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ARJEN: A Solar PV–Micro-Hydropower Hybrid System for Rural Electrification in Pipikoro, Central Sulawesi

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ABSTRACT

How can reliable electricity be supplied to remote communities where geographical constraints and limited hydrological data complicate energy planning? This study presents ARJEN (Arunika Jentera), a hybrid smart microgrid model designed for rural electrification in Pipikoro Subdistrict, Sigi Regency, Central Sulawesi, Indonesia. The system integrates solar photovoltaic (PV), micro-hydropower (MHPP), and battery energy storage to utilize local renewable resources. The NRECA model was applied to estimate river discharge under limited hydrological data, while HOMER Pro was used to simulate and evaluate the system configuration based on electricity demand and renewable resource availability. The optimized configuration consists of 80 kW of PV capacity, a 20 kW micro-hydropower plant, 300 kWh of lead-acid battery storage, and a 30 kW converter. The simulation yielded an annual electricity production of 217,702 kWh and a renewable fraction of 100%. However, the system recorded an unmet load of 3.52% and a capacity shortage of 3.97%, indicating that renewable generation did not fully satisfy the modeled demand at all times. Annual excess electricity reached approximately 107,926 kWh, highlighting the potential for further refinement of system sizing and energy utilization. These findings demonstrate the technical potential of integrating solar PV and micro-hydropower for remote electrification while identifying supply reliability and excess generation as key considerations for further system improvement.

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1. INTRODUCTION

Ensuring equitable access to electricity remains a major challenge in Indonesia, particularly in remote regions with difficult geographical conditions and limited grid infrastructure. The 2025–2029 National Medium-Term Development Plan (RPJMN) prioritizes energy security, improved energy access, and renewable energy development. Decentralized energy systems based on local resources offer an alternative for areas inadequately served by centralized electricity networks (Kanna & Singh, 2022) (Harsono et al., 2025) Their effectiveness depends on resource availability, electricity demand, generation capacity, and supply reliability.

Sigi Regency, Central Sulawesi, faces electricity supply challenges associated with mountainous terrain, isolated settlements, and limited infrastructure. These conditions are particularly relevant in Pipikoro Subdistrict, where access to conventional electricity infrastructure remains constrained. Data from the Central Statistics Agency (BPS) of Sigi Regency (2025) indicate a reported 28% gap between electricity production and consumption. This condition highlights the need to evaluate alternative electricity systems that utilize local renewable resources and accommodate the geographical characteristics of remote settlements.

A hybrid smart microgrid integrating solar photovoltaic (PV), micro-hydropower (MHPP), and a battery energy storage system (BESS) offers a potential solution for rural electrification. Smart microgrids combine multiple energy sources and control technologies to improve electricity management and supply reliability (Dawn et al., 2024; Meliani et al., 2021) . Their ability to operate independently of the main grid makes them suitable for remote areas (Babayomi et al., 2023). Combining solar and hydropower can diversify electricity generation, while batteries store excess energy for periods of insufficient renewable generation(Datta et al., 2021; GhoshThakur et al., 2024).

Pipikoro has potential for hybrid electricity generation using solar energy and the flow of the Lariang River. Solar PV output depends on solar irradiance, whereas micro-hydropower generation depends on river discharge and available hydraulic head(Hadi et al., 2023). Batteries can store surplus electricity and supply loads when renewable generation is insufficient (Datta et al., 2021). Seasonal variations in solar irradiance and river discharge can affect total energy production and supply reliability. Estimating these resources is essential for determining suitable generation and storage capacities.

Previous studies have investigated solar PV–micro-hydropower hybrid systems for rural electrification using techno-economic simulation and optimization tools such as HOMER Pro (Ashraful Islam et al., 2024;Iweh & Gyamfi, 2026;Kanna & Singh, 2022) . Separately, rainfall–runoff modeling studies have examined the use of hydrological models, including NRECA, to estimate water availability under data-constrained conditions. However, the integration of hydrological discharge estimation under limited data conditions with technical modeling of a solar PV–micro-hydropower–battery system remains insufficiently addressed for Pipikoro. This gap is important because estimated river discharge influences hydropower output, while solar availability and electricity demand affect the required PV and battery capacities. Combining the NRECA hydrological model with HOMER Pro simulation enables resource estimation to inform system configuration and technical performance assessment.

This study develops ARJEN (Arunika Jentera) as a hybrid smart microgrid model for rural electrification in Pipikoro, integrating solar PV, micro-hydropower, and battery storage. The NRECA model is used to estimate the discharge of the Lariang River under limited hydrological data conditions (Putri et al., 2025). HOMER Pro is then used to evaluate hybrid system configurations based on renewable resource availability and the electricity demand profile. The study aims to estimate hydrological potential, determine a suitable system configuration, quantify annual electricity generation, and assess supply reliability using technical indicators such as unmet load and capacity shortage.

2. METHODS

2.1 Research Design

This study employed a simulation-based methodology to assess the technical and economic feasibility of a hybrid renewable energy system for rural electrification in Pipikoro District, Sigi

Regency, Central Sulawesi, Indonesia. The research integrated meteorological data, hydrological modeling using the NRECA method, electricity load profiling, and hybrid energy system simulation using HOMER Pro.

Solar resource data, ambient temperature, and rainfall data were used to characterize the available renewable energy resources. The NRECA model was applied to estimate river discharge based on the available hydrological inputs(Andawayanti et al., 2026). The resulting resource estimates, together with the electricity load profile, were used to represent the operating conditions of the proposed hybrid microgrid in HOMER Pro.

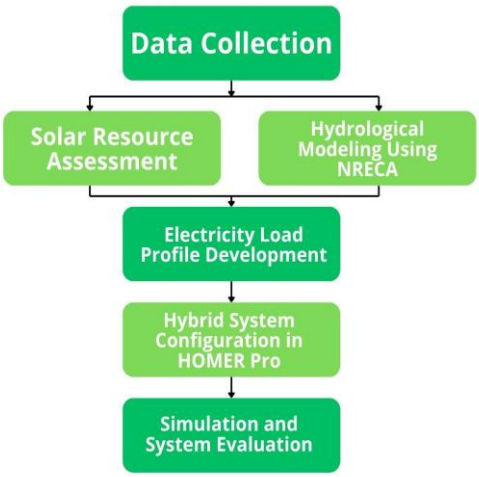


Figure 1. ARJEN Research Design

2.2 Location of Research Area

The study focused on Pipikoro District, Sigi Regency, Central Sulawesi, Indonesia, as the geographical area for assessing the potential application of a hybrid renewable energy system combining solar photovoltaic (PV) and micro-hydropower technologies. The study area was selected based on its rural characteristics and the relevance of renewable energy resources to decentralized electricity supply. The geographical context of the study area is presented in Figure 2.



Figure 2. Map of Pipikoro District

This study relied entirely on secondary data obtained from publicly available online sources. No field measurements, direct site observations, interviews, or community surveys were conducted.

Solar irradiation and ambient temperature data were obtained from the NASA Prediction of Worldwide Energy Resources (NASA POWER) database. Rainfall and other regional information were obtained from publicly accessible statistical publications and online references, as applicable. These data were used to characterize the study area and establish the input parameters for the subsequent renewable energy resource assessment and hybrid system simulation.

The collected data were organized according to their respective sources, temporal resolutions, and applications in the analysis. Solar irradiation and temperature data were used to characterize the solar energy resource, while rainfall data were used as input for the hydrological analysis using the NRECA method. The resulting resource estimates, together with the assumed electricity demand profile and system configuration, provided the basis for evaluating the proposed hybrid renewable energy system using HOMER Pro. As the study was based on secondary data and simulation, the results represent model-based estimates rather than direct measurements of actual system performance at the study site.

Table 1. Data Sources and Characteristics

Data Parameter	Data Source	Temporal Resolution	Data Period	Application
Solar irradiation	NASA POWER	Monthly	2025, subject to verification	Solar resource assessment
Ambient temperature	NASA POWER	Monthly	2025, subject to verification	PV system modeling
Rainfall	Statistics of Pipikoro District	Monthly	2025, subject to verification	NRECA hydrological modeling
Population and household data	Official regional statistics	Annual	Specify the actual year	Electricity demand context

2.3 Environmental Parameter Data

Environmental parameters were collected from publicly available online databases and secondary sources to characterize the renewable energy resources in Pipikoro District, Sigi Regency, Central Sulawesi, Indonesia. Solar irradiation and ambient temperature data obtained from the NASA Prediction of Worldwide Energy Resources (NASA POWER) database were used to assess the solar energy resource and support the evaluation of PV system performance. Rainfall data were used as input for hydrological analysis using the NRECA method to estimate potential river discharge for micro-hydropower generation.

The collected data were organized according to their respective temporal resolutions and measurement units before being used in the analysis. Solar irradiation and temperature data represented the meteorological conditions relevant to PV energy generation, whereas rainfall data supported the estimation of water availability through the NRECA model. The resulting resource estimates were subsequently used as inputs or supporting parameters for the hybrid renewable energy system assessment. Since no field measurements were conducted, the analysis relied on secondary data and model-based estimates.

Table 2. Environmental Parameter Data

Month	Solar Irradiation (kWh/m²/day)	Average Air Temperature (°C)	Rainfall (mm/month)
January	4.69	19.52	55.90
February	5.02	18.93	58.00
March	5.11	19.61	64.60
April	5.06	19.55	69.60
May	5.06	20.12	32.40
June	4.61	19.25	112.50
July	4.92	19.41	21.20
August	4.72	19.12	4.50
September	5.42	19.65	20.00
October	5.33	19.91	11.50
November	5.09	19.71	42.50
December	4.87	19.72	0.00
Average	**5.00**	**19.55**	**41.06**

The monthly environmental data provided the basis for characterizing the temporal variation of the available renewable energy resources. Solar irradiation data were used to represent the availability of solar energy throughout the year, while ambient temperature data supported the assessment of PV operating conditions. Rainfall data were used in the NRECA hydrological model to estimate river discharge. These estimates were intended to represent the potential availability of water for micro-hydropower generation and were not treated as direct measurements of river flow at the study site.

2.4 Hydrological Potential Analysis of the Lariang River Using the NRECA Method

Hydrological analysis was conducted using the NRECA (National Rural Electric Cooperative Association) method to estimate the potential water availability for micro-hydropower generation in the study area (Salac et al., 2024) . The analysis relied on secondary meteorological data and model parameters rather than direct river-flow measurements. Rainfall data were used as the primary hydrological input, while the catchment characteristics and soil-moisture parameters were represented by the assumptions specified in the model. The NRECA method was applied to estimate the hydrological response of the catchment and the resulting water discharge. The estimated discharge was then considered in assessing the potential contribution of micro-hydropower to the proposed hybrid renewable energy system.

2.4.1 Modeling the NRECA Mathematical Equations

The NRECA (National Rural Electric Cooperative Association) model, developed by Norman H. Crawford, estimates catchment runoff based on the water balance principle. The general water balance relationship considers precipitation, evapotranspiration, changes in water storage, and runoff:

$$\text{Precipitation} - \text{Evapotranspiration} + \text{Change in Storage} = \text{Runoff}$$

The NRECA model separates runoff into two components: direct runoff and baseflow (Hidayat et al., 2021). The model represents soil-moisture storage and groundwater storage as interconnected components of the catchment water balance. Changes in storage are determined by the difference between the storage conditions at the beginning and end of each time step. Soil-moisture storage is influenced by rainfall, evapotranspiration, and excess moisture, while groundwater storage is influenced by groundwater recharge and baseflow(Camporese et al., 2025).

The NRECA calculations involve the estimation of actual evapotranspiration (EACT), excess soil moisture (ESM), groundwater recharge (RECH), direct runoff (QDIR), and baseflow (QBASE). The following equations describe the mathematical relationships used in the model. All original equations and their numbering are retained as presented in this study.

- Actual evapotranspiration is estimated as a function of the rainfall-to-potential-evapotranspiration ratio (RAIN/EPOT) and the soil-moisture ratio (SMOLD/SMNOM). SMNOM represents nominal soil moisture and is defined in the original model formulation as (100 mm + 0.2 × uniform rainfall).

$$\frac{EACT}{EPOT} - \frac{RAIN}{EPOT}\left[1 - 0.5\frac{SMOLD}{SMNOM}\right] + \frac{0{,}5.SMOLD}{SMNOM} \quad (1)$$

- The condition under which actual evapotranspiration is set equal to potential evapotranspiration (EPOT) is presented in Equation (2). SMOLD denotes the soil-moisture storage at the beginning of the relevant calculation step.

$$\text{If } \frac{SMOLD}{SMNOM} \geq 2 \; or \; \frac{RAIN}{EPOT} \geq 1 \text{ then } EACT = EPOT \quad (2)$$

- Groundwater recharge (RECH) represents the portion of excess soil moisture transferred to groundwater storage. It is calculated using the excess soil moisture (ESM) and the recharge coefficient (KRECH).

$$RECH = ESM \times KRECH \quad (3)$$

The relationship used to estimate ESM based on rainfall, actual evapotranspiration, and the soil-moisture condition. The original mathematical expression in Equation (4) is retained without modification.

$$ESM = 0.5\left[1 + tgh\left(2\frac{SMOLD}{SMNOM}\right) - 2\right] \times (RAIN - EACT) \quad (4)$$

- Direct runoff (QDIR) is calculated as the difference between excess soil moisture and groundwater recharge, as shown in Equation (5). This component represents the portion of excess moisture that does not enter groundwater storage through the modeled recharge process.

$$Q_{DIR} = ESM - RECH \quad (5)$$

- Groundwater storage is represented by GW, while GWOLD denotes the groundwater content at the beginning of the time step. Baseflow (QBASE) is calculated using GWOLD, RECH, and the baseflow coefficient (KBASE), according to Equation (6). Together, the direct runoff and baseflow components represent the runoff generated by the model.

$$Q_{BASE} = (GWOLD + RECH) \times KBASE \quad (6)$$

The NRECA model requires hydrological parameters to represent the catchment's soil-moisture and groundwater responses. Parameter values must be specified based on the selected model formulation, available data, and documented assumptions. Where direct streamflow measurements are unavailable, model outputs should be interpreted as estimated hydrological values rather than field-validated discharge measurements (Sudinda, 2000) .

2.4.2 Parameter Model NRECA

The NRECA model parameters represent the catchment characteristics and hydrological processes used to estimate runoff in the Lariang River catchment, Pipikoro District, Sigi Regency, Central Sulawesi, Indonesia. The parameters include catchment area, nominal soil moisture, the groundwater recharge coefficient, the baseflow recession coefficient, and initial soil moisture. The parameter values adopted in this study are summarized in Table 3. Since the study relied on secondary data and did not include field measurements, the parameter values should be interpreted as model inputs based on the available information and stated assumptions rather than values calibrated using observed river discharge.

Table 3. NRECA Model Parameters

Parameter Code	Input Value	Unit	Parameter Description	Basis for Parameter Selection
A	100,00	km^2	Catchment Area	Catchment area of the Lariang River tributary at the Pipikoro intake point
SMNOM	150,00	mm	Nominal Soil Moisture	Characteristics of wet tropical mountainous forest soil
KRECH	0,35	-	Infiltration Coefficient	Mountain soil infiltration rate
KBASE	0,50	-	Baseflow Recession Coefficient	Consistency of river baseflow recession
SMOLD	100,00	mm	Initial Soil Moisture	Initial soil moisture in January

The selected parameters were used as inputs for the NRECA calculations to represent the catchment area, soil-moisture conditions, groundwater recharge, and baseflow response. Catchment area defines the spatial extent represented by the model, while the soil-moisture parameters describe the assumed storage conditions. The recharge and baseflow coefficients determine how excess moisture is partitioned into groundwater recharge and how groundwater storage contributes to baseflow. Because observed river discharge was not available for field calibration in this study, the resulting estimates depend on the adopted parameter values and should be interpreted with this limitation in mind.

2.4.3 NRECA Results

The NRECA model was applied to the available monthly rainfall data for Pipikoro, Sigi Regency, over a 12-month period. The calculations were implemented in Google Sheets using the hydrological parameters listed in Table 3. The resulting monthly discharge estimates for the Lariang River are presented in Table 4. Based on the current model output, the highest estimated discharge occurred in January, at approximately 0.37336 in the discharge unit used in the calculations, whereas the December estimate was approximately 0.25 L/s, as reported in the original analysis. These values represent model-derived estimates rather than direct river-flow measurements because no field discharge measurements were conducted in this study.

Table 4. Results of Lariang River Discharge Analysis Using the NRECA Method

Month	RAIN	EPOT	SMOLD	EACT	EXC	GWRECH	DRO	GWOLD	BASE	Total Runoff	Discharge (Q)
01	55.9	100	100	70.6	0	0	0	20	10	10	0.37336
02	58	95	85.3	68.52	0	0	0	10	5	5	0.20668
03	64.6	105	74.78	74.67	0	0	0	5	2.5	2.5	0.09334
04	69.6	100	64.70	76.16	0	0	0	2.5	1.25	1.25	0.04822
05	32.4	110	58.15	47.44	0	0	0	1.25	0.625	0.625	0.02333
06	112.5	100	43.11	100	0.68	0.24	0.44	0.625	0.43	0.88	0.03380
07	21.2	105	54.93	36.54	0	0	0	0.43	0.22	0.22	0.00806
08	4.5	110	39.58	18.42	0	0	0	0.22	0.11	0.11	0.00403
09	20	115	25.66	28.13	0	0	0	0.11	0.06	0.06	0.00208
10	11.5	110	17.54	17.26	0	0	0	0.05	0.03	0.03	0.00101
11	42.5	100	11.78	44.76	0	0	0	0.03	0.01	0.01	0.00052
12	0	95	9.52	3.01	0	0	0	0.01	0.00675	0.00675	0.00025

The monthly discharge estimates provide an initial indication of the seasonal variability represented by the NRECA model. However, the estimated discharge alone is insufficient to establish the actual electricity generation potential of the micro-hydropower system. Further assessment requires consistent discharge units and consideration of the available hydraulic head, turbine and generator efficiency, and the flow required for other river uses. Since the model was not calibrated

against observed streamflow data, the results should be interpreted as preliminary estimates for the subsequent hybrid renewable energy system assessment.

2.5 HOMER Pro Analysis Method

2.5.1 Energy System Modeling

The electrification system in Pipikoro District, Sigi Regency, Central Sulawesi, Indonesia, was assessed using HOMER Pro (Hybrid Optimization of Multiple Energy Resources). HOMER Pro was used to simulate and evaluate the technical and economic performance of a hybrid renewable energy system under the specified resource conditions, electricity demand, component configurations, and economic assumptions(Kavadias & Triantafyllou, 2021;Khalil et al., 2020). The assessment focused on the interaction between renewable electricity generation, energy storage, power conversion, and electrical demand.

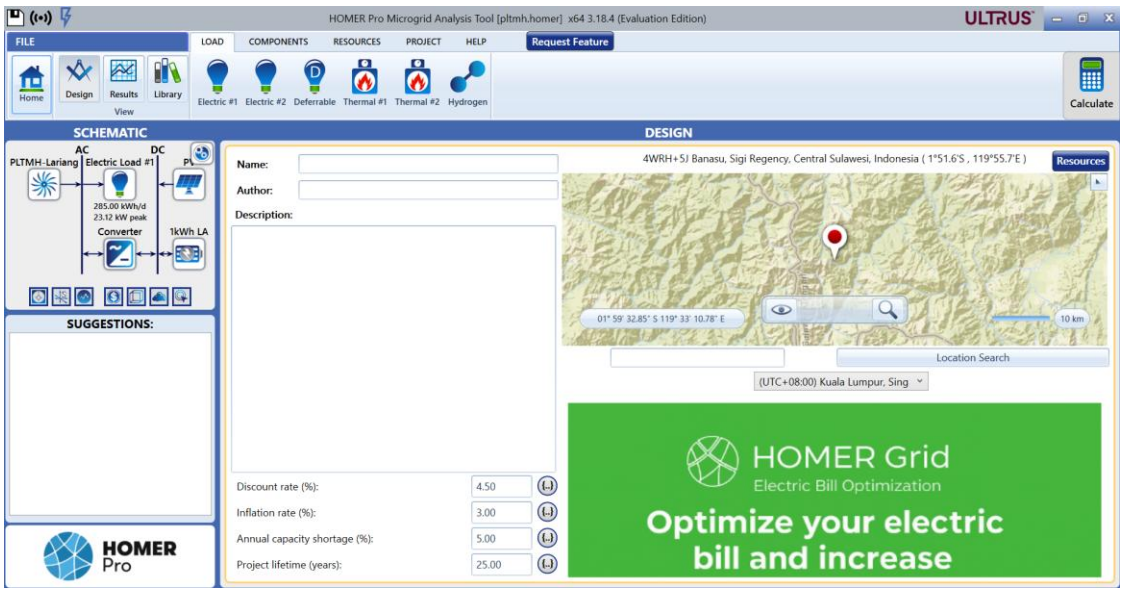


Figure 3. HOMER Pro Software Interface

The modeled hybrid energy system comprised a solar photovoltaic (PV) system, a micro-hydropower plant associated with the Lariang River, a lead-acid battery bank, and a power converter (Moteane Thabo Melamu & Aboalez Bellville, 2021). Solar PV and micro-hydropower were represented as electricity generation sources, while the battery bank provided energy storage to support the balance between electricity generation and demand. The converter represented the power conversion interface required by the modeled system configuration. These components were considered together to assess the technical performance of the proposed hybrid system.

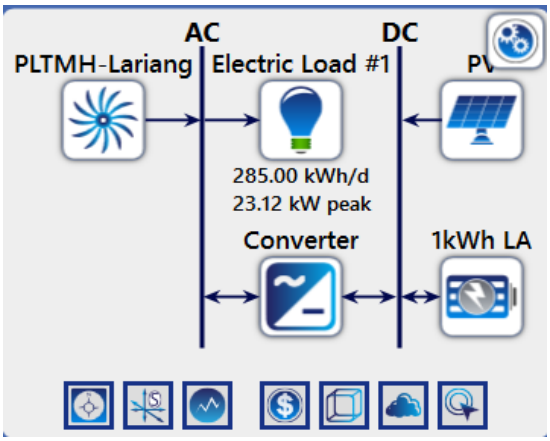


Figure 4. Hybrid Energy System Configuration

The system configuration evaluated in this study consisted of an 80 kW solar PV system, a 20 kW micro-hydropower plant, a 300 kWh battery bank, and a 30 kW converter. The battery operation was modeled using the Cycle Charging strategy in HOMER Pro. Under this strategy, the dispatch controller determines how operating generators supply the load and charge the battery according to the modeled operating conditions and control settings (Palanisamy & Lala, 2024). The configuration and dispatch strategy were used as the basis for evaluating the system's technical and economic performance.

2.5.2 Simulation and Optimization

The simulation process incorporated the electricity load profile and the renewable energy resource data used to represent the operating conditions of the proposed hybrid system (Ribó-Pérez et al., 2021). HOMER Pro was used to evaluate system operation according to the specified electricity demand, resource availability, component characteristics, and dispatch settings. The electricity load profile used in the analysis is presented in Figure 5.

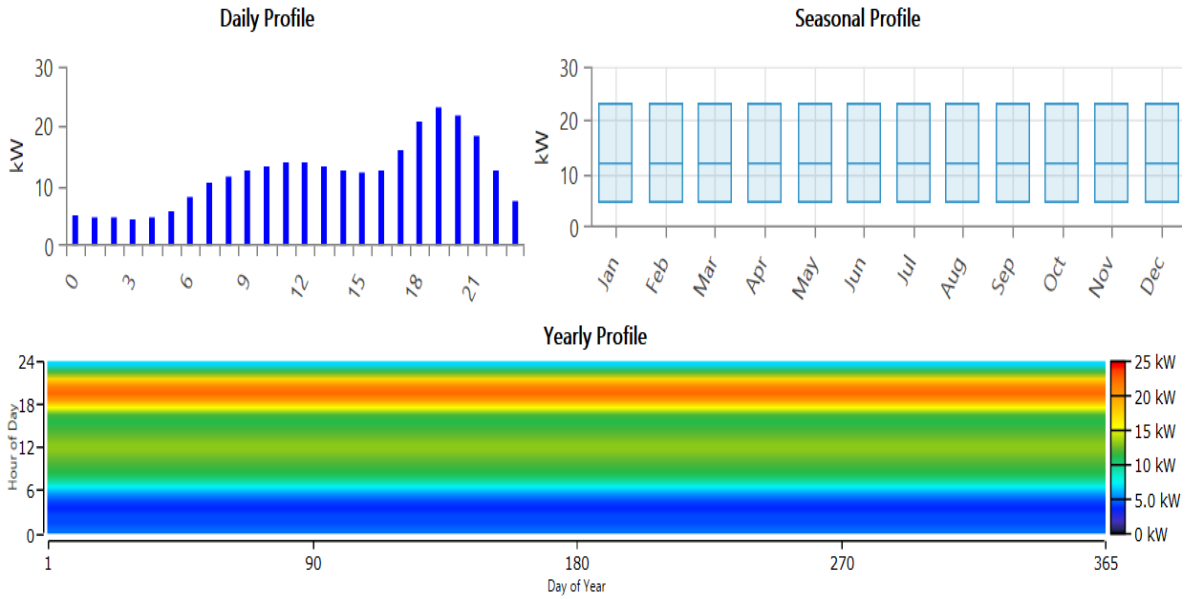


Figure 5. Electricity Load Profile

The system was assessed using technical and economic indicators, including Net Present Cost (NPC), Levelized Cost of Energy (LCOE), unmet electrical load, capacity shortage, renewable fraction, and annual energy production (Mohammed et al., 2026) . These indicators were used to characterize the modeled system's cost, ability to supply electricity demand, utilization of renewable energy, and electricity generation performance.

NPC represents the present value of the total costs associated with the system over the project lifetime, including applicable initial capital, replacement, operation and maintenance, and other modeled costs (Sayed et al., 2024). LCOE represents the average cost per unit of electricity supplied or served, according to the software's calculation basis (Shahgholian et al., 2023). Unmet electrical load represents the demand that the system fails to serve, while capacity shortage indicates the extent to which the system's available supply falls short of the required demand or capacity criterion (Bekele et al., 2024). Renewable fraction indicates the share of electricity supplied by renewable energy sources, and annual energy production represents the total electricity generated over a year (Obiora et al., 2024) .

The interpretation of these indicators depends on the input data, component specifications, economic assumptions, and simulation settings. As this study relied on secondary data and model-based analysis rather than direct field measurements, the results describe the performance of the

modeled system under the specified assumptions and should not be interpreted as measured operating performance at the study site.

3. RESULTS AND DISCUSSION

3.1. Electricity Demand and Renewable Energy Potential in Pipikoro

A comparison of electricity demand and energy production reveals a discrepancy between annual energy sufficiency and supply reliability. The HOMER Pro load profile records a Primary Load (AC) consumption of 100,361 kWh/year, while system production reaches 217,702 kWh/year. Production equivalent to approximately 2.17 times the annual demand appears adequate in aggregate, but simulation results still show an unmet load of 3.52%. This finding indicates that the magnitude of annual production cannot be used as the sole indicator of system adequacy. The key issue to analyze is whether energy is available when the load requires it; therefore, configuration decisions must consider the temporal alignment between generation and consumption.

Regarding solar energy sources, an average radiation level of 5.00 kWh/m^2/day provides a relevant basis for PV utilization, but monthly variations result in an uneven contribution. PV production of 130,137 kWh/year or 59.8% of total production indicates that PV is the largest energy contributor in the simulated configuration. This means that the system's adequacy depends heavily on the performance of the solar power plant. However, this annual contribution does not yet indicate how effectively PV meets the load during specific hours. Therefore, the radiation values must be interpreted in conjunction with monthly production patterns and load profiles to assess whether PV production helps cover periods when the contribution from hydroelectric sources decreases.

On the hydro side, NRECA's estimates show a decline in discharge from 373.36 L/s in January to 0.25 L/s in December. If these figures are valid, this change indicates that the potential contribution of small hydroelectric power plants may not be stable throughout the year. However, discharge data alone is insufficient to calculate available electrical power, as the effective head and conversion efficiency also determine the plant's output. Thus, NRECA's results cannot yet be taken as proof that small hydro plants will definitely experience power shortages in a given month. The main implication is that the contribution of hydro must be evaluated based on modeled power and production, while flow rate estimates need to be verified before being used to explain system limitations. This analysis serves as the basis for assessing how PV and small hydro plants contribute to electricity demand in a hybrid configuration.

3.2 HOMER Pro Simulation Results

3.2.1 Optimal System Configuration

The HOMER Pro optimization results yielded an ARJEN configuration consisting of an 80-kW solar power plant, a 20-kW Sungai Lariang hydroelectric power plant, a 300-kWh lead-acid battery bank, and a 30-kW converter. The selection of this combination reflects the need to integrate energy sources with different production characteristics so that the system can meet the modeled electricity demand.

The dominance of the solar PV capacity over the small hydroelectric plant may be related to the year-round solar radiation potential available in Pipikoro. An average irradiance of 5.00 kWh/m^2/day provides a resource base that supports solar power generation. However, the selected capacity is determined not only by the magnitude of solar potential but also by the load profile, the hydroelectric power plant's production characteristics, and component constraints within the model. These optimization results indicate the best configuration among the evaluated alternatives based on simulation inputs; they do not constitute proof that this combination is necessarily the best choice for all operational conditions in the field.

The inclusion of a small hydroelectric power plant (PLTMH) in the selected configuration is also important because it allows the system to utilize energy sources other than solar. Meanwhile, the battery provides the ability to shift some energy from the time of production to a different time of consumption. The converter supports power distribution according to the system's needs. Thus, each component has interrelated functions, but the effectiveness of their integration must be assessed based on energy production and the resulting reliability indicators.

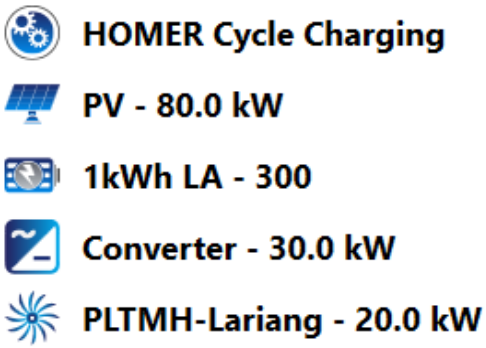


Figure 6. System Configuration Resulting from HOMER Pro Optimization

3.2.2 Energy Production

The results of the HOMER Pro simulation show a total electricity production of 217,702 kWh/year, of which 130,137 kWh/year (59.8%) comes from solar panels (PV) and 87,565 kWh/year (40.2%) from the small hydroelectric power plant (PLTMH). The larger contribution from PV is related to its installed capacity of 80 kW and the availability of solar radiation, while the 20-kW small hydroelectric plant provides power by harnessing the energy of the river's flow. This difference in contribution indicates that PV is the primary source of production, while the small hydroelectric plant still accounts for about two-fifths of the total annual energy.

Table 5. Annual Energy Production

Energy Source	Energy Production (kWh/year)	Contribution
Solar PV	130.137	59,8%
Micro-hydropower	87.565	40,2%
Total	217.702	100%

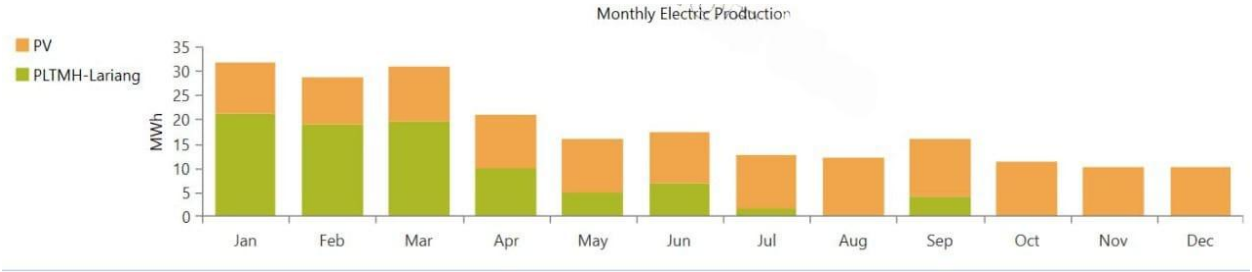


Figure 7. Monthly Electricity Production from Solar PV and Micro-Hydropower

The monthly production patterns in Figure 7 show how the contributions of the two sources vary throughout the year. PV production follows variations in solar radiation, while PLTMH production is influenced by water flow availability. These differing characteristics create opportunities for the two sources to complement each other in meeting electricity demand. The actual degree of complementarity depends on how well the production schedules of each source align with the load profile. Monthly data may reveal seasonal variations, whereas assessing the ability of both sources to mitigate supply shortfalls requires analysis on a more granular time scale.

3.2.3 System Reliability

The HOMER Pro simulation results show a renewable fraction of 100%, with an unmet electric load of 3.52%, a capacity shortage of 3.97%, and excess electricity of 107,926 kWh/year, or 49.6% of total energy production. These results indicate that the full use of renewable energy does not yet guarantee that all electricity needs will be met. The magnitude of the surplus occurring alongside a supply shortage suggests a possible temporal mismatch between electricity production and demand. A summary of the system's electrical analysis results is shown in Figure 8.



Production	kWh/yr	%
Generic flat plate PV	130,137	59.8
Hydro	87,565	40.2
Total	217,702	100

Consumption	kWh/yr	%
AC Primary Load	100,361	100
DC Primary Load	0	0
Deferrable Load	0	0
Total	100,361	100

Quantity	kWh/yr	%
Excess Electricity	107,926	49.6
Unmet Electric Load	3,664	3.52
Capacity Shortage	4,128	3.97

Quantity	Value	Units
Renewable Fraction	100	%
Max. Renew. Penetration	729	%

Figure 8. System Electricity Analysis Based on HOMER Pro Simulation

An electricity surplus can occur when PV and PLTMH production exceeds the load and the battery is unable to absorb all the excess energy. A supply shortage may arise during periods when production declines and stored energy is insufficient. The 300 kWh battery capacity and 30 kW converter need to be evaluated based on battery charging patterns and peak load. Variations in the flow rate of the Lariang River also have the potential to affect hydroelectric power plant (PLTMH) production. These factors are still potential causes that require verification through hourly operational data. Annual data alone is not sufficient to determine the dominant cause of unmet load.

Two strategies worth exploring are increasing battery capacity and implementing demand-side management (DSM) and productive use of energy (PUE). Additional batteries have the potential to store surplus electricity for use when production declines, while DSM and PUE can shift flexible consumption to periods of high production for example, for water pumping or agricultural processing. The effectiveness of each strategy depends on surplus patterns and actual electricity demand. Further simulations with varying battery capacities and load schedules are needed to compare their impacts on excess electricity, unmet load, and capacity shortages.

Beyond its technical implications, the ARJEN case study provides a practical context for connecting fundamental physics concepts with renewable energy applications. The simulated contributions of photovoltaic and micro-hydropower systems illustrate energy conversion, while the coexistence of excess electricity and unmet load highlights the importance of distinguishing energy availability from the timing of power supply and demand. These findings could be incorporated into simulation-based physics learning activities to help students explore energy transformation, electrical power, and energy storage in a real-world context. However, this educational application remains a potential extension of the study, as its effectiveness in improving student learning has not been evaluated.

4. CONCLUSION

Overall, the simulation results show that the combination of a solar power plant (SPP), a micro-hydro power plant (MHPP), and a battery can serve as an alternative renewable energy-based electrification system for the Pipikoro region. The integration of the solar power plant and the small hydroelectric power plant allows the system to leverage the distinct characteristics of these two energy sources. The solar power plant generates energy primarily during periods of available solar radiation, while the small hydroelectric power plant can contribute to power generation based on the availability of water resources from the Lariang River.

The inclusion of a 300 kWh battery provides energy storage, allowing electricity generated when production exceeds demand to be utilized during other periods. However, the unmet load of 3.52% indicates that the system's capacity is still insufficient to meet the entire electricity demand continuously. From an environmental and energy perspective, achieving a 100% renewable fraction demonstrates the dominance of renewable energy sources within the system. Therefore, the implementation of the system in Pipikoro must take into account the community's ability to make the initial investment, battery replacement costs, and their ability to pay for electricity.

DECLARATION OF GENERATIVE AI USAGE IN THE WRITING PROCESS

During the preparation of this work, the authors used DeepL, Gemini AI, and ChatGPT for the purpose of refining language and improving readability. Following the use of these tools, the authors reviewed and revised the content as necessary and take full responsibility for the final content of the publication.

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