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# Assessing the Contribution of Microgrids to Sustainable Agriculture and Community Development at the Masia Development Centre

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**Abstract:** Despite ongoing efforts to expand rural electrification in developing countries, many communities still lack reliable and affordable electricity. Low population densities, limited economic activity, and modest energy demand make grid extension costly and impractical in remote areas. As a result, renewable energy microgrids are increasingly viewed as viable alternatives for supporting local development. While prior research highlights their technical feasibility, limited attention has been given to how these systems operate as integrated socio-technical interventions that connect energy access with agricultural productivity and broader community outcomes. In South Africa, persistent challenges such as load shedding, unstable grid supply, and limited access to modern energy services continue to disrupt farming activities and constrain education and healthcare delivery. Although renewable energy initiatives have been introduced, evidence of their long-term performance, institutional sustainability, and contribution to livelihoods remains fragmented. In particular, there is limited empirical understanding of how financial, technical, and institutional factors interact to influence microgrid success. This paper addresses this gap by examining the design and implementation of a renewable energy microgrid at the Masia Development Centre in Limpopo Province using a systems thinking approach. It analyses the interactions between technical performance, community participation, agricultural needs, and environmental conditions. By moving beyond purely technical assessments, the study provides context-specific insights into how microgrids can be designed and governed to enhance sustainability, resilience, and rural development outcomes.

**Keywords:** Renewable Energy; Rural Development; Systems Thinking; Energy Access; Limpopo Province

## 1. Introduction

Rural electrification has become a central development priority in many developing countries as part of efforts to advance the Sustainable Development Goals. Access to reliable electricity supports productive activities, enhances agricultural value chains, reduces poverty, and improves education and health outcomes, particularly in rural settings [1,2]. Despite these recognised benefits, large segments of rural populations continue to experience limited or unreliable electricity access. Low population densities, high costs of extending national grids to remote areas, and limited household purchasing power constrain both cost recovery and long-term investment in conventional grid infrastructure [3]. Within this context, renewable energy microgrids have emerged as a viable alternative, offering decentralised and flexible solutions that integrate low-carbon energy sources and can be tailored to local demand and resource conditions [4,5]. Beyond improving basic energy access, microgrids are increasingly recognised for their potential to contribute to sustainable agriculture and community development. By providing reliable electricity for irrigation, agro-processing, cold storage, and digital services, microgrids can enhance agricultural productivity and support livelihood diversification in rural communities [6]. However, evidence shows that the performance and sustainability of microgrids are highly context-specific, shaped by local energy demand profiles, renewable resource availability, storage requirements, and socio-economic conditions [7–9]. While existing studies have largely focused on technical design and cost optimisation, fewer have examined how these context-specific factors influence the broader developmental contributions of microgrids, particularly in relation to agriculture and community well-being.

In South Africa, the need to assess the developmental role of microgrids is especially urgent. Evidence from rural areas in Mpumalanga and Limpopo provinces points to persistent dissatisfaction with existing energy options due to rising electricity tariffs, low household incomes, and continued reliance on firewood for cooking and heating [10–12]. Although electrification coverage has expanded, many rural communities continue to experience unreliable supply and frequent load shedding, which disrupt farming activities, constrain small enterprise development, and reinforce social and economic marginalisation. These challenges highlight the limitations of grid-dependent approaches and underscore the potential value of decentralised microgrid systems in supporting rural development.

Against this backdrop, this study assesses the contribution of renewable energy microgrids to sustainable agriculture and community development at the Masia Development Centre in Limpopo Province. Using a systems thinking approach, the research examines how microgrid design, operation, and governance interact with local agricultural practices, institutional arrangements, and socio-economic conditions. The study evaluates technical, financial, and governance barriers to reliable energy access and explores implementation models that may enhance long-term viability and community ownership. By situating microgrids within the broader rural development system, the paper provides context-specific insights into how decentralised energy solutions can support sustainable agriculture, strengthen livelihoods, and promote inclusive community development in rural South Africa.

### 1.1. Rural Energy Access Challenges

Rural energy access remains a persistent challenge in South Africa, particularly in communities located outside major urban centres, where high levels of energy poverty continue to constrain development. Limited grid coverage and frequent load shedding have been shown to undermine rural economic activities and service delivery, especially in provinces such as Limpopo, the Eastern Cape, and KwaZulu-Natal [12]. Although electrification has expanded considerably since 1994, grid connection has not consistently translated into reliable or affordable electricity for rural households and institutions. Ongoing challenges, including rolling blackouts, voltage instability, and rising tariffs, continue to limit energy security and reduce the developmental benefits of electrification [13]. These conditions underscore the need to assess alternative energy systems that can provide dependable and context-appropriate power in rural settings.

International evidence highlights the growing potential of renewable energy microgrids to contribute not only to energy access but also to sustainable agriculture and community development. Studies of hybrid microgrid systems integrating solar PV, wind, micro-hydro, biogas, and battery storage demonstrate that decentralised energy solutions can achieve favourable economic, environmental, and social outcomes when aligned with local needs [14,15]. The inclusion of employment creation and local infrastructure development as performance indicators reflects the broader developmental role of microgrids, including their contribution to inclusive economic growth and resilient rural infrastructure [16]. Research on advanced storage solutions further indicates that hybrid configurations, such as hydrogen–battery systems, can enhance reliability and reduce emissions in remote communities, strengthening the viability of microgrids as long-term development interventions [17,18]. Related studies within the water–energy nexus also show that well-designed renewable microgrids can support essential services such as water supply while minimising environmental impacts.

In the South African context, unreliable electricity supply continues to disrupt the operation of community facilities that play a central role in agricultural support, youth training, health awareness, and small enterprise development. Power interruptions limit the continuity of programmes, reduce productivity, and weaken the capacity of such centres to contribute to local development. These disruptions deepen existing inequalities by constraining educational opportunities, digital access, and income generation in rural areas. Against this backdrop, assessing the contribution of renewable energy microgrids to sustainable agriculture and community development is critical. Focusing on the Masia Development Centre in Limpopo Province, this study responds to this need by examining how microgrid-based energy systems can support agricultural activities, strengthen community services, and contribute to more inclusive and resilient rural development pathways.

### 1.2. Renewable Energy Solutions

In response to South Africa's persistent rural energy challenges, renewable energy has increasingly been promoted as a practical pathway for improving access, reliability, and sustainability [19]. Technologies such as solar photovoltaic (PV), wind, small hydropower, and biogas have been identified as key contributors to rural energy security. Among these, solar PV has emerged as the most prominent option, largely due to South Africa's high solar irradiance and the rapid decline in global technology costs [20,21]. These technologies are well-suited to off-grid and mini-grid applications, as they allow communities to bypass the constraints of the centralised national grid and adopt decentralised, locally managed energy solutions.

Several initiatives illustrate the potential of renewable energy in rural settings. Pilot solar PV microgrids in provinces such as Limpopo and the Eastern Cape have enabled schools, clinics, and households to access reliable lighting, digital services, and cold storage for medicines, directly supporting improved education and health outcomes [22]. Similarly, biogas digesters implemented in agricultural communities have demonstrated the ability to convert animal and household waste into clean cooking fuel, reducing dependence on firewood while improving sanitation and environmental conditions [23]. Together, these examples show how renewable energy interventions can address energy needs while simultaneously supporting broader development objectives when designed in line with local conditions.

However, comparative evidence, as summarised in **Table 1**, points to a consistent pattern across rural renewable energy initiatives: technology alone is insufficient to ensure long-term sustainability. Experiences from Limpopo Province and the Eastern Cape indicate that donor-funded projects frequently fail once external technical support and institutional oversight are withdrawn [24,25]. By contrast, successful cases such as community-managed micro-hydro systems in Nepal and solar home system programmes in Bangladesh highlight the importance of strong governance structures, meaningful community ownership, and financing models that are adapted to local socio-economic realities.

**Table 1.** Comparative Evidence of Rural Renewable Energy Projects and Outcomes.

| Region/Case | Technology Used | Key Success/Failure Factors | Outcome | Sources |
|---|---|---|---|---|
| Limpopo, South Africa | Biogas digesters & solar PV pilots | Weak community ownership; poor technical training; reliance on donor funds | Many systems abandoned after 2–3 years | Kiptoo et al. [11]; Mohlakoana et al. [26] |
| Kenya & Tanzania | Community solar microgrids | Strong community buy-in; flexible tariffs; local technicians trained | High reliability and expansion to nearby villages | Netshipise and Semenya [15] |
| India | Solar home systems & microgrids | Subsidies reduced upfront cost; but weak institutional coordination led to duplication and waste | Mixed: rapid adoption but long-term sustainability uncertain | Kothari et al. [9] |
| Nepal | Micro-hydro schemes | Cooperative ownership; clear governance; community contributions for maintenance | Long-term sustainability and local income generation | Zahedi et al. [12] |
| South Africa (Eastern Cape) | Off-grid solar systems | Limited technical support; weak policy follow-up after pilot | Systems failed after donor exit | Qudrat-Ullah [20]; Nhamo et al. [21] |
| Bangladesh | Solar home systems (SHS) | Microfinance + after-sales support + national program integration | World's largest SHS adoption (>4 million households) | Kiptoo et al. [11]; Alluraiah and Vijayapriya [8] |

The effectiveness of renewable energy in rural South Africa is closely tied to issues of affordability, scalability, and governance. While technology costs have decreased significantly, initial capital investment remains prohibitive for many rural households and small enterprises [27]. This makes access to financing mechanisms such as microcredit, subsidies, and community financing models essential for uptake [26]. Moreover, renewable energy adoption is not simply a technical exercise but requires integration into existing socio-economic systems. For example, studies reveal that community buy-in, training, and ownership models are as critical to the success of rural renewable projects as the technology itself. Where community engagement is lacking, projects often face sustainability issues, including poor maintenance, vandalism, or underutilization.

## 2. Materials and Methods

### 2.1. Research Design

This study adopts a qualitative systems thinking research design, guided by the systems framework proposed by Matsa et al. [28], to examine how renewable energy initiatives can support sustainable agriculture and community development at the Masia Development Centre in Limpopo Province, South Africa. Systems thinking is appropriate for this study because rural energy interventions operate within complex socio-technical systems, where outcomes are shaped by interactions between technology, users, institutions, and environmental conditions, rather than by technical performance alone. A scoping review was conducted to establish the conceptual and contextual foundation of the study. The review included peer-reviewed journal articles, government policy documents, institutional reports, and technical studies related to renewable energy implementation, rural electrification, and sustainable agricultural development in South Africa and comparable contexts. This process enabled the identification of recurring themes such as energy access inequalities, barriers to renewable energy adoption, institutional coordination challenges, capacity-building needs, and the socio-economic impacts of decentralised energy systems. These themes informed both the analytical framework and the interpretation of the case study. Document analysis was also undertaken to examine policy and planning instruments influencing renewable energy development in the study area. Key documents included the Integrated Resource Plan (IRP), the Limpopo Green Economy Plan, and relevant Integrated Development Plans (IDPs). These documents were analysed to assess alignment between national renewable energy policy objectives and local development priorities, particularly those linked to agriculture, skills development, and community services.

### 2.2. Comprehensive Energy Solution Planning (CESP) Framework and Data Sources

Comprehensive Energy Solution Planning (CESP) was adopted as a systems-based methodological framework to guide data collection and analysis in this study. Consistent with systems thinking principles [28], CESP enables the examination of renewable energy interventions as part of interconnected socio-technical systems that link energy infrastructure, agricultural activities, institutional arrangements, financial mechanisms, and human capacity. The framework was used to structure empirical inquiry at the Masia Development Centre and to organise the analysis of multiple data sources.

**Figure 1** presents the CESP framework as a systems thinking diagram, illustrating the five interrelated stages and the feedback loops between them. The diagram emphasises that energy planning is not a linear process but an adaptive system in which learning, institutional interaction, and changing demand continuously influence system performance and sustainability.

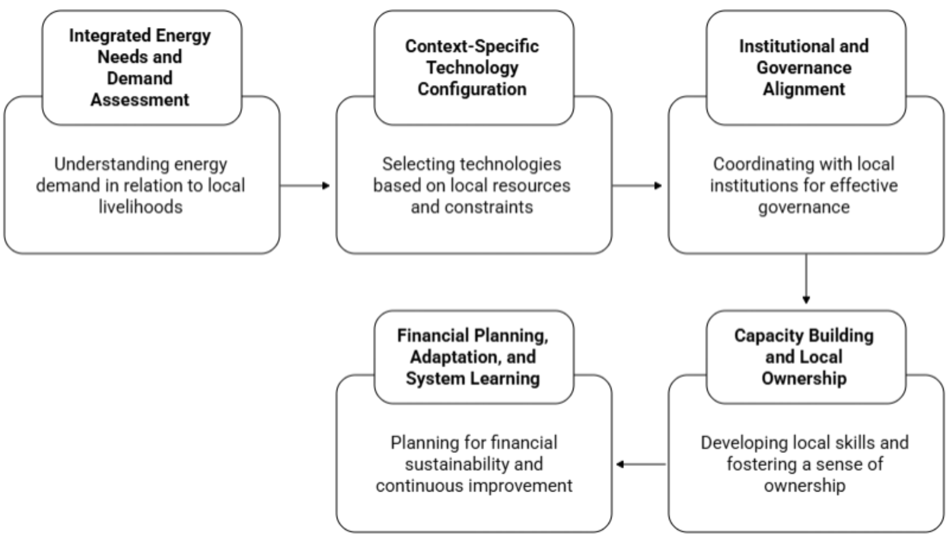


**Figure 1.** Comprehensive Energy Solution Planning (CESP): Conceptual Stages and Application.

#### 2.2.1. Stage 1: Integrated Energy Needs and Demand Assessment

Stage 1 focused on understanding energy demand in relation to livelihood activities and development functions at the Masia Development Centre. Data for this stage were drawn from direct site observations, operational records, and institutional documents, including agricultural production plans and training schedules. Observations were used to identify energy-use patterns associated with irrigation, agro-processing, training facilities, and digital learning infrastructure. Document analysis supported the identification of seasonal demand variations and peak-load periods. Where available, informal discussions with centre staff and technical personnel were used to clarify operational practices. This triangulation of documents, observations, and stakeholder inputs enabled a contextualised assessment of energy demand consistent with systems-based planning approaches.

#### 2.2.2. Stage 2: Context-Specific Technology Configuration

Stage 2 examined the suitability and configuration of renewable energy technologies in relation to local resources and operational constraints. Data sources included technical system documentation, site observations of installed infrastructure, and interviews with system operators and technical support personnel. Document analysis provided information on system design specifications and component selection, while observations enabled assessment of system integration, functionality, and maintenance conditions. Interviews were used to explore practical challenges related to technology operation, spare-part availability, and user competence. This stage applied systems thinking by evaluating technology choices within their broader institutional and human context rather than as isolated technical components.

#### 2.2.3. Stage 3: Institutional and Governance Alignment

Stage 3 focused on institutional arrangements and governance structures shaping system operation and sustainability. Data were drawn primarily from policy and planning documents, including the Integrated Resource Plan (IRP), Limpopo Green Economy Plan, Integrated Development Plans (IDPs), and institutional governance records of the Masia Development Centre. Semi-structured interviews with institutional representatives and management staff were used to examine coordination mechanisms, roles and responsibilities, and decision-making processes. Observational data from engagement meetings and site visits complemented document and interview data. This stage aligned with the systems thinking emphasis on institutional interaction and coordination as critical determinants of system outcomes.

#### 2.2.4. Stage 4: Capacity Building and Local Ownership

Stage 4 assessed capacity development initiatives and local ownership processes supporting system sustainability. Data sources included training records, programme reports, and direct observations of system operation and maintenance practices. Interviews with trained youth, centre staff, and management provided insight into skill acquisition, confidence in system operation, and perceived ownership of the energy infrastructure. Observations were used to assess how training translated into day-to-day operational practices. This stage reflects systems thinking perspectives that recognise human capacity and ownership as integral components of socio-technical systems.

#### 2.2.5. Stage 5: Financial Planning, Adaptation, and System Learning

Stage 5 examined financial planning mechanisms and adaptive system management processes. Data sources included financial records, maintenance logs, project budgets, and institutional planning documents. Interviews with management and technical personnel were used to explore approaches to operation and maintenance financing, component replacement, and system upgrading. Observational data provided insight into how financial constraints influenced maintenance practices and system performance. This stage explicitly incorporated feedback loops, as depicted in **Figure 1**, by examining how operational experiences and user feedback informed financial decision-making and system adjustments over time, consistent with adaptive systems thinking approaches.

**Figure 1** illustrates the Comprehensive Energy Solution Planning (CESP) framework as a systems thinking model applied in this study. The diagram presents five interrelated stages: integrated energy needs and demand assessment, context-specific technology configuration, institutional and governance alignment, capacity building and local ownership, and financial planning, adaptation, and system learning. These stages are shown as interconnected components rather than a linear sequence, highlighting the feedback loops through which operational experience, institutional interaction, and user behaviour inform ongoing system adjustment. By situating energy infrastructure within broader agricultural, institutional, and community development systems, the framework emphasises adaptive planning and continuous learning as central to the long-term sustainability of decentralised rural energy systems.

Together, these five CESP stages demonstrate how renewable energy systems can be planned and implemented as integrated development solutions rather than isolated technical projects. Applied to the Masia Development Centre, the CESP framework provides a practical pathway for aligning energy infrastructure with sustainable agriculture, skills development, and community empowerment. This conceptualisation reinforces the value of CESP as a planning and implementation approach for rural renewable energy initiatives operating within complex socio-technical systems.

### 2.3. Data Collection

In addition to the secondary sources reviewed, this study gathered contextual information about the Masia Development Centre through multiple qualitative data sources, including institutional records, project reports, and local narratives detailing the centre's current energy situation. The purpose was to develop a comprehensive understanding of both the technical and social systems influencing renewable energy implementation in the area. Institutional records and project documentation provided information on existing infrastructure, energy consumption patterns, grid reliability issues, and previous renewable energy interventions at the centre. These sources helped establish the technical baseline and identify opportunities for integrating renewable solutions such as biogas, solar photovoltaic systems, or hybrid models suitable for agricultural and community use.

Complementing the technical data, local accounts and stakeholder perspectives were gathered through informal discussions and interviews with individuals involved in the centre's management, local authorities, and community members who interact with the facility. These qualitative insights offered a deeper understanding of the social dimensions of energy use, including stakeholder roles, community participation, perceptions of renewable energy, and capacity gaps in maintenance, training, and institutional coordination. This combination of documentary evidence and contextual input allowed the study to capture the interconnected nature of technical and social systems at Masia. It also enabled the mapping of feedback loops, for example, how energy access influences agricultural productivity and how community involvement affects the sustainability of energy projects. All data sources were selected purposefully to align with the systems thinking framework, ensuring that both quantitative indicators (such as energy demand and infrastructure data) and qualitative insights (such as user experiences and institutional dynamics) were integrated into the analysis.

### 2.4. Data Analysis

Data analysis followed a thematic systems mapping approach consistent with the principles of Sovacool and Dworkin's [29] systems framework. This approach allowed the study to move beyond linear cause-and-effect relationships and instead examine the dynamic interactions among the various elements influencing renewable energy implementation at the Masia Development Centre. Information gathered from the literature, policy documents, institutional reports, and local contextual data was organized and coded thematically. The coding process focused on identifying major system components such as energy generation and demand, storage capacity, financing mechanisms, institutional governance, and community participation. Each component was analyzed for its role within the broader system and its connections to other components. Once initial themes were established, the data were further examined to reveal interdependencies and feedback loops within the system. Reinforcing loops, for instance, how improved energy access can enhance agricultural productivity and community livelihoods, were distinguished from balancing loops that might constrain system growth, such as maintenance challenges or limited financial support. The analysis also considered potential unintended consequences, like increased energy demand outpacing capacity or policy misalignment hindering project sustainability. Through this process, leverage points for intervention were identified as areas within the system where targeted actions could produce significant positive change, such as improving technical training, enhancing coordination between institutions, or promoting inclusive financing models. The final stage of analysis involved synthesizing the findings into a conceptual framework that illustrates the interconnections between renewable energy systems, agricultural productivity, and community development. This framework serves as a basis for designing adaptive and context-sensitive renewable energy interventions at Masia and offers insights applicable to similar rural development settings.

In summary, this study employed a qualitative systems thinking approach to explore pathways for renewable energy implementation that support sustainable agriculture and community development at the Masia Development Centre. The research design combined a scoping review of literature and policy documents with contextual data from institutional records and local stakeholder inputs. This integration of multiple data sources provided both the technical and social perspectives necessary to understand the complexity of rural energy systems. Data were analyzed thematically and mapped within Meadows' systems framework to uncover interconnections, feedback loops, and leverage points for intervention. The resulting conceptual framework provides a foundation for adaptive and inclusive renewable energy strategies tailored to rural contexts like Masia.

## 3. Results

The study examined the role of renewable energy microgrids at the Masia Development Centre in supporting sustainable agriculture and community development. Data from institutional records, project reports, and stakeholder interviews highlighted energy reliability, community engagement, and institutional support as key determinants of system performance and developmental impact. Results are presented under system performance, community participation, operational challenges, and improvements over time.

### 3.1. System Performance

The Masia microgrid, combining a 20 kW rooftop solar photovoltaic (PV) system, battery storage, and a 5 kWh Hydrogen fuel, provided reliable electricity for agricultural, educational, and community activities. Peak energy demand occurred during irrigation and post-harvest processing, requiring an estimated 35–40 kWh/day. Battery storage ensured availability during low-generation periods, maintaining over 95% operational uptime. System efficiency was closely linked to local involvement. The institutions reported 20% fewer interruptions compared to when users were not trained. Institutional support from local municipalities and development agencies facilitated timely maintenance, reducing average downtime from 12 h/week to 3 h/week over the study period.

### 3.2. Community Participation and Ownership

Community engagement strongly influenced adoption and responsible use. Of the 50 stakeholders trained in system operation, 80% actively participated in maintenance and monitoring activities. Participants reported prompt resolution of technical issues, improved energy scheduling for irrigation, and alignment with school or training program requirements. Areas without active engagement showed underutilization, with energy demand reaching only 60–70% of potential capacity.

### 3.3. Operational Challenges

Key operational constraints were identified:

- Dependence on external support: The institutions relied on external technical assistance for maintenance, indicating a vulnerability to disruptions if support ceased.
- Technical and financial limitations: Battery replacements accounted for approximately 25% of unplanned operational costs, limiting the centres' capacity to self-manage.
- Equity in participation: Training opportunities were evenly distributed; only 40% of women and 35% of youth reported receiving formal operational training.

### 3.4. System Improvements Over Time

Adjustments in biogas feedstock management and solar PV load scheduling increased energy availability by 15% over 12 months. Partnerships with vocational training institutions and local authorities enabled 20 additional community members to gain technical skills, increasing the pool of trained operators by 40%. Integration of energy services into agricultural programs improved irrigation scheduling and post-harvest processing efficiency, demonstrating cumulative socio-economic benefits.

### 3.5. Summary of Findings

Renewable energy microgrids at Masia delivered measurable improvements in energy access, agricultural productivity, and community services as shown in **Table 2**. Performance depended on reliable technical operation, active community engagement, equitable training, and sustained institutional support. When these factors were addressed, systems achieved over 95% uptime, improved irrigation and processing efficiency by 15–20%, and empowered community members through skills development, illustrating a clear pathway toward sustainable rural development.

**Table 2.** Key Performance and Impact Metrics of the Masia Development Centre Microgrid.

| Component/Indicator | Metric/Observation | Impact/Insight |
|---|---|---|
| Energy Capacity | 18 kW Solar PV, 100 kWh Battery | Ensured reliable supply for irrigation, processing, education, and community activities. |
| System Reliability | 95% uptime | High operational consistency; reduced downtime from 12 h/week to 3 h/week. |
| Energy Demand Fulfillment | Peak 35–40 kWh/day | Battery and biogas complemented PV output to meet peak agricultural needs. |
| Technical Training | 50 stakeholders trained, 20 new trainees over 12 months | Reduced interruptions by 20%; improved self-management and problem-solving. |
| Community Participation | 80% of trained users actively involved | Encouraged responsible system use and local ownership. |
| External Support Dependency | 60% relied on external maintenance | Indicates vulnerability if external assistance stops; highlights need for capacity building. |
| Equity in Training | 30% women, 35% youth trained | Reveals gaps in inclusivity; suggests targeting marginalized groups. |
| System Efficiency Improvements | 15% increase in energy availability | Achieved through load management and feedstock coordination. |
| Socio-Economic Benefits | Enhanced irrigation, digital learning, agricultural processing | Demonstrates cascading benefits beyond energy access; supports sustainable livelihoods. |

## 4. Case Application: Masia Development Centre

The Masia Multipurpose Development Centre, located in Masia Village, Vhembe District, Limpopo Province, serves as a key rural hub for agricultural development, skills training, digital learning, and enterprise incubation. The Centre supports farming operations, youth development programmes, and community services, making reliable electricity essential to its mandate. Although grid infrastructure, including a transformer and connection hardware, has been installed, the Centre remains unconnected to the national electricity grid due to unresolved utility connection charges and historical administrative constraints. In addition, regional grid performance is severely affected by load shedding and voltage instability. As a result, the Centre operates as an entirely off-grid institution, relying exclusively on on-site renewable energy systems for electricity. This situation positions Masia as a grid-available but grid-constrained rural facility, where a renewable microgrid is not a supplementary option but the primary and enabling energy system for institutional functionality and community impact.

### 4.1. Site Description: Masia Development Centre

The Masia Development Centre constitutes the empirical case study for this research. The site description and system characteristics presented here are based on primary site inspections, system design documentation, and operational observations conducted by the authors within the framework of the Masia Village Water–Energy–Food (WEF) Nexus Project. The Centre is located in a rural setting where the national grid infrastructure is physically present. A transformer and associated connection hardware have been installed at the site; however, the Centre remains unconnected to the national electricity grid due to unresolved utility connection charges and longstanding administrative constraints. Compounding this situation, regional grid performance is characterised by frequent load shedding and voltage instability. Consequently, despite being grid-ready in infrastructural terms, the Centre operates without any active grid electricity supply. This condition places Masia in a distinct category of grid-available but grid-constrained rural institutions, where the absence of grid connection is not a matter of remoteness but of affordability and institutional barriers. As a result, renewable energy systems are not supplementary or backup solutions but constitute the primary and enabling energy infrastructure for all institutional functions.

### 4.2. Overview of the Microgrid System

The Masia Development Centre in Limpopo operates an off-grid hybrid renewable microgrid designed to support rural electrification and community development as described further in **Table 3**. The system integrates an 18 kW solar photovoltaic (PV) array with a 10 kW electrolyser coupled with a 5 kW PEM fuel cell and 120 kg hydrogen storage and a 5 kW hydrogen generation and storage unit, supplying energy to the Centre's ICT lab, main administration block and small-scale agricultural operations. This configuration was chosen to provide clean, reliable power. The microgrid represents a practical demonstration of how renewable energy can enhance rural productivity. Its hybrid design allows for continuous operation even during cloudy conditions, offering a resilient model for other off-grid communities.

**Table 3.** Systems-level assessment of electricity access, energy capacity, and socio-economic implications at the Masia Development Centre under off-grid operation.

| Theme | Strong Findings | Evidence/Source | Implications |
|---|---|---|---|
| Electricity Reliability | The Centre experiences chronic energy vulnerability due to total dependence on off-grid renewable systems without grid redundancy, exposing operations to system performance fluctuations. | Project and technical reports (WEF Nexus Project, 2024). | Off-grid dependence reduces operational resilience and limits the Centre's ability to deliver uninterrupted services. |
| Energy Capacity | The installed solar PV capacity is structurally insufficient relative to institutional energy demand, creating a persistent supply deficit that affects core activities. | Energy audit and system monitoring records. | Inadequate capacity results in recurring power shortages, constraining training, ICT use, and evening programmes. |
| Backup System | The hydrogen fuel system represents a technically viable backup solution, but its developmental impact is constrained by limited operational integration and skills capacity. | DSI project documentation and field assessment. | Without technical capacity building, advanced backup technologies remain underutilised and fail to deliver expected reliability gains. |
| Operational Impact | Energy instability directly disrupts institutional effectiveness, particularly digital learning delivery, administrative functions, and community-based training programmes. | Institutional records and staff interviews. | Disruptions weaken service continuity and reduce the Centre's effectiveness as a development platform. |
| Socio-economic Effects | Persistent energy constraints limit the Centre's contribution to youth empowerment, skills development, and local enterprise support. | Observations and stakeholder consultations. | Energy insecurity translates into reduced livelihood opportunities and weaker local economic stimulation. |
| Intervention Project | The WEF Nexus Project demonstrates an intentional shift toward integrated, systems-based solutions that recognise the interdependence of energy, water, and food security. | Department of Science and Innovation (DSI) project documentation. | Integrated approaches offer greater potential for sustainable rural development than isolated sectoral interventions. |
| Institutional Role | The Centre operates as a living laboratory for renewable energy innovation, policy learning, and rural development experimentation. | DSI reports and Centre records. | Strengthens the Centre's strategic value as a replication and learning hub for similar rural contexts. |
| Location and Context | The Centre's rural location and socio-economic setting make it a representative case for examining off-grid renewable energy implementation challenges in Limpopo Province. | Geographic and administrative data. | Findings from the Centre can inform scalable rural energy and development policies in South Africa. |

To address persistent energy access constraints, the Masia Development Centre operates a fully off-grid hybrid renewable energy microgrid. The system is a hydrogen and lithium-ion-based energy storage unit consisting of an on-site electrolysis unit, a 10 kW electrolyser, 1,000 kg hydrogen storage, a 5 kW fuel cell conversion, a 40 kWh lithium-ion battery, and an 18 kW solar photovoltaic (PV) generation array as the primary source, enabling long-duration renewable energy storage and dispatchable power supply. Electricity generated by the system supplies critical institutional and productive loads, which include the ICT laboratory, administrative buildings, and small-scale agricultural operations. Solar PV supplies connected loads during daylight hours, while surplus generation is converted to hydrogen for longer-duration energy storage. The stored hydrogen is reconverted to electricity via a fuel cell during periods of low solar availability and at night, enabling continuous operation independent of the national grid. This configuration extends system autonomy beyond what battery-only storage would allow and enhances resilience under variable climatic and load conditions. Importantly, the microgrid functions as the sole source of electricity for the Centre rather than as a backup to the grid supply. It therefore provides a realistic, practice-based demonstration of how hybrid PV–hydrogen systems can support institutional, digital, and agricultural energy demands in rural contexts where grid access is technically available but economically or administratively constrained.

As summarised in **Table 3**, the Masia Development Centre represents a distinctive case for analysing hybrid renewable microgrids within a systems-oriented rural development framework. The Centre demonstrates how decentralised energy infrastructure can sustain institutional functionality and enable agricultural production, skills development, and community services in the absence of grid connectivity. While **Table 2** shows high levels of technical reliability, including consistent system uptime and stable operation of the hybrid microgrid, **Table 3** highlights system performance in relation to evolving institutional energy demand. As agricultural activities, irrigation cycles, and Centre operations expanded over time, peak energy loads periodically exceeded the originally installed system capacity, resulting in short-term supply constraints despite the system remaining operationally reliable.

Several factors help explain these limitations. The microgrid was initially designed based on projected energy demand at the time of installation, which underestimated subsequent growth in agricultural production, training activities, and administrative functions. Energy demand at the Centre is also highly seasonal, with irrigation cycles and post-harvest processing creating concentrated peaks that place additional strain on generation and storage capacity. Technical assessments conducted during a site visit further revealed vulnerabilities in both the hydrogen and solar PV systems, including an uncommissioned electrolyser, water ingress causing system tripping, a malfunctioning battery, temporary removal of the charge controller, and reliance on rainfall for panel cleaning. These findings highlight the need for a structured maintenance plan, clear cost estimates, defined timelines, and personnel training to support ongoing system upkeep. Collectively, the dynamic energy demand, seasonal load variations, and technical limitations demonstrate that while the microgrid maintains operational reliability, its capacity to fully meet evolving institutional and agricultural needs requires careful load management, targeted system upgrades, and strengthened maintenance strategies.

## 4.3. Systems Thinking Framework for Renewable Energy Implementation

### 4.3.1. Socio-Technical Components Shaping Microgrid Performance at Masia Development Centre

At the Masia Development Centre, several factors influence the effectiveness and sustainability of renewable energy initiatives. Energy demand is a central consideration, as it determines the scale and type of technologies needed to meet agricultural, and institutional needs [30]. Observations indicate that energy use fluctuates seasonally, particularly during irrigation periods and agro-processing activities, which affects both the capacity required and the timing of maintenance schedules. Solar photovoltaic (PV) and hydrogen fuel cell formed the primary sources of electricity at Masia Development Centre. The reliability of these technologies depends not only on the quality of installation but also on how well they are integrated with existing infrastructure and the technical competence of local operators [24,29]. Hybrid configurations combining solar and fuel cells were particularly useful in managing intermittent supply; however, their long-term performance is influenced by the availability of spare parts and operator skills. Battery storage plays an essential role in ensuring energy availability during periods of low generation [31]. Inadequate maintenance knowledge and limited funding for battery replacement were identified as key factors that sometimes disrupted service and reduced user confidence.

Community involvement emerged as a critical determinant of successful operation. When local residents participated in planning, training, and decision-making, they demonstrated stronger ownership and more responsible usage patterns. Conversely, projects implemented through top-down approaches often experienced neglect, limited local knowledge, and weak accountability [32]. Similarly, support from institutions including technical training, policy guidance, and coordination between local municipalities, agricultural extension services, and development agencies proved essential in maintaining operations. Gaps in coordination or inconsistent support, however, frequently constrained reliability and reduced the perceived value of renewable energy investments. Financial resources also shaped the sustainability of these initiatives. Limited funding for maintenance, upgrades, or expansion was found to affect the long-term functioning of systems and their ability to meet growing energy demands. Where technical competence, community engagement, and institutional support aligned, electricity supply became more reliable, agricultural and educational activities improved, and confidence in renewable energy grew. Conversely, weaknesses in any of these areas, such as insufficient maintenance skills, poor financing, or lack of community participation could undermine system performance and limit broader development benefits [33]. Overall, the experience at Masia underscores that renewable energy projects are successful not simply because of technology, but when technical, social, and institutional elements operate in harmony. The combination of reliable equipment, engaged communities, and consistent institutional support enables sustainable electricity access, strengthens livelihoods, and encourages local adoption of renewable energy technologies.

### 4.3.2. Microgrid Implementation

A key principle of the systems thinking approach is the recognition that interventions within complex systems often produce outcomes beyond their initial intentions. The analysis revealed several unintended consequences that emerge when renewable energy projects are introduced without sufficient attention to social dynamics, technical design, and long-term sustainability mechanisms [33]. One recurring issue identified at the Masia Development Centre and similar rural contexts is the risk of dependency on external actors. When renewable systems such as solar PV or biogas digesters are installed through top-down initiatives without embedding local ownership, communities tend to rely on external agencies or donors for maintenance, repairs, and decision-making. Over time, this dependency weakens local capacity, erodes motivation for self-management, and jeopardizes system continuity once project funding ends.

Another unintended outcome relates to technical system design and lifecycle costs. Poorly sized systems or inadequate component quality, particularly in battery storage units, were found to reduce operational lifespan, leading to unanticipated replacement costs. These expenses often exceed the financial capacity of households or community institutions, resulting in system abandonment or reduced utilization. Such outcomes illustrate how narrowly focusing on initial installation targets, rather than full lifecycle planning, can generate new forms of vulnerability [23]. Additionally, the analysis noted that renewable energy projects can inadvertently reinforce existing social inequalities if participation is uneven. For instance, when training or maintenance opportunities are offered selectively, certain groups, such as youth or women may be excluded from capacity-building processes, limiting the social inclusivity of the intervention. Recognizing these potential risks is critical for designing adaptive and equitable implementation strategies. Measures such as participatory design processes, transparent cost-sharing mechanisms, and local capacity development can mitigate dependency and ensure communities remain active custodians of their energy systems. By anticipating unintended consequences early in the planning phase, implementers can strengthen resilience and promote a more balanced and sustainable transition toward renewable energy in rural settings.

#### 4.3.3. Implementation and Resilience in Microgrid Systems

The final theme, Adaptive Implementation, highlights the capacity of renewable energy systems and their supporting institutions to learn, adjust, and respond to changing conditions over time. Within a systems thinking perspective, adaptation is not a one-time adjustment but a continuous process of feedback, reflection, and improvement that strengthens system resilience and long-term sustainability. At the Masia Development Centre, adaptive implementation was observed in the way local managers and stakeholders modified operational practices in response to technical and social challenges. For example, when the biogas digester underperformed due to inconsistent feedstock supply, the management team collaborated with local farmers to establish a coordinated waste collection schedule. This adjustment not only improved system efficiency but also fostered community ownership by linking energy generation directly to agricultural activity.

Similarly, the solar PV–battery system benefited from adaptive management practices. Routine monitoring and user feedback led to incremental improvements in system use, such as adjusting load schedules to match peak solar generation periods. These seemingly minor adaptations contributed significantly to improved reliability and user satisfaction, demonstrating how responsive management can extend system lifespan and reduce operational costs. Institutional flexibility also emerged as an important enabler of adaptive implementation. Partnerships between the Masia Development Centre, local government, and development agencies allowed for the pooling of expertise and the integration of renewable energy goals into broader community development plans. However, the analysis also revealed that adaptation is often constrained by rigid funding models, bureaucratic delays, and insufficient technical training. Without mechanisms for ongoing learning and reinvestment, systems risk stagnation or decline after initial success.

## 5. Systems Thinking as a Lens for Analysing Rural Energy Transitions

A growing body of literature highlights the transformative role of microgrids in improving food security, water access, and energy reliability across diverse contexts, ranging from La Guajira in Colombia to the Arctic and Palestine [33]. Dawood et al. [22] examined the effects of small-scale renewable energy systems on indigenous communities in La Guajira and found that while microgrids improved access to water and food, they also accelerated groundwater depletion. This trade-off is particularly critical in arid regions, where increased energy access can intensify pressure on already fragile aquifers. Supporting the positive link between renewable energy and food security, Winkler [23] analysed interconnected food, energy, and water systems in remote Alaskan communities. Their findings point to strong potential for renewable energy integration to strengthen FEW security, especially when systems are designed with local conditions in mind.

In the context of rural South Africa, the complexity of renewable energy implementation calls for an analytical approach that extends beyond linear planning models. Systems thinking offers a useful framework for capturing the interdependencies between technical, social, institutional, and environmental factors that shape energy outcomes. Rather than isolating individual variables, this perspective focuses on feedback loops, dynamic interactions, and unintended consequences, making it well-suited to settings where multiple actors and conditions jointly influence success or failure. The systems thinking approach illustrates that rural energy projects operate within wider socio-technical systems. Their success depends not only on technology but also on factors such as user training, affordability, institutional support, and how well they fit into existing community structures. Feedback loops help explain why some interventions thrive while others fail. For example, improved energy access can reinforce positive outcomes like better learning conditions and further investment, while high maintenance costs can discourage use and lead to system collapse.

### 5.1. Technical Performance of Renewable Energy Systems

The rooftop solar PV–battery system at the Masia Development Centre demonstrated that reliable energy supply is dependent not only on technology selection but also on alignment with local energy demand patterns. Seasonal fluctuations in agricultural activities, such as irrigation and agro-processing, directly influenced energy use and storage requirements, highlighting the importance of proper system sizing [23,33]. Hybrid solutions integrating solar PV and biogas provided additional flexibility in meeting energy needs, yet their effectiveness depended on local technical competence and access to spare parts [5,15]. Inadequate maintenance capacity and limited funding for battery replacement were observed to reduce system reliability, emphasizing the need for sustainable technical support mechanisms.

### 5.2. Community Engagement and Ownership

Community participation emerged as a key determinant of system sustainability. Active involvement of local stakeholders in planning, operation, and maintenance fostered a sense of ownership and accountability, resulting in more responsible use and reduced system downtime [22,27]. Youth training programs strengthened local technical capacity, enabling timely maintenance and troubleshooting, which further enhanced system reliability. These findings are consistent with experiences in Kenya's Makueni County, where participatory planning significantly improved the performance and longevity of solar irrigation systems [15]. Conversely, top-down interventions with limited community engagement were more prone to neglect, underutilization, and operational failures.

### 5.3. Institutional Support and Financing Mechanisms

Institutional support, including coordination with local municipalities, agricultural cooperatives, and vocational training institutions, played a critical role in sustaining energy initiatives. These partnerships ensured oversight, facilitated technical training, and addressed maintenance needs, which collectively contributed to system stability [13]. Financing mechanisms, such as microcredit and cooperative ownership, enabled rural households and small enterprises to adopt renewable energy despite limited financial capacity, aligning with findings from Bangladesh and other African contexts [1,11]. Projects that relied heavily on external donor support without integrated local capacity frequently faced sustainability challenges once funding or oversight ceased [8,15].

### 5.4. Socio-Economic and Developmental Contributions

Integration of renewable energy systems with community engagement and institutional support created broader socio-economic benefits. Reliable electricity enabled improved agricultural productivity, enhanced learning conditions, and facilitated small enterprise development, illustrating the role of energy access in supporting rural livelihoods [12,18]. Furthermore, participatory approaches promoted local capacity building, which strengthened social cohesion and community resilience. These results underscore that renewable energy projects can function as development catalysts when technical, social, and financial elements are synergistically aligned.

### 5.5. Contribution to Rural Energy Implementation Models

The Masia case demonstrates the importance of designing renewable energy interventions that are context-specific, participatory, and supported by strong local institutions. Aligning technical systems with governance structures, skills development, and financing mechanisms ensures not only operational reliability but also sustained socio-economic impact [1, 8, 11]. This analytical perspective reinforces the argument that decentralized, community-centered planning, combined with capacity building and inclusive financing, is essential for achieving long-term sustainability in rural energy initiatives.

## 6. Integrating Renewable Energy for Sustainable Agriculture and Community Development: Insights from Masia Development Centre

The analysis of renewable energy implementation at the Masia Development Centre demonstrates that sustainable rural energy transitions require a holistic integration of technical, social, financial, and institutional elements. The findings show that technologies such as rooftop solar photovoltaic systems with battery storage and biogas digesters can act as catalysts for improving agricultural productivity, environmental sustainability, and socio-economic development. However, their effectiveness depends not only on technical performance but on how well these technologies are embedded within supportive community structures and institutional arrangements [1,18]. When renewable energy systems are introduced as isolated technical solutions, their long-term contribution to rural development remains limited. Evidence from Masia confirms that technical capacity alone is insufficient to sustain system performance over time. Reliable energy provision depended on the availability of locally trained operators, clear maintenance arrangements, and financial mechanisms capable of supporting routine operation as well as the replacement of critical components such as batteries and biogas infrastructure [9,33]. These findings align with broader literature emphasizing that the longevity of rural renewable energy systems is closely tied to ongoing capacity-building initiatives and locally anchored technical skills rather than one-off installations [12,15]. In contexts where these complementary elements were weak or absent, system reliability declined and dependence on external actors increased.

Community engagement emerged as a decisive factor shaping adoption, effective utilization, and system sustainability. Participatory approaches strengthened local ownership, encouraged responsible energy use, and enabled knowledge transfer among youth and other community members [8,12]. At Masia, involvement in planning and basic system management improved user confidence and reduced response times to technical challenges. Similarly, institutional support, including coordination with local municipalities, vocational training institutions, and agricultural cooperatives, provided governance and oversight structures that enabled coherent planning, responsive maintenance, and integration of energy services into broader development programmes [12,33]. Where institutional alignment was weak, energy systems struggled to deliver consistent benefits despite adequate technical design.

From a socio-economic perspective, integrating renewable energy with local governance and capacity-building initiatives generated multiple development outcomes. Improved energy reliability supported digital learning, agricultural training, irrigation scheduling, and small-scale processing activities, demonstrating how energy interventions can produce cascading benefits beyond basic electricity access [7, 28]. These outcomes reinforce the argument that energy systems function as enabling infrastructure within rural development systems, rather than as standalone interventions. The Masia case further illustrates that aligning renewable energy initiatives with sustainable livelihood and circular economy principles enhances their developmental contribution by linking energy access to skills development, agricultural productivity, and local income opportunities.

The findings also point to the relevance of Comprehensive Energy Solution Planning (CESP) as an appropriate planning and implementation framework for addressing the type of multi-dimensional challenges observed at Masia. CESP is designed to respond to complex rural energy contexts by integrating energy demand assessment, technology selection, financing, governance, and capacity development into a single, coordinated planning process. Rather than prioritising technology deployment alone, CESP emphasizes understanding how energy systems interact with local agricultural practices, institutional capacities, and socio-economic conditions. In the Masia context, a CESP-informed approach helps explain why system performance improved when energy planning was aligned with agricultural cycles, training programmes, and institutional support mechanisms [34]. Applying a CESP lens to Masia highlights the importance of synchronising energy solutions with local development objectives. For example, aligning solar PV generation and biogas production with irrigation schedules and agro-processing activities improved system utilization and reduced energy shortfalls. Similarly, incorporating skills development and maintenance financing into energy planning reduced reliance on external technical support and strengthened local ownership. These outcomes reflect the core premise of CESP: that sustainable energy solutions emerge when technical design, social engagement, financial planning, and institutional coordination are addressed together rather than in isolation.

The practical contribution of this study lies in demonstrating the conditions under which renewable energy systems can transition from isolated technological interventions to integrated, sustainable development solutions. By identifying critical subsystems, Energy Capacity, Technical Skills, Financing Mechanisms, Community Engagement, and Institutional Support, the Masia case highlights the interdependencies required for resilience, adaptability, and long-term socio-economic impact [35]. Evidence suggests that reinforcing these interconnections through a CESP-oriented approach can shift rural communities away from cycles of dependency and underutilization toward pathways of innovation, self-sufficiency, and resilience, offering a model applicable to similar rural contexts in South Africa and beyond [25,28]. Overall, the Masia experience contributes to the literature by showing that the developmental potential of renewable energy extends well beyond technical performance. Long-term impact is realised when energy interventions are embedded in participatory, institutionally supported, and financially viable frameworks that align with local development priorities. Framing renewable energy planning through Comprehensive Energy Solution Planning provides a structured and context-sensitive pathway for achieving sustainable agriculture, empowered communities, and resilient rural livelihoods.

## 7. Conclusions

This study concludes that renewable energy presents a viable and necessary response to the persistent energy challenges facing rural South Africa, but its success depends on more than technical performance alone. Evidence from the Masia Development Centre shows that reliable and sustainable energy access is a socio-technical challenge shaped by the interaction between infrastructure, institutions, and people. The application of a systems thinking framework reveals how interconnected components, including solar PV, battery storage, hydrogen systems, financing arrangements, institutional partnerships, and community engagement, collectively influence system outcomes through reinforcing and balancing feedback processes.

### Recommendations

Future research on small-scale renewable energy microgrids should place stronger emphasis on resilience and adaptation, particularly in contexts exposed to climate, economic, and institutional shocks. There is also a need to explore innovative business and ownership models that can improve long-term financial viability, alongside investigations into smart grid technologies that enhance system monitoring, flexibility, and operational efficiency. Beyond technical performance, cross-sectoral impact assessments are essential for capturing wider socio-economic and environmental effects, especially across energy, water, food, and livelihoods. Equally important is research on policy and regulatory frameworks that enable supportive, context-sensitive microgrid deployment. Finally, adopting human-centred design approaches that incorporate indigenous knowledge systems can help assess and strengthen the social and environmental inclusivity of microgrid initiatives.

## Author Contributions

Conceptualization, S.T.M., T.R. and D.T.; methodology, S.T.M. and T.R.; formal analysis, S.T.M. and T.R.; investigation, T.R.; data curation, T.R.; writing—original draft preparation, T.R.; writing—review and editing, S.T.M., T.R. and D.T.; visualization, T.R.; supervision, D.T.; project administration, S.T.M.; funding acquisition, S.T.M. and D.T. All authors have read and agreed to the published version of the manuscript.

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## Institutional Review Board Statement

The study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of the University of Venda.

## Informed Consent Statement

Informed consent was obtained from all participants involved in the study.

## Data Availability Statement

Data supporting the findings of this study are available from the corresponding author upon reasonable request. No publicly archived datasets were generated or analyzed.

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## Conflicts of Interest

The authors declare no conflict of interest.

## AI Use Statement

During the preparation of this work, the authors used ChatGPT and Grammarly for language refinement. The authors subsequently reviewed and edited the content as necessary and take full responsibility for the final content of the published article.

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