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Design and Management of Renewable Energy Systems for Isolated Communities with No Grid Connection

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Abstract

The growing demand for energy and the need to reduce dependence on non-renewable sources have driven the research and application of sustainable technologies. In this context, an integrated solution that combines distributed energy generation from renewable sources, such as wind and hydro, with efficient management of household energy consumption is proposed. This study focuses on the hybrid renewable energy system simulation analysis designed to meet the demand of an off-grid household in a self-consumption mode. This combination of technologies allows adaptation to geographical location, resource availability, and consumer-specific needs, where only renewable resources are available to power non-grid-connected local communities in less developed areas. Given that wind and hydroelectric energy are variable resources over time, either seasonally or hourly, the aim is to find an optimal balance that maximizes electricity demand coverage for the longest possible time. A system is designed to integrate both energy sources, with one acting as a backup source, if necessary, thus ensuring a constant supply of electricity without oversizing the systems. This approach aims to maximize energy efficiency and contributes to closing the electricity access gap in communities not connected to the conventional electricity grid. The detailed analysis of this hybrid system provides valuable information for designing and implementing decentralized energy solutions in isolated communities. The paper represents a unique contribution to the state of the art in wind energy and hydropower hybrid renewable energy systems for isolated communities. It represents an advanced study on managing this type of installation by applying energy efficiency protocols and methods to optimize the system's performance.

Keywords

Renewable power sources for isolated communities; wind and hydropower hybrid system design and management; non-grid connected local network; implementation of clean and sustainable power supply in less developed areas

1. Introduction

Human development and the quest for thermal comfort increase electric energy dependence in modern society [1-4]; heating and refrigeration systems, household appliances, gadgets, intelligent lighting devices, and electronic equipment are, among others, electric eaters [5-8]. In parallel with higher energy demand, a cleaner and more sustainable power source development is run, contributing to a less polluted environment and a more reliable power supply [9-12]. A report from the Technical and Scientific Information Office depending on the Department of Energy of the United States of America (DOE-USA) shows that fossil fuel consumption cuts by 74% for the gasoline, 35% for diesel, and 37% for gas [13]. The progressive implementation of renewable energies in the power mix compensates for fossil fuel depletion and contributes to mitigating climatic change, reducing GHG emissions [14-17]. According to the Renewable Energies International Agency report, electrification powered by renewable sources, especially solar and wind, is critical for achieving the climatic objectives, requiring a fast and systematic transformation of the global energy system [18].

Despite the many efforts developed by governments, public institutions, and private organizations, many families and communities do not have access to grid electricity, because of a remote location or lack of adequate infrastructure [19-21]. According to the United Nations Development Program (UNDP) 733 million people do not have access to electricity [22]. In sub-Saharan regions the problem worsens with 75% of the population leaving without electric energy [23].

This work also proposes solutions for isolated communities with no grid connection. Since electricity is a must for many human activities, health, and education, the electric power supply is critical for human development and welfare; therefore, easy access to electric energy improves people's way of living [24, 25]. Renewable power sources like solar photovoltaic or wind energy represent a clean, easy, and sustainable electricity supply for remote areas where electric companies do not distribute energy because of the high distribution costs and complex infrastructure [26-29]. Among the various renewable power sources, wind energy and hydroelectric are very relevant, with a power supply of 2304 and 4211 TWh in 2023 [30].

This study covers the gap in analyzing non-grid-connected local communities powered by wind and hydropower systems since previous studies only deal with individual renewable sources like wind farms or solar PV arrays [31-35]. Other studies deal with heuristic and metaheuristic methods, representing solid support for the analysis of the problem [36-42].

The analysis of the energy balance in self-consumption facilities without grid connection, powered by wind turbines and a hydroelectric generator is developed. The analysis studies the interaction between renewable power sources and energy demand, evaluating the power supply efficiency, reliability, and sustainability. Considering standard energy consumption for isolated communities in remote areas, a power supply based on wind and hydroelectric energy for household facilities is designed and developed.

The power supply system design looks to cover the community energy demand at all times, using a hydropower system as a secondary power source to compensate for energy deficits when wind resources are insufficient. The designed system proposes a power distribution based on hybridizing wind and hydroelectric systems with a control protocol to suppress local load fluctuations.

Designing an adequate protocol to control the energy balance when using ancillary services is critical for optimizing renewable energy integration and ensuring energy demand coverage and power supply quality.

The principal motivation of this work is to give a feasible solution to isolated communities and less developed areas where electric energy is not accessible due to the electric companies' restrictive policy because of the high grid-connection costs.

The proposed solution has enormous potential for local renewable energy development and power supply, improving the inhabitants ' lives, giving them access to modern services and facilities, and increasing people's prosperity in less-developed areas.

2. Fundamentals

Wind power generation derives from the kinetic energy conversion into electricity using wind turbines. Mathematically:

$$P_w = \frac{1}{2} C_P \eta_{tr} \eta_{gen} \rho_{air} A u^3 \tag{1}$$

C_P is the wind turbine power coefficient, η is the efficiency, with sub-index *tr* accounting for mechanical transmission and *gen* for electric generation, ρ_{air} is the air density, A is the wind turbine cross-section, and u is the wind speed.

Hydroelectric power generation depends on the fluid flow, $\dot{V}$, fluid specific weight, γ_w, and hydraulic height, H, as in:

$$P_h = \eta_t \gamma_w \dot{V} H \tag{2}$$

η_t is the hydraulic turbine efficiency.

Wind energy cannot be stored because of its nature; however, hydraulic energy is suitable for storage using a reversible power generator; therefore, when power generation from wind turbine exceeds the energy demand, the hydroelectric system operates in reversed mode, consuming the energy surplus and storing mechanic energy for later use.

Because wind energy is variable and intermittent, hydroelectric power generation works as an energy buffer system, supplying or storing energy when necessary. To this goal, the hydroelectric system operates depending on the energy balance between wind power generation and facility energy demand. Mathematically:

$$P_h = P_w - \xi \tag{3}$$

If P_h is negative, the hydroelectric system operates as a power source; otherwise, it works as a storage system.

Power generation and energy storage in a hydroelectric plant work on the same system, a reversible electric generator; nevertheless, the efficiency in generating power differs from the one in storing energy because the hydroelectric turbine is not fully reversible; therefore, the energy balance should be expressed as:

$$\xi = \begin{cases} \frac{1}{2} C_P \eta_{tr} \eta_{gen} \rho_{air} A u^3 + \eta_t \gamma_w \dot{V} H & (\xi > P_w) \\ \frac{1}{2} C_P \eta_{tr} \eta_{gen} \rho_{air} A u^3 - \eta_p \gamma_w \dot{V} H & (\xi < P_w) \end{cases} \tag{4}$$

η_p is the hydraulic turbine efficiency in pumping mode.

Since hydraulic height includes mechanic losses, the parameter *H* can be expressed in terms of differential geometrical height, *h*, as in:

$$H = h - f \frac{L}{D_h} \frac{v^2}{2g} \tag{5}$$

f is the friction or Darcy factor, *L* is the carrying water duct length, D_h is the hydraulic diameter, and *v* is the water flow speed.

The Darcy factor depends on the Reynolds number and duct inner rugosity. It has a relevant influence on mechanic losses, hence the importance of properly selecting the type of duct material and the circulating water flow rate.

Applying the continuity equation to water flow, replacing in Equation 5, and combining with Equation 4, the energy balance results:

$$\xi = \begin{cases} \frac{1}{2} C_P \eta_{tr} \eta_{gen} \rho_{air} A u^3 + \eta_t \gamma_w \dot{V} h - \eta_t \rho_w f \frac{8 \dot{V}^3 L}{\pi^2 D_h^5} & (\xi > P_w) \\ \frac{1}{2} C_P \eta_{tr} \eta_{gen} \rho_{air} A u^3 - \eta_p \gamma_w \dot{V} h - \eta_p \rho_w f \frac{8 \dot{V}^3 L}{\pi^2 D_h^5} & (\xi < P_w) \end{cases} \tag{6}$$

Provided all parameters are constant except the fluid flow and wind speed, Equation 6 transforms into:

$$\xi = \begin{cases} C_1 u^3 + C_2 \dot{V} - C_3 \dot{V}^3 & (\xi > P_w) \\ C_1 u^3 - C_2 \dot{V} - C_3 \dot{V}^3 & (\xi < P_w) \end{cases} \tag{7}$$

With:

$$C_1 = \frac{1}{2} C_P \eta_{tr} \eta_{gen} \rho_{air} A; \quad C_2 = \eta_t \gamma_w h; \quad C_3 = \eta_t \rho_w f \frac{8L}{\pi^2 D_h^5} \tag{8}$$

The energy demand calculation derives from the appliance power, *P*, and daily using time, *t*; mathematically:

$$\xi = \sum_{i=0}^{24} P_i t_i \tag{9}$$

Appliances daily using time distribution is difficult to establish since every family, commercial center, or industry follows a different energy consumption pattern; therefore, a standard daily energy consumption distribution to operate should be defined (Figure 1).

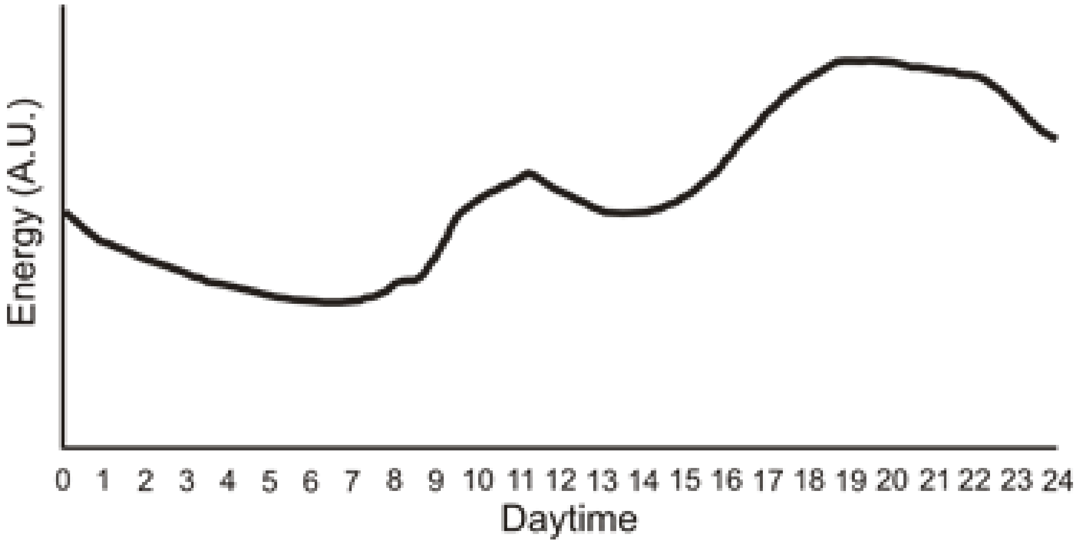


Figure 1 Standard daily energy consumption (arbitrary units U.A.).

3. Engineering Design

The proposed system includes a wind farm, a hydroelectric power plant, and a generic energy consumption facility. A hydroelectric power plant collects water from a river. Figure 2 shows the schematic view of the system. The system applies to any place with a water reservoir, river, lake, pond, or basin nearby and enough wind resources to produce electricity for the selected facility.

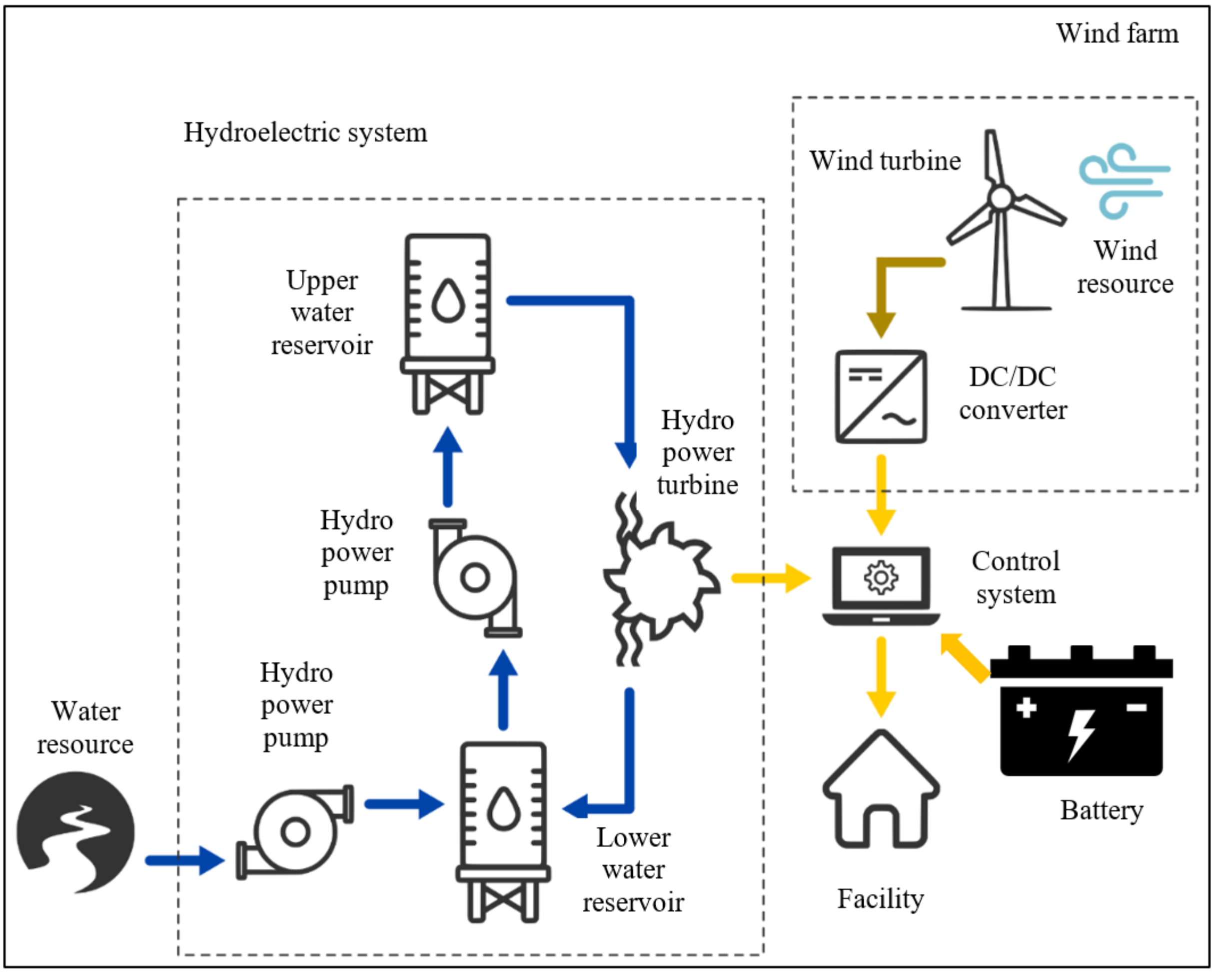


Figure 2 Layout of the system.

The hydroelectric system comprises two water reservoirs, upper and lower, at different heights. A hydropower pump makes the water flow from the river to the lower reservoir and from the lower to the upper reservoir to store mechanical energy when there is a surplus. A hydropower turbine connects upper and lower water reservoirs to generate electricity when necessary.

A control system regulates the energy injection into the facility, collecting energy from the wind turbine as the primary source and from the hydroelectric power plant if the energy demand exceeds the wind power generation.

The system includes a battery block to supply energy during the transient time when the control system commutes from wind power to hydroelectric generation.

The selected wind turbine has the following characteristics [43]:

Electric generator

- Power: 20 kW
- Current: Alternate triphasic 500 V
- Transmission: Direct

Rotor

- Three blades, horizontal axis, leeward operation
- Power: 10 kW, limited by software
- Starting speed: 1.85 m/s
- Cut-off speed: 30 m/s

- Diameter: 9.8 m
- Surface: 75.4 m^2

Figure 3 shows the wind turbine power curve. The black continuous line corresponds to the Weibull distribution.

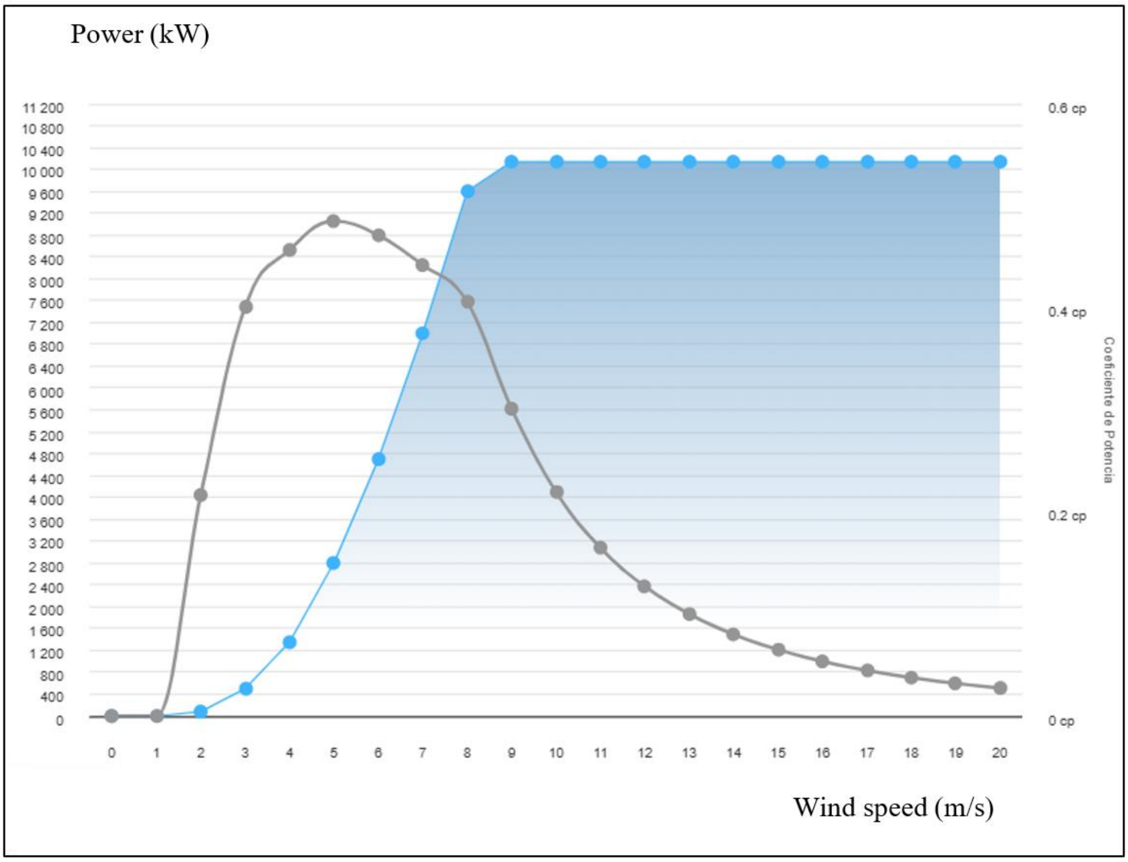


Figure 3 Wind turbine power curve (Blue) and Weibull distribution (black).

3.1 Technical Limitations

Technical limitations to the engineering design derive from the renewable resource and the system's energy efficiency. A high-power wind or hydropower system capable of supplying enough power to cover energy demand is designed. Nevertheless, if the renewable resource lowers, the system efficiency does too since the design operates at specific power generation to achieve the highest energy efficiency possible. This situation applies to wind and hydro turbines operating in a power range for optimum performance.

This problem can be solved by designing a wind and hydro turbine system with multiple units of lower output power, connecting and disconnecting units according to community energy demand. This configuration, however, represents a more complex design, increases the installation investment, reduces economic reliability, and lowers global efficiency.

On the other hand, in the case of powering the local community with a single renewable source, the resource lowering may produce a shortage or interruption in power supply with unexpected consequences. An alternative to avoid the power supply shortage or interruption is the installation of a storage system to supply energy when the renewable resource is missing or diminishes; this solution, however, increases the system’s size, the installation investment, and the maintenance cost since the storage system, currently a battery block, suffers from quick aging compared with the power system.

Therefore, wind and hydropower hybridization limits dependence on a single renewable resource, reduces the individual system size, avoids the storage system need, and optimizes the installation performance.

4. Project Development

For the project development, an area near a river is selected with high wind resources and locally isolated communities. The area is characterized by two climatic seasons, summer and winter; in summer, there are sunny and windy days, while winter corresponds to the rainy season and lower wind speed days. Therefore, the system operates in two opposite situations, one with high wind power and moderate to low hydric resources and another with high water precipitation and hydroelectric power generation but with a lower wind energy supply.

The project development is structured as follows to facilitate the reader's comprehension.

- Wind energy represents the principal power source covering the community energy demand.
- Hydropower is a complementary source if wind energy cannot cover energy demand.
- Therefore, the first action is evaluating the standard energy demand.
- The second step is evaluating the wind power generation; the calculation is based on the wind energy resource (wind speed).
- The energy balance is determined once the energy demand and wind power generation are calculated.
- The calculation of the required hydropower energy supply to cover the energy imbalance when using wind power generation follows.
- The hydropower system characteristics and sizing are determined according to the required hydropower generation.

4.1 Energy Demand

Based on statistical data, the energy demand in a household facility for isolated communities derives from lighting and refrigeration, with other appliances representing minor energy consumption. According to official reports, only 3% of people living in remote areas use electricity for cooking. Figure 4 shows the energy consumption distribution by appliances.

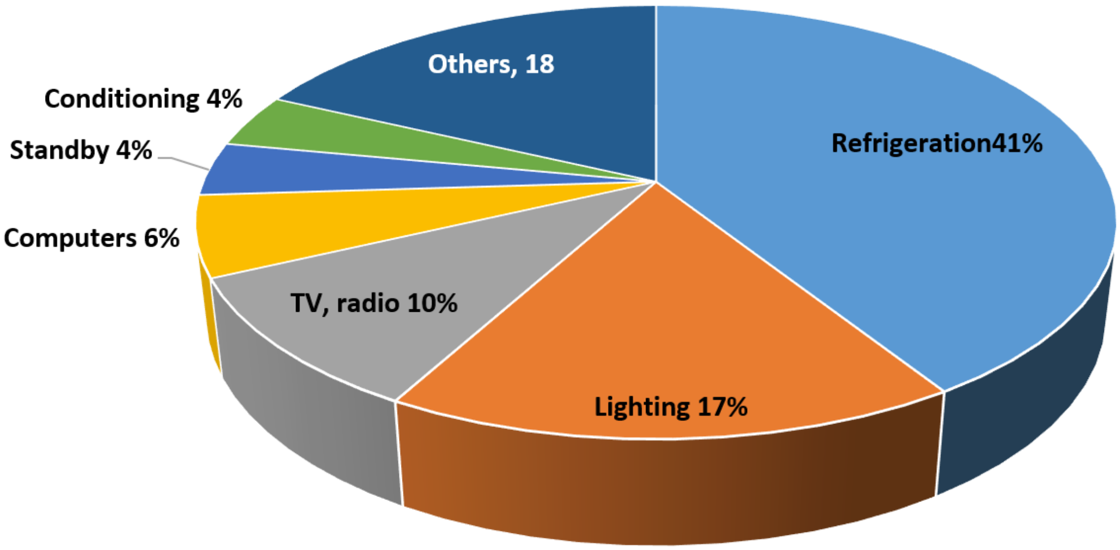


Figure 4 Generic energy demand distribution by appliance [44].

Applying the current use time for every appliance, the daily energy demand is (Table 1):

Table 1 Energy demand distribution by appliance.

Appliance	Power (W)	Use time (h)	Monthly days use	Daily energy (kWh)	Monthly energy (kWh)
Lighting	200	6	30	1.2	36
Television	100	5	30	0.5	15
Refrigeration	300	10	30	3	90
Boiling	1000	0.1	30	0.1	3
Cooking	1500	0.5	30	0.75	22.5
Coffee machine	700	0.16	30	0.112	3.36
Washer	500	2	4	1	4
Iron machine	1000	1	10	1	10
Radio	20	5	30	0.1	3
Computer	40	5	30	0.2	6
Cellular	20	1	30	0.02	0.6
Standby	30	24	30	0.72	21.6
				8.702	**215.06**

A standard family of four people was regarded as a reference for the study and analysis. Figure 5 shows the daily energy demand distribution by hours.

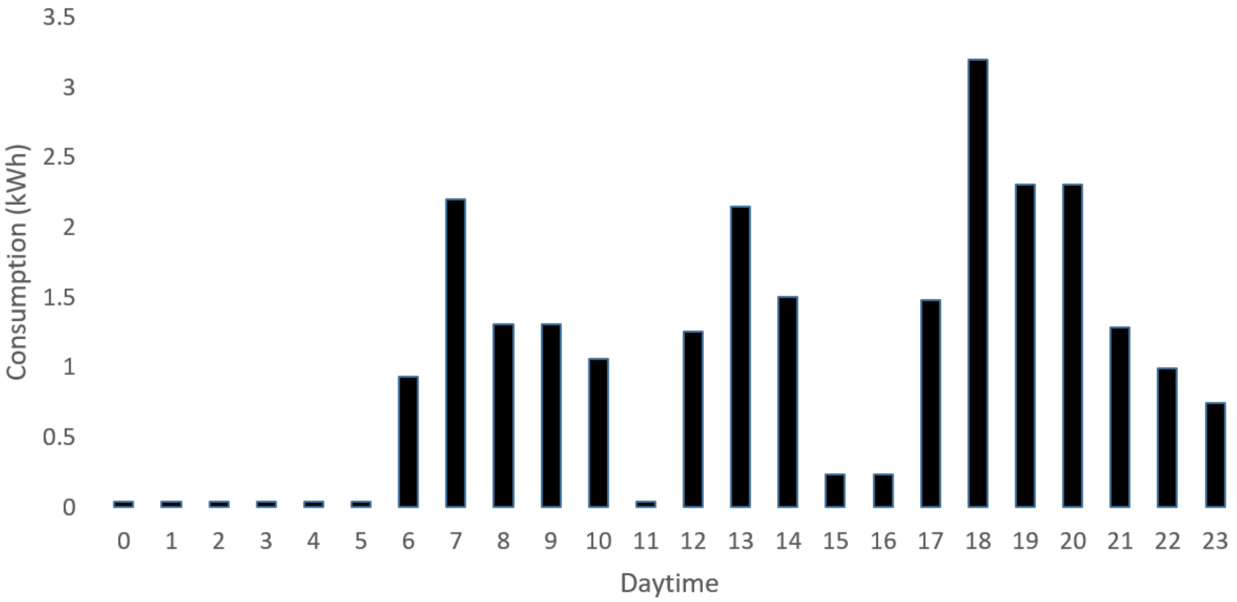


Figure 5 Daily energy demand distribution by hours for the selected community.

It can be observed that in some hours the energy demand is null or negligible, 0 to 5 am, 11 am, and 3 to 4 pm. In these periods, if the wind blows, there is a power generation surplus, and the energy excess should be stored by pumping water from the lower to the upper reservoir.

4.2 Wind Power Generation

Data for wind power generation come from the nearest meteorological station and extend for a year [45]. Figure 6 shows the yearly wind speed evolution in the selected location.

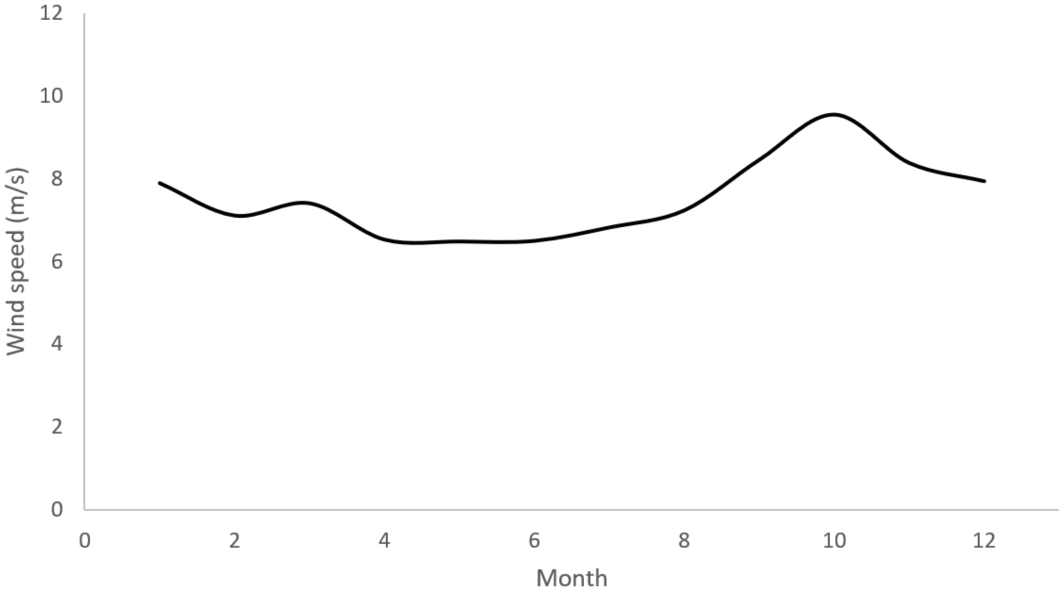


Figure 6 Yearly wind speed trends at the selected location.

Decomposing the yearly wind speed distribution in daily hourly values, we have (Figure 7).

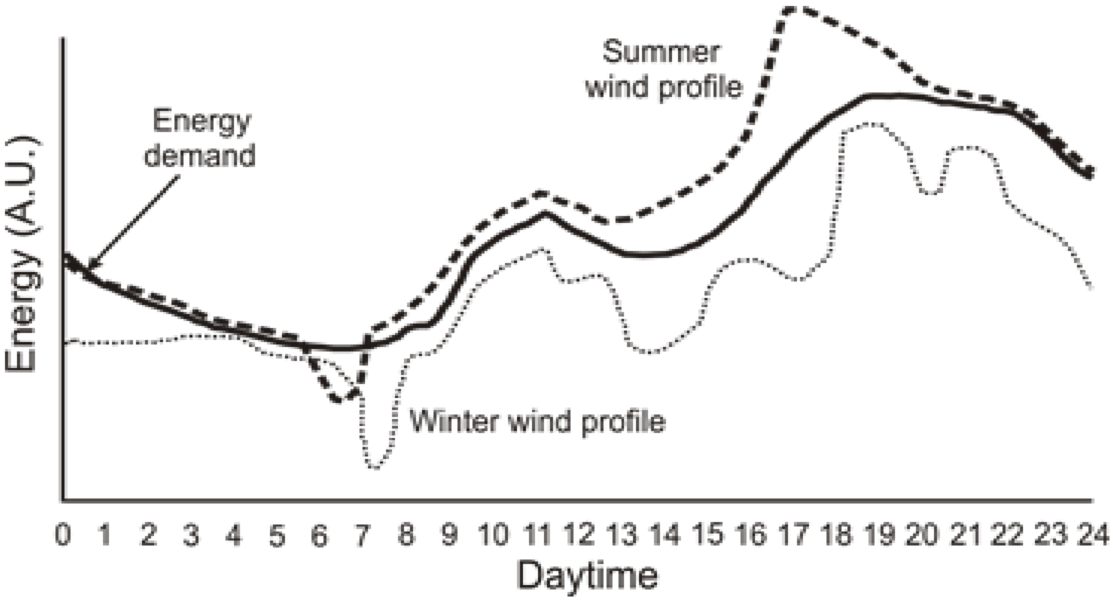


Figure 7 Daily hourly wind speed distribution at the selected location.

It should be noticed that in the summer, the wind resource is higher, as predicted, with power supply above the energy demand all over the day except from midnight to 2 am and from 1 to 3 pm. However, in the winter, the wind resource lowers, showing a power supply below the energy demand for the whole day, which requires the assistance of the hydroelectric power plant to cover the energy demand.

Wind turbine does not operate at constant speed; therefore, there is an uncertainty in the power generation expressed by the following equation:

$$\varepsilon_w = \left[\sum_{i=1}^{n}\left(\frac{dP_w}{P_w}\right)\right]^{1/2} \tag{10}$$

Operating with the wind speed values shown in Figure 6, considering all parameters constant except the wind speed in Equation 1, and operating, it results in ε = 0.077, representing an uncertainty of 7.7% in wind power generation.

4.3 Energy Balance

Since data in Figure 6 correspond to monthly values and data in Figure 5 are in hourly values, it is necessary to decompose monthly wind speed data in hourly data to determine the energy balance; by doing so, we obtain for June (Figure 8):

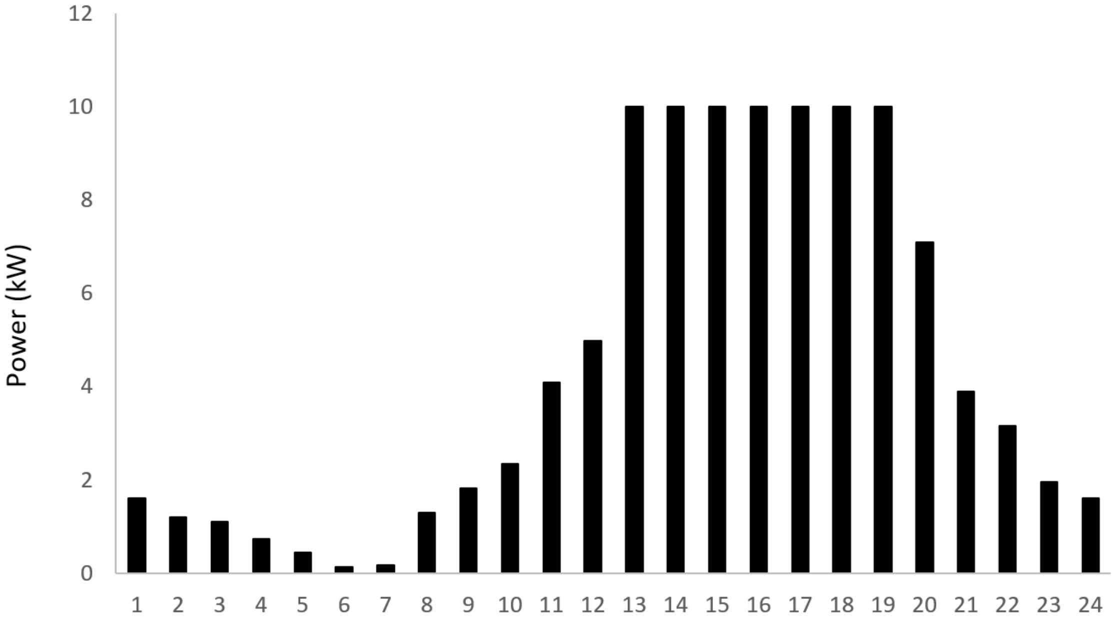


Figure 8 Hourly wind power generation at the selected location.

Combining data from Figure 5 for energy consumption with wind power generation from Figure 8, the energy balance is obtained (Figure 9).

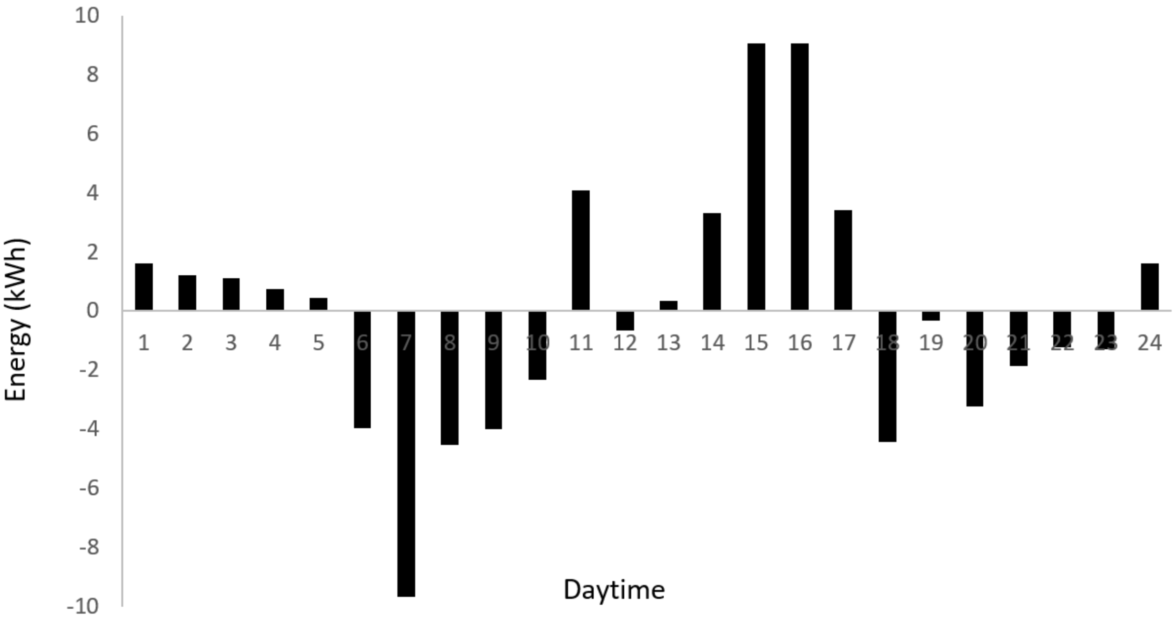


Figure 9 Hourly energy balance for wind power generation.

The reader can realize that from 6 am to 10 am, at midday, and from 6 pm to 11 pm, the energy balance is negative, requiring hydropower assistance.

Based on results from Figure 9, it is noticed that the global daily energy balance is practically null; therefore, considering that the energy surplus is stored in batteries and released at the energy deficit periods within a 97.65% accuracy, we may rely on the power supply.

Regarding the ease of implementation, it should be mentioned that a 10 kW wind turbine is a commercial model of easy access at a relatively moderate cost.

4.4 Hydroelectric Power Generation

Since hydroelectric power must cover the energy deficit at any time, the system generates a maximum deficit of 9.68 kWh, corresponding to 7 am. To produce this energy, Equations 2 and 5 apply, yielding:

$$P_h = \eta_t \left(\gamma_w \dot{V} h - \rho_w f \frac{8\dot{V}^3 L}{\pi^2 D_h^5} \right) \tag{11}$$

Because there are many variables in Equation 11, the water duct's geometrical characteristics, length and diameter, and type of material are set up; therefore, considering the turbine efficiency constant, the hydropower generation depends on water flow and geometric height. Table 2 shows the characteristics of the hydroelectric power system.

Table 2 Hydroelectric power system characteristics.

Characteristic	Value
Turbine efficiency	80%
Water density	1000 kg/m^3
Darcy factor	0.02
Duct length	15 m
Duct diameter	0.2 m

Applying Equation 11, a program is run to optimize the water flow and height values, generating the maximum required hydroelectric power to compensate for the energy deficit. To do so, the hydropower is calculated for water flow between 0.17 and 0.17 m^3/s and height between 9.5 and 12 meters. This height range is selected since below 9.5 m, there is no mathematical solution for Equation 11, and above 12 m, the height is too high. The program results show the following compatible values (Table 3):

Table 3 Water flow and height for optimum operating conditions in the hydroelectric power system.

	Water flow (m^3/s)					
	0.170	0.149	0.136	0.127	0.119	0.112
Height (m)	9.5	10	10.5	11	11.5	12

Table 3 provides a multiple selection for generating the required maximum power from the hydroelectric system.

Since water is pumped to the upper reservoir during the energy storage process, it is necessary to calculate the required pumping power to optimize the water flow and height; applying Equation 2 for the pump, having (Table 4):

Table 4 Optimum water flow and height for minimum pumping power.

	Water flow (m^3/s)					
	0.170	0.149	0.136	0.127	0.119	0.112
Height (m)	9.5	10	10.5	11	11.5	12
Power (kW)	15.85	14.63	14.02	13.64	13.37	13.17

Therefore, according to data from Table 4, the optimum configuration corresponds to a water flow of 0.112 m^3/s and a reservoir at 12 m high from the hydropower station.

On the other hand, the reservoir capacity depends on the water flow and operation time; working on an hourly basis, the reservoir capacity, according to data from Table 4, is:

$$V_{tk} = \dot{V} t_p = (0.112)(3600) = 403.2 m^3 \tag{12}$$

Because the system operates on an hourly basis.

Considering a cylindrical reservoir, and combining height and diameter to achieve the required capacity shown in Equation 12, it results in the following options (Table 5):

Table 5 Reservoir dimensions for the various water flow values.

	Water flow (m^3/s)					
	0.170	0.149	0.136	0.127	0.119	0.112
Height (m)	5	4.5	4	3.5	3	2.5
Diameter (m)	10.14	10.68	11.33	12.11	13.08	14.33

Unifying the diameter for the average value, 12 m, the corresponding tank height is 3.6 m; therefore, the proposed reservoir tank is a cylinder of 3.6 m high and 12 m in diameter.

Applying error analysis to determine the hydropower uncertainty, we have:

$$\frac{dP_h}{P_h} = \frac{\gamma_w \dot{V} dh}{\gamma_w \dot{V} h - \frac{8\rho_w f L \dot{V}^3}{\pi^2 D_h^5}} + \frac{\gamma_w h d\dot{V}}{\gamma_w \dot{V} h - \frac{8\rho_w f L \dot{V}^3}{\pi^2 D_h^5}} - \frac{24\rho_w f L}{\pi^2 D_h^5} \frac{\dot{V}^2 d\dot{V}}{\gamma_w \dot{V} h - \frac{8\rho_w f L \dot{V}^3}{\pi^2 D_h^5}} \tag{13}$$

Considering:

$$\gamma_w \dot{V} h \gg \frac{8\rho_w f L \dot{V}^3}{\pi^2 D_h^5} \tag{14}$$

Equation 13 transforms into:

$$\frac{dP_h}{P_h} = \frac{dh}{h} + \frac{d\dot{V}}{\dot{V}} - \frac{24 f L}{g\pi^2 D_h^5} \frac{\dot{V} d\dot{V}}{h} \tag{15}$$

Replacing values from Table 5, and operating:

$$\varepsilon_h = \left[\sum_{i=1}^{n}\left(\frac{dP_w}{P_w}\right)\right]^{1/2} = 0.090 \tag{16}$$

Representing a 9% uncertainty in the hydropower generation.

The selected wind and hydropower turbines operate at comparable efficiencies to conventional systems for the same power range operation.

4.5 Electric Storage System

The transient period when the control system commutes from wind to hydroelectric power system requires an electric power source to avoid energy supply interruptions; therefore, a battery should be included in the engineering design to manage the transient periods whenever they happen.

The battery should have enough capacity to supply energy for the transient period, no matter how long. Since in our installation, the process repeats every time the control unit connects the pumping system; the battery energy capacity should match the power in the transient process; mathematically:

$$C_{bat} = N\frac{P_p t_{ts}}{V_{bat}} \tag{17}$$

C_{bat} and V_{bat} are the battery capacity and voltage, P_p is the pumping system power, and *this* is the transient time. *N* is the number of daily transient events.

Applying the classical equation for pumping power, and replacing in Equation 17, yields:

$$C_{bat} = N\frac{\gamma_w \dot{V} H t_{ts}}{V_{bat}} \tag{18}$$

The battery voltage selection depends on the discharge current; for a 12 V battery, the discharge current is:

$$I_D = \frac{P_p}{V_{bat}} = \frac{13167.3}{12} = 1097.3A \tag{19}$$

The discharge current obtained in Equation 19 is too high and requires a complex and expensive wiring system; therefore, we decided to raise the battery voltage ten times to reduce the discharge current by the same factor for a final value of 109.73 A. This value is compatible with current wiring for high discharge rates.

Retrieving data from pumping power, P_p, in Equation 19, considering a battery voltage of 120 V, a transient time of 15 seconds, and 50 transient events per day, having:

$$C_{bat} = 50\frac{(13167.3)(15/3600)}{120} = 22.86Ah \tag{20}$$

The battery block engineering design corresponds to the drawing in Figure 10.

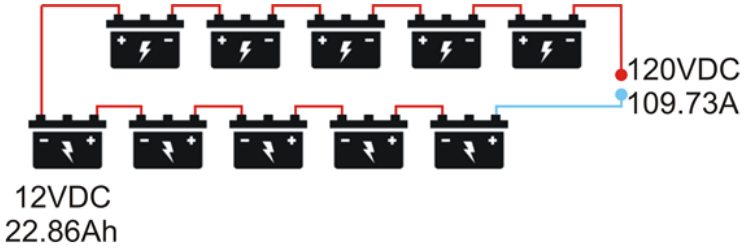


Figure 10 Battery block assembling.

Because out of the transient periods, the batteries are in standby mode, under the flotation charge process, the lithium batteries are not suitable due to their low resistance to flotation processes; therefore, lead-acid batteries are used since this type of batteries stand for flotation for a long time. Besides, lead-acid batteries are cheaper, and their weight and size do not represent a problem in a fixed installation like the one proposed.

Lead-acid battery's lifespan is shorter than lithium-ion; nevertheless, operating with stationary units, the selected type, the lifespan difference shortens from an initial value of 15 years to a minimum of 5 years, reducing the replacement interval by a factor of 3.

On the other hand, the present methodology to recycle battery components is more efficient for lead-acid, with a 99% recycling index, than lithium, which barely achieves a 70% recycling level.

In terms of investment, lead-acid batteries represent a reduction of 40%, making them more suitable for low-cost installations, which is one of our system goals.

The battery charge process stands on the wind power supply; according to data from our installation, the charging time is:

$$t_C = \frac{\xi_{bat}}{P_w} = \frac{C_{bat}V_{bat}}{P_w} = \frac{10(22.86)(12)}{9.68 \times 10^3} = 0.28h = 17\text{min} \tag{21}$$

It should be noted that the battery charging time does not interfere very much with the power supply since it represents less than 1.5% of wind power generation.

5. Control System

For the hydroelectric power plant, the control system manages the following items:

- Water level: using floodgates and valves, the control system regulates the water level in the reservoir to ensure a constant water supply to the hydroelectric turbine.
- Flow: electronic valves control the opening of the fluid duct, regulating the water supply to the turbine to maximize power generation and protect the turbine from overloading.
- Hydropower turbine speed: the system ensures that the turbine operates within limits to optimize efficiency and prevent possible damages. The control system regulates the turbine turning speed.
- Active power: the control system adjusts the water flow and turbine blade position to regulate the power generation as a function of the energy demand.
- Reactive power: the system searches to maintain the stability and quality of the supplied energy when the system uses synchronic electric generators.
- Vibrations: the control system monitors the turbine vibration using sensors and dampers and reduces the vibration level, avoiding damage to the mobile parts.

- Predictive management: online data and predictive analysis are used through sensors and algorithms to anticipate and prevent failures.
- Security: specific sensors and alarm systems warranty people and equipment security
- Data acquisition and survey: using the SCADA protocol, the control system surveys and manages hydroelectric power plant operation.
- Environment: a control process to monitor and manage the environmental impact of hydroelectric power plant operation is implemented, respecting the local and national environmental protection regulations.
- Ecology water flow: the control system ensures that the collected water flow for power generation preserves the ecology water flow.

Additionally, the control system manages the wind farm, the power supply to the facility for energy demand coverage, the battery connection and disconnection process, and the battery charging. All these tasks run on a protocol specifically developed, aiming to optimize the power generation when using the wind farm and the hydroelectric power plant. The control system looks for the best performance in managing the energy balance, avoiding power supply interruptions, minimizing power losses, and maximizing system efficiency.

The protocol that rules the control system is adaptive to variations in the operating conditions like changes in wind speed, water flow, or energy demand. The protocol continuously evaluates the installation parameters to determine which action the control system should take.

The protocol evaluates the wind resource and energy demand in every cycle, activating or deactivating the wind, hydro, or battery power supply depending on operating conditions. The control system prioritizes maintaining the upper water reservoir full or at the highest possible level, using the wind energy surplus. Battery charging is the second priority process if the energy balance is positive. Figure 11 and Figure 12 show the control system protocol flowchart.

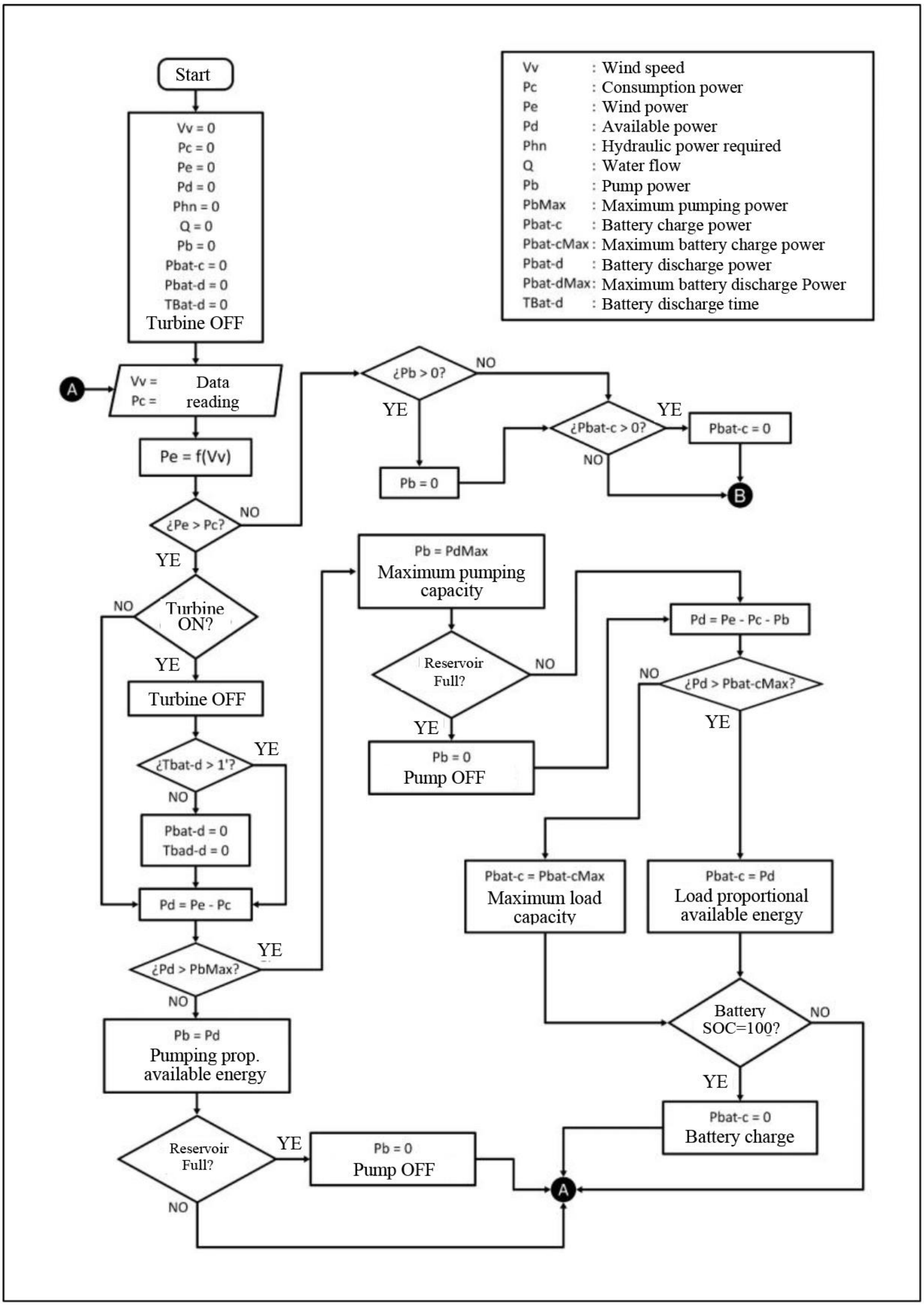
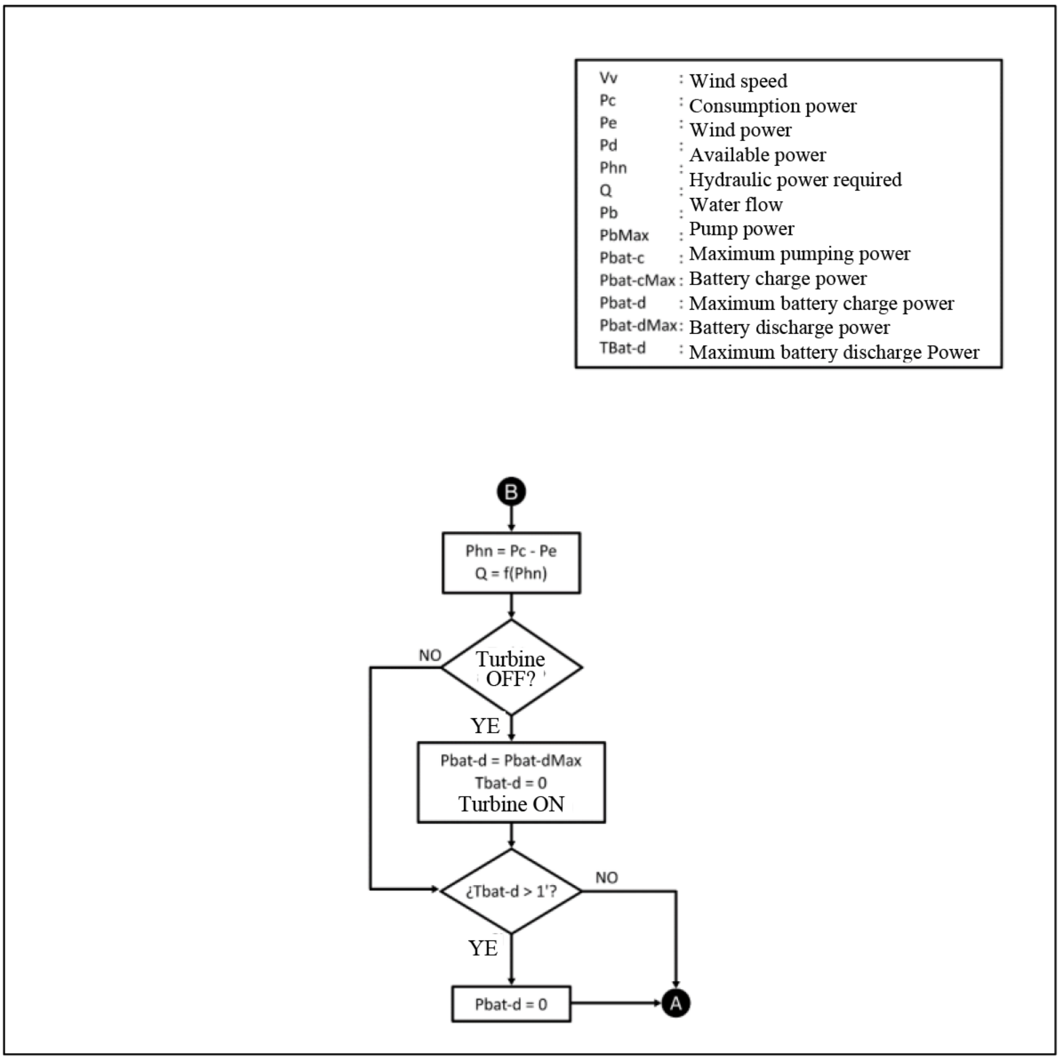


Figure 11 Control system protocol (Part A).



Vv	Wind speed
Pc	Consumption power
Pe	Wind power
Pd	Available power
Phn	Hydraulic power required
Q	Water flow
Pb	Pump power
PbMax	Maximum pumping power
Pbat-c	Battery charge power
Pbat-cMax	Maximum battery charge power
Pbat-d	Battery discharge power
Pbat-dMax	Maximum battery discharge Power
TBat-d	

Figure 12 Control system protocol (Part B).

The control system reads critical variables in every cycle, like wind speed and available water level in the reservoir. The readings are essential to managing the power sources, prioritizing efficiency, and minimizing water waste.

In the event of a failure or breakdown, the control system reacts by triggering the release of energy from the battery bank to compensate for the missing energy generation corresponding to the failing system. If the battery block cannot supply enough power, the control system prioritizes the power supply over energy efficiency.

6. Simulation

After developing the protocol for the control system, we run tests to evaluate improvement in the process, making adjustments and corrections to guarantee the system responds adequately to variations in the operating conditions and fulfills reliability and efficiency goals.

A graphic interphase based on Java Script to simulate is developed since it is valid for any browser. Figure 13 shows the control panel schematic view. The reader can notice the processes associated with the power generation system, wind farm, hydroelectric power plant, and battery block for the transient periods, the energy balance state, and the daily consumption.

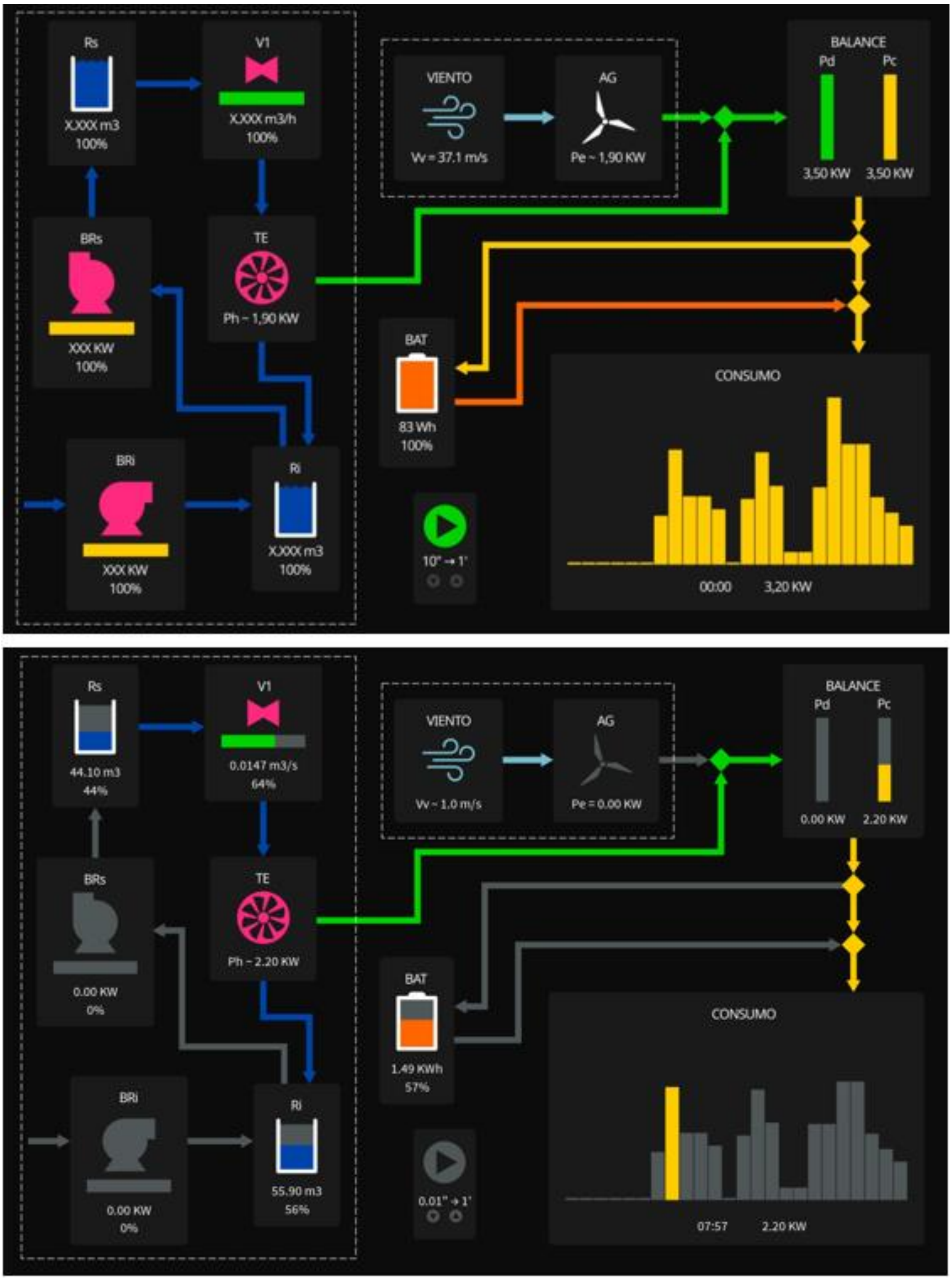


Figure 13 Schematic view of the control system software for the protocol application.

Although software runs on Java Script, migration to Java and Phyton is feasible with minor arrangements.

7. Economic Assessment

Because the project is designed for isolated communities in remote areas with low purchasing power, the implementation cost is critical; therefore, the system should use cheap and easily manageable solutions suitable for this type of community. To this goal, an economic proposal is shown, which can be implemented at a relatively low cost. Prices in Table 6 are indicative and are subject to changes depending on regional market prices.

Table 6 System implementation costs.

	Equipment or device	Items	Cost (€)
Wind farm	Wind turbine 10 kW	1	2790
Hydroelectric system	Lower reservoir pump 500 W	1	206
	Upper reservoir pump 3.8 kW	1	650
	Hydraulic turbine 3.2 kW	1	884
	Upper and lower reservoir	2	1116
Control system	Raspberry Pi Processor	1	132
	Monitor 10"	1	83
	Power analyzer (P-IN/P-OUT)	1	50
Transient system	Lead-acid battery, 250 Ah	1	165
Mounting supplies	Wiring and connector	1	500
	Stands	1	500
	Pipes and connections	1	500
Assembly	Labor	1	1000
		Total	8,728.00

The global cost may look high for poor people but represents an affordable cost if financed over the long term, 20 years or more, or partially subsidized through development aid or funds to support the implementation of renewable energy in underdeveloped areas.

Commercially available wind turbines range between 5 kW for small residential turbines and 5 MW for large-scale utilities. Wind turbines are 20% to 40% efficient at converting wind into energy. The typical life span of a wind turbine is 20 years, with routine maintenance required every six months [46]. Today, the wind turbine yearly maintenance cost represents 3.4% of the investment [47]; therefore, the economic impact is about 95€.

Considering a similar maintenance cost for the hydropower turbine and pumps, the economic impact is less than 60€ per year; the water reservoir maintenance cost is less than 10€ per year. In summary, the yearly wind and hydropower system maintenance costs around 165€, representing 1.8% of the global investment.

Since the “Maintenance Free” model is selected, lead-acid batteries do not have maintenance costs. Electronic equipment does not require maintenance. Since the battery block should be replaced every ten years, on average, and the turbines and pumps last for 20 years, the additional investment for the system life cycle assessment is 3630€, 181.50€ per year, on average.

On the other hand, the grid-extension implementation is out of focus due to the abrupt orography that makes the electric companies avoid this option.

In less developed areas, where the purchasing power is low, even a budget like the one shown in Table 6, which is accessible for a developed society, looks inaccessible; in such a case, people can resort to public or private subsidies such as those from the Inter-American Development Bank (IDB), the Energy Transition Accelerator Financing Platform (ETAF), or government aids to the implementation of renewable energy projects like the Rural Energy for America Program Renewable Energy Systems & Energy Efficiency Improvement supported by the US Department of Agriculture (USDA), The Latin America and Caribbean Investment Facility (LACIF), one of the European Union's regional blending facilities, the European Investment Bank (EIB), or the Economic Commission for Latin-American and the Caribbean (CEPAL).

8. Conclusions

Renewable energy systems development and management for off-grid communities, based on wind and hydroelectric energy, has proven to be a viable and effective solution for energy self-consumption. The main conclusions derived from the analysis and simulation of the project are listed below.

8.1 Novelty of the Proposal

The proposal presented in this work represents an advance in implementing renewable energy systems in areas where grid connections are not accessible, using the natural resources available in the zone. The proposal also contributes to improving the state of the art regarding renewable energy sources hybridization by combining wind and hydropower systems to power isolated local communities. So far, there are no known installations of this type, so the current proposal represents a significant advance in the study and analysis of this type of system.

8.2 Feasibility of the Hybrid System

The combination of wind and hydroelectric energy has proven to be adequate to cover the energy needs of a typical home. The energy source hybridization allows for higher stability in power generation, adapting to the variability of weather conditions and resource availability.

8.3 Efficiency and Energy Management

The evaluation of the interaction between demand and energy generation has shown that the designed system manages energy consumption efficiently. The developed control algorithms allow for adequate optimization of the use of the generated energy, ensuring continuous and reliable delivery.

8.4 Development of Interface and Control Tools

The developed management interface provides an effective tool for visualizing and monitoring energy generation and consumption. Freely available software use and development in an environment such as JavaScript has allowed for an affordable and accessible implementation for end users.

8.5 System Simulation and Testing

Simulations using current data have validated the system's performance under practical conditions. The results confirm that the system may operate effectively in the local environment, offering a reliable energy self-consumption solution.

8.6 Implementation and Future Applications

Raspberry Pi use for system implementation in the local environment has been identified as a suitable solution due to its low cost and processing capacity. This approach facilitates the adaptation and scalability of the system, allowing future improvements and applications in similar contexts.

8.7 Economic and Environmental Considerations

The system design considers cost reduction, using low-cost components and design optimization techniques, providing an economical solution, and promoting environmental sustainability by reducing dependence on non-renewable energy sources and minimizing the installation's carbon footprint.

8.8 Recommendations for Future Research

It is recommended to identify areas for the system's monitoring and evaluation improvement and optimization under local conditions. In addition, other renewable energy sources should be integrated, like solar photovoltaic, and emerging technologies developed, thus complementing and improving the system's performance.

Another suggested topic for future research is studying and analyzing the hybrid renewable system performance in variable climatic and meteorological environments and implementing any hybrid configuration in different regional contexts.

The project has achieved the expected objectives, demonstrating the viability of a renewable energy management system for self-consumption in isolated communities. The successful implementation and the results offer a solid basis for this technology application in local environments and its potential to contribute to the transition toward a more sustainable energy model.

Furthermore, this project shows a close connection with the Sustainable Development Goals (SDGs) through the United Nations' Actions for a healthy planet, pursuing to limit the energy generation dependence on fossil fuels, promoting the implementation of power generation based on local renewable energy sources, reducing the carbon emissions, improving the air quality, and preserving water resources and soil.

Author Contributions

Carlos Armenta-Déu: Conceptualization; Formal analysis; Results evaluation; Writing and revision. Ángela Trujillo: Data collection; Project development; Results evaluation.

Competing Interests

The authors have declared that no competing interests exist.

References

1. Armaroli N, Balzani V. Towards an electricity-powered world. Energy Environ Sci. 2011; 4: 3193-3222.
2. Niu S, Jia Y, Wang W, He R, Hu L, Liu Y. Electricity consumption and human development level: A comparative analysis based on panel data for 50 countries. Int J Electr Power Energy Syst. 2013; 53: 338-347.
3. Yang L, Yan H, Lam JC. Thermal comfort and building energy consumption implications–A review. Appl Energy. 2014; 115: 164-173.
4. Holmes MJ, Hacker JN. Climate change, thermal comfort and energy: Meeting the design challenges of the 21st century. Energy Build. 2007; 39: 802-814.
5. Traore NH. Energy Eaters and Energy Feeders [Internet]. Philadelphia, PA: The Teachers Institute of Philadelphia, University of Pennsylvania; 2019. Available from: https://theteachersinstitute.org/wp-content/uploads/2019/07/traore-unit.pdf.
6. Strengers Y, Nicholls L, Maller C. Curious energy consumers: Humans and nonhumans in assemblages of household practice. J Consum Cult. 2016; 16: 761-780.
7. Rosak-Szyrocka J, Żywiołek J. Qualitative analysis of household energy awareness in Poland. Energies. 2022; 15: 2279.
8. Rusek R, Melendez Frigola J, Colomer Llinas J. Influence of occupant presence patterns on energy consumption and its relation to comfort: A case study based on sensor and crowd-sensed data. Energy Sustain Soc. 2022; 12: 13.
9. Poizot P, Dolhem F. Clean energy new deal for a sustainable world: From non-CO_2 generating energy sources to greener electrochemical storage devices. Energy Environ Sci. 2011; 4: 2003-2019.
10. Nautiyal A, Ramlal A. Clean energy sources for a better and sustainable environment of future generations. In: Energy: Crises, challenges and solutions. Hoboken, NJ: John Wiley & Sons Ltd.; 2021. pp. 151-168.
11. Qazi A, Hussain F, Rahim NA, Hardaker G, Alghazzawi D, Shaban K, et al. Towards sustainable energy: A systematic review of renewable energy sources, technologies, and public opinions. IEEE Access. 2019; 7: 63837-63851.
12. Hoffmann P. Tomorrow's energy, revised and expanded edition: Hydrogen, fuel cells, and the prospects for a cleaner planet. Cambridge, MA: MIT Press; 2012.
13. Mai TT, Jadun P, Logan JS, McMillan CA, Muratori M, Steinberg DC, et al. Electrification futures study: Scenarios of electric technology adoption and power consumption for the United States. Golden, CO: National Renewable Energy Lab.; 2018; NREL/TP-6A20-71500.
14. Mostafaeipour A, Bidokhti A, Fakhrzad MB, Sadegheih A, Mehrjerdi YZ. A new model for the use of renewable electricity to reduce carbon dioxide emissions. Energy. 2022; 238: 121602.
15. Granovskii M, Dincer I, Rosen MA. Greenhouse gas emissions reduction by use of wind and solar energies for hydrogen and electricity production: Economic factors. Int J Hydrog Energy. 2007; 32: 927-931.
16. Dassanayake NP, Preethika DD, Chathumini KK, Wadanambi RT, Wandana LS, Arachchige US. The role of renewable energy in reducing GHG emissions. J Res Technol Eng. 2021; 2: 12-21.
17. Panwar NL, Kaushik SC, Kothari S. Role of renewable energy sources in environmental protection: A review. Renew Sustain Energy Rev. 2011; 15: 1513-1524.

18. International Renewable Energy Agency. World Energy Transitions Outlook 2023 [Internet]. Abu Dhabi, United Arab Emirates: IRENA; 2023 [cited date 2024 August 17th]. Available from: https://www.irena.org/Digital-Report/World-Energy-Transitions-Outlook-2023.
19. Lamère MM. Energy Poverty in Developing Countries: The problem of lack of access to electricity and Flywheel Energy Storage system as an appropriate technology. Proceedings of the EWB-UK & EAP Education Conference 2012; 2012 March 26th; London, UK. London: Engineers Against Poverty.
20. Blimpo MP, Cosgrove-Davies M. Electricity access in Sub-Saharan Africa: Uptake, reliability, and complementary factors for economic impact. Washington, D.C.: World Bank Publications; 2019.
21. Doll CN, Pachauri S. Estimating rural populations without access to electricity in developing countries through night-time light satellite imagery. Energy Policy. 2010; 38: 5661-5670.
22. United Nations Development Program. Data Future Exchanges [Internet]. New York, NY: United Nations Development Program; 2024 [cited date 2024 October 8th]. Available from: https://sdgdiagnostics.data.undp.org/.
23. United Nations Development Program. Energy Access [Internet]. New York, NY: United Nations Development Program; [cited date 2024 August 8th]. Available from: https://www.undp.org/energy/.
24. López-González A, Ferrer-Martí L, Domenech B. Sustainable rural electrification planning in developing countries: A proposal for electrification of isolated communities of Venezuela. Energy Policy. 2019; 129: 327-338.
25. Andrade CS, Rosa LP, Da Silva NF. Generation of electric energy in isolated rural communities in the Amazon Region a proposal for the autonomy and sustainability of the local populations. Renew Sustain Energy Rev. 2011; 15: 493-503.
26. Sánchez AS, Torres EA, Kalid RD. Renewable energy generation for the rural electrification of isolated communities in the Amazon Region. Renew Sustain Energy Rev. 2015; 49: 278-290.
27. Cherni JA, Hill Y. Energy and policy providing for sustainable rural livelihoods in remote locations–The case of Cuba. Geoforum. 2009; 40: 645-654.
28. Blair N, Pons D, Krumdieck S. Electrification in remote communities: Assessing the value of electricity using a community action research approach in Kabakaburi, Guyana. Sustainability. 2019; 11: 2566.
29. Miravet-Sánchez BL, García-Rivero AE, Yuli-Posadas RA, Inostroza-Ruiz LA, Fernández-Guzmán V, Chávez-Juanito YA, et al. Solar photovoltaic technology in isolated rural communities in Latin America and the Caribbean. Energy Rep. 2022; 8: 1238-1248.
30. Our World in Data. Renewable Energy [Internet]. Oxford, England: Our World in Data; 2020 [cited date August 8th]. Available from: https://ourworldindata.org/renewable-energy.
31. Saravana BS, Srinivasan K, Jeyapradha RB. Future prospects of non-grid-connected wind power in India. Proceedings of the 2011 Annual IEEE India Conference; 2011 December 16th-18th; Hyderabad, India. Piscataway Township: IEEE.
32. Karunakaran P, Lau AK, Reddy AN. Photovoltaic versus micro-hydropower for rural non-grid connected areas of equatorial Sarawak. J Telecommun Electr Comput Eng. 2016; 8: 129-133.
33. Fang Y, Li J, Wang M. Development policy for non-grid-connected wind power in China: An analysis based on institutional change. Energy Policy. 2012; 45: 350-358.

34. Zhou L, Min F. Research on application of non-grid-connected wind power in less developed areas. Proceedings of the 2009 World Non-Grid-Connected Wind Power and Energy Conference; 2009 September 24th; Nanjing, China. Piscataway Township: IEEE.
35. Ranaboldo M. Design of off-grid renewable energy community electrification projects: Analysis of micro-scale resource variations and development of optimization methods. Barcelona, Spain: Universitat Politècnica de Catalunya; 2015.
36. Güven AF, Yücel E. Sustainable energy integration and optimization in microgrids: Enhancing efficiency with electric vehicle charging solutions. Electr Eng. 2025; 107: 1541-1573.
37. Güven AF. Heuristic techniques and evolutionary algorithms in microgrid optimization problems. In: Microgrid. Boca Raton, FL: CRC Press; 2024. pp. 260-301.
38. Güven AF, Yörükeren N, Mengi OÖ. Multi-objective optimization and sustainable design: A performance comparison of metaheuristic algorithms used for on-grid and off-grid hybrid energy systems. Neural Comput Appl. 2024; 36: 7559-7594.
39. Güven AF, Yörükeren NU, Tag-Eldin E, Samy MM. Multi-objective optimization of an islanded green energy system utilizing sophisticated hybrid metaheuristic approach. IEEE Access. 2023; 11: 103044-103068.
40. Güven AF, Mengi OÖ. Assessing metaheuristic algorithms in determining dimensions of hybrid energy systems for isolated rural environments: Exploring renewable energy systems with hydrogen storage features. J Clean Prod. 2023; 428: 139339.
41. Güven AF, Yörükeren N, Samy MM. Design optimization of a stand-alone green energy system of university campus based on Jaya-Harmony Search and Ant Colony Optimization algorithms approaches. Energy. 2022; 253: 124089.
42. Güven AF, Samy MM. Performance analysis of autonomous green energy system based on multi and hybrid metaheuristic optimization approaches. Energy Convers Manag. 2022; 269: 116058.
43. Ryse Energy. Wind Turbine ENAIR E200L [Internet]. Castalla, Alcoià: Ryse Energy; [cited date 2024 October 9th]. Available from: https://www.enair.es/es/aerogeneradores/e200l.
44. Osinergmin. Informe de Resultados Consumo y Usos de la Electricidad, Encuesta Residencial de Consumo y Usos de Energía – ERCUE 2018 [Internet]. Perú: Osinergmin; 2018. Available from: https://cdn.www.gob.pe/uploads/document/file/1414562/ERCUE%20Electricidad%202018.pdf.
45. Visual Crossing. Historical weather data for Cusco [Internet]. Reston, VA: Visual Crossing; 2024 [cited date August 8th]. Available from: https://www.visualcrossing.com.
46. United States Environmental Protection Agency. Renewable Energy Facts Sheet: Wind Turbines Internet]. Washington, D.C.: United States Environmental Protection Agency; 2013.
47. Blewett, D. Wind Turbine Cost: How Much? Are they worth it in 2025? [Internet]. Williamstown, MA: Weather Guard Lightning Tech; 2024. Available from: https://weatherguardwind.com/how-much-does-wind-turbine-cost-worth-it/#:~:text=%241%2C300%2C000%20USD%20per%20megawatt.,on%20wind%20turbine%20operational%20cost.