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# Design and Performance Evaluation of a Standalone Hybrid PV–Biogas–Battery Microgrid for Enhanced Energy Resilience in Rural Morocco

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**Keywords:** Hybrid Energy System, Photovoltaic (PV), Biogas, Battery Storage, Energy Management System, Rural electrification, MATLAB/Simulink, Economic Resilience

**Abstract.** In rural Morocco, electrification is still a difficult problem because of gaps in infrastructure and the changing prices of traditional energy sources. This research develops and evaluates a standalone hybrid microgrid integrating photovoltaic (PV) arrays, a biogas generator, and battery storage, specifically designed for a six-person household in Skoura. The system architecture features a PV array with a P&O MPPT controller, a 48 V battery bank (100–200 Ah), and a biogas unit fuelled by local livestock waste (2 cows, 3 sheep, 1 goat). Using MATLAB/Simulink under semi-arid conditions, simulations confirm full 24-hour autonomy. The PV system covers daytime loads with a 1.3 kW peak, keeping battery State of Charge (SOC) strictly between 20% and 90%. Crucially, the Energy Management System (EMS) stabilizes the 48V DC bus by triggering the biogas generator only during the evening peak (19:00–21:00). This setup prevents deep battery discharge. By replacing butane with local biomethane, this architecture offers a technically viable and economically robust solution for off-grid communities.

## 1. Introduction

Access to electricity remains limited in many semi-arid regions of Morocco, where grid connections are scarce and climatic conditions are highly variable. Despite the progress achieved through the national PERG electrification program, several isolated households continue to rely on costly butane and traditional energy sources to meet their daily needs [1]. Under these conditions, solar photovoltaic (PV) systems have been widely adopted due to the country's high solar potential. However, standalone PV systems are inherently constrained by the intermittent nature of solar irradiance, which limits their ability to supply electricity during nighttime periods or adverse weather conditions [2]. This limitation highlights the need for more robust hybrid energy configurations.

Biogas production from livestock waste represents a complementary and locally available energy source that is particularly relevant for agrarian communities. In this study, livestock residues are considered as an energy resource rather than waste, enabling both electricity generation and improved organic waste management [3]. Biomethane can be used to supply thermal loads and power generators, thereby compensating for the variability of solar production. Previous studies conducted in Ghana have demonstrated that integrating biogas units into solar battery systems can reduce operational costs and improve supply continuity compared to PV only configurations [4,5]. In parallel, modelling efforts in Morocco indicate that hybrid PV–biogas–battery systems can significantly reduce dependence on fossil fuels in off-grid applications [6].
The reliable operation of such hybrid systems nevertheless depends on coordinated control of generation, storage, and backup units. An Energy Management System (EMS) is therefore required to regulate PV production, manage battery charge–discharge cycles, and schedule biogas generator

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dispatch in response to household demand [7]. In this paper, we design and simulate a standalone hybrid microgrid for a six-person household located in Skoura, using site-specific load profiles and realistic livestock data. We evaluate the proposed system in terms of 24-hour autonomy and DC-bus voltage stability. Section 2 presents the system architecture, Section 3 discusses the simulation results, and Section 4 summarizes the implications for rural electrification.

## 2. System Design and Methodology

The architecture of the proposed hybrid energy system revolves around the integration of photovoltaic generation, biogas-based power production, and battery energy storage, all synchronized via an intelligent Energy Management System (EMS). We developed the entire modelling framework within the MATLAB/Simulink environment, ensuring that the simulations reflect the actual irradiance fluctuations and household load demands typical of the Skoura region. As depicted in Figure 1, the system's topology is anchored by a common 48 V DC bus. This design choice was deliberate; by centralizing the power distribution on a DC bus, we significantly curtail the conversion losses that usually plague multi-source off-grid systems. The energy flow is partitioned into three distinct functional routes. First, the PV path utilizes a DC-DC boost converter coupled with a P&O MPPT algorithm to aggressively track the maximum power point. Second, the storage path relies on a bidirectional converter to regulate the lithium battery bank, which serves as the system's primary energy buffer. Lastly, the backup path integrates a biogas generator through an AC-DC rectifier, providing a strategic power injection when solar and battery reserves are insufficient to meet the demand.

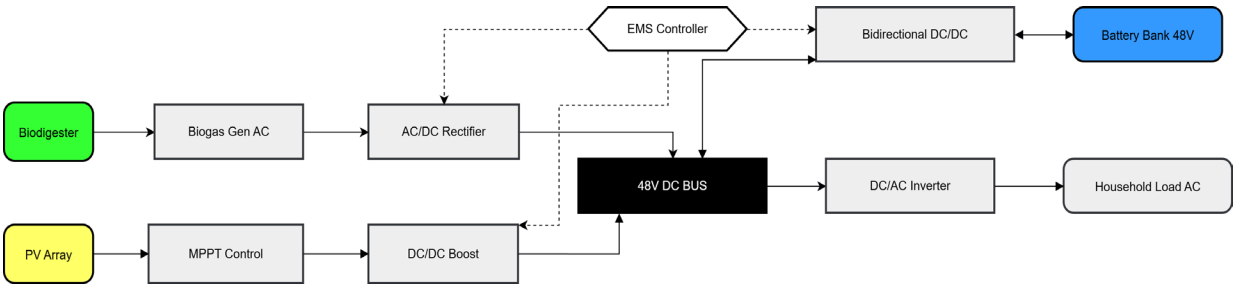



*Fig. 1. Schematic diagram of the proposed hybrid PV-biogas-battery system connected to a common 48 V DC bus.*

*2.1 PV subsystem modelling.*

The photovoltaic (PV) subsystem is modelled using the classical single-diode equivalent circuit, which offers an effective trade-off between modelling accuracy and computational simplicity. The current–voltage relationship is given by: $I = I_{\text{ph}} - I_0(e^{\frac{V+IR_S}{nV_t}} - 1) - \frac{V+IR_S}{R_{\text{sh}}}$ (Eq. 1)

where $I_{\text{ph}}$is the irradiance-dependent photocurrent, $I_0$the diode saturation current, $R_s$and $R_{\text{sh}}$the series and shunt resistances, $n$the diode ideality factor, and $V_t$the thermal voltage. This model is widely used and validated in PV simulation studies [8].

The PV array is implemented using Simulink's *PV Array* block with time-varying irradiance and temperature representative of semi-arid conditions in Skoura.

*2.2 DC-DC boost converter and MPPT control*

A DC–DC boost converter interfaces the PV array with the 48 V bus, regulated by a Perturb and Observe (P&O) MPPT algorithm. We selected P&O for its balance between tracking accuracy and low computational load suitable for the region's irradiance patterns [9].

The controller continuously adjusts the duty cycle $D$ to lock the array onto the Maximum Power Point (MPP) despite solar variations.

*2.3. Battery storage modelling*

The energy storage unit consists of a 48 V lithium battery bank interfaced to the DC bus through a bidirectional DC–DC converter. The battery is modelled with a voltage–current relation based on a simple Rint model, expressed as:

$$V_{\text{bat}} = V_{\text{oc}}(\text{SOC}) - I_{\text{bat}} R_{\text{int}} \qquad \text{(Eq. 2)}$$

where $V_{\text{oc}}$ is the SOC-dependent open-circuit voltage, $I_{\text{bat}}$ the current (positive during discharge), and $R_{\text{int}}$the internal resistance. The evolution of the State of Charge (SOC) is governed by the integral of the battery current, where $C_{\text{bat}}$is the nominal capacity expressed in ampere-hours.

$$\text{SOC}(t) = \text{SOC}(0) - \frac{1}{C_{\text{bat}}} \int_0^t I_{\text{bat}}(\tau)\, d\tau \qquad \text{(Eq. 3)}$$

This formulation is consistent with validated dynamic battery models used in hybrid microgrid and electric vehicle simulations [10]. Upper and lower SOC limits are enforced to protect the battery from over-charge and excessive depth-of-discharge.

*2.4 Biogas generator modelling.*

The biogas subsystem is powered by biomethane produced from the household's livestock (two cows, three sheep and one goat) and domestic organic waste. Such quantities have been shown to sustain daily biogas production suitable for standalone digesters in rural households [11,12]. The available mechanical power from biogas is approximated as

$$P_{\text{bio,avail}} = \dot{m}_{\text{CH}_4}\, \text{LHV}_{\text{CH}_4}\, \eta_{\text{eng}} \qquad \text{(Eq. 4)}$$

where $\dot{m}_{\text{CH}_4}$is the methane mass flow rate, $\text{LHV}_{\text{CH}_4}$the lower heating value of methane and $\eta_{\text{eng}}$ the generator efficiency. In the electrical model, the biogas generator is represented as a controlled AC voltage source limited by a maximum active power $P_{\text{bio, max}}$, rectified and injected into the DC bus. The reference power command is constrained according to

$$0 \le P_{\text{bio,ref}}(t) \le P_{\text{bio,max}} \qquad \text{(Eq. 5)}$$

ensuring safe and realistic operation during backup generation periods.

*2.5 Load profile characterization.*

The load profile reflects typical rural Moroccan appliance usage (lighting, refrigeration, TV) with a daily consumption of 1–3 kWh, consistent with demand in similar developing regions [13]. The time-varying curve incorporates realistic daily peaks and nighttime patterns.

*2.6 Energy Management System (EMS)*

The EMS provides real-time coordination of power flows between the PV array, the battery bank and the biogas generator. The remaining load after photovoltaic generation is first computed using: $P_{\text{rem}} = P_{\text{load}} - P_{\text{PV}}$ (Eq. 6) and used to determine the battery dispatch. When solar power is insufficient and the SOC exceeds its minimum limit, the battery supplies power according to

$$P_{\text{bat,ref}} = \min\left(P_{rem}, P_{bat,\,dis}^{max}\right) \qquad \text{(Eq. 7)}$$

while in the presence of photovoltaic surplus and an SOC below its upper threshold, the battery is charged following: $P_{\text{bat, ref}} = \max\left(P_{rem}, -P_{bat,\,ch}^{max}\right)$ (Eq. 8)

ensuring protection from overcharge. The remaining unmet demand is then obtained through and used to activate the biogas generator as a controlled backup source.

$$P_{rem2} = P_{load} - P_{PV} - P_{bat,ref} \quad (\text{Eq. 9})$$

The control algorithm prioritizes direct solar self-consumption but strictly constrains this goal to prevent deep cycling of the battery. By enforcing this hierarchy, the system secures a stable output voltage while adhering to established off-grid management protocols [14,15].

## 3. Results and Discussion

### *3.1 Energy flow dynamics and source coordination*

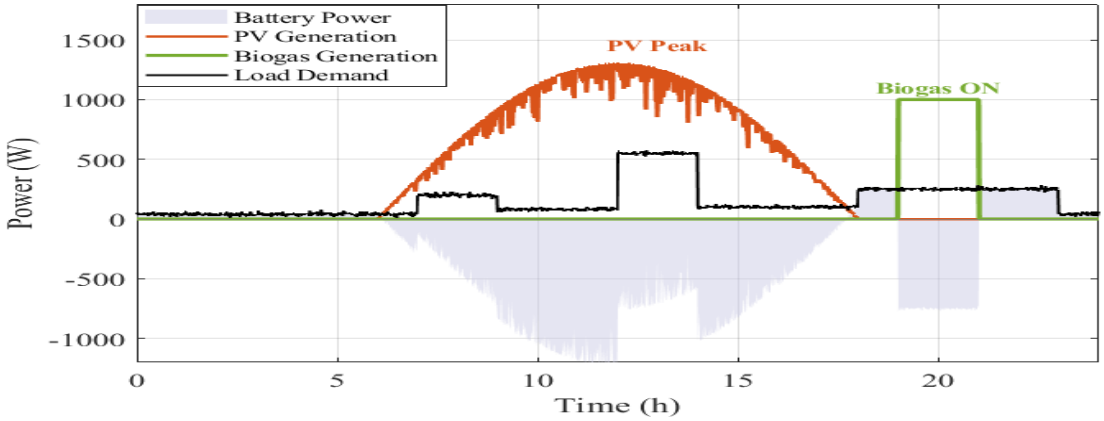



*Fig. 2. Simulated power profiles over a representative 24-hour period, showing PV generation, biogas production, load demand, and battery charge/discharge behavior.*

Figure 2 illustrates the power dynamics of the proposed hybrid system over a complete daily cycle under rural conditions. The photovoltaic (PV) output peaks at approximately 1.3 kW around midday, consistent with the solar potential reported for Skoura and comparable North African locations [1,2]. During this period, sustained PV surplus enables effective battery charging, confirming appropriate PV sizing and correct calibration of the Maximum Power Point Tracking (MPPT) strategy, in line with previous storage-oriented studies [16,17].

As solar irradiance decreases in the late afternoon, the system load is gradually shifted to the battery, indicating that the Energy Management System (EMS) anticipates the reduction in PV generation rather than reacting to abrupt voltage variations. Such predictive operation is essential in standalone microgrids to limit electrical stress and avoid voltage instability associated with hard switching events [14,18]. The most critical operating condition occurs during the evening peak demand (19:00–21:00), when the control strategy activates the biogas generator to inject approximately 1 kW into the DC bus while bypassing the battery. This intentional dispatch limits battery depth of discharge and reduces cycle-induced degradation, allowing the biogas unit to function as a lifetime-preserving reserve rather than a simple emergency backup. Similar dispatch strategies have been reported in recent hybrid renewable energy systems [5,11,18].

### *3.2 Storage behaviour and DC-bus stability*

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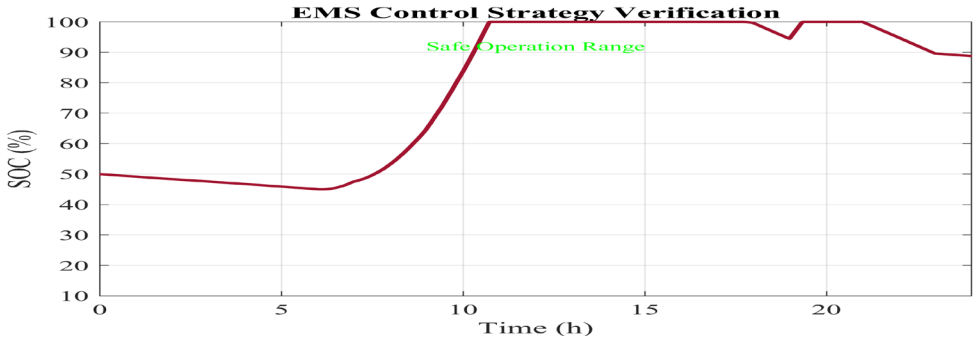



Fig. 3. *Battery SOC under the EMS supervisory strategy, demonstrating controlled charge discharge cycles across the 24-hour period.*

Figure 3 shows that the battery State of Charge (SOC) remains within the 20%–90% operating window throughout the daily cycle. Enforcing this lower limit is essential, as deep discharge conditions accelerate irreversible degradation mechanisms in off-grid battery systems. The gradual daytime increase in SOC indicates an effective balance between photovoltaic (PV) generation and household consumption, consistent with standard lithium-ion battery behaviour under controlled depth-of-discharge conditions [10].

The smooth SOC profile, characterized by the absence of abrupt variations, suggests limited current stress and reduced thermal accumulation. In this configuration, high-variability demand is primarily supplied by the biogas generator, allowing the battery to function mainly as a voltage stabilization unit rather than a peak-power source. This operating regime mitigates rapid micro-cycling, a known contributor to premature battery aging in standalone systems.

Figure 4 confirms the effectiveness of DC-bus voltage regulation over the daily operating cycle. The bus voltage remains close to the nominal 48 V reference under all operating conditions, with only minor deviations observed during biogas generator activation at 19:00. The Energy Management System (EMS) promptly adjusts the battery-side converter to restore voltage stability, demonstrating the robustness of the proposed control strategy.

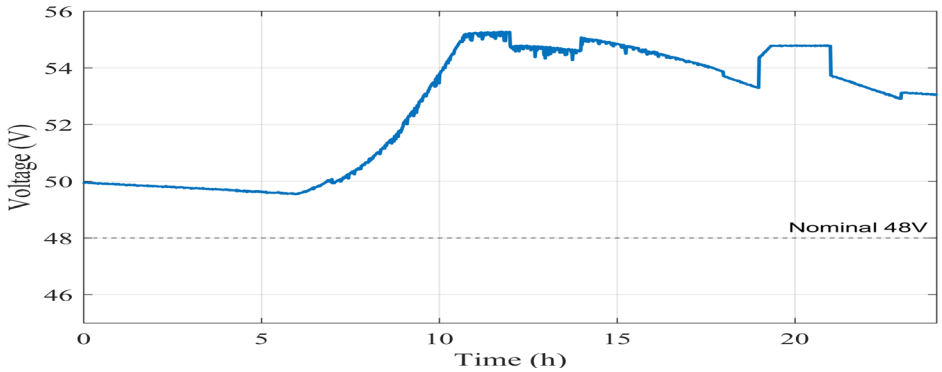



*Fig. 4. DC-bus voltage profile over the full 24-hour simulation, highlighting overall voltage stability around the nominal 48 V level.*

The observed system response highlights the fast dynamic behaviour of the DC/DC converter and the stabilizing role of the battery in DC-bus regulation, in agreement with stability analyses reported for standalone DC microgrids operating under variable conditions [14,17]. As shown in Figures 3 and 4, the hybrid configuration enables controlled battery cycling while maintaining voltage stability across a wide range of operating scenarios. By combining photovoltaic generation, battery storage, and biogas-based backup, the system keeps the storage unit within safe

operating limits and ensures reliable DC-bus regulation throughout the daily cycle, consistent with previous PV–biogas–battery microgrid studies [4,7,19].

*3.3 Discussion: implications, strengths, and future extensions*

The simulation results show that the proposed hybrid configuration behaves as a coordinated energy system rather than a set of independent components. In this operating scheme, the photovoltaic (PV) array primarily supplies the household base load, while the battery is used for short-term balancing and DC-bus voltage regulation. The biogas generator is activated only during periods of elevated demand or reduced solar availability. This operating logic limits excessive battery cycling, which is a critical factor given that the battery represents the costliest and degradation-sensitive component of the system. Similar operational benefits have been reported in recent studies on the long-term performance of hybrid microgrids deployed in rural contexts [20]. This system design explicitly exploits the different operational characteristics of electrochemical and biological energy storage. Batteries are particularly vulnerable to deep discharge cycles and frequent high-power fluctuations, whereas biogas generators can tolerate irregular and demand-driven operation without significant performance degradation. By allocating the evening peak load to the biogas generator, the system takes advantage of this asymmetry to preserve battery health and extend its effective service life. Such a control philosophy is consistent with current research trends in biomass-supported hybrid energy systems, where biological fuels are increasingly treated as dispatchable reserves rather than continuous power sources [21].

First, we propose the integration of IoT sensors to monitor digester metrics such as temperature and pH for real-time supervision [22]. Second, we aim to replace the existing rule-based logic with machine learning algorithms. This would enable the energy management system (EMS) to predict demand rather than merely responding to it. Additionally, data-driven management has proven effective in similar remote applications [23]. However, there are limitations to our study. We rely on a 24-hour cycle and assume constant biogas availability. Additionally, we did not model factors such as seasonal temperature variations or the long-term aging of batteries. Therefore, physical prototyping is necessary to validate these variables before we can consider community-scale deployment.

## 4. Conclusion

We designed and validated a standalone hybrid microgrid (PV-biogas-battery) for a rural household in Skoura. To verify the system's limits, we utilized MATLAB/Simulink to simulate real-world irradiance and load conditions. The architecture incorporates a photovoltaic (PV) array with Perturb and Observe control, a 48V battery bank, and a biogas generator powered by livestock waste. This combination effectively addresses the intermittency issue associated with solar-only systems by using biogas as a backup, which aligns with contemporary stability protocols for off-grid systems [14,15].

The results indicate that the system effectively achieves 24-hour autonomy. The photovoltaic (PV) array peaks at 1.3 kW, which allows it to cover daytime energy loads and charge the storage unit. Additionally, the Energy Management System (EMS) maintains the battery's State of Charge (SOC) within a strict range of 20% to 90%. This approach prevents deep discharge cycles that could compromise battery longevity. The voltage on the 48V DC bus remains stable, exhibiting only minor transients when the 1 kW biogas generator activates during the evening peak demand.

Moving forward, we plan to validate these findings through the development of a physical prototype. In this phase, we will incorporate IoT sensors to monitor key digester variables, such as pH, temperature, and methane flow, in real time [24]. Building on these measurements, future work may leverage meteorological data together with biodigester input parameters to support predictive generation profiles and to extend the existing rule-based Energy Management System (EMS) toward reinforcement learning–based control for improved dispatch optimization under

dynamic operating conditions [19]. Lastly, we plan to conduct a comprehensive Levelized Cost of Energy (LCOE) analysis to assess the economic viability of scaling the proposed model to community-level microgrids or integrating wind energy [14,19].

**Declaration of Generative AI and AI-Assisted Technologies in the Writing Process:**
The authors used AI-assisted tools (QuillBot) exclusively for grammar checking and language refinement. No generative AI tools were used for the development of the scientific content, methodology, analysis, or interpretation of results, which were entirely conducted by the authors.

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