy access. However, current approaches remain fragmented due to the frequent separation of technical design from local governance, financing, maintenance capacity, and municipal regulation. The proposed framework integrates four interdependent layers: technical architecture, community governance, financing, and policy alignment. It positions solar PV and battery-enabled microgrids as community-level infrastructure, supported by smart metering, demand management, targeted subsidies, local maintenance skills, and clear municipal implementation rules. The paper contributes by transitioning the discourse from general electrification to an implementation-ready decentralised renewable energy framework for low-income housing, with recommendations directly linked to identified barriers and case-study insights.

1 Introduction

Access to electricity is widely recognised as a core requirement for social welfare, education, health services and local economic activity. Yet the meaning of electricity access has changed. A household may be counted as electrified even if it still experiences unreliable supply, unaffordable energy use, or limited capacity to support productive activities. This distinction is important in South Africa, where formal electrification has expanded substantially, but load shedding, rising tariffs, ageing infrastructure and uneven municipal capacity continue to restrict the quality of energy access, especially in low-income and informal housing areas [1-5].

As of 2025, Africa was still the least electrified continent, with almost 600 million people without access to electricity [1]. South Africa differs from many countries in the region because the national grid reaches a large share of households. Nevertheless, its energy access challenge remains acute because connected households are exposed to supply interruptions and affordability constraints. Recent South African electricity statistics show the continued dominance of coal in the national energy mix, although renewables have increased their share of electricity production from a very low base [3]. This context makes decentralised renewable energy systems relevant not as replacements for the grid, but as complementary infrastructure that can improve reliability and affordability at the settlement or community scale. The research gap addressed in this paper is that existing discussions of decentralised renewable energy in South Africa often treat technology, policy, finance and community participation as separate issues. In low-income housing, this separation weakens implementation because solar PV or mini-grid deployment can fail if tariff design, maintenance capacity, user acceptance and municipal approval are not integrated into the project model. The objective of this paper is therefore to synthesise the literature and propose an integrated decentralised renewable energy framework that links technical design, local governance, financing and policy alignment for low-income housing.

The main contributions of this research survey are four main research contributions:

1. Development of a context-specific decentralised renewable energy framework for low-income housing in South Africa by proposing an integrated framework that combines solar photovoltaic

* Corresponding author: 223257121@student.uj.ac.za

systems, battery energy storage, smart microgrid architecture, community participation, financing mechanisms, and supportive policy instruments to improve electricity access in low-income and underserved settlements.

2. This study synthesises the challenges associated with electricity access in South Africa, emphasising a research gap focused on decentralised renewable energy systems (DRES). It extends beyond a general examination of electricity supply by demonstrating how factors such as load shedding, ageing grid infrastructure, affordability constraints, spatial inequality, and limited grid extension necessitate the implementation of decentralised renewable energy systems, particularly in low-income housing contexts.

This study conducts a structured assessment of decentralised renewable energy systems (DRES) models and the barriers to their implementation. It systematically compares existing DRES approaches, including solar villages, solar home systems, community mini-grids, market-based solar distribution, and community-led maintenance models, to identify their strengths, weaknesses, scalability limitations, and relevance to low-income settlements in South Africa.

The translation of review findings into practical policy, technical, and community-level implementation pathways is crucial. This study connects its findings to actionable recommendations by demonstrating how innovations in financing, local skills development, smart metering, grid modernisation, community ownership, and clearer regulation can enhance the long-term sustainability and equity of the deployment of Distributed Renewable Energy Systems (DRES) in South Africa.

The remaining part of the study is organised as follows: Section 2 presents the structured review methodology adopted. Section 3 examines South Africa's energy access context and the need for decentralised renewable energy systems in low-income housing. Section 4 analyses relevant DRES models and the implementation barriers they pose. Section 5 presents the proposed decentralised renewable energy framework. Section 6 discusses the implications of the framework for policy, practice, and community-level deployment, while Section 7 concludes the study and outlines future research directions.

2 Methodology

The study employs a structured narrative review and a conceptual framework design approach, which is appropriate given that the paper does not present new field measurements or simulations. Instead, it synthesises existing evidence to develop an implementation framework. The review addresses four key questions: what energy access constraints affect low-income housing in South Africa; which decentralised renewable energy technologies are most pertinent; what barriers hinder deployment; and which institutional and financial mechanisms are necessary for scalable implementation. The literature was sourced from three categories. The first category includes official and institutional sources, such as International Energy Agency reports, World Bank energy access data, Statistics South Africa energy statistics, Eskom operational information, and South African energy policy documents [1-5]. The second category consists of peer-reviewed articles on energy poverty, decentralised energy systems, embedded generation, off-grid solar, community participation, and rooftop solar adoption in South Africa and Sub-Saharan Africa [6-14]. The third category comprises case-oriented sources on solar villages, community mini-grids, market-based solar distribution, and local skills models used to assess implementation lessons [8], [11-15].

The synthesis followed a four-step procedure. First, the national energy context was condensed to the factors that directly justify decentralised renewable energy in low-income housing. Second, the reviewed decentralised energy approaches were compared according to technical capacity, affordability, scalability, governance requirements, and suitability for low-income settlements. Third, barriers were grouped into financial, technical, regulatory, social and institutional categories. Fourth, these barriers were mapped to framework components, so that the recommendations are not generic but derived from the findings. Because the review is conceptual, the ranking used in the case-study comparison is qualitative and should be interpreted as an analytical synthesis rather than a statistical score.

The main limitation of this method is that the paper depends on published and institutional sources rather than primary household survey data. To reduce this limitation, the framework is presented as a design and policy tool that requires pilot validation through settlement-level load assessment, willingness-to-pay analysis, user acceptance testing and techno-economic modelling in future work.

3 South African Energy Access Context

South Africa's electricity infrastructure remains highly centralised and historically reliant on coal-based generation. Eskom continues to play a predominant role in both generation and grid operations, while municipalities share responsibility for distribution across numerous urban and peri-urban areas [4, 5]. This institutional framework has facilitated large-scale electrification; however, it has also introduced vulnerabilities when the central generation fleet underperforms or municipal distribution networks lack adequate maintenance funding. Consequently, the issue of energy access in low-income housing is multifaceted. Firstly, reliability is compromised by load shedding and local distribution failures. Secondly, affordability is constrained by low household incomes, tariff increases, and the costs of appliances and prepaid electricity. Thirdly, productive use is limited when electricity is available only intermittently or at insufficient capacity.

Fourthly, grid extension to informal or peripheral settlements is often delayed due to land tenure, planning, and infrastructure constraints. These challenges underscore the necessity for decentralised renewable energy systems that are technically modular, socially inclusive, and financially accessible. It is imperative that South Africa not conceptualise decentralised renewable energy solely as private rooftop solar for middle-income households. Without targeted policy design, such adoption may exacerbate energy inequality, as wealthier consumers can self-supply while poorer households remain reliant on unreliable public supply. Therefore, low-income housing necessitates community-scale or municipally supported models that integrate solar PV, battery storage, smart metering, local maintenance, and affordability protection

4 Synthesis of decentralised renewable energy options

Solar photovoltaic (PV) systems, battery energy storage, smart metering, and mini-grid control systems represent the most pertinent technological clusters for low-income housing. Solar PV is modular and aligns well with South Africa's resource base, while battery storage facilitates the transfer of daytime production to meet evening demand and mitigates the impact of outages. Smart meters and local energy management systems enable prepaid access, demand response, fault detection, and transparent consumption records. In settlements proximate to the grid, a grid-interactive microgrid can integrate local generation with import and export capabilities. Conversely, in areas where grid extension is delayed or impractical, a standalone mini-grid can deliver essential and productive electricity services. The reviewed case concepts indicate that technology alone does not guarantee success. Solar village models illustrate the benefits of community-scale electrification but may encounter challenges when demand exceeds the original design. Models akin to the Barefoot Engineer demonstrate that local skills and women-centred technical training can enhance maintenance and ownership, yet they necessitate sustained institutional support. Market-based solar distribution can rapidly disseminate small solar products; however, lanterns and small solar home systems are insufficient for meeting higher household or productive energy demands. Community empowerment models enhance acceptance and local development outcomes, but scaling these models requires well-defined financial and governance frameworks.

5 Case-study comparison and effectiveness ranking

Table 1 [9]converts the case-study discussion into an analytical comparison. The ranking is based on suitability for low-income housing in South Africa, using five criteria: reliability contribution, affordability pathway, scalability, maintenance feasibility and governance fit. A higher rank indicates stronger alignment with the proposed framework, not an absolute judgement of technological superiority.

6 Proposed decentralised renewable energy framework

Figure 1 illustrates the proposed framework, structured around the principle that access to energy for low-income populations requires integrating four distinct layers. The technical layer encompasses the electricity infrastructure, including solar photovoltaic systems, battery storage, smart meters, protection devices, and a local energy management system. The institutional layer delineates ownership, user participation, operational and maintenance responsibilities, safety regulations, and municipal approval processes. The financial layer incorporates targeted subsidies, pay-as-you-go options, microfinance, community maintenance funds, and blended finance. The policy layer connects the project to embedded generation regulations, municipal electrification planning, tariff regulation, and social protection measures.

Table 1. Analytical comparison of decentralised renewable energy case concepts for low-income housing [9].

Case Concept	Main strength	Main weakness	Best-fit role	Effectiveness rank	Framework implication
Community solar microgrid / solar village	Can supply basic and shared community loads with local PV and storage	High upfront cost and risk of undersizing as demand grows	Core settlement-scale supply model	1	Use phased sizing, shared BESS and maintenance fund
Grid-interactive shared rooftop PV and BESS	Improves reliability where the grid exists, but the supply is weak	Requires clear metering, tariff and interconnection rules	Urban and peri-urban low-income housing blocks	2	Link municipal approval, smart meters and service-priority control
Barefoot Engineer-type local skills model	Strengthens maintenance, ownership and local employment	Needs sustained training and quality assurance	Operations and maintenance support model	3	Combine community technicians with accredited supervision
Market-based solar home products	Fast diffusion and lower entry cost	Limited power capacity for refrigeration, study, business and shared services	Transitional access or backup lighting	4	Use only as a complement, not a main housing energy solution
Donor-led empowerment programme	Strong social inclusion and livelihood focus	Pilot dependency and weak scalability if funding ends	Community mobilisation and inclusion mechanism	5	Convert pilots into municipal procurement and finance models

The framework begins with a settlement-level needs assessment that includes household load profiling, essential service mapping, affordability assessment, grid proximity, land and roof suitability, security considerations, and local governance capacity. These data inform the technical architecture. For grid-connected settlements, the preferred design is a grid-interactive community microgrid with local photovoltaic systems and shared battery storage. For isolated settlements, the preferred design is a phased standalone mini-grid that can later interconnect with the grid where technically and legally feasible.

Energy management should prioritise essential loads such as lighting, refrigeration, study needs, communication, health posts, and small productive activities. A straightforward control objective can be articulated as minimising the weighted sum of unmet demand, battery degradation cost, grid import cost, and user tariff burden, subject to power balance, battery state-of-charge, inverter capacity, and service-priority constraints. Practically, the control system should charge batteries during periods of high solar availability, reserve energy for evening peaks, and maintain minimum service levels during outages.

The governance mechanism is equally crucial. A community energy committee or housing association, supported by the municipality and technical service provider, should oversee user registration, tariff communication, local fault reporting, and maintenance accountability. This structure mitigates the risk that installed systems will become non-operational after project handover. It also ensures transparency in the financing mechanism, as a defined portion of revenue can be allocated for operations, maintenance, and battery replacement.

7 Proposed decentralised renewable energy framework

The synthesis yielded four principal findings. Firstly, the energy issue in South African low-income housing extends beyond mere access deficits to encompass reliability and affordability deficits. This necessitates evaluating decentralised renewable energy systems based on service quality rather than solely on connection numbers. Secondly, while solar photovoltaic (PV) and battery-enabled microgrids are technically viable, they require settlement-specific sizing, as undersized systems rapidly erode user trust as demand increases. Thirdly, community participation is integral to the operational model, as tariff compliance, maintenance reporting, and system protection depend on local acceptance. Fourthly, financing is the primary condition for equity. Without targeted subsidies and low-cost financing directed at low-income users, decentralised renewable energy will predominantly benefit households and firms capable of private investment.

These findings directly address the weaknesses identified in the original paper. Instead of providing general policy recommendations, the revised framework aligns each recommendation with a specific barrier. Financial barriers necessitate targeted subsidies and blended finance. Technical barriers require standardised mini-grid design, smart monitoring, and maintenance planning. Regulatory barriers necessitate simplified rules for embedded generation and mini-grids. Social barriers require participatory planning and the establishment of local energy committees. Skills barriers necessitate technician training and local maintenance contracts.

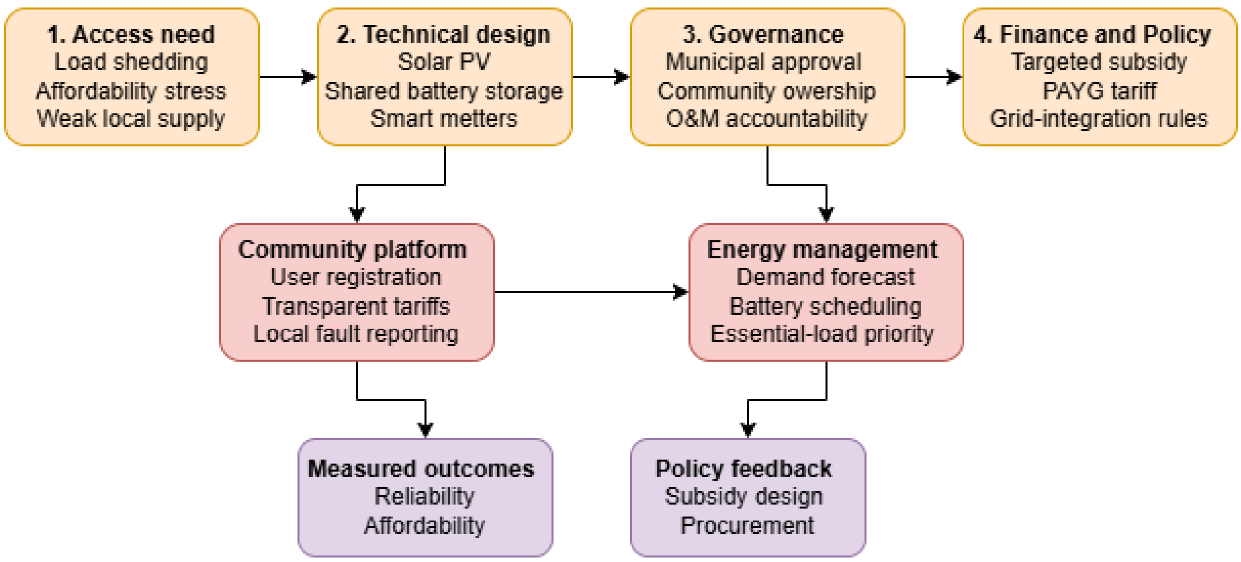

Fig. 1. Integrated DRES framework for low-income housing.

8 Proposed decentralised renewable energy framework

The initial recommendation posits that municipalities should integrate decentralised renewable energy systems into low-income housing infrastructure, rather than treating them as optional household equipment. This integration would facilitate planning for solar photovoltaic systems, batteries, smart meters, and local distribution upgrades, in conjunction with housing, sanitation, public lighting, and community services. The second recommendation advocates for the development of standardised municipal guidelines for low-income microgrids, encompassing safety requirements, ownership models, tariff principles, maintenance responsibilities, and procedures for future grid interconnection. The third recommendation emphasises the need to direct financial support towards communities with limited capacity for self-investment. A strategic combination of capital subsidies, concessional loans, pay-as-you-go tariffs, and maintenance funds can mitigate upfront costs while ensuring the quality of long-term service. The fourth recommendation suggests employing community-based maintenance models supported by accredited technicians. This approach not only reduces downtime but also generates local employment opportunities; however, it should be coupled with formal technical oversight to prevent unsafe installations. The fifth recommendation underscores the importance of embedding performance monitoring in every project. Key indicators should include outage hours avoided, cost per useful kilowatt-hour, battery availability, tariff collection rate, maintenance response time, user satisfaction, and productive-use outcomes. Finally, national and provincial policies should endorse municipal pilot projects across various settlement types. These pilots should evaluate standalone mini-grids, grid-interactive community systems, and shared rooftop solar-and-storage models. The evidence gathered from these pilots can inform procurement standards, subsidy design, and future integration with distribution network planning.

9 Proposed decentralised renewable energy framework

This study is constrained by its reliance on published literature and institutional sources, and lacks primary household survey data, detailed electrical network simulations, or comprehensive life-cycle cost optimisation. Consequently, the effectiveness ranking of case concepts remains qualitative. Future research should validate the proposed framework through pilot projects in selected low-income settlements, incorporating measured load profiles, household affordability surveys, reliability modelling, life-cycle cost analysis, and social acceptance assessments. Additionally, further investigation should explore regulatory pathways for peer-to-peer energy sharing and municipal revenue protection within low-income community microgrid models.

10 Proposed decentralised renewable energy framework

This study developed a decentralised renewable energy framework for improving energy access in low-income housing in South Africa. The review showed that although South Africa has achieved relatively high electrification coverage, many low-income households still experience unreliable, unaffordable, and inadequate electricity access due to load shedding, ageing grid infrastructure, rising tariffs, and spatial inequalities in energy service delivery. These challenges demonstrate that grid connection alone is not sufficient to achieve meaningful energy access, particularly in vulnerable communities. This study established that decentralised renewable energy systems, especially solar photovoltaic systems, battery energy storage, smart microgrids, and community-based energy management models, provide a practical pathway for strengthening energy reliability and reducing dependence on the centralised grid. However, the successful deployment of these systems requires more than technical installation. It depends on appropriate financing models, clear regulatory support, local skills development, community participation, and long-term operation and maintenance structures. The proposed framework contributes to existing knowledge by integrating the technical, economic, institutional, and social dimensions of decentralised renewable energy deployment into a single implementation pathway for low-income housing. It shows that decentralised energy access must be treated as a socio-technical intervention rather than only an engineering solution. By linking renewable energy technologies with community ownership, smart energy management, and inclusive policy support, the framework provides a practical basis for improving energy access, affordability, and resilience in underserved settlements. Overall, decentralised renewable energy systems can play a complementary role in South Africa’s just energy transition by supporting energy security, reducing energy poverty, and advancing Sustainable Development Goal 7. Future research should focus on pilot-scale implementation of the proposed framework, techno-economic optimisation of system sizing, household-level affordability assessment, and performance evaluation under real operating conditions in low-income housing communities.

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