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Reliability-Driven Techno-Economic Assessment of an Off-Grid PV–Battery System for Small-Scale Irrigation Pumping in Lafia, Nigeria

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Abstract: Reliable electricity supply is essential for small-scale irrigation pumping systems that operate within narrow and time-sensitive windows. In Lafia, Nigeria, persistent grid unreliability has sustained heavy reliance on diesel generators for irrigation, exposing operators to high operating costs, fuel price volatility, and frequent service interruptions. This study presents a reliability-driven techno-economic assessment of an off-grid photovoltaic (PV)–battery system with diesel backup for small-scale irrigation pumping under local operating conditions. A representative irrigation load of 10 kWh/day, characterized by fixed morning (06:00–09:00) and evening (17:00–19:00) pumping windows, is evaluated under a zero-unmet-load reliability constraint and benchmarked against a diesel-only generation alternative. System performance is assessed using technical and economic indicators including load served, renewable energy fraction, battery operation, generator runtime, fuel consumption, net present cost (NPC), and levelized cost of energy (LCOE). Results show that the hybrid PV–battery system fully serves the annual irrigation demand (≈3,650 kWh/yr) with near-zero unmet load and a renewable fraction of approximately 78%. Annual PV generation of about 4,750 kWh reduces generator operation to roughly 220 h/yr and fuel consumption to approximately 300 L/yr, compared with 1,460 h/yr and 1,460 L/yr for diesel-only supply. Over a 10-year lifetime, the hybrid system achieves a lower NPC (≈₦10.8 million) and LCOE (≈₦190/kWh) than diesel-only operation (≈₦18.6 million and ≈₦330/kWh). The findings demonstrate that reliability-oriented PV–battery systems offer a technically robust and economically viable alternative to diesel-only generation for small-scale irrigation in fuel-dependent off-grid environments.

Keywords: *Off-Grid Energy Systems; Photovoltaic–Battery Systems; Irrigation Pumping; Reliability-Driven Design; Diesel Displacement; Techno-Economic Analysis.*

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I. INTRODUCTION

Reliable electricity supply is a critical requirement for small-scale irrigation pumping systems because operation is typically restricted to narrow and time-sensitive windows [1]. Interruptions during scheduled irrigation periods often translate directly into unmet water delivery, crop stress, and operational inefficiencies [2]. Although renewable energy technologies are increasingly deployed to support irrigation and other productive uses of energy, their technical performance and economic viability remain strongly influenced by local operating conditions, particularly in off-grid and weak-grid environments [3].

In Lafia, Nigeria, irrigation pumping activities are predominantly supported by diesel generators due to persistent grid unreliability, limited rural electrification coverage, and fuel-dependent energy practices [4]. While diesel generation offers operational flexibility, it exposes irrigation operators to high recurring fuel costs, frequent maintenance requirements, and vulnerability to fuel price volatility [5]. These challenges are particularly acute for time-constrained irrigation loads, where delayed or curtailed operation cannot be easily compensated outside scheduled pumping windows.

Recent advances in photovoltaic (PV) generation and battery storage have enabled hybrid energy systems capable of improving supply reliability while reducing fuel dependence [6]. However, many existing assessments emphasize cost minimization or renewable penetration without explicitly enforcing reliability constraints relevant to irrigation pumping. As a result, system configurations that appear economically attractive may still permit unmet load during critical operating periods, undermining practical usability.

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This study presents a reliability-driven techno-economic assessment of an off-grid PV–battery system with diesel backup designed for small-scale irrigation pumping under the local geo-climatic and economic conditions of Lafia. A representative irrigation load characterized by fixed morning and evening pumping windows is evaluated under a zero-unmet-load constraint and benchmarked against a diesel-only generation alternative. By focusing explicitly on uninterrupted load service and lifecycle cost performance, the study aims to quantify the technical and economic benefits of hybrid PV–battery systems for reliability-sensitive irrigation applications in off-grid environments.

II. RELATED WORKS

Hybrid renewable energy systems have been widely investigated as alternatives to diesel-based electricity supply for off-grid and weak-grid applications, particularly where fuel cost, logistics, and environmental concerns are significant [7]. Photovoltaic-driven pumping systems represent one of the earliest and most common renewable applications for irrigation, offering direct coupling between solar availability and water pumping demand [8]. However, systems relying solely on PV generation often struggle to meet irrigation requirements during early morning or evening periods, when solar availability is limited and operational flexibility is required [9].

To mitigate the intermittency limitations of standalone PV systems, several studies have incorporated battery storage and advanced energy management strategies to enable temporal energy shifting and improved load coverage. Recent investigations demonstrate that integrating battery storage with photovoltaic systems enhances reliability, supports demand smoothing, and reduces dependence on conventional backup generation [6], [10]. Similarly, hybrid renewable configurations employing optimized storage control and intelligent dispatch strategies have shown improved system stability and operational resilience in off-grid and rural electrification contexts [11], [12].

PV–battery hybrid systems have consistently demonstrated improved reliability performance and significant diesel displacement in off-grid agricultural and farm applications. Studies evaluating hybrid PV/biomass/diesel/battery systems report substantial reductions in generator operating hours when storage is integrated [13]. Complementary techno-economic investigations further emphasize that battery lifetime-aware sizing strategies enhance system resilience and minimize fuel dependency in predictable load environments [14], [15]. Nevertheless, a substantial portion of the hybrid renewable energy literature emphasizes techno-economic optimization, cost minimization, and renewable penetration maximization as primary design objectives. Recent studies have evaluated PV–battery microgrids primarily through techno-economic and environmental performance metrics across diverse contexts [16], [17]. Similarly, optimization-based frameworks employing particle swarm algorithms, metaheuristic dispatch models, and performance tuning approaches typically prioritize cost efficiency and generation management objectives [18], [19], [20]. While these contributions significantly advance hybrid system design methodologies, explicit enforcement of strict zero-unmet-load reliability constraints—particularly for time-sensitive agricultural applications—remains comparatively less emphasized. Consequently, system designs may tolerate limited unmet load, which is unacceptable for irrigation applications operating within narrow and time-critical windows.

Hybrid PV–battery–diesel systems have therefore emerged as a pragmatic solution, combining renewable energy utilization with dispatchable backup generation [12], [7], [21]. Prior studies consistently report reductions in generator operating hours and fuel consumption relative to diesel-only supply, alongside improved economic performance over the system lifetime. However, the majority of these analyses consider generalized or aggregated load profiles, such as residential or mixed-use demand, rather than irrigation pumping loads whose operational timing is non-negotiable.

Furthermore for [16], [18], and [19], while techno-economic simulation frameworks have become standard tools for evaluating hybrid renewable energy systems, most studies focus primarily on cost, optimization performance, or renewable penetration metrics. Even in PV-based pumping applications, simulation efforts often emphasize system efficiency or MPPT control strategies rather than explicitly linking electrical demand to hydraulic pumping equations or enforcing strict zero-unmet-load reliability constraints [8], [13], [22].

This gap limits the practical applicability of existing results to reliability-sensitive irrigation contexts, particularly in regions characterized by unreliable grid access and exposure to fuel price volatility. Against this backdrop, the present study advances a reliability-driven system design framework for small-scale irrigation pumping under localized operating conditions. By enforcing a zero-unmet-load reliability constraint, physically grounding the irrigation demand profile in hydraulic pumping relationships, and benchmarking hybrid PV–battery performance against diesel-only generation, the study extends existing work toward a more application-relevant assessment of off-grid irrigation energy systems in fuel-dependent environments.

III. MATERIALS AND METHODS

➢ *Study Area*

The study is situated in Lafia, Nasarawa State, Nigeria; a region characterized by high solar resource availability and persistent electricity supply constraints. Despite proximity to grid infrastructure, power availability remains unreliable, particularly for productive applications such as irrigation pumping. As a result, diesel generators are commonly employed to meet agricultural energy needs, exposing operators to fuel supply risks, high operating costs, and maintenance challenges. These local conditions provide a suitable context for evaluating off-grid hybrid energy systems designed to deliver reliable electricity for time-sensitive

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irrigation loads. The physical characteristics of the representative smallholder irrigation plot used in this study, including spatial extent, perimeter, and elevation range, are summarized in Figure 1.

Fig 1 Measured Characteristics of the Irrigation Area

Figure 2 shows the monthly average solar global horizontal irradiance (GHI) and clearness index for Lafia, indicating consistently high solar availability throughout the year, with moderate seasonal variation [REF]. This resource profile provides a strong basis for PV-based electricity generation for irrigation applications.

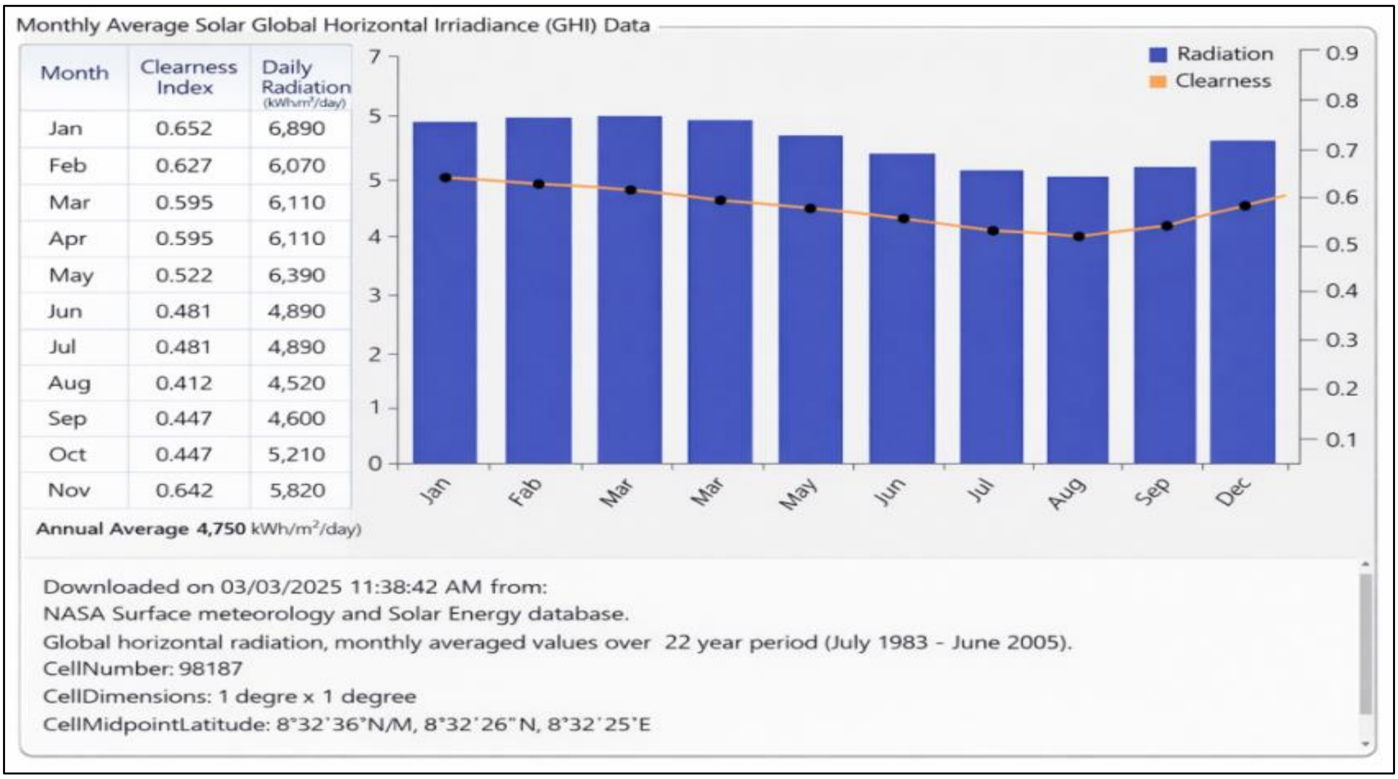

Fig 2 Monthly Variation of Solar Global Horizontal Irradiance (GHI) and Clearness Index for Lafia, Nigeria, Indicating Seasonal Solar Resource Availability Used for PV System Modeling.

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➢ *Irrigation Load Modeling*

The electrical load considered in this study represents a small-scale irrigation pumping application operating within fixed morning and evening windows, reflecting common irrigation practice in the study area. The load is characterized by two daily operating periods—morning (06:00–09:00) and evening (17:00–19:00)—with a total average energy demand of approximately 10 kWh/day; and a peak demand of about 2.5 kW (Figure 3). This operating pattern reflects the time-critical nature of irrigation pumping, where missed operation cannot be easily shifted or recovered outside scheduled windows.

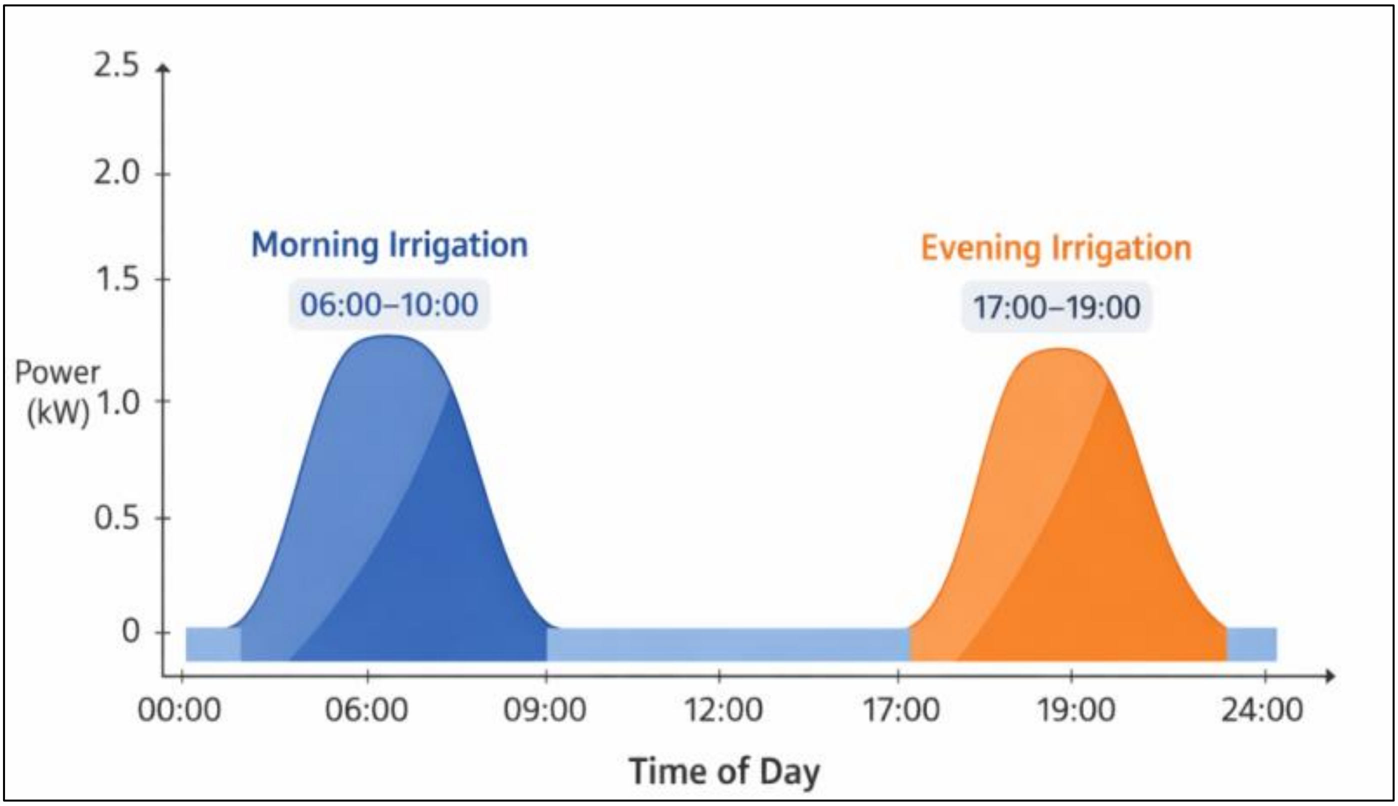

Fig 3 Irrigation Load Profile (10 kWh/day), Showing Morning (06:00 – 09:00) and Evening (17:00 19:00) Operating Windows

To strengthen the physical basis of the load profile, the irrigation electrical load is derived from standard hydraulic pumping relationships (Azizoğlu & Koçyiğit, 2025), where the required electrical power is calculated from the volumetric flow rate, total dynamic head, and combined pump–motor efficiency. Thus:

$$P_{elec} = \frac{\rho g Q H}{\eta_p \eta_m} \tag{1}$$

Where:

P_{elec} = Electrical Power Demand of the Irrigation Pump

ρ = Density of water ($\approx$ 1000 kg/m^3)

g = Acceleration due to gravity (9.81m/s^2)

Q = Volumetric flow rate (m^3/s)

H = Total Dynamic Head (m)

η_p = Pump Hydraulic Efficiency (dimensionless)

η_m = Motor Efiiciency (dimensionless)

And, for a pumping duration t (hours/day), the daily electrical energy demand is:

$$E_{daily} = P_{elec} \times t \tag{2}$$

The irrigation demand corresponds to a representative smallholder plot of approximately 0.5 ha, consistent with typical irrigated field sizes in the Lafia area. Water delivery requirements are translated into pumping power using standard hydraulic formulations that account for volumetric flow rate, total dynamic head, and pump efficiency. Electrical demand is subsequently obtained by incorporating motor efficiency and system losses. While detailed agronomic modeling is beyond the scope of this study, this approach ensures that the electrical load reflects realistic pumping behavior rather than purely assumed demand. Seasonal variation in irrigation intensity is implicitly represented through monthly load distribution, capturing increased pumping activity during dry periods. The irrigation pump is represented in HOMER Pro as a primary AC load with fixed operating windows and zero allowable capacity shortage. The corresponding hourly load definition, used as input to the simulation, is presented in Figure 4.

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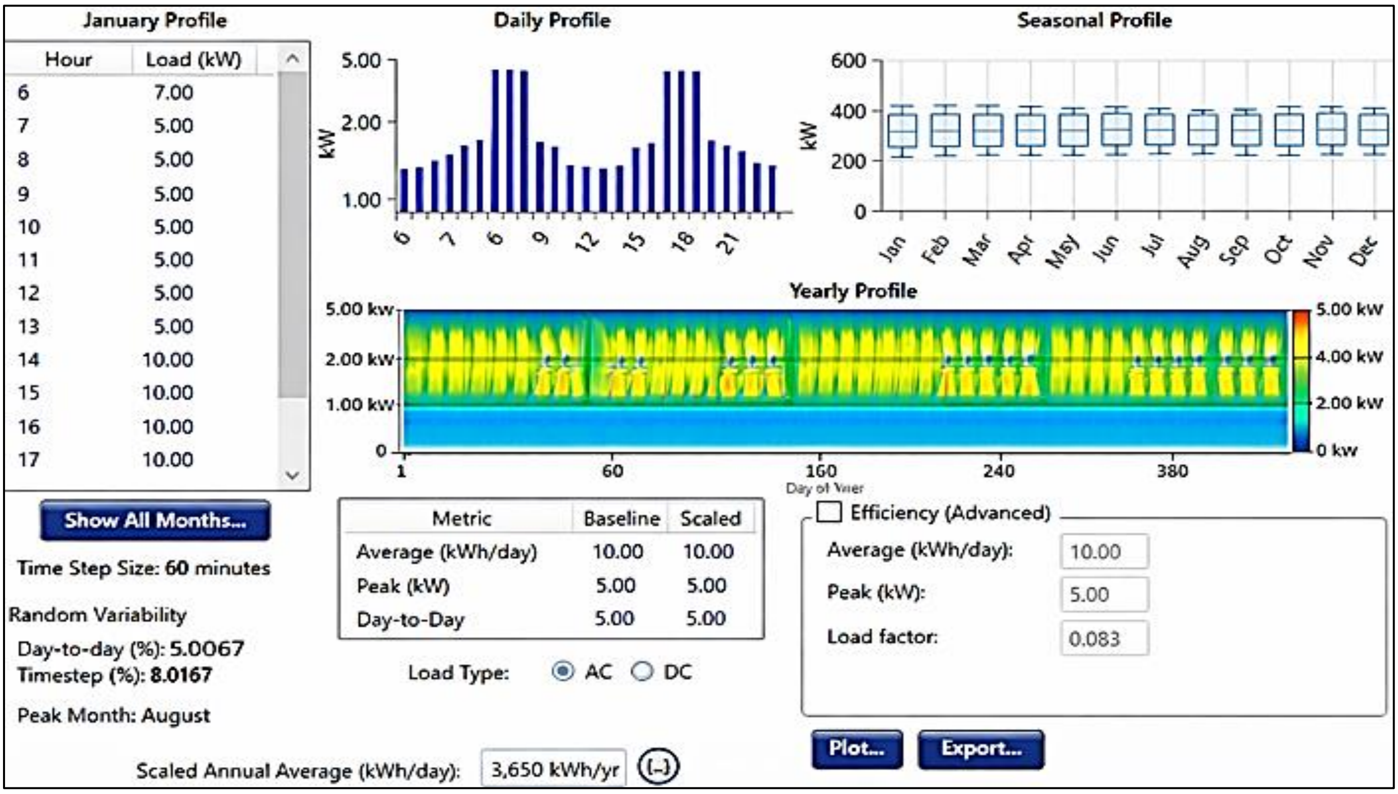

Fig 4 Hourly Electrical Load Profile for the Irrigation Pump (Scenario A), Showing fixed Morning (06:00–09:00) and Evening (17:00–19:00) Operating Windows, Peak Demand of 5 kW, and an Annual Electrical Energy Requirement of Approximately 3,650 kWh.

➢ *System Configuration and Sizing*

Two energy supply configurations are evaluated. The first is a diesel-only generation system serving as the baseline, representing prevailing irrigation energy practice in the study area. The second is a hybrid photovoltaic (PV)–battery system with diesel backup, designed to prioritize renewable energy utilization while maintaining uninterrupted load service and reliability.

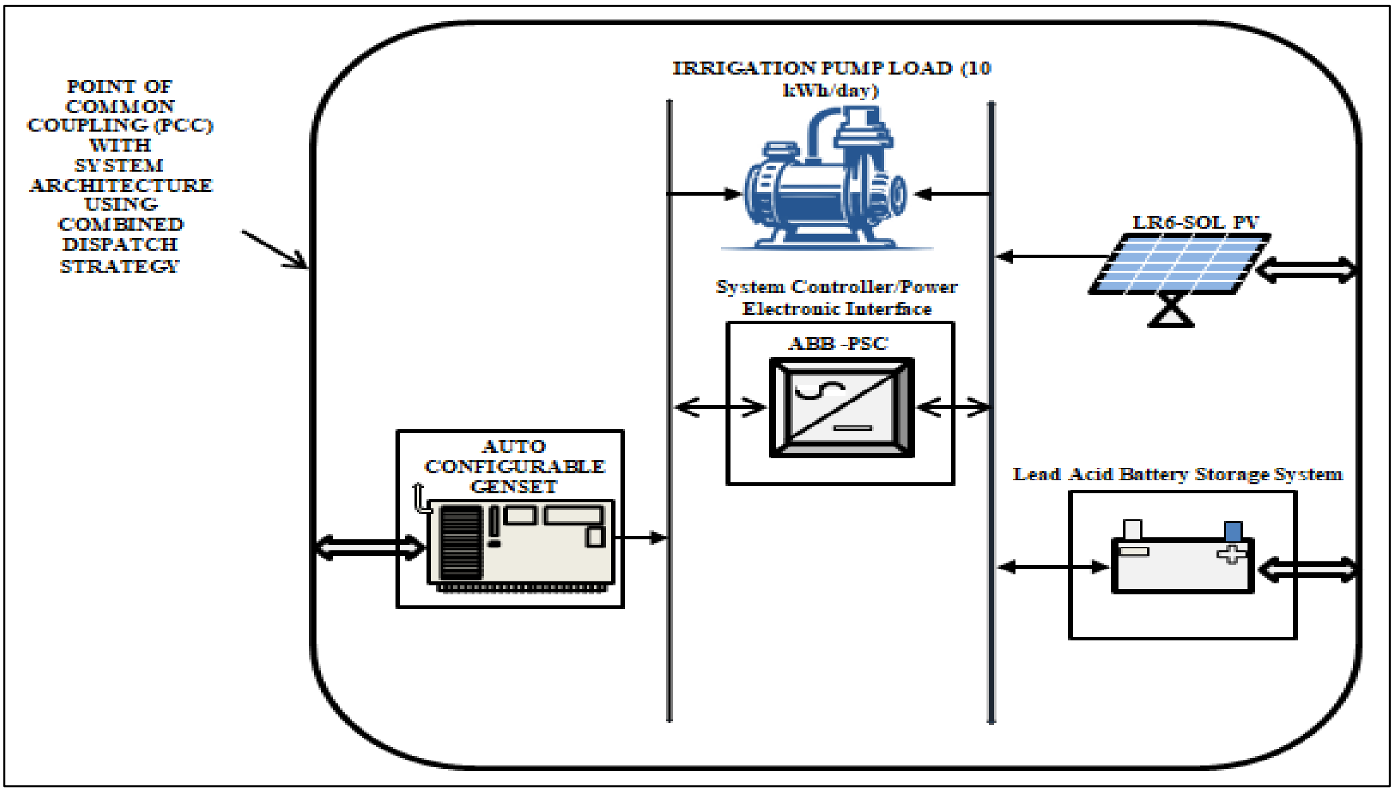

Fig 5 The System Architecture

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In the hybrid configuration, PV generation serves the irrigation load directly when available, excess generation is stored in the battery system, and the diesel generator operates only when PV and battery resources are insufficient to meet demand. System dispatch is configured to enforce a zero-unmet-load constraint, ensuring uninterrupted electricity supply during all irrigation operating periods. The system architecture adopted in this study is shown schematically in Figure 5, illustrating the coupling of PV generation, battery storage, power conditioning, and diesel backup at a common point of connection under a reliability-driven dispatch strategy.

System components in the configuration include a solar PV array, a lead–acid battery storage system, a bidirectional inverter/converter, and an autosizeable diesel generator. Component sizing follows a reliability-oriented philosophy, whereby the system is conservatively sized to ensure uninterrupted operation during periods of reduced solar availability rather than optimized solely for average conditions.

The PV array is sized to exceed the annual irrigation electricity demand, targeting an annual PV production of approximately 4,750 kWh to serve a load of about 3,650 kWh/yr. Battery storage is sized to provide diurnal load shifting and reliability buffering, enabling supply during early morning and evening irrigation windows. The inverter is rated above the peak electrical demand of the irrigation pump, while the diesel generator is modeled as an autosizeable unit with an upper capacity limit of 8 kW, operating strictly as a backup resource.

➢ *Simulation Framework and Dispatch Strategy*

System modeling and techno-economic evaluation are performed using HOMER Pro, which conducts hourly time-series simulations over an 8760-hour annual period. The software integrates a performance model, which evaluates energy production and consumption under varying resource availability, and an economic model, which computes lifecycle costs using discounted cash flow analysis. The overall simulation workflow adopted in this study follows the HOMER Pro performance and economic modeling structure, which integrates component modeling, resource inputs, load profiles, dispatch algorithms, and techno-economic evaluation, as illustrated in Figure 6.

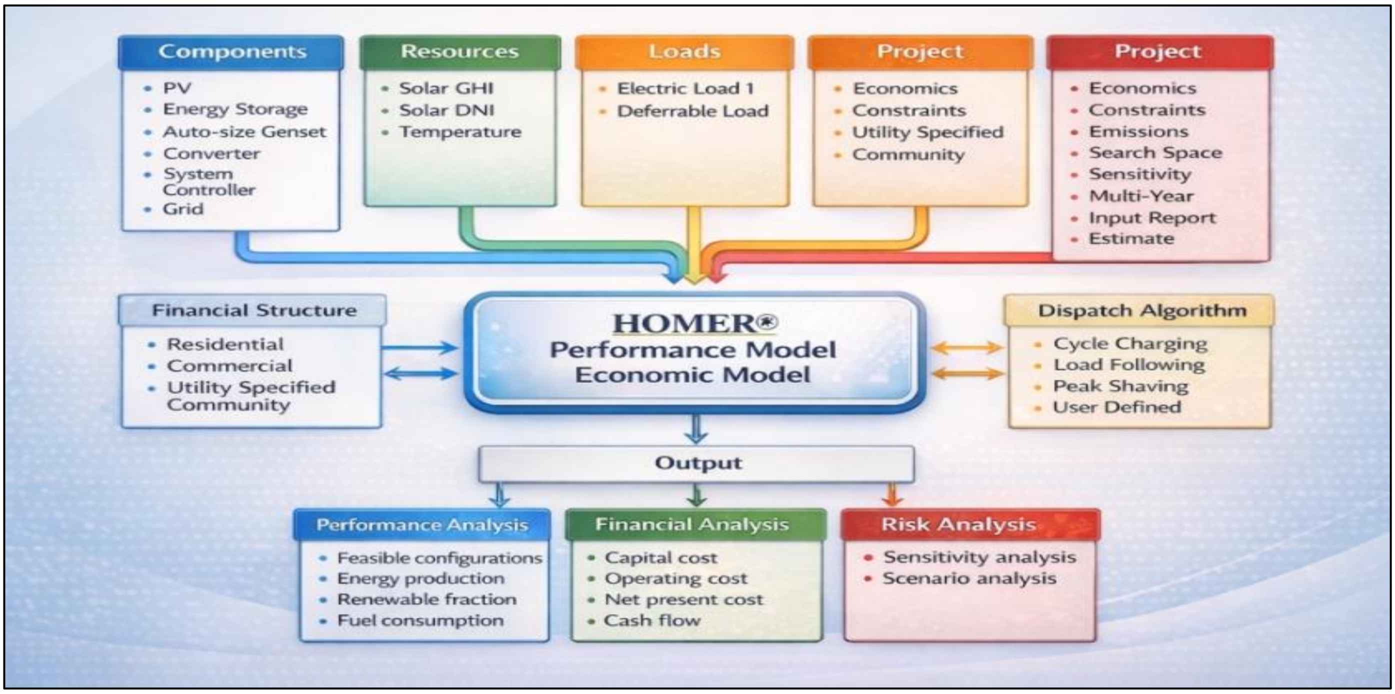

Fig 6 Homer Pro Working Structure

A cycle-charging dispatch strategy is adopted for the hybrid system. Under this strategy, PV generation supplies the load directly when available, excess energy is stored in the battery, and the diesel generator operates only when PV and battery resources are insufficient. Generator operation simultaneously serves the load and charges the battery to a predefined state-of-charge threshold. A zero-unmet-load constraint is enforced throughout the simulation to ensure uninterrupted electricity supply during all irrigation operating periods.

➢ *Economic Modeling, Performance Indicators and Data Analysis*

The economic evaluation adopts a project lifetime of 10 years, reflecting conservative planning horizons for small-scale off-grid systems incorporating battery storage. All costs are expressed in Nigerian Naira. Key economic assumptions include a real discount rate of 8% and an inflation rate of 2%, consistent with prevailing regional financial conditions.

System economic performance is assessed using the net present cost (NPC) and levelized cost of energy (LCOE). The

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total NPC represents the present value of all costs incurred over the project lifetime, including capital investment, component replacement, operation and maintenance, and fuel costs, minus salvage value. Following standard HOMER formulations, net present cost is calculated as:

$$C_{NPC} = C_{Cap} + C_{Rep} + C_{O\&M} + C_{Fuel} + C_{emis} - (C_{Salv} + C_{GSales}) \quad (3)$$

Where:

C_{Cap}= Initial Capital Cost

C_{Rep}= Replacement Costs

$C_{O\&M}$= Cost of Operation & Maintenance

C_{Fuel}= Cost of Fuel

C_{emis}= Emission Penalties

C_{Grid}= Grid Purchases

C_{Salv}= Salvage Value

C_{GSales}= Sales of Excess Energy

The levelized cost of energy (LCOE) is calculated as (following HOMER Pro documentation):

$$LCOE = \frac{C_{ann,tot} - H_{served}}{E_{served}} \quad (4)$$

where:

$C_{ann,tot}$= total annualized cost of the system [$/yr]

H_{served}= total thermal load served [kWh/yr]

E_{served}= total electrical load served [kWh/yr]

Technical performance indicators include total electrical load served, unmet load, renewable energy fraction, excess electricity generation, battery state-of-charge behavior, generator operating hours, and diesel fuel consumption. Simulation outputs are analyzed on daily, monthly, and annual bases to capture both short-term operational dynamics and long-term lifecycle performance.

The system performance is evaluated using a set of technical and economic indicators. Technical indicators include total electrical load served, unmet load, renewable energy fraction, excess electricity generation, battery state-of-charge behavior, generator operating hours, and diesel fuel consumption. Economic performance is assessed using net present cost (NPC) and levelized cost of energy (LCOE). Simulation outputs are analyzed on daily, monthly, and annual bases to capture both short-term operational behavior and long-term lifecycle performance.

IV. RESULTS

➢ *Electrical Load Service and Reliability Performance*

The hybrid PV–battery system fully satisfies the irrigation electricity demand over the annual simulation period, delivering approximately 3,650 kWh/yr with near-zero unmet load under the enforced reliability constraint. As shown in Figures 7 and 8, all scheduled irrigation demand during the morning and evening operating windows is served without interruption, confirming the effectiveness of the zero-unmet-load dispatch strategy. In contrast, the diesel-only configuration achieves load service at the expense of continuous generator operation.

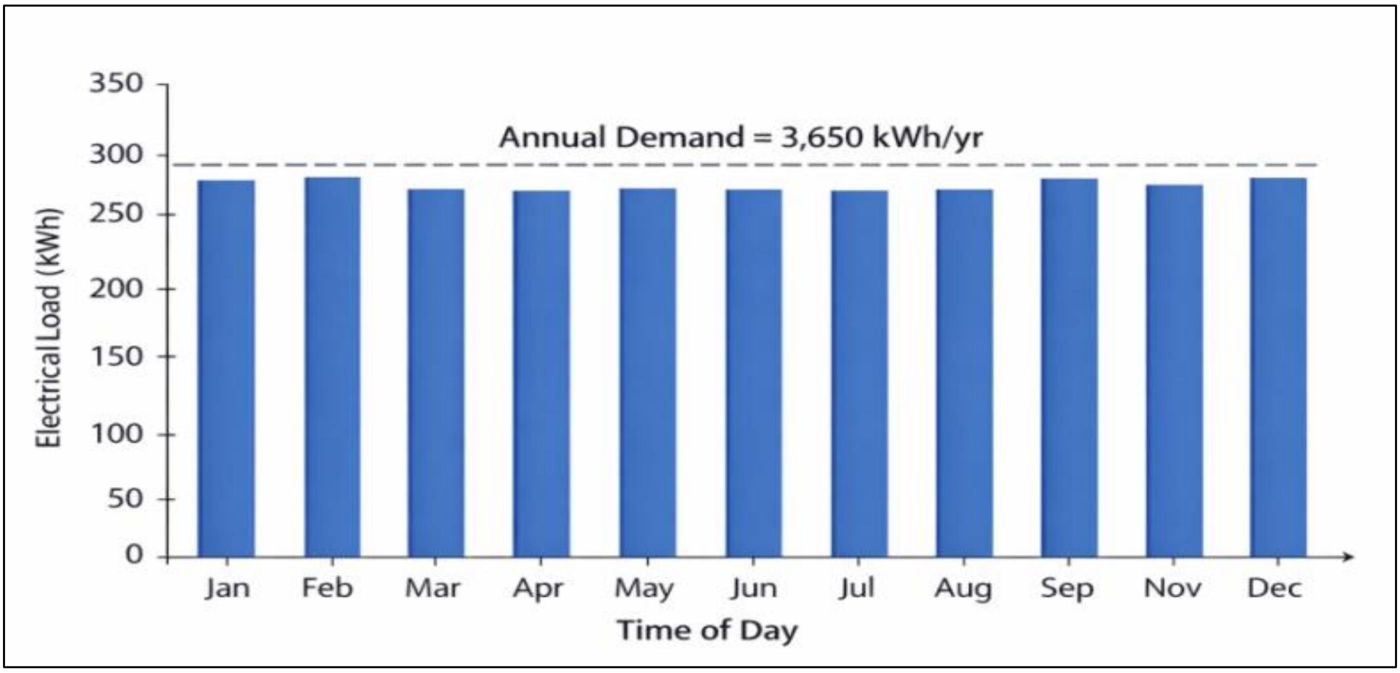

Fig 7 Monthly Electrical Load Served for the Hybrid PV-Battery System Under Zero un-met Load Reliability Constraint, Indicating full Service of Annual Demand (3,650kWh/yr)

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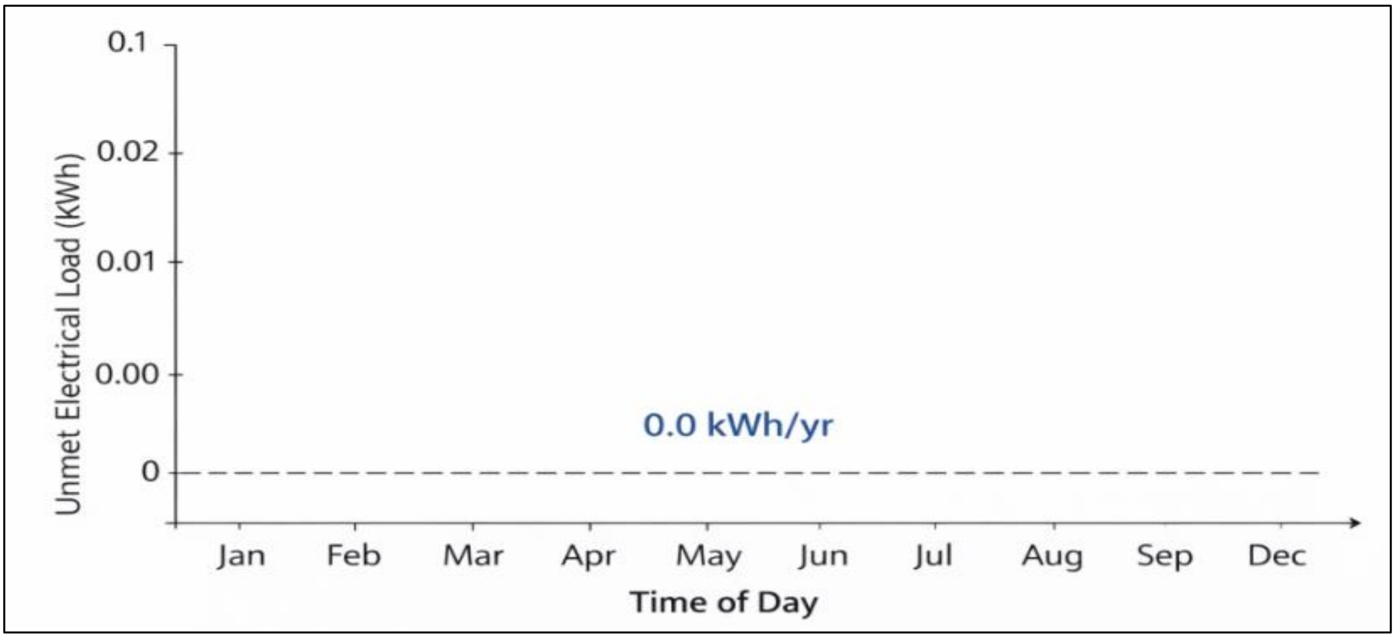

Fig 8 Unmet Electrical Load for the Hybrid PV- Battery System Demonstrating Near Zero Unmet Demand, Over the Constraint Period

➢ *Energy Production and System Energy Balance*

Annual energy balance results for the hybrid configuration are summarized in Figure 9. The PV array generates approximately 4,750 kWh/yr, supplying the majority of the irrigation load either directly or through battery charging. Diesel generator contribution is limited to about 800 kWh/yr, primarily during periods of reduced solar availability. Excess electricity generation amounts to approximately 820 kWh/yr, reflecting conservative system sizing adopted to preserve reliability. The resulting renewable energy fraction is approximately 78%, indicating substantial displacement of diesel-based generation.

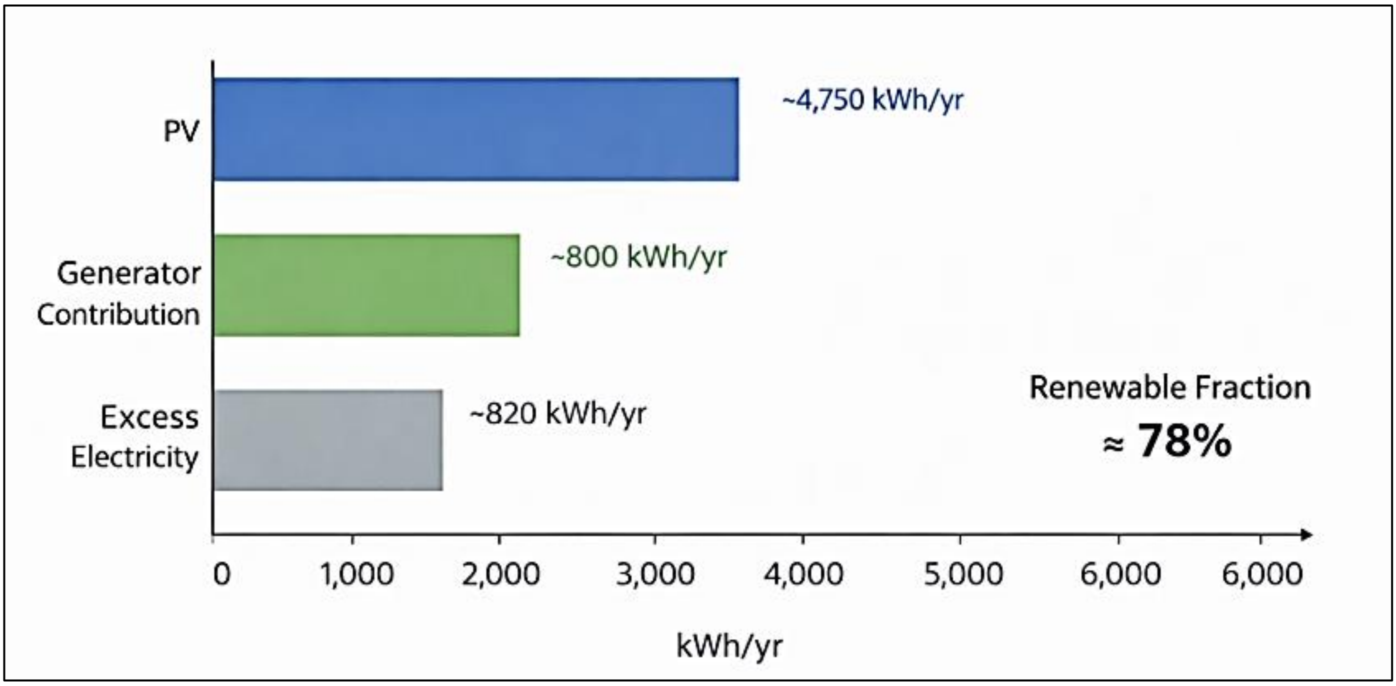

Fig 9 Annual Energy Balance Hybrid Configuration, showing PV Production, (≈ 4,750kWh/yr), Generator Contribution (≈ 800kWh/yr) and Excess Electricity (≈ 820kWh/yr), Corresponding to a Renewable Fraction of Approximately 78%

➢ *Battery Operation and State-of-Charge Behavior*

Figure 10 illustrates the representative daily battery state-of-charge (SOC) profile. Battery charging is predominantly driven by daytime PV generation, while discharge supports irrigation demand during early morning and evening windows. Throughout the simulation period, SOC remains within prescribed operational limits, demonstrating effective energy buffering and avoidance of deep discharge conditions that could compromise reliability or battery lifespan.

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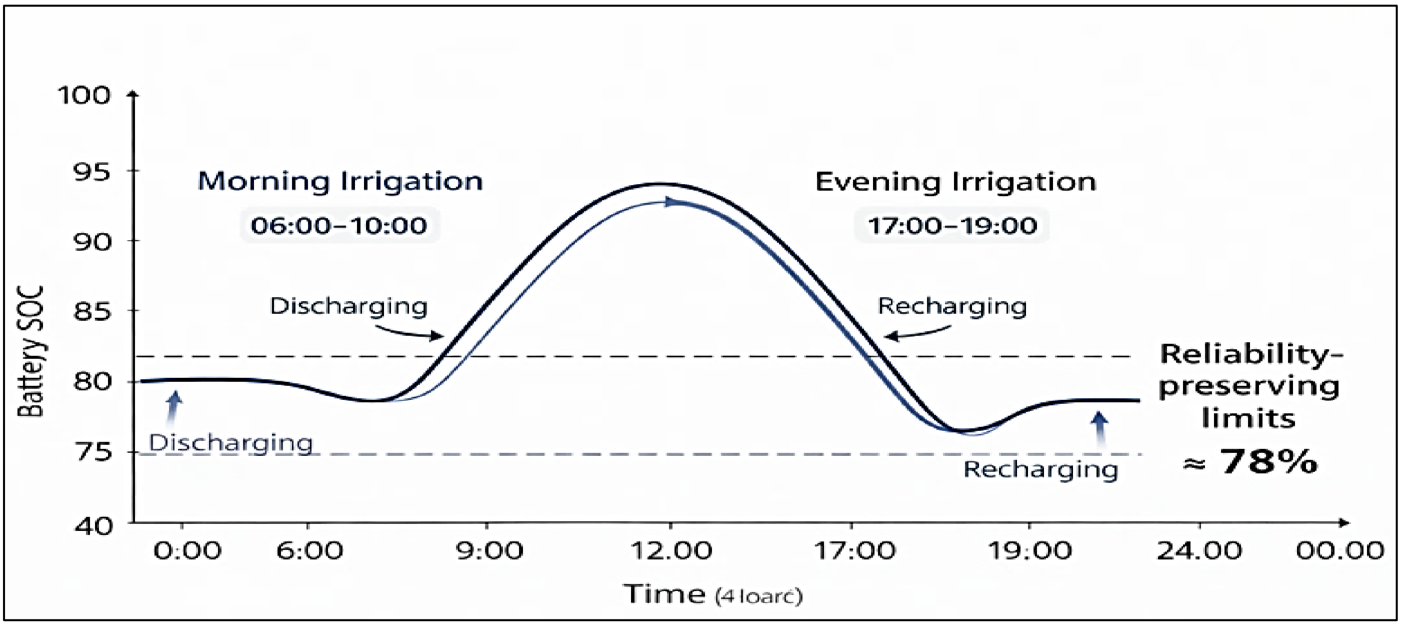

Fig 10 Daily Battery State-of-Charge (SOC) Profile for the Hybrid System, Illustrating PV-Driven Recharge During Daylight Hours and Discharge Support During Morning and Evening Irrigation Windows, with SOC Remaining within Reliability-Preserving Limits

➢ *Generator Utilization and Fuel Consumption*

Generator performance metrics for the hybrid and diesel-only systems are compared in Figure 11. Under hybrid operation, annual generator runtime is reduced to approximately 220 h/yr, with corresponding fuel consumption of about 300 L/yr. By comparison, the diesel-only system requires roughly 1,460 h/yr of generator operation and consumes approximately 1,460 L/yr of fuel to serve the same irrigation load. These results highlight a substantial reduction in fuel dependence and generator wear achieved through PV–battery integration.

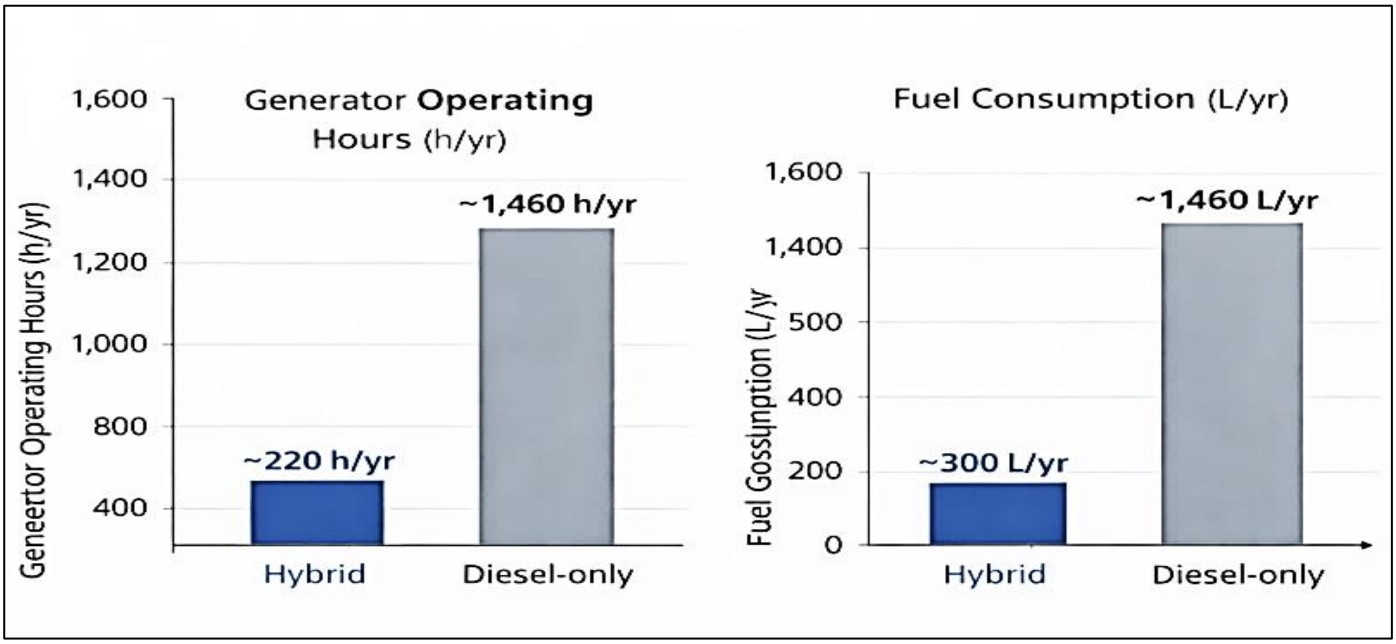

Fig 11 Generator Utilization Showing Reduced Annual Runtime (≈ 220kh/yr) and Fuel Consumption (≈ 300L/yr) for the Hybrid System Relative to Diesel-Only Supply (≈ 1460L/yr).

➢ *Techno-Economic Performance*

Economic performance indicators are summarized in Figure 12. Over the 10-year project lifetime, the hybrid PV–battery system achieves a net present cost (NPC) of approximately ₦10.8 million, compared with about ₦18.6 million for diesel-only operation. The corresponding levelized cost of energy (LCOE) is approximately ₦190/kWh for the hybrid system and ₦330/kWh for the diesel-only alternative. Despite higher initial capital investment, the hybrid configuration benefits from significantly lower operating costs due to reduced fuel consumption and generator runtime.

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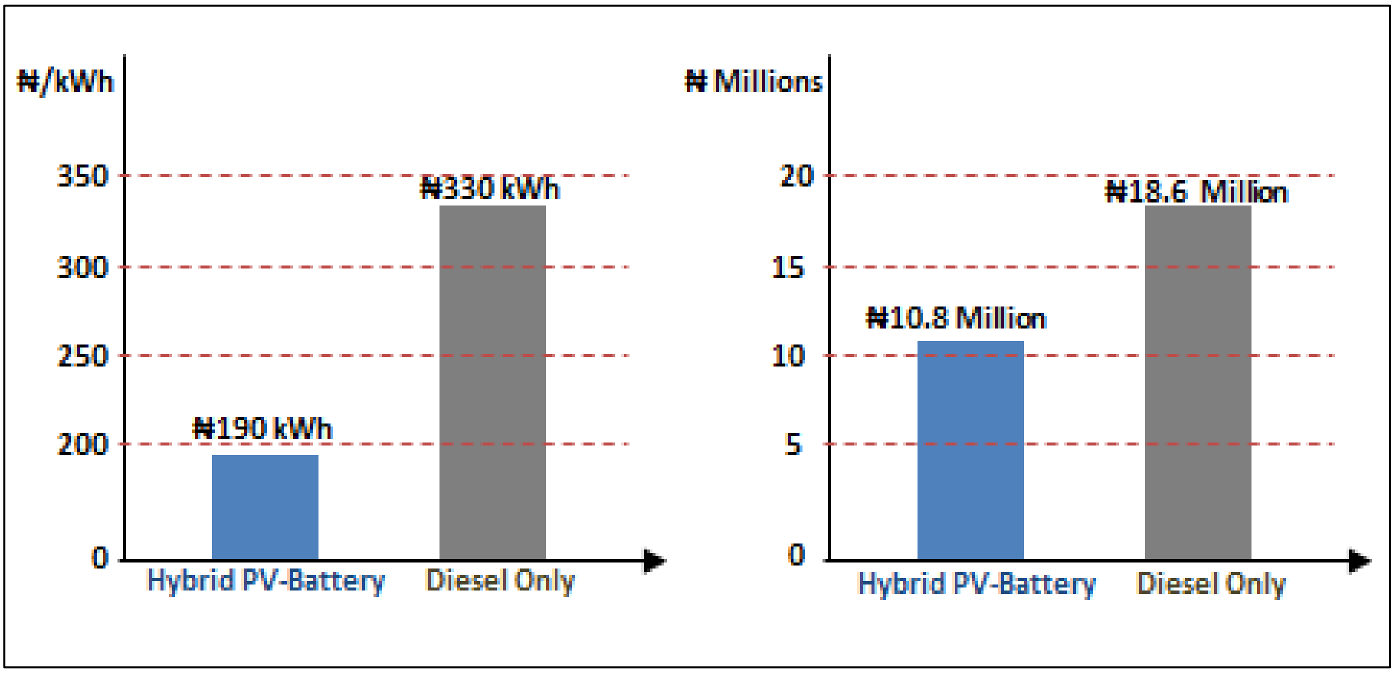

Fig 12 Economic Comparison of Hybrid PV-Battery vs Diesel-only Systems, Illustrating a 42% lower Levelized Cost of Energy (₦190 vs ₦330 Per kWh) and Net Present Cost (₦10.8 Million vs ₦18.6 Million over a 10-year Period), for the Hybrid System

➢ *Sensitivity to Diesel Fuel Price*

Sensitivity analysis results show that the economic advantage of the hybrid system increases with rising diesel fuel prices. As fuel costs escalate, the NPC and LCOE of the diesel-only system increase sharply, while the hybrid system exhibits greater cost stability due to its high renewable energy contribution and limited generator reliance.

V. DISCUSSION

The results demonstrate that explicitly enforcing reliability as a primary design constraint fundamentally shapes both system configuration and performance outcomes for small-scale irrigation pumping. Under the zero-unmet-load requirement, the hybrid PV–battery system successfully delivers the full annual irrigation electricity demand of approximately 3,650 kWh without interruption during the fixed morning (06:00–09:00) and evening (17:00–19:00) pumping windows. This confirms that reliability-oriented dispatch is essential for irrigation applications, where deferred or curtailed operation cannot be recovered outside scheduled periods. While previous hybrid system studies report improved load coverage through renewable integration (Silinto et al., 2025; Nyarko et al., 2023), the present results extend this body of work by explicitly enforcing a strict zero-unmet-load reliability constraint tailored to time-critical agricultural operation.

The system energy balance highlights the dominant role of photovoltaic generation in meeting irrigation demand. Annual PV production of approximately 4,750 kWh supplies the majority of the load either directly or through battery charging, resulting in a renewable energy fraction of about 78%. Diesel generator contribution is limited to roughly 800 kWh/yr, indicating that backup generation is required only during periods of low solar availability or depleted battery state-of-charge. The presence of approximately 820 kWh/yr of excess electricity reflects conservative system sizing adopted to eliminate supply risk rather than inefficient operation. Similar diesel displacement trends have been observed in hybrid farm-scale energy systems (Emezirinwune et al., 2024), although most prior analyses emphasize renewable penetration or cost metrics rather than reliability-guaranteed load service. In reliability-sensitive irrigation contexts, controlled excess generation represents a deliberate design tradeoff to ensure uninterrupted operation.

Battery storage is central to achieving this reliability. The observed state-of-charge profiles show consistent daytime charging driven by PV generation and controlled discharge during early morning and evening irrigation windows. Throughout the simulation period, the battery operates within prescribed limits, maintaining a minimum SOC of 40% and avoiding deep discharge conditions that could compromise system lifespan. While storage integration has been widely investigated for cost optimization and renewable fraction maximization (Razmjoo et al., 2024; Turcios et al., 2025), the present analysis demonstrates the operational significance of battery-supported load shifting for guaranteeing uninterrupted service in time-constrained irrigation applications. This distinction reinforces the value of reliability-driven rather than purely cost-driven system design.

Hybridization yields substantial reductions in generator utilization and fuel dependence. Annual generator runtime is reduced to approximately 220 h/yr, with corresponding diesel fuel consumption of about 300 L/yr, compared with 1,460 h/yr and 1,460 L/yr, respectively, for diesel-only supply. This represents an over 80% reduction in generator operating hours. Comparable reductions have been reported in hybrid renewable configurations across off-grid agricultural and rural electrification contexts (Emezirinwune et al., 2024; Silinto et al., 2025). However, in contrast to generalized or mixed-load studies, the present work quantifies diesel displacement under fixed irrigation windows and enforced reliability, thereby linking hybrid performance directly to the operational realities of pumping-based water delivery.

From an economic perspective, the reliability-oriented hybrid system achieves a net present cost (NPC) of approximately ₦10.8 million over 10 years, compared with ₦18.6 million for diesel-only operation. The corresponding levelized cost of energy (LCOE) decreases from approximately ₦330/kWh to ₦190/kWh. These findings align with broader techno-economic assessments of PV–battery systems that report lifecycle cost advantages driven by fuel displacement (Tufail et al., 2026; Shrivastav et al., 2025). However, unlike optimization frameworks primarily centered on cost minimization (Yakout et al., 2026; Shehu et al., 2026), the present configuration emerges from a reliability-first design philosophy. Notably, strict reliability enforcement does not impose a lifecycle cost penalty; instead, reduced fuel consumption and generator wear offset higher initial capital expenditure.

Sensitivity analysis further indicates that the economic advantage of the hybrid configuration increases with rising diesel fuel prices, reinforcing findings from regional studies highlighting the vulnerability of diesel-dependent systems to fuel price volatility (Nyarko et al., 2023). In fuel-dependent off-grid environments such as Lafia, reduced exposure to price shocks constitutes a critical resilience benefit beyond purely economic metrics. These findings suggest that reliability-constrained design frameworks should be prioritized in hybrid system modeling for agricultural applications where operational flexibility is limited.

Overall, the work confirms that reliability-driven system design—rather than cost minimization alone—is a decisive factor in achieving technically robust and economically viable energy solutions for irrigation pumping. By aligning system sizing, dispatch strategy, and storage capacity with the operational characteristics of hydraulic pumping demand, hybrid PV–battery systems can deliver sustained performance benefits in off-grid, fuel-dependent regions while addressing a methodological gap in the current hybrid energy systems literature.

VI. CONCLUSIONS, IMPLICATIONS, LIMITATIONS, AND FUTURE WORK

➢ *Conclusions*

This study presented a reliability-driven techno-economic assessment of an off-grid photovoltaic (PV)–battery system with diesel backup for small-scale irrigation pumping under the local operating conditions of Lafia, Nigeria. By enforcing a zero-unmet-load constraint during fixed morning and evening irrigation windows, the analysis prioritized uninterrupted service as a primary design objective.

The hybrid PV–battery configuration fully served the annual irrigation electricity demand of approximately 3,650 kWh with near-zero unmet load. Annual PV generation of about 4,750 kWh enabled a renewable energy fraction of approximately 78%, limiting diesel generator contribution to roughly 800 kWh/yr. Generator operation was reduced to about 220 h/yr with fuel consumption of approximately 300 L/yr, compared with 1,460 h/yr and 1,460 L/yr, respectively, for diesel-only supply. From a lifecycle perspective, the hybrid system achieved a lower net present cost (≈₦10.8 million over 10 years) and levelized cost of energy (≈₦190/kWh) than diesel-only operation (≈₦18.6 million and ≈₦330/kWh). These results demonstrate that reliability-oriented hybridization can deliver both technical robustness and economic advantage for time-sensitive irrigation loads.

➢ *Practical and Policy Implications*

The findings indicate that off-grid PV–battery systems can substantially reduce fuel dependence, operating costs, and generator wear while guaranteeing uninterrupted irrigation power supply. For irrigation operators in fuel-dependent regions, such systems offer improved operational resilience and reduced exposure to fuel price volatility. For planners and energy practitioners, the results underscore the importance of incorporating explicit reliability constraints in system design, particularly for applications where load curtailment is unacceptable.

➢ *Limitations*

The analysis employs a representative irrigation load profile derived from simplified hydraulic pumping relationships and fixed operating schedules. While this approach ensures physical plausibility, actual irrigation loads may vary with pump characteristics, water delivery requirements, and seasonal practices. In addition, cost and performance parameters reflect prevailing local conditions and may evolve with changes in technology pricing and fuel markets.

➢ *Future Work*

Future studies could integrate field-measured pump operating data to validate and refine the derived load profile under real operating conditions. Expanded analysis incorporating multiple pump sizes, dynamic water demand, and component degradation effects would further strengthen system design guidance. Field deployment and long-term monitoring would also provide valuable insight into operational reliability and economic performance beyond simulated outcomes.

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