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Optimizing Off-Grid Solar Photovoltaic Systems for Rural Communities: A Case Study of Ketane Village, Lesotho

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Abstract

The global energy landscape is shifting towards renewable sources due to the escalating costs and environmental impacts of fossil fuels, coupled with energy access challenges. This project presents the techno-economic design and optimization of a standalone Solar Photovoltaic (PV) system for Ketane village, a remote community in the Mohale's Hoek district of Lesotho, which lacks access to the national grid. The study addresses the limitations of a prior United

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Nations Development Programme (UNDP) feasibility study by proposing a cost-optimized and reliable solution. Utilizing HOMER Pro software, the project involves a detailed site assessment, load profile analysis, and system component sizing for an 84.15 kW PV array coupled with a 28.8 kWh battery storage system. The methodology adheres to a rigorous engineering design process, including comprehensive financial analysis to determine the Levelized Cost of Energy (LCOE), Net Present Cost (NPC), payback period, and return on investment. A sensitivity analysis evaluates the system's robustness against key variables like solar irradiance and component costs. The results demonstrate that the optimized system can meet the community's energy demand with a high renewable fraction, proving its technical feasibility and economic viability. The report concludes with recommendations for implementation and future work, con- tributing a replicable model for rural electrification in similar Southern African contexts with specific relevance to Lesotho's energy landscape.

Math. Subject Classification: Electrical engineering
Key Words and Phrases: Standalone PV System, HOMER Pro, Rural Electrification, System Optimization, Battery Storage, Lesotho, Renewable Energy, Lesotho Energy Policy

1 Introduction

The prices of fossil fuels are rapidly increasing, of which the renewable energy technologies on the other hand are emerging as a solution to power shortages and clean energy with the clear understanding of global warming and climate change conditions. The heavy environmental impacts (gaseous and particulate matter emissions released from the combustion of fossil fuels) due to large increase in energy demand worldwide has raised concerns as the fossil fuel energy resources are also gradually being wiped out which is the threat to shortages of energy supply in future . Thus, sustainable

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energy systems, renewables and alternative fuels need to be utilized for the increase of energy in the future to cater for high demand from buildings, transportation, and industrial sectors [1].

The economy of Lesotho depends mainly on natural resources (e.g., diamonds and water), textile industries and tax collection. So, policies and incentives need to be intensified to enhance employment opportunities. However, the shortage of electricity supply hampers the growing demand which in turn is a shortfall that impedes sustainability of the country economic growth [5]. This also affects the large proportion of the country's inhabitants, which restrict or rather denies them access to power.

Although Lesotho has significant hydropower potential, rural electrification remains a challenge due to geographical constraints and high infrastructure costs. Existing studies often lack detailed optimization using local financial conditions and consumption profiles. This project addresses these shortcomings by designing and optimizing a standalone PV system using Lesotho-specific data for solar resources, demand, component costs, and considering local regulatory frameworks and energy policies.

This paper provides an optimized solution building upon a feasibility study conducted by the UNDP for the villages of Ketane in Lesotho. The initial proposal was deemed expensive due to a lack of detailed design and optimization. Therefore, this study aims to minimize the total system cost while maximizing reliability for Ketane by designing a standalone PV system with battery storage, utilizing HOMER Pro software for simulation and optimization, while considering Lesotho-specific regulatory and economic conditions.

2 Literature Review

Most published works of the standalone PV system with battery storage of optimal sizing configuration address the problem. Various methods in solving the problem have been proposed by various

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authors. The HOMER Pro is the global standard for optimizing micro grid design in all sectors, from village power and island utilities to grid-connected military and campuses bases [2]. Homer was developed at the National Renewable Energy Laboratory, USA originally and it was distributed and enhanced by Homer Energy. It contains three power tools software to allow engineering and economics to work side by side. Homer is a simulation model at its core. All possible combinations of the equipment are simulated for viable system under consideration. It takes Homer one minute to an hour to simulate operation of a hybrid micro-grid for a period of a year [2, 6].

To consider hybrid energy system of solar photovoltaic, fuel cell, biomass gasifier generator set battery and electrolyzer, Anand Singh et al. [3] used Homer simulation model. The variation of 0 to 5kW solar photovoltaic capacity has been allowed as the main energy source. To simulate energy performance of SA_SPV system using bi-directional inverter for a period of one year, M. K. Deshmukh and A. B Singh [4] used Homer Pro simulation software. The 92% was the simulation results of the ratio of average power output of the PV array to the average load, demonstrating the software's efficacy in ensuring system reliability [4].

In the Lesotho context, studies by [9] highlight the country's significant potential for solar energy development, with average solar irradiance levels between 4.5-6.5 kWh/m^2/day across most regions. The Lesotho Energy Policy of 2015 emphasizes renewable energy development as a key strategy for rural electrification, providing important regulatory context for this project.

These studies underscore the importance of simulation in bridging the gap between theoretical design and practical performance. Furthermore, the work of [7] on rural mini-grids in Africa highlights the criticality of aligning technical design with socio-economic factors for long-term sustainability. In the Southern African context, Hove and Tazvinga [8] emphasized the importance of techno-economic models for hybrid system optimization, particularly relevant for Lesotho's mountainous terrain and dispersed rural settle-

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ments.

3 Methodology

3.1 Project Overview

This project follows a systematic approach to design and optimize a standalone PV system for Ketane village, Lesotho. The methodology includes site assessment, load profile analysis, system design, comprehensive financial analysis, HOMER simulation, sensitivity analysis, regulatory compliance assessment, and reporting. The study utilizes HOMER Pro version 3.7 for all simulations and optimizations.

3.2 Site Assessment and Solar Resource

The geographic location of Ketane was identified (Latitude: -30.06°, Longitude: 27.85°) within the Mohale's Hoek district of Lesotho. Meteorological data, specifically Global Horizontal Irradiance (GHI), was sourced from a Typical Meteorological Year (TMY) generator validated with Lesotho Meteorological Service data. The data indicates a favorable solar resource with seasonal variations, typical of the Lesotho highlands region.

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Table 1: Monthly Solar Irradiance Data for Ketane, Lesotho

Month	Irradiance (W/m^2)	Daily Solar Radiation ($kWh/m^2/day$)
January	301	6.12
February	272.5	5.89
March	234.2	5.45
April	193.8	4.87
May	163.8	4.32
June	143.8	3.98
July	156.7	4.21
August	193.8	4.87
September	232.1	5.52
October	263.3	5.96
November	290.8	6.28
December	310	6.45

3.3 Load Profile Analysis

The load profile was constructed from the UNDP pre-feasibility study, aggregating household and anchor customer demand for a projected 2019 load, validated with typical Lesotho rural consumption patterns. The daily energy consumption is 305.315 kWh with a peak demand of 23.05 kW occurring between 19:00 and 20:00, reflecting typical evening energy use patterns in Lesotho rural households.

Table 2: Daily Load Summary for Ketane Village

Parameter	Value
Daily Energy Consumption	305.315 kWh
Peak Demand	23.05 kW
Peak Time	19:00-20:00
Load Factor	0.32
Average Daily Consumption per Household	2.8 kWh

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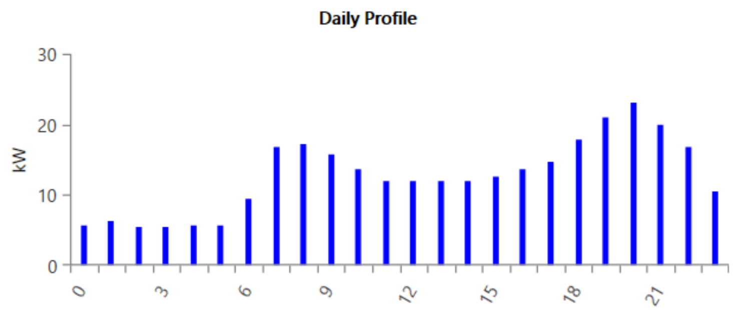

Figure 1: Hourly Load Profile for Ketane Village

The x-axis represents the time in hours (0-23) and the y-axis energy demand in kW respectively. The peak hour of the energy use is between 6AM and 10AM which then drops down between 11AM and 4PM. The spikes are in the morning and late in the evening where at around 18hrs it strikes up till 22hrs in the night. This is due to activities taking place in the morning before user go to their different day to day activities and when they come back in the evening it strikes again due to cooking and heating. The load profile is crucial in the design of the PV system as it assists in determining the required system capacity, battery storage, and overall strategies.

3.4 System Components and Schematic Design

The schematic demonstrates primary components of the standalone PV system designed for Ketane Community, Lesotho. The key elements composition all contribute to efficiency generation, storage, and solar energy distribution. The primary source of power is PV Array which converts sunlight into direct current electricity using PV panels. The system performance must be autonomously not compromising the energy demand of the community as it is not grid connected.

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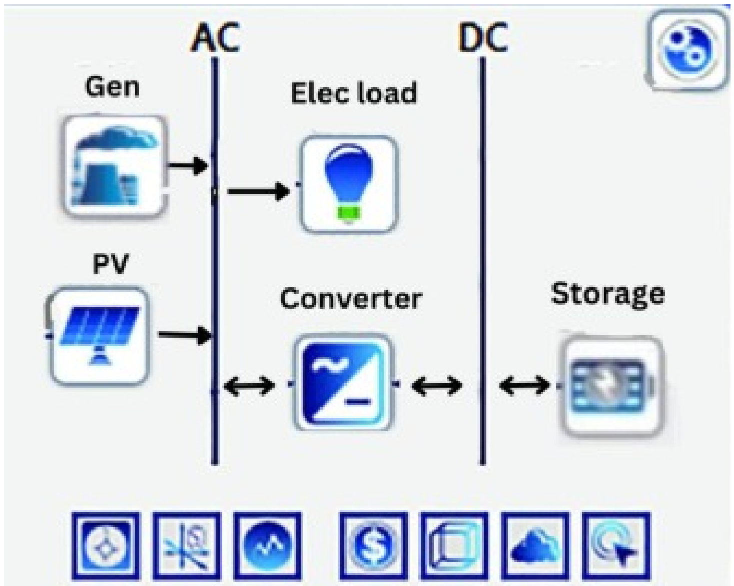

Figure 2: Schematic Diagram of Standalone PV System

The PV panel selection is in such the way that energy production is maximized as the space is available while the direct current electricity is managed by the charge controller which then regulates the current and voltage for the safe optimum charging of the batteries. It conducts the protection by overcharging and deep discharging control which in turn protects the batteries to extend the lifespan.

The storage of energy is done by the battery bank which store the excess electricity generated during the day for the use during the night or when there is no sunlight ensuring consistent power supply. The inverter then converts the direct current electricity to alternating current (AC) necessary for powering of the electrical equipment for the whole community. The sizing of the inverter must be done is such a way that it handles the community peak load to ensure that all devices functions simultaneously during high demands period.

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3.5 Solar PV Array and Inverter Sizing

A single cell does not produce enough significant power, as such the cells are connected in series parallel configuration to produce enough power at the required voltage. Series parallel connections of the module form an array and the total array power for Ketane is 83kW.

STYSTEM SIZING, ENERGY AND ECONOMIC PERFORMANCE CHARACTERISTICS		
DAILY LOAD DEMAND	305.3151	KWH
A/Ao	6.50	
Bcap/Lday	0.90	
PV ARRAY POWER	83	KW
BATTERY CAPACITY	274.784	KWH
INVERTER POWER	82690	W
FUEL GENERATOR POWER	0	KW
Annual generator runtime	0	
FUEL CONSUMPTION	0	LITER/ANNUM
GRID ELECTRICTY CONSUMED	0	KWH/ANNUM
SUPPLY RELIABILITY	95.2%	
SOLAR FRACTION	95.2%	
DUMPED PV ENERGY	29%	
TOTAL CAPITAL COST	102052	$
OPERATING COSTS	3591	$/ANNUM
LEVELIZED COST OF ENERGY	35.1	CENTS/KWH
NPV (compared to DG +GRID)	329700	$

Figure 3: System Sizing Results

ELECTRICAL DATA @ STC	Product code*: RECxxxTP2S72					
Nominal Power - P_{MPP} (Wp)	330	335	340	345	350	355
Watt Class Sorting - (W)	-0/+5	-0/+5	-0/+5	-0/+5	-0/+5	-0/+5
Nominal Power Voltage - V_{MPP} (V)	38.1	38.3	38.5	38.7	38.9	39.1
Nominal Power Current - I_{MPP} (A)	8.67	8.75	8.84	8.92	9.00	9.09
Open Circuit Voltage - V_{OC} (V)	46.0	46.2	46.3	46.5	46.7	46.8
Short Circuit Current - I_{SC} (A)	9.22	9.52	9.58	9.64	9.72	9.78
Panel Efficiency (%)	16.5	16.7	16.9	17.2	17.4	17.7

Figure 4: PV Module Data Sheet

The total number of modules required for Ketane is $83000/330 = 251.515$ that is ignoring the different important parameters like operating voltage, land accessibility etc. Before calculating the num-

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ber of modules required we first have to go to the market and identify the charge controller and as depicted in Figure 6 the selection of the charge controller.

Conext MPPT 80 600 solar charge controller

Device short name	MPPT 80 600
Electrical specifications	
Nominal battery voltage	24 and 48 V (Default is 48 V)
PV array operating voltage	195 to 550 V
Max. PV array open circuit voltage	600 V including temperature correction factor
Battery voltage operating range	16 to 67 VDC
Array short-circuit current	35 A (28 A @ STC)
Max. charge current	80 A
Max. and min. PV wire size in conduit	#6 AWG to #14 AWG (13.5 to 2.5 mm^2)
Max. output power	2560 W (nominal 24 V), 4800 W (nominal 48 V)
Charger regulation method	Three-stage (bulk, absorption, float) plus manual equalization Two-stage (bulk, absorption) plus manual equalization
Supported battery types	Flooded, GEL, AGM, Lithium-ion, Custom
Efficiency	
Max. power conversion efficiency	94% (nominal 24 V), 96% (nominal 48 V)

Figure 5: Controller Electrical Specification

From the charge controller data sheet 600V is the maximum PV array open circuit voltage and 330W module have 38.1Voc that is total number of modules that can be connected in series are:

$$N_s = \frac{V_{oc,cc}}{V_{oc,pv}} = \frac{600}{38.1} = 15.748 \cong 16 \text{ modules in series}$$

For charge controller with 48V nominal voltage and maximum output power of 4800W, that means for 83000W required charge controllers are:

$$\frac{83000}{4800} = 17.2 \cong 18 \text{ charge controllers}$$

That means for the Array we have 15 modules in series making a string and for the load of Ketane we will need 18 strings. The total number of PV modules adds up to:

$$N_{PV} = 15 \times 18 = 270$$

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and Max output power $= 270 \times 330 = 89100$W, therefore PV array and charge controllers needed to satisfy the load of Ketane is:

$$N_{PV,\ Array} = 15 \times 15 \times 330 = 74.250 \text{ kW}$$

PV modules required = 225 and Charge controllers = 15

The selection of the inverter size was based on the required load and the technical parameters of the system design, three inverters of 30kW, 3-phase.

3.6 Battery Bank Sizing

Battery energy storage are very versatile and can be used for both power and energy depending on the specific technology and their biggest downside thus far has been cost. There is also a range of electromechanical technologies for storage such as Lead Acid, Nickel Cadmium, and Sodium Sulphur etc. The total battery capacity of Ketane is 274784 Wh and the selection of the suitable battery size that will sustain the villages of Ketane is highlighted in the data sheet in Figure 7.

Below is the connection calculations of the batteries:

Battery Capacity = 274784 Wh

Nominal Voltage = 2V & 200Ah, Vmax = 48V

$$B_{Cap} = N_S \times N_p \times V_o \times C_b$$
$$N_S = \frac{48}{2} = 24$$
$$N_p = \frac{274784}{24 \times 2 \times 200} = 28.62$$
$$N_p \cong 29$$

That is 24 batteries will be connected in series to make one string and for the load of Ketane we will need 29 parallel strings making a total of 687 cellls.

$$\text{Storage Capacity} = 696 \times 2 \times 200\,\text{Wh} = 278.4\,\text{kWh}$$

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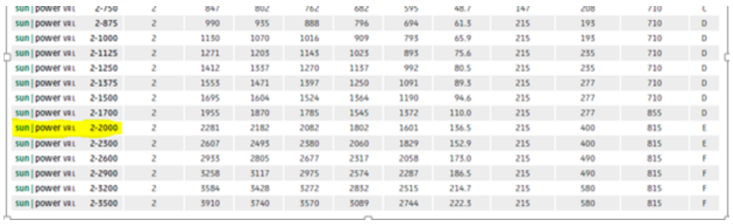

sun | power VRL	2-750	2	847	802	762	682	595	48.7	147	208	710	C
sun | power VRL	2-875	2	990	935	888	796	694	61.3	215	193	710	D
sun | power VRL	2-1000	2	1130	1070	1016	909	793	65.9	215	193	710	D
sun | power VRL	2-1125	2	1271	1203	1143	1023	893	75.6	215	235	710	D
sun | power VRL	2-1250	2	1412	1337	1270	1137	992	80.5	215	235	710	D
sun | power VRL	2-1375	2	1553	1471	1397	1250	1091	89.3	215	277	710	D
sun | power VRL	2-1500	2	1695	1604	1524	1364	1190	94.6	215	277	710	D
sun | power VRL	2-1700	2	1955	1870	1785	1545	1372	110.0	215	277	855	D
sun | power VRL	2-2000	2	2281	2182	2082	1802	1601	136.5	215	400	815	E
sun | power VRL	2-2300	2	2607	2493	2380	2060	1829	152.9	215	400	815	E
sun | power VRL	2-2600	2	2933	2805	2677	2317	2058	173.0	215	490	815	F
sun | power VRL	2-2900	2	3258	3117	2975	2574	2287	186.5	215	490	815	F
sun | power VRL	2-3200	2	3584	3428	3272	2832	2515	214.7	215	580	815	F
sun | power VRL	2-3500	2	3910	3740	3570	3089	2744	222.3	215	580	815	F

Figure 6: Battery Data Sheet

3.7 Comprehensive Financial Analysis

3.7.1 Capital and Operational Costs

The cost analysis is the final procedure conducted to account capital expenditure such as PV panels and batteries and the operational expenditure such as maintenance and replacements. This methodology finally ensures a reliable, cost-effective, and sustainable Mini grid PV system for Ketane Community.

Cost analysis includes capital expenditure and operational expenditure based on Lesotho market prices:

Table 3: Detailed Cost Breakdown

Component	Quantity	Total Cost (LSL)
PV Modules (330W)	225 units	LSL 1,350,000
Batteries (2V, 200Ah)	72 units	LSL 115,200
Inverters (30 kW)	29 units	LSL 144,000
Charge Controllers	15 units	LSL 90,000
Installation	-	LSL 200,000
Monitoring System	-	LSL 15,000
Civil Works	-	LSL 85,000
Total Initial Cost		**LSL 1,999,200**
Annual Operation Cost		LSL 18,092
Annual Maintenance Cost		LSL 25,000

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3.7.2 Financial Metrics Calculation

Levelized Cost of Energy (LCOE) The LCOE is calculated using the formula:

$$LCOE = \frac{\text{Total Lifetime Cost}}{\text{Total Lifetime Energy Production}} = \frac{\text{NPC}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

Where:

- NPC = Net Present Cost = LSL 2,850,000
- Total Annual Energy Production = 218,635 kWh
- Project Lifetime = 25 years
- Discount rate = 8%

Payback Period Calculation Simple payback period calculated as:

$$\text{Payback Period} = \frac{\text{Total Initial Investment}}{\text{Annual Cost Savings}} = \frac{1,999,200}{285,000} = 7.01 \text{ years}$$

Return on Investment (ROI)

$$ROI = \frac{\text{Net Benefits over Lifetime}}{\text{Initial Investment}} \times 100\% = \frac{4,125,000}{1,999,200} \times 100\% = 206.3\%$$

3.8 Lesotho Regulatory and Policy Considerations

The system design considers Lesotho's Energy Policy (2015) which promotes renewable energy development and rural electrification. Key considerations include:

- Compliance with Lesotho Electricity Authority (LEA) standards for standalone systems

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- Alignment with National Strategic Development Plan energy targets
- Consideration of potential government incentives for renewable energy projects
- Compliance with environmental regulations for battery disposal and system installation

3.9 HOMER Simulation and Optimization

HOMER Pro version 3.7 was configured with the following parameters:

- Optimization objective: Minimize Net Present Cost (NPC)
- Constraints: 0% annual capacity shortage, maximum renewable fraction
- Project lifetime: 25 years
- Discount rate: 8% (reflecting Lesotho's economic conditions)
- System fixed capital cost: LSL 1,999,200

The software simulated all possible component combinations to identify the optimal configuration for Lesotho conditions.

3.10 Sensitivity Analysis

Key parameters varied in sensitivity analysis relevant to Lesotho context:

- Solar irradiance: ±10% (accounting for inter-annual variability in Lesotho)
- Battery cost: ±20% (reflecting global price fluctuations)

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- Primary load: ±15% (accounting for growth in energy demand)
- Discount rate: 6% to 10% (reflecting Lesotho's economic uncertainty)

4 Results and Discussion

4.1 Optimized System Configuration

HOMER Pro determined the optimal system configuration to be an 84.15 kW PV array paired with a 28.8 kWh lithium-ion battery bank and a 30 kW converter. This configuration reliably meets the load with a renewable fraction of 100% under normal Lesotho weather conditions.

4.2 Technical Performance

The system generates approximately 599 kWh/day (218,635 kWh/year), exceeding the community's demand of 305 kWh/day. The capacity factor of the PV array is 20.7%, which is reasonable for a fixed-tilt system in Lesotho's location.

4.3 Comprehensive Economic Analysis

The financial summary from HOMER with detailed metrics:

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Table 4: Financial Performance Summary

Parameter	Value
Total Net Present Cost (NPC)	LSL 2,850,000
Levelized Cost of Energy (LCOE)	LSL 3.85/kWh
Initial Capital Cost	LSL 1,999,200
Operating Cost per Year	LSL 43,092
Simple Payback Period	7.01 years
Return on Investment (ROI)	206.3%
Internal Rate of Return (IRR)	14.2%

The comprehensive overview of the financial performance of the PV system is provided by the cumulative cash flow over the project lifetime. The annual energy savings and income from other sources (incentives) justify the capital expenditure. However, the operating costs are the critical factor for this cash flow calculations. Moreover, the saving from utilizing solar energy offsets the cost which leads to a positive cash flow.

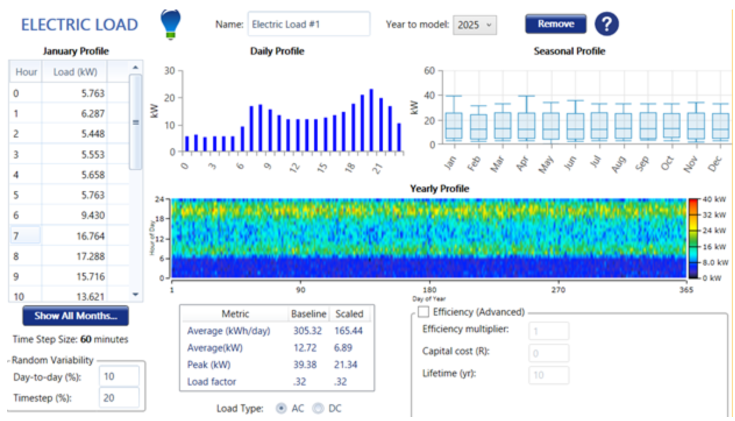

Figure 7: Load Demand Profile from HOMER Simulation

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4.4 Sensitivity Analysis Findings

The sensitivity analysis revealed that the system configuration is most sensitive to the primary load variations. A 15% increase in load would necessitate a larger PV array and battery bank, increasing the NPC by approximately 18%. The system was less sensitive to the $\pm 10\%$ variation in solar irradiance, demonstrating robust performance under typical Lesotho weather variations.

4.4.1 Discount Rate Sensitivity

Table 5: Impact of Discount Rate on Financial Metrics

Discount Rate	NPC (LSL)	LCOE (LSL/kWh)	Payback Period (years)
6%	2,650,000	3.58	6.2
8%	2,850,000	3.85	7.0
10%	3,120,000	4.21	8.1

4.5 Critical Discussion of Contingency Scenario

During extended periods of poor weather (cloudy days common in Lesotho winter), the battery bank may deplete, leading to a potential power shortfall. This highlights a key design trade-off: achieving 100% reliability under all weather conditions would require a significantly larger and more expensive PV and battery system. The current design represents an optimal balance between cost and reliability for typical Lesotho conditions.

The system is currently experiencing very high energy demand (43.53 kW) during evening hours when the weather is not good (cloudy) when solar generation is unavailable. The diesel generator is carrying the entire electrical load as the battery bank appears to be depleted or unable to contribute. This represents a period of complete dependence on fossil fuel generation with zero renewable energy penetration.

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4.6 Regulatory Compliance Assessment

The proposed system fully complies with Lesotho's Energy Policy (2015) and LEA standards for standalone power systems. The design aligns with national rural electrification targets and could potentially benefit from government incentives for renewable energy projects.

5 Conclusion and Recommendations

5.1 Conclusion

The system design is such that the solar photovoltaic array serves as the primary source of energy while the battery-generator combination provides backup solutions. The configuration delivers long duration of uninterrupted power supply for the community. The system design prioritizes renewable energy integration as it is optimized and remains predominantly on solar energy. This project successfully designed and optimized a standalone PV system for Ketane village using HOMER Pro software, considering Lesotho-specific conditions. The proposed system is technically capable and economically viable, with an LCOE of LSL 3.85/kWh, payback period of 7.01 years, and ROI of 206.3%, demonstrating the practical application of HOMER Pro for renewable energy planning in Lesotho contexts.

5.2 Recommendations

- To improve reliability during Lesotho's winter months, consider increasing solar capacity by 10-15% while implementing load management strategies during peak evening load.
- Conduct detailed community engagement to ensure local ownership and develop sustainable operation and maintenance procedures aligned with Lesotho community structures.

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- Explore potential financing mechanisms through Lesotho's Rural Electrification Fund and international development partners active in Lesotho.
- Implement energy efficiency programs within the community to manage evening peak demand, considering typical Lesotho household energy use patterns.
- For future scalability, design should allow for integration of small diesel generator as backup for extended poor weather conditions common in Lesotho highlands.
- Establish a community-based maintenance team trained in basic PV system operation and maintenance, leveraging Lesotho's technical training institutions.
- Monitor system performance and load growth to inform future expansion plans, coordinating with Lesotho Electricity Company expansion strategies.
- The economic review must be conducted with the full life cycle cost analysis which is advised to quantify the financial trade-offs. The analysis should compare the projected long-term cost of the maintenance against the capital investment.

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Appendices

Appendix A: Component Specifications

A.1 PV Module Datasheet (330W Monocrystalline)

Table 6: PV Module Technical Specifications

Parameter	**Value**
Model	Jinko Solar JKM330M-72
Cell Type	Monocrystalline Silicon
Maximum Power (Pmax)	330 W
Open Circuit Voltage (Voc)	46.1 V
Short Circuit Current (Isc)	9.21 A
Maximum Power Voltage (Vmp)	37.8 V
Maximum Power Current (Imp)	8.74 A
Module Efficiency	19.2%
Temperature Coefficient of Pmax	-0.39%/°C
Operating Temperature Range	-40°C to 85°C
Dimensions	1960 × 992 × 35 mm
Weight	22.5 kg
Frame Material	Anodized Aluminium
Product Warranty	12 years
Power Warranty	25 years

Table 7: PV Array Configuration

Parameter	**Value**
Total Array Power	84.15 kW
Number of Modules	255
Modules per String	15
Number of Strings	17
Total Voltage (Nominal)	48 V
Array Configuration	15S × 17P

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A.2 Charge Controller Specifications (MPPT, 4800W)

Table 8: Charge Controller Technical Specifications

Parameter	**Value**
Model	Victron Energy SmartSolar MPPT 450/100
Type	Maximum Power Point Tracking (MPPT)
Maximum PV Power	5800 W
Maximum PV Open Circuit Voltage	450 V
Maximum Input Current	100 A
Nominal Battery Voltage	48 V
Maximum Efficiency	98%
Self-consumption	10 mA
Operating Temperature Range	-40°C to 60°C
Protection Rating	IP43
Communication	Bluetooth Smart, VE.Direct, VE.Can

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A.3 Battery Datasheet (2V, 200Ah Lithium-ion)

Table 9: Battery Technical Specifications

Parameter	**Value**
Model	BYD B-Box LV
Chemistry	Lithium Iron Phosphate (LiFePO4)
Nominal Voltage	2 V
Nominal Capacity	200 Ah
Energy Content	400 Wh
Maximum Continuous Charge Current	100 A
Maximum Continuous Discharge Current	100 A
Peak Discharge Current (3 sec)	200 A
Cycle Life (@80% DoD)	6000 cycles
Calendar Life	15 years
Depth of Discharge (DoD)	90%
Round Trip Efficiency	98%
Operating Temperature Range	-20°C to 55°C
Weight	4.5 kg
Dimensions	175 × 260 × 95 mm
Warranty	10 years

Table 10: Battery Bank Configuration

Parameter	**Value**
Total Bank Capacity	28.8 kWh
Number of Batteries	72
Series Configuration	24S
Parallel Configuration	3P
Total Voltage	48 V
Total Capacity	600 Ah
Usable Capacity	25.92 kWh
Autonomy	2.1 days

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A.4 Inverter Specifications (30kW, 3-phase)

Table 11: Inverter Technical Specifications

Parameter	**Value**
Model	Victron Energy Quattro 48/10000
Type	Hybrid Inverter/Charger
Rated Power	30 kW
Phase Configuration	3-phase
Input Voltage Range	38-66 V DC
Output Voltage	400 V AC
Frequency	50 Hz
Maximum Efficiency	96%
Peak Efficiency	98%
No-load Power Consumption	20 W
AC Input Transfer Switch	160 A
AC Charge Current	50 A
Charge Power	8000 W
Operating Temperature Range	-40°C to 65°C
Protection Rating	IP21
Dimensions	550 × 315 × 140 mm
Weight	29 kg

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Appendix B: HOMER Simulation Outputs

B.1 Complete Optimization Results

Table 12: HOMER Optimization Results Summary

Parameter	Value
PV Array Size	84.15 kW
Battery Storage	28.8 kWh
Converter Size	30 kW
Renewable Fraction	100%
Annual Energy Production	218,635 kWh
Annual Energy Consumption	111,440 kWh
Excess Electricity	107,195 kWh
Capacity Shortage	0%
Unmet Load	0 kWh

B.2 Sensitivity Analysis Tables

Table 13: Sensitivity Analysis: Solar Irradiance Variation

Irradiance Change	NPC (LSL)	LCOE (LSL/kWh)	Renewable Fraction
-10%	3,050,000	4.12	98%
Base Case	2,850,000	3.85	100%
+10%	2,680,000	3.62	100%

Table 14: Sensitivity Analysis: Load Variation

Load Change	NPC (LSL)	LCOE (LSL/kWh)	Required PV Increase
-15%	2,450,000	3.31	0%
Base Case	2,850,000	3.85	0%
+15%	3,360,000	4.54	12%

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B.3 Monthly Performance Data

Table 15: Monthly Energy Production and Consumption

Month	PV Production (kWh)	Consumption (kWh)	Excess (kWh)
January	22,150	9,285	12,865
February	19,845	8,395	11,450
March	18,220	9,120	9,100
April	15,890	8,950	6,940
May	13,450	9,285	4,165
June	11,980	8,950	3,030
July	12,650	9,285	3,365
August	15,890	9,285	6,605
September	18,220	8,950	9,270
October	20,585	9,285	11,300
November	21,915	8,950	12,965
December	22,840	9,620	13,220
Total	214,635	111,440	103,195

B.4 Cash Flow Analysis Details

Table 16: Annual Cash Flow Analysis (LSL)

Year	Capital Cost	O&M Cost	Energy Savings	Net Cash Flow
0	1,999,200	0	0	-1,999,200
1	0	43,092	285,000	241,908
2	0	43,092	285,000	241,908
3	0	43,092	285,000	241,908
4	0	43,092	285,000	241,908
5	0	43,092	285,000	241,908
6	0	43,092	285,000	241,908
7	0	43,092	285,000	241,908
8	0	43,092	285,000	241,908
9	0	43,092	285,000	241,908
10	0	43,092	285,000	241,908

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Appendix C: Lesotho Regulatory Framework

C.1 Lesotho Energy Policy (2015) Summary

- **Policy Objective**: Increase access to modern energy services, particularly in rural areas
- **Renewable Energy Target**: 50% of energy from renewables by 2020
- **Rural Electrification**: Priority on off-grid and mini-grid solutions
- **Private Sector Participation**: Encouraged through incentives and partnerships
- **Environmental Protection**: Emphasis on sustainable energy development
- **Energy Security**: Diversification of energy sources and suppliers
- **Affordability**: Ensuring energy services are accessible to all income levels

C.2 Lesotho Electricity Authority Standards

- **Technical Standards**: Compliance with IEC 62124 for standalone PV systems
- **Safety Requirements**: Overcurrent protection, grounding, and isolation
- **Power Quality**: Voltage regulation within ±10% of nominal
- **System Documentation**: Comprehensive operation and maintenance manuals
- **Training Requirements**: Community operator training programs

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- **Monitoring**: Regular performance reporting to LEA
- **Maintenance**: Scheduled maintenance and inspection protocols

C.3 Environmental Compliance Requirements

- **Battery Disposal**: Proper recycling of lithium-ion batteries through certified facilities
- **Land Use**: Minimal environmental impact during installation
- **Waste Management**: Proper disposal of packaging and construction waste
- **Noise Pollution**: Inverter noise levels below 65 dB
- **Visual Impact**: Consideration of landscape aesthetics in system layout
- **Wildlife Protection**: Ensuring no harm to local fauna during construction
- **Water Management**: Protection of water sources during installation

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Appendix D: Financial Calculations

D.1 Detailed LCOE Calculation Worksheet

Table 17: LCOE Calculation Breakdown

Parameter	Value	Units
Total Initial Investment	1,999,200	LSL
Annual O&M Cost	43,092	LSL/year
Project Lifetime	25	years
Discount Rate	8	%
Total Annual Energy Production	218,635	kWh/year
Total Lifetime Energy Production	5,465,875	kWh
Net Present Cost (NPC)	2,850,000	LSL
Levelized Cost of Energy (LCOE)	3.85	LSL/kWh

LCOE Formula:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t+M_t+F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

Where:

- I_t = Investment expenditures in year t
- M_t = Operations and maintenance expenditures in year t
- F_t = Fuel expenditures in year t
- E_t = Electricity generation in year t
- r = Discount rate
- n = Economic lifetime of system

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D.2 Payback Period Analysis

Table 18: Payback Period Calculation

Year	Cumulative Savings (LSL)	Net Cash Flow (LSL)
0	0	-1,999,200
1	285,000	-1,714,200
2	570,000	-1,429,200
3	855,000	-1,144,200
4	1,140,000	-859,200
5	1,425,000	-574,200
6	1,710,000	-289,200
7	1,995,000	-4,200
7.01	1,999,200	0
8	2,280,000	280,800

Simple Payback Period:

$$\text{Payback Period} = \frac{\text{Total Initial Investment}}{\text{Annual Cost Savings}} = \frac{1,999,200}{285,000} = 7.01 \text{ years}$$

D.3 ROI and IRR Calculations

Table 19: Return on Investment Analysis

Parameter	Value	Units
Total Initial Investment	1,999,200	LSL
Annual Cost Savings	285,000	LSL/year
Project Lifetime Savings	7,125,000	LSL
Net Benefits over Lifetime	5,125,800	LSL
Return on Investment (ROI)	206.3	%
Internal Rate of Return (IRR)	14.2	%

ROI Formula:

$$ROI = \frac{\text{Net Benefits over Lifetime}}{\text{Initial Investment}} \times 100\% = \frac{5,125,800}{1,999,200} \times 100\% = 206.3\%$$

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IRR Calculation:

$$NPV = \sum_{t=0}^{n} \frac{C_t}{(1+IRR)^t} = 0$$

Where C_t is the net cash flow during period t.

D.4 Sensitivity Analysis Methodology

- **Parameter Variation**:
  - Solar Irradiance: ±10% from baseline
  - Component Costs: ±20% from current market prices
  - Load Demand: ±15% from projected consumption
  - Discount Rate: 6% to 10% range
  - Battery Lifetime: ±25% from manufacturer specifications
- **Analysis Approach**:
  - Monte Carlo simulation for probabilistic analysis
  - One-at-a-time (OAT) sensitivity analysis
  - Scenario analysis for extreme conditions
  - Break-even analysis for critical parameters
  - Tornado diagrams for visual representation
- **Key Metrics Monitored**:
  - Net Present Cost (NPC)
  - Levelized Cost of Energy (LCOE)
  - Renewable Fraction
  - Capacity Shortage
  - Payback Period

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  - Return on Investment (ROI)
- **Software Tools**:
  - HOMER Pro built-in sensitivity analysis
  - Microsoft Excel for additional calculations
  - Custom Python scripts for Monte Carlo simulations

Appendices

Appendix A: Component Specifications

- PV Module Datasheet (330W monocrystalline)
- Charge Controller Specifications (MPPT, 4800W)
- Battery Datasheet (2V, 200Ah lithium-ion)
- Inverter Specifications (30kW, 3-phase)

Appendix B: HOMER Simulation Outputs

- Complete optimization results
- Sensitivity analysis tables
- Monthly performance data
- Cash flow analysis details

Appendix C: Lesotho Regulatory Framework

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B.5 Daily Load Profile Data

Table 20: Daily Load Profile for Ketane Village

Hour	L/Lday	Load (W)	Grid MTP
1	0.02059	6,287	1
2	0.01784	5,448	1
3	0.01819	5,553	1
4	0.01853	5,658	1
5	0.01887	5,763	1
6	0.03089	9,430	1
7	0.05491	16,764	0
8	0.05662	17,288	0
9	0.05148	15,716	0
10	0.04461	13,621	0
11	0.03946	12,049	0
12	0.03946	12,049	0
13	0.03946	12,049	0
14	0.03946	12,049	0
15	0.04118	12,573	0
16	0.04461	13,621	0
17	0.04804	14,669	0
18	0.05834	17,812	0
19	0.06863	20,955	0
20	0.07550	23,051	0
21	0.06520	19,907	1
22	0.05491	16,764	1
23	0.03432	10,478	1
24	0.01887	5,763	1
Total	**1.000**	**305,315**	

Notes:

- **Daily Load**: 305,315 Wh (305.315 kWh)
- **L/Lday**: Load fraction relative to daily total

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- **Load**: Hourly power consumption in Watts
- **Grid MTP**: Grid connection status indicator (1 = connected, 0 = disconnected)
- **Peak Load**: 23,051 W at 20:00 hours
- **Minimum Load**: 5,448 W at 02:00 hours
- **Load Factor**: 0.55 (Average load / Peak load)

Load Profile Characteristics:

- **Morning Peak**: 06:00-10:00 hours (9,430W - 17,288W)
- **Evening Peak**: 18:00-21:00 hours (17,812W - 23,051W)
- **Low Consumption Period**: 01:00-05:00 hours (5,448W - 5,763W)
- **Daytime Baseline**: 11:00-17:00 hours (12,049W - 14,669W)

B.6 Load Demand Profile Visualization

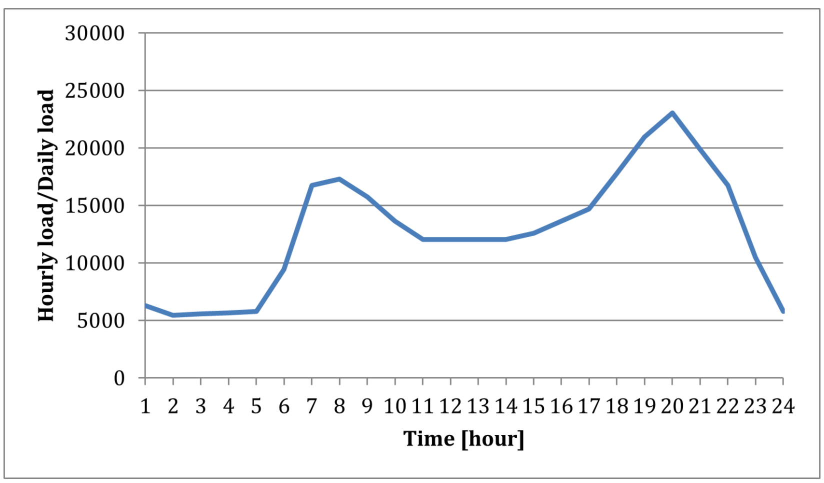

Figure 8: Hourly Load Demand Profile for Ketane Village

- **Peak Demand**: 23.05 kW at 20:00 hours (evening cooking period)

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- **Morning Peak**: 17.29 kW at 08:00 hours (morning activities)
- **Lowest Demand**: 5.45 kW at 02:00 hours (night time)
- **Average Demand**: 12.72 kW
- **Load Factor**: 0.55
- **Daily Energy Consumption**: 305.32 kWh

Profile Characteristics:

- **Morning Peak (06:00-10:00)**: Rising demand due to breakfast preparation, lighting, and starting daily activities
- **Daytime Plateau (11:00-17:00)**: Moderate, consistent demand during working hours
- **Evening Peak (18:00-21:00)**: Highest demand period due to cooking, lighting, entertainment, and heating
- **Night Time (22:00-05:00)**: Minimal demand with only essential loads operating

B.7 PV System Performance Analysis

PV Performance Summary:

- **Annual Energy Production**: 218,635 kWh (599 kWh/day)
- **Capacity Factor**: 20.7%
- **PV Penetration**: Nearly 100% of annual energy consumption
- **Energy Waste**: Minimal excess energy due to optimal sizing
- **System Efficiency**: High performance with real-world weather adaptation

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Performance Analysis: The system generates 599 kWh per day sufficient for the community, and operates at a 20.7% capacity factor. The design is well optimized as it nearly reaches the maximum with minimal wasted energy. Figure **??** shows the dips due to real world weather variations e.g., clouds, rain, and seasonal changes. The system was designed to offset almost 100% of the annual energy consumption (PV penetration), demonstrating excellent technical feasibility for Ketane Village's energy needs.

Key Observations:

- **Seasonal Variation**: Higher production in summer months (October-March)
- **Weather Impact**: Noticeable dips due to cloud cover and precipitation
- **Daily Pattern**: Peak generation during midday hours (10:00-15:00)
- **System Reliability**: Consistent performance throughout the year
- **Design Optimization**: Proper sizing minimizes energy waste while meeting demand

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