Design of a hybrid photovoltaic-wind and water pumping system for the Second Beach of Puerto Mocho in Barranquilla, Colombia

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Executive Summary

This project aims to design a sustainable, off-grid energy system for beachfront restaurants in Puerto Mocho, Barranquilla, with the objective of reducing energy consumption, lowering operational costs, and minimizing direct greenhouse gas emissions (Scope 1). The goal is to deliver an optimized, cost-effective, and environmentally friendly solution tailored to the local context.

The project is structured into three main phases:

1. Research, Site Analysis, and Planning: Understanding the community's energy needs, and available renewable resources and technologies. The team will also develop a project proposal outlining the approach and timeline.
2. Preliminary Design and Simulation: Use HOMER Pro to design and simulate different system configurations, calculate energy costs, emissions, and water-related energy use.
3. System Optimization and Final Report: Refining the design for maximum efficiency and preparing a comprehensive report detailing earnings, costs, and environmental impact.

The proposed hybrid renewable energy system includes eight solar panels, three horizontal-axis wind turbines, and fourteen lead-acid batteries connected in parallel. The energy system supplies three restaurants, with all equipment installed on a single rooftop. No backup diesel generators are included, as low renewable energy production typically coincides with reduced customer demand due to poor beach weather.

The electrical load includes lighting, ceiling and wall fans, refrigeration units, sound systems, and decorative LED lighting, televisions, and kitchen appliances distributed across the three establishments.

In addition to energy generation, the project integrates a clean water supply and purification system, featuring a 10,000L main tank and a 3,000L secondary tank fed by river water using a pump. Water undergoes pre-filtration, sand filtration, and UV purification. For the distribution of water between the main tank and the other components, the system utilizes gravity to reduce energy use, ensuring access to both utility and potable water.

Economic and environmental Performance:

- Initial cost: $20,142 USD
- Annual operating cost: $781 USD
- Annual revenue/savings: $7,151 USD
- Payback period (PBP): 3.16 years
- Internal Rate of Return (IRR): 31%
- Levelized Cost of Energy (LCOE): $0.35 USD/kWh
- Annual life cycle emissions: ~3,106 kg CO_2

This project demonstrates that a well-designed renewable energy and water system can meet the needs of remote businesses, significantly reduce carbon emissions, and deliver strong economic returns, making it a viable model for sustainable development in similar off-grid coastal communities.

INTRODUCTION

The aim of this project is to design a hybrid renewable energy and water system for Puerto Mocho, a coastal off-grid town in Barranquilla, Colombia. The region is vulnerable to climate change and lacks access to a reliable electricity supply, refrigeration, and drinking water. Our objective was to design a cost-effective and technically viable solution that leverages local renewable resources primarily solar and wind to achieve the daily energy and water requirements of the community with minimized greenhouse gas emissions. The project employed HOMER Pro to simulate and optimize several system configurations using sustainability, cost, and technical performance criteria.

OBJECTIVES

Environmental and Design Objectives

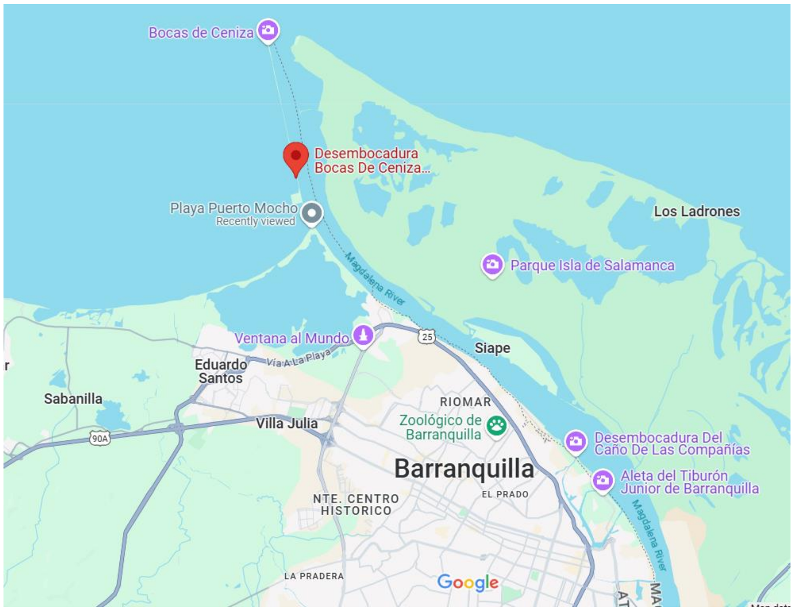
- Design a hybrid renewable energy system for the climate and load of Puerto Mocho.
- Minimize Scope 1 and Scope 2 GHG emissions through the elimination of fossil fuels and grid dependence.
- Provide a solar- and wind-powered water pumping system that reacts to the daily demand for clean water.
- Ensure system components follow life cycle sustainability best practices.

DETAILED ANALYSIS OF THE ASSIGNED SITE AND POTENCIAL

- **Geographical and Environmental Context**

Puerto Mocho, a coastal community in Barranquilla, Colombia, is characterized by a dry tropical climate. Located at coordinates N. 11° 03’ 51.5” - W. 74° 50’ 40.8”, it lies between the mouth of the Magdalena River at "Bocas de Cenizas" and Punta Sabanilla in the municipality of Puerto Colombia, as shown in Figure 1. The environmental dynamics of the area have been altered by the construction of the directional dike, affecting the ecosystem, mangrove forest, and sand quality. The local climate presents maximum temperatures of 31°C and minimums of 23°C, with a rainy season from May to October [1].

In **Figure 1-a**, a broader view of Puerto Mocho Beach in relation to the city of Barranquilla is shown. In **Figure 1-b**, a closer view of its location is presented. Both images were obtained using *Google Maps*.



(a)

(b)

Figure 1. *Geographical view of Puerto Mocho Second Beach.*

- **Local Population and Economic Activities**

The local population consists mainly of fishermen and merchants who have lived in the area for decades. Recently, training programs in partnership with SENA have been implemented to certify skills in food handling, basic cooking, bar service, marketing and sales, ethics and values, complemented by bilingual education to enhance entrepreneurial skills [2].

Traditional economic activities include artisanal fishing and local commerce. However, with the official opening of Puerto Mocho Beach on November 30, 2024, sustainable tourism has emerged as a new source of income. The area of interest for the application of this project is the second beach, also located in Puerto Mocho. Unlike the main beach, which has over one kilometer of beach equipped with tents, chairs, picnic tables, dining areas, and sales points, this one only offers the presence of three restaurants and additional services from street vendors. However, it also benefits from the tourism attracted by the main beach [3].

- **Infrastructure and Sustainability Initiatives**

The Government of Atlántico introduced the 2024-2027 Development Plan to enhance infrastructure and public services by modernizing the road network, optimizing access to water and sanitation, and expanding fluvial transportation. In terms of environmental sustainability, it prioritizes ecosystem conservation, climate change mitigation, and environmental education. Notably, the plan includes the expansion of electricity coverage in rural areas and the extension of household gas services, reaffirming the commitment to improving the quality of life for the most vulnerable communities [4].

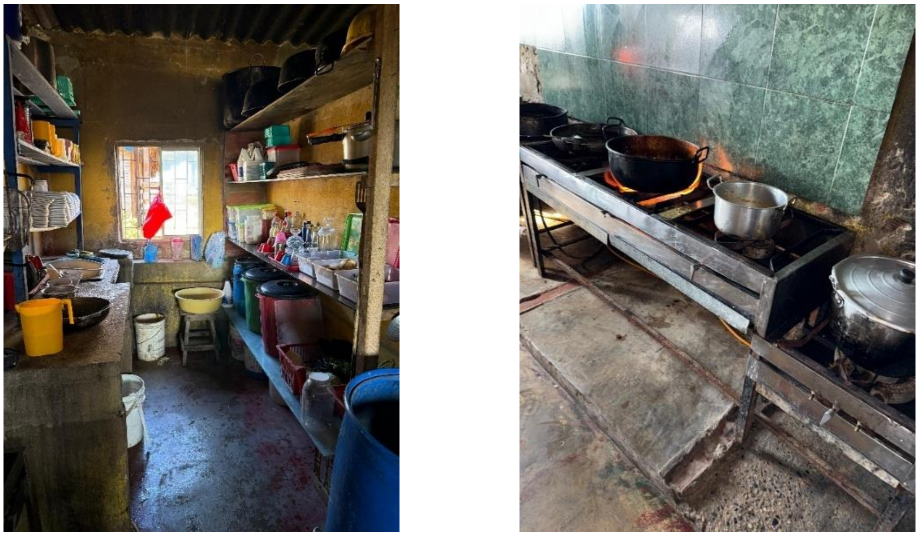
- **Previously Collected Information on the Community and Infrastructure**

During the academic **semester 2024-03**, a field visit was conducted to the second beach to gather as much information as possible about the community. This data collection aimed to better understand their needs and propose an improved system.

- **Infrastructure and Business Operations:** Local businesses, mainly restaurants, operate daily from 6:00 a.m. to 6:00 p.m. They serve an average of 20 meals on weekdays, with demand rising to around 70 meals per day on weekends.

- **Fuel Usage:** Cooking is done using liquefied petroleum gas (LPG). A 100-pound tank, costing approximately 200,000 COP (about USD 45), lasts for around 15 days. Additionally, a smaller 33-pound tank is sometimes used as a backup. Fuel also plays a crucial role in the local economy, as it powers the motors of fishing boats. This information will be considered during the project's economic analysis phase to determine the payback period for the investment in installing a renewable energy system.

In **Figure 2-a**, a general view of the kitchen in one of the restaurants is shown. As observed, no electrical appliances such as microwaves, food choppers, or blenders are used. All food is prepared using gas burners, which are displayed in **Figure 2-b**.



(a) (b)

Figure 2. *General View of a Restaurant Kitchen and Cooking Equipment.*

- **Water Supply:** Water is sourced from the nearby river and treated with sulfate and chlorine, though it remains unsafe for drinking. Despite this, the river water is freely accessible.

The continued reliance on untreated or inadequately treated river water poses significant health risks to the community. Contaminated water and poor sanitation contribute to the spread of diseases such as cholera, dysentery, hepatitis A, typhoid fever, and poliomyelitis. Exposure to biologically or chemically polluted water increases the likelihood of infections, particularly in vulnerable populations such as children. The presence of harmful substances like arsenic, fluoride, and lead in groundwater sources further exacerbates health concerns. Additionally, limited water access may discourage proper handwashing practices, facilitating the transmission of diarrheal diseases. The lack of effective water management also creates breeding grounds for disease-carrying insects, increasing the risk of vector-borne illnesses such as dengue [5]. Addressing these issues through improved water treatment and sanitation infrastructure will be one of the key points in the proposed new system.

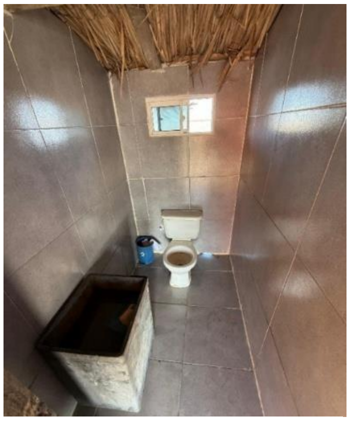


Figure 3. *Sanitation Facilities in a Restaurant.*

Figure 3 shows the restroom of one of the restaurants. As observed, there is no sink; instead, river water, treated by the users themselves, is directly used for flushing the toilet and personal hygiene.

- **Electricity Access:** There is almost no electricity in Puerto Mocho. The only available lighting at night comes from two solar-powered lamps that were donated to the community, one of which is shown in **Figure 4.**

Figure 4. *Solar-Powered Lamp Used for Nighttime Lighting*

Figure 5. *Ice Storage for Beverage Cooling*

- **Refrigeration Systems:** Nonexistent. Cold beverages are stored in coolers with ice, with peak weekend consumption reaching approximately 100 bags of ice per day, as shown in **Figure 5**.

- **Observed Challenges:** Financial constraints and logistical challenges have hindered the adoption of energy systems. The lack of reliable and affordable energy restricts opportunities for energy-dependent activities, emphasizing the need for customized, sustainable energy solutions. Additionally, the available space is limited, as shown in **Figure 6-a**, where the restaurant area is located between the river and the sea. Most of the available land <u>is occupied by the roadway for vehicle circulation, the beach area, and the restaurant zone</u>. The restaurants consist of simple structures without an evidently rigid framework, as can be inferred from **Figure 6-b**. These spatial limitations and the structural characteristics of the buildings must be considered during the technology evaluation phase of this project.

(a) (b)

Figure 6. *Spatial Constraints and Structural Characteristics of the Restaurant Area*

- **Community Priorities:** The community has shown significant interest in improving energy access and water safety. There is growing awareness of solar technology and curiosity about its benefits, though financial and logistical barriers remain. Key priorities include reliable lighting, refrigeration capacity, and access to safe drinking water.

- ***Identify current energy and water usage patterns***

The current energy and water usage patterns in Puerto Mocho second beach are primarily influenced by the daily operations of the restaurants in the area. Regarding water usage patterns, it is important to note that there is no piped water system in this location; all water is extracted directly from the river. As a result, restaurants workers are unable to determine the exact amount of water consumed daily, and they do not receive a water bill either. Therefore, the water consumption figures presented here are estimates.

For the estimation, the presence of three restaurants was considered, all of which primarily serve meals during midday, with the remaining meals served in the evening. To conduct the analysis, it is essential to estimate the periods that represent peak hours for water and energy consumption.

Based on field investigations, the average meal sold consists of **fried fish, rice, mashed and fried plantain, salad, and soup.** According to restaurant workers, each establishment serves approximately 20 meals on weekdays and 70 on weekends, operating from 6 a.m. to 6 p.m. Assuming that, based on the number of burners available in the kitchen, it takes 30 minutes to cook 5 to 6 fish, the estimated active cooking time is around 7 hours on weekends and 2 to 3 hours on weekdays.

According to these data, the total water consumption for preparing one meal is estimated at **20 liters**, considering both food cleaning and preparation activities. Additionally, the bathrooms rely on river water, with an estimated **6 liters** used per flush. The restroom is used twice every hour on weekdays and five times per hour on weekends.

- **Estimation of hour-by-hour water demand:**

The system's water consumption exhibits a consistent pattern throughout most of the day (36 liters per hour), with significant peaks occurring between 12:00–13:00 and 16:00–17:00, particularly on weekends, when usage triples compared to weekdays. Total daily consumption ranges from 1,632 liters on weekdays to over 4,000 liters on weekends, indicating a higher demand during those days.

To determine peak water usage periods, it was assumed that 60% of the meals are served around midday, while the remaining 40% are served in the evening. This results in a significant water demand spike during **lunch hours**. Additionally, water is used for sanitation purposes, with the community relying on river water for flushing toilets. The estimation assumes that the bathroom is used twice per hour on weekdays and five times per hour during peak periods on Fridays and Saturdays, with each flush consuming 6 liters of water.

Figure 7 illustrates the estimated hourly and daily water consumption. This analysis highlights the crucial role of water in daily operations and underscores the need for a more sustainable and reliable water supply system for the community.

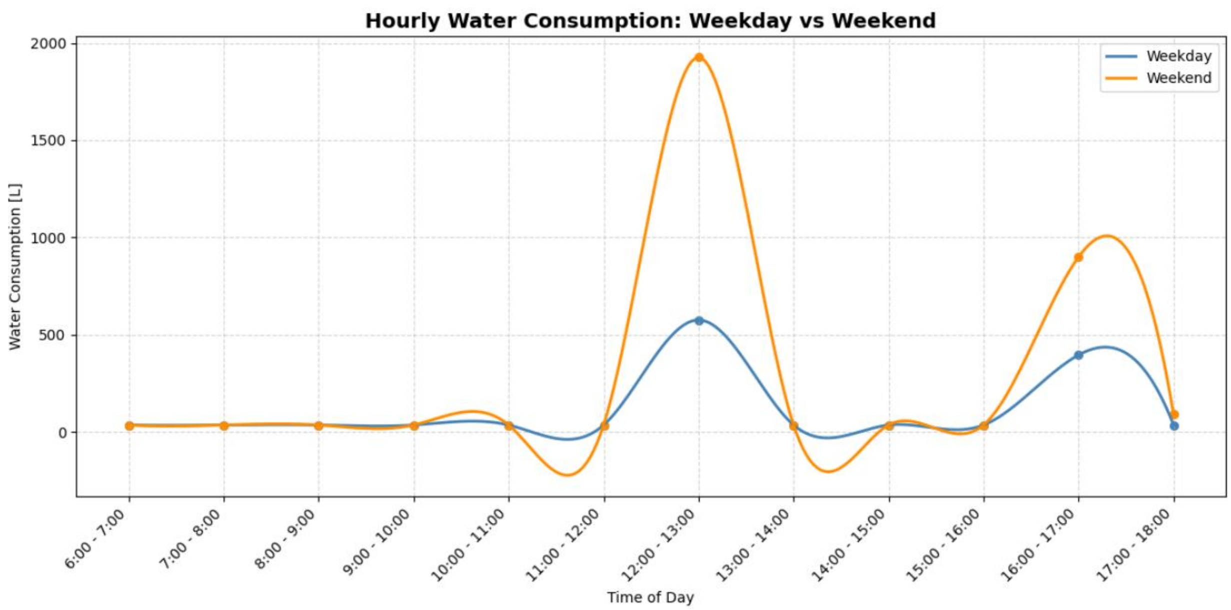


Figure 7. *Water usage patterns.*

- **Estimation of hour-by-hour energy demand:**

The current energy usage in Puerto Mocho's second beach is minimal, limited primarily to the operation of a solar-powered lamp at night. Due to this low consumption, a detailed load analysis was not initially conducted. The buildings in this area are not connected to the national electrical grid; instead, residents rely on a basic solar panel setup to power a lamp and a battery-operated stereo system. Consequently, the overall electricity demand remains low and relatively stable throughout the day.

Given the absence of electrical appliances in the current setting, the proposed energy solution focuses on potential usage scenarios, particularly for restaurants operating in the area. To this end, a *list of hypothetical appliances was developed*, assuming future availability of a renewable energy supply. The selection includes only essential equipment, prioritizing basic needs such as lighting, refrigeration, and entertainment.

This estimation adopts a conservative approach, reflecting the community's limited economic resources. The appliance selection is tailored to support key income-generating activities, mainly tourism and restaurant services, while avoiding excessive financial strain on the residents.

Table 1 presents the assumed electrical appliances for a typical restaurant along with their power ratings and estimated total power demand.

Table 1: Hypothetical electrical appliances.

Assumed electrical devices	Quantity	Potency [kW]	Potency total [kW]
Light bulb (kitchen)	9	0.015	0.135
Light bulb (bathroom)	3	0.015	0.045
Ceiling fan (interior)	6	0.055	0.33
Ceiling fan (kitchen)	3	0.055	0.165
wall-mounted fan (kitchen)	3	0.05	0.15
stereo equipment (interior)	3	0.16	0.48
Led Strip Lamp (interior)	6	0.008	0.048
Led Strip Lamp (exterior)	6	0.008	0.048
Fridge (kitchen)	6	0.041	0.25
TV	3	0.06	0.18
Water pump	1	0.1	0.1

Table 2 shows the estimated hourly energy consumption for weekdays and weekends across the community.

Table 2: Estimated Hourly Energy Consumption.

Hour/day	Energy Consumption on Weekdays (kWh)	Energy Consumption on Weekends (kWh)
6:00 - 7:00	0.398	0.490
7:00 - 8:00	0.490	0.490
8:00 - 9:00	0.283	0.283
9:00 - 10:00	0.283	0.283
10:00 - 11:00	0.283	0.283
11:00 - 12:00	0.283	0.283
12:00 - 13:00	1.836	1.836
13:00 - 14:00	1.629	1.836
14:00 - 15:00	1.577	1.951
15:00 - 16:00	0.835	1.951
16:00 - 17:00	0.494	1.788
17:00 - 18:00	0.494	1.218
Total Energy cosumption (kWh)	8.887	12.694

To accommodate potential load variations and future system expansion, the electrical demand was deliberately oversized by 15%. Additionally, the power requirements of the proposed water storage and distribution system were incorporated into the total load estimation. The resulting load profile follows an hourly distribution as shown in **Figure 8**, representing the combined demand of all three restaurants included in the proposal.

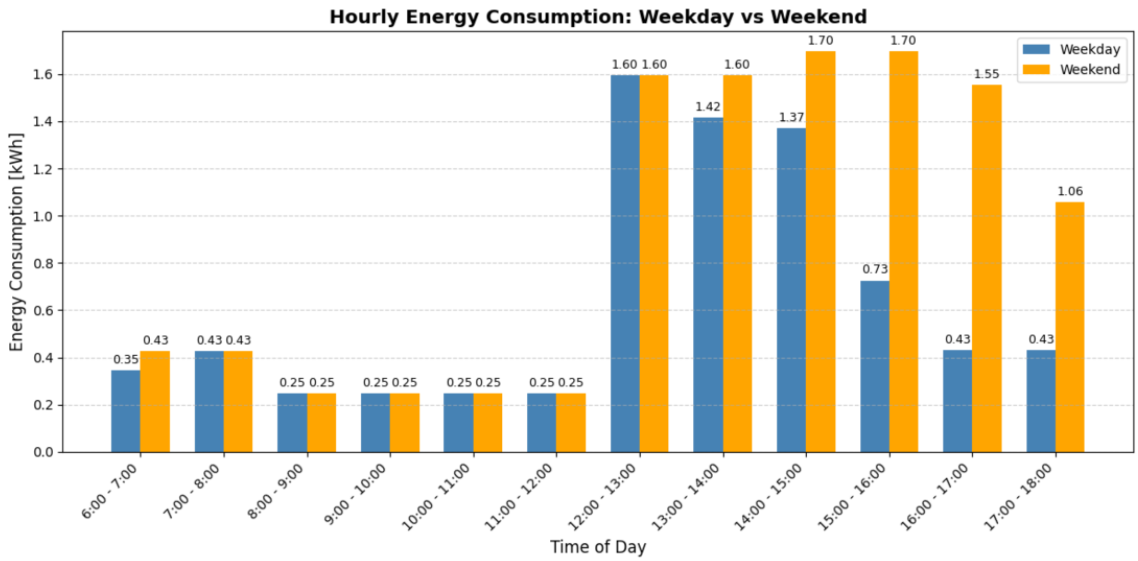


Figure 8. *Energy consumption of Puerto Mocho Second Beach.*

The peak hours for electricity demand occur between 12:00 p.m. and 3:00 p.m. on weekdays and between 12:00 p.m. and 5:00 p.m. on weekends. This corresponds to a total electricity consumption of **8.91 kWh for weekdays and 12.57 kWh for weekends.**

- **Key Opportunities and Renewable Energy Potential in Puerto Mocho:**

Puerto Mocho Second Beach, despite being a **narrow strip of land between a river and the sea**, benefits from **abundant renewable energy potential**. The absence of a conventional electrical grid makes it an ideal location for the development of **offshore wind or solar power systems**. Additionally, the unique geographical characteristics of the area offer the possibility of **harnessing salinity gradient energy**, and even **a hybrid energy system combining multiple renewable sources** could be explored.

Currently, the lack of electricity in the area means that residents do not use electric appliances. This presents a **unique opportunity to introduce technological advancements** that could significantly **improve the quality of life** within the community. Specifically, **modernizing local restaurants** with reliable electricity would make them **more comfortable and attractive to tourists**, increasing potential revenue. Furthermore, this project provides an opportunity to **evaluate the financial feasibility of energy system implementation** by comparing investment costs with the expected long-term economic benefits.

Feasibility for wind turbines in Barranquilla

Puerto Mocho demonstrates promising wind conditions for renewable energy applications. Regional wind speed data indicate that average wind speeds range between **4 and 8 m/s**, which aligns well with the operational requirements for wind power systems [6]. According to established benchmarks, **horizontal-axis wind turbines** typically require average wind speeds **above 3.5 m/s** to operate efficiently and generate meaningful electricity output [7]. This confirms that the site has favorable conditions for integrating wind power, either as a **standalone energy solution** or as part of a **hybrid renewable system**.

A study conducted for **Barranquilla's Ernesto Cortissoz Airport** provides an estimate of the **maximum recoverable wind power density**, regardless of turbine type. This value ranges from **1.22 W/m² in October** to **33 W/m² in February**, reflecting seasonal variations in wind availability. It is important to note that these values are based on **average wind conditions**, rather than peak wind speeds, as turbine systems are designed to optimize performance under typical rather than extreme scenarios.

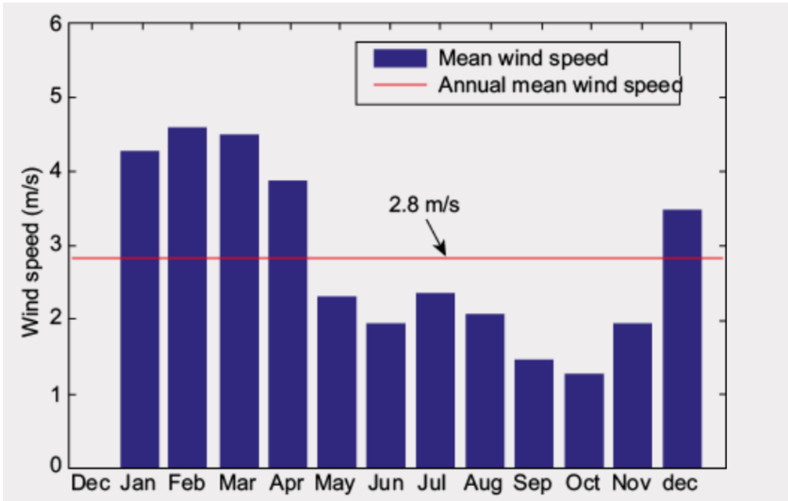


Figure 9. *Diagram of wind speed in Barranquilla. Taken from [8]*

Based on the reported wind power density values, the estimated daily energy generation ranges from **0.029 kWh/(day·m²)** in October to **0.792 kWh/(day·m²)** in February. To meet the projected daily demand of **12.57 kWh**, the required wind capture area would vary significantly: approximately **429 m²** under low wind conditions and just **16 m²** under favorable conditions. These calculations assume continuous wind availability and do not account for system inefficiencies or downtime, so actual system sizing should include appropriate safety margins and site-specific measurements.

In conclusion, the integration of wind energy in Puerto Mocho appears technically feasible. However, due to the **seasonal variability** shown in Figure 15 and the **preliminary nature of the data**, a **site-specific wind assessment** is recommended before final system design. This will ensure accurate sizing and reliable performance throughout the year.

Feasibility for salient gradient in Barranquilla

The river estuaries of the Magdalena, Atrato, and León rivers are identified as high-potential sites for salinity gradient energy (SGE) generation in Colombia. Bocas de Ceniza, where the Magdalena River meets the Caribbean Sea, presents a favorable salinity gradient for energy production. The site has an average salinity of 0.0634 ± 0.0002 g/L in the river and 36.3 ± 0.1 g/L in the sea, resulting in a gradient of 36.2 ± 0.1 g/L, which is suitable for energy extraction [9].

Feasibility for solar panels in Barranquilla

One of the **strongest opportunities for renewable energy implementation** in the region is its **high solar energy potential**. The **Boca de Ceniza** area has an estimated solar energy generation potential of **2,119 kWh/m²** [10]. Although this represents an ideal value, it is important to consider that **high temperatures in the region may reduce equipment efficiency**. These data were obtained from the **Solar ATLAS platform** [10].

The feasibility of solar panels in Barranquilla, Colombia, is supported by the region's high solar potential and favorable meteorological conditions, which make it well-suited for photovoltaic (PV) installations. Barranquilla benefits from significant solar irradiation, ensuring high performance of solar energy systems[11].

Furthermore, **climatic phenomena such as El Niño and La Niña** can influence solar energy production. **El Niño**, typically associated with reduced cloudiness and rainfall in northern Colombia, may enhance solar output by increasing sunlight availability. In contrast, **La Niña** tends to bring **more frequent and intense rainfall**, potentially lowering solar system efficiency due to higher humidity, increased cloud cover, and occasional soiling of panels. These factors should be considered in long-term performance forecasting and system design.

SYSTEM DATA AND DESIGNS

- **Alternative selection analysis**

To determine the three most suitable energy alternatives for the project, **12 simulations** were performed using **HomerPro** software. The methodology involved generating and comparing hybrid system configurations, comprising **PV panels, wind turbines, generators, converters, and lead-acid/lithium-ion batteries**, based on economic and sustainability metrics, the configurations can be seen in Figure 10.

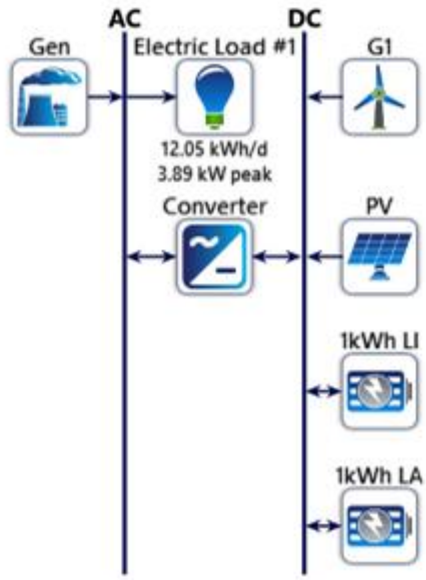


Figure 10. *HomerPro schematic. Taken from Homer Pro interface.*

Key simulation assumptions included a **25-year project lifespan**, **8% discount rate**, **6% inflation rate**, and a **0% capacity shortage target**, ensuring full demand coverage. The platform enabled quantitative comparisons between system setups under realistic financial and technical conditions.

Using the simulation results, alternatives were evaluated through a **multi-criteria decision analysis (MCDA)** framework, integrating **sustainability, economic viability, and energy efficiency**. Each parameter was weighed by project relevance, and alternatives were scored on a **1-to-3 scale** (low to high performance). The top three configurations were selected based on their overall weighted scores.

See **Table 3** for the criteria and assigned weights.

Table 3: Parameters for MCDA.

Criteria	Category	Percent weight (%)
Cost/LCOE ($/kWh)	Costs	30
System/Ren Frac (%)	Sustainability	20
System/Total Fuel (L/yr)	Sustainability	15
IRR (%)	Economic feasibility	15

CO_2 Emitted (kg/yr)	Sustainability	20

The results of the analysis, including the scores assigned to each of the 12 simulated alternatives, are shown in **Table 4.**

Table 4: Alternatives considered to be analyzed in the multi-criteria decision analysis

Alternative	Description	Mark
1	PV system, Wind turbine, generator, Li on battery, converter	2.1
2	PV system, generator, Li on battery, converter	1.95
3	PV System, Wind turbine, generator, Lead acid battery, converter	2.45
4	PV system, Wind turbine, Li on battery, converter	2.45
5	PV System, generator, Lead acid battery, converter	1.85
6	PV System, Wind turbine, Lead acid battery, converter	2.55
7	PV System, Li on battery, converter	2.4
8	PV System, Lead acid battery, converter	2.4
9	Wind turbine, generator, Li on battery, converter	1.3
10	Wind turbine, generator, Lead acid battery, converter	1.3
11	Wind turbine, Li on battery, converter	2.1
12	Wind turbine, Lead acid battery, converter	2.1

Based on the multi-criteria decision analysis presented in Table 4, **Alternative 6** achieved the highest evaluation score of **2.55**. This configuration includes a **PV system, wind turbines, and lead-acid battery with a converter**, and it was identified as the most technically and economically balanced solution. Its superior performance reflects an optimal trade-off between energy efficiency, sustainability, and cost-effectiveness under the project's defined criteria.

- **Solar and wind system:**

To size the hybrid system, the first step was the selection of a suitable wind turbine. The EN-600W-HX vertical axis wind turbine was chosen due to its compact dimensions, quiet operation, and ability to begin generating electricity at low wind speeds. This model incorporates Darrieus-type blades and offers a rated output of 600 W at 10 m/s, with a cut-in speed as low as 1.5 m/s. Its fiberglass blades and aluminum alloy chassis, combined with an aerospace-grade coating, provide mechanical durability and resistance to harsh environmental conditions. With output voltage options of 12 V, 24 V, and 48 V, this turbine is well-suited for integration in off-grid systems [12].

From **Figure 11**, a representative wind speed of 8 m/s was used for Barranquilla, which corresponds to an approximate power output of 300 W per turbine.

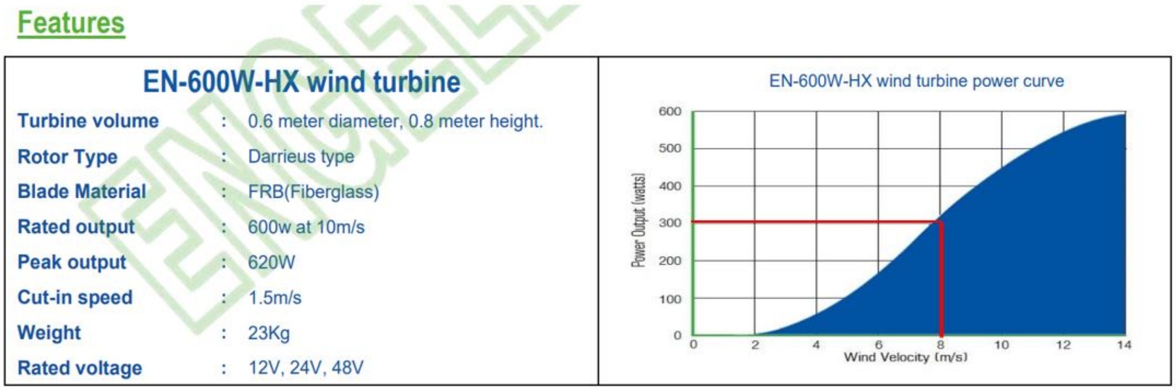


Figure 11. *Wind Speed Profile for Barranquilla Used for Turbine Sizing (8 m/s Reference)*

Based on this value and a system output voltage of 48 V, the electrical current generated by a single turbine was calculated using the basic power equation:

$$I = \frac{P}{V} = \frac{300\ W}{48\ V} = 6.25\ A$$

This current served as a reference in the preliminary design to appropriately size the electrical components and determine system configuration. Taking into account the compatibility with the charge controller and system voltage limits, it was feasible to connect three wind turbines in the setup. This configuration contributes a total of 900 W to the system's capacity.

To complement the wind contribution and fully meet the energy demand, the remaining power requirement was calculated and used to determine the number of additional solar panels needed. Polycrystalline solar panels were selected for the system. These panels are composed of multiple silicon fragments melted together, a process that improves material efficiency and reduces production waste. While their efficiency ranges between 13–17%, they are durable, cost-effective, and perform well under high temperatures and low-light conditions [13].

Each panel used in the design provides a rated power output of 320 Wp under STC conditions, with an operating voltage of 35.86 V and a current of 8.93 A. The module features an efficiency of 16.5%, a silver anodized aluminum frame, and tempered 4 mm glass, all enclosed in a structure with an IP65-rated junction box for environmental protection. The panel dimensions are 1954 × 990 × 40 mm, with a weight of 25.8 kg [14].

The total energy demand for a typical weekend day was estimated as Equation 1.

$$E_{req} = \frac{12.57\ kWh}{0.72} = 17.46\ kWh \tag{1}$$

Based on solar irradiance data for Barranquilla, the average daily solar peak hours are 5.76 h/day. Therefore, to meet the energy demand within these hours, the minimum power required from the solar subsystem is in the Equation 2.

$$p_{req.min} = \frac{E_{req}}{SPK} = 3\ kW \tag{2}$$

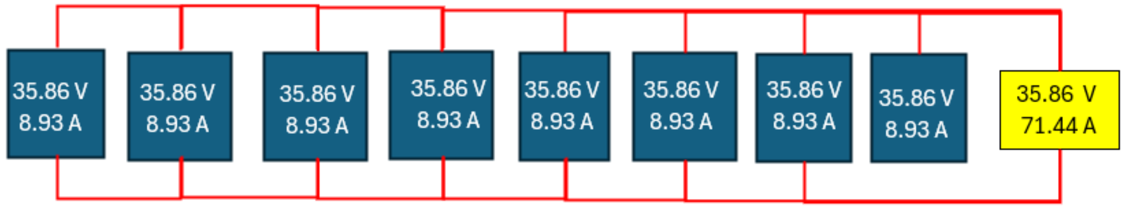
Subtracting the contribution from the wind turbines, the remaining power to be supplied by the solar panels is as shown in Equation 3.

$$N_{mod} = \frac{P_{req.min-}P_{wind\ turb.}}{P_{mod}} = \frac{3000\ W - 1200\ W}{320\ W} = 7\ modules \tag{3}$$

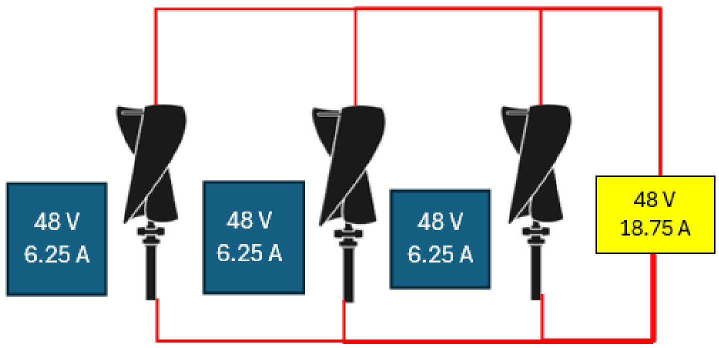
Each panel occupies approximately 1.93 m^2. Thus, the total area required to install seven panels is 13.51 m^2.

This configuration requires an estimated 20 m², which is available on-site, confirming that the hybrid solar-wind option is technically viable for the proposed application.

Figure 12 illustrates the configuration of the selected for both proposed system setups.



(a)



(b)

Figure 12. *Configuration of selected renewable technologies for each hybrid system setup. solar system. a) PV system b) Wind turbine setup*

For the configurations presented above, a charge controllers were selected. It is shown in **Figure 13**: Victron SmartSolar MPPT 150/70 Controller, was chosen for hybrid system options. This high-efficiency device is designed for 12 to 48 V battery systems and features ultra-fast MPPT tracking, which maximizes energy harvest even under partial shading conditions. Although primarily intended for photovoltaic systems, it can also be integrated into hybrid setups that include wind power, provided the wind turbine delivers a DC output with appropriate voltage regulation.

Figure 13. *Victron SmartSolar MPPT 150/70 charge controller used for hybrid solar-wind configurations [15].*

Based on the system's energy requirements, the number of batteries was estimated and a suitable configuration was designed. A 300 Ah, 12 V GEL battery from Tensite was selected due to its deep cycle capability, maintenance-free operation, and high durability in off-grid solar installations [16]. The battery is shown in **Figure 14.**

Figure 14. *Selected Battery for the System Configuration [16]*

Based on an assumed system autonomy of two days and a nominal battery system voltage of 24 V, the analysis determined that a total of 14 GEL batteries (12 V, 300 Ah each) would be required to meet the energy demand of approximately 17.46 kWh. Considering a depth of discharge (DOD) of 80% and a system efficiency of 92%, the total capacity needed was estimated at 1976.7 Ah. To achieve the required voltage and capacity, a configuration of **2 batteries in series** and **7 parallel strings** was proposed, ensuring reliable energy storage and continuity of supply during periods without solar or wind generation. The battery configuration resulting from the sizing analysis is illustrated in **Figure 15.**

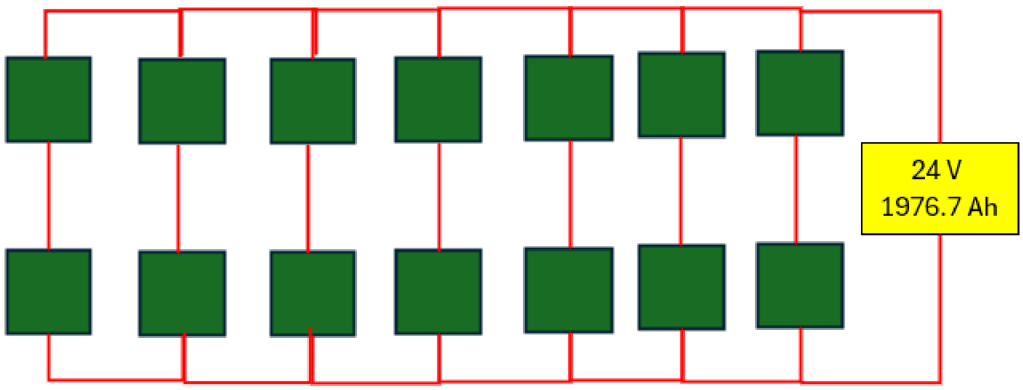


Figure 15. Proposed battery bank configuration using 12V 300Ah GEL batteries (2S–7P arrangement)

For the inverter selection, it was necessary to account for inductive loads such as pumps and the refrigerator compressor, which require higher starting power. To accommodate these demands, the system's nominal power requirement of 1.83 kW was multiplied by a factor of three, resulting in a peak power estimate of 5.49 kW. Based on this calculation, the inverter model CSI-5K-T400 was selected, offering a maximum DC power input of 6 kW. The selected inverter is shown in **Figure 16**.

Figure 16. *Selected CSI-5K-T400 Inverter with 6 kW Max DC Input Capacity*

3.1.1. Comparison with the simulation in Homer Pro

The selected system was also simulated using Homer Pro to facilitate a comparative analysis between the calculated and simulated results, thereby assessing their consistency. However, the simulation configuration in Homer Pro exhibited certain discrepancies when compared to the theoretically modeled system. Consequently, the simulated results deviated from the calculated values. Some of the most significant of these variations will be examined and discussed in detail in the subsequent sections.

1. Rated capacity of the solar panel configuration:

The simulation results from Homer Pro indicate that the optimal rated capacity for the solar panel configuration should be 2.7 kW, corresponding to approximately nine solar panels. In contrast, the theoretically calculated system employs eight solar panels with a rated capacity of 2.6 kW. Given the minimal discrepancy between the simulated and calculated values, it can be concluded that the simulation aligns closely with the theoretical model.

2. Number of wind turbines:

According to the Homer Pro simulation results, a single wind turbine is deemed sufficient to meet the energy demand. However, theoretical calculations indicate that three wind turbines are required. This discrepancy arises because the software's wind turbine catalog does not include a 300 W model, which was used in the theoretical analysis. Instead, the closest available option in Homer Pro is a 650 W turbine. Despite the difference in turbine specifications, both configurations, one 650 W turbine and three 300 W turbines, are logically capable of supplying the same electrical load.

3. Number of batteries:

The simulation results indicated that only seven lead-acid batteries would be required, whereas theoretical calculations determined a need for fourteen batteries. While both models utilized 12V lead-acid batteries, the simulation employed a 230Ah unit compared to the 300Ah battery specified in the theoretical model. Although this capacity difference contributes to the variance, it fails to fully account for the substantial discrepancy between the results.

Two key methodological differences explain this divergence. First, Homer Pro's simulation did not incorporate any days of autonomy for the battery bank, in contrast to the theoretical model, which accounted for two days of autonomy. Second, the software employs an hourly computational model, while the theoretical approach used a daily energy balance based on total consumption rather than hourly load profiles. These fundamental differences in modeling methodology significantly impact the system's configuration requirements.

4. Levelized cost of energy (LCOE):

The simulation results yielded a Levelized Cost of Energy (LCOE) of 0.0959 $USD/kWh, where as the manually calculated LCOE was approximately 0.35 $USD/kWh, a significantly higher value. It should be emphasized that the actual system implementation would likely incur greater costs than the simulated scenario, despite using identical component prices. This cost differential stems from several critical factors: the quantity of batteries, solar panels, and wind turbines directly impacts overall system costs, including maintenance, operational, and installation expenses.

Furthermore, notable discrepancies exist between the input data used in Homer Pro and the theoretical calculations. The software employs more optimistic solar irradiance values (ranging from 5.5 to 6 kWh/m²/day) compared to the conservative 4.7 kWh/m²/day [ref] used in manual calculations. Similarly, wind velocity data in Homer Pro appears inflated relative to the reference values. These data variations substantially influence system design requirements, as lower renewable resource availability necessitates greater capacity to meet energy demands. Consequently, the energy production calculations differ, directly affecting the resulting LCOE.

Despite these methodological differences, both LCOE values remain within economically viable parameters, demonstrating the project's financial feasibility. The variance between simulated and calculated results primarily reflects distinct modeling approaches rather than fundamental flaws in system design.

3.2. Water system

The water supply system is designed to extract water from a nearby river utilizing a combination of gravity-fed and pumped mechanisms, supported by comprehensive filtration and distribution infrastructure. As illustrated in **Figure 17**, the system begins with a water intake and initial filtration stage, where a coarse filter removes large debris to prevent downstream obstructions. A pumping system then transports the water through a sand filter, which further refines its physical quality, rendering it suitable for non-potable uses such as cleaning and sanitation. The filtered water is stored in a 10,000-liter ground-level tank, connected to an elevated distribution tank positioned one meter above ground to facilitate gravity-fed distribution, thereby minimizing energy consumption.

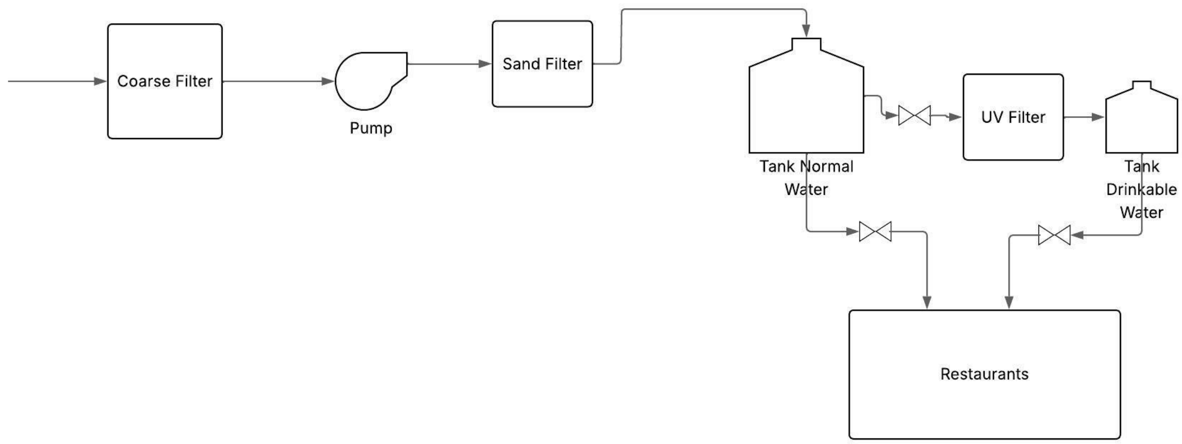


Figure 17. *Diagram of the water system.*

To ensure potable water supply, a UV purification system treats a portion of the stored water before it is transferred to a secondary elevated tank with a 3,000-liter capacity, maintaining strict separation between potable and non-potable supplies in compliance with hygiene standards. The distribution network, comprising pipes and valves, efficiently delivers both water types to individual restaurant units, ensuring flexibility and resource management. This integrated approach leverages local water sources while incorporating treatment and storage solutions to guarantee a reliable, sustainable supply with stringent quality control measures. The system's design prioritizes adaptability, energy efficiency, and compliance with safety regulations, making it a robust solution for continuous water provision.

3.2.1. Components for the pumping water system

1. Course filter

Figure 18. *Course filter. Taken from* [ref]

The coarse filter is a new, high-quality component designed for use in pumping water systems, constructed from durable stainless steel (304-grade) with a silver finish. Its stainless-steel mesh, available in various mesh counts ranging from 5 to 400, ensures effective removal of large debris while maintaining resistance to acids, alkalis, corrosion, and high temperatures. The filter exhibits high tensile strength, toughness, and wear resistance, making it suitable for long-term use in demanding environments. Its simple, maintenance-free design does not require additional surface treatment, and its versatile processing allows for diverse applications. This filter is widely used across industries, including mining, oil, chemical processing, food and beverage, pharmaceuticals, machinery manufacturing, construction, and aerospace. The product includes one stainless steel wire mesh, with minor size variations of 1–3 mm due to manual measurement. Note that color representation may vary slightly across monitors. [ref]

2. Water pump 100 W

Figure 19*. Water Pump. Taken from [ref]*

The 100 W automatic booster pump available on MercadoLibre is a compact surface-mounted pump. With a rated power of 100 watts, it operates at 115 V, making it directly compatible with the standard Colombian electrical grid. The pump delivers a nominal flow rate of 1.8 m^3/h (30 L/min) and a nominal head of 9 meters, making it suitable for applications such as supplying water to elevated tanks, garden irrigation, or low-pressure boosting in plumbing lines.

Unlike submersible pumps, this model is installed outside the water source, which simplifies maintenance and makes it ideal for indoor or accessible installations. Its durable construction and quiet performance make it a practical solution for users looking for steady and controlled water movement in domestic setups. [ref]

3. Sand filter

***Figure 20**. Sand filter. Taken from [ref]*

For our off-grid water treatment system, we selected the Panda FPD16T sand filter, a passive filtration unit designed for long-term durability and minimal maintenance. This model features a 16-inch reinforced plastic tank, rated for up to 35 GPM (132 L/min) and a maximum pressure of 50 PSI (3.4 bar), making it more than sufficient for our operating flow of 1,100 L/h (4.8 GPM). The filter is equipped with a top-mounted multiport valve, allowing for easy backwashing and media replacement. Its UV-resistant construction ensures long life in outdoor environments, and its simple design makes it ideal for remote installations where reliability and ease of use are critical. Given its robust build and compatibility with standard silica or glass media, this sand filter is expected to last 15–25 years, with media replacement required every 5–7 years for sand. With proper maintenance, this unit provides an effective and low-cost solution for primary water filtration in off-grid settings. [ref]

4. Water storage tank

***Figure 21**. Water storage tank. Taken from [ref]*

The sand filter will be integrated with a 10,000-liter potable water storage tank constructed from fiberglass reinforced polyester (PRFV), designed for outdoor installation. This durable tank features high resistance to weathering and extreme temperatures while maintaining hygienic conditions for water storage. With dimensions of 260 cm in height and 252 cm in diameter, the white matte-finished tank includes essential fittings: 1" threaded nipples for inlet, outlet, drainage, and overflow connections, along with a secure lid. The fiberglass construction provides static-free, stackable, and lightweight properties (though specific weight isn't specified), facilitating transportation and maintenance. Backed by a 36-month manufacturer's warranty against defects, this Colombian-made tank meets rigorous standards for potable water containment. The accompanying sand filter will work in conjunction with this storage system to ensure comprehensive water treatment, though its specific technical parameters would require additional details to fully describe the integrated filtration process. Note that product images are representational and may not reflect exact colors or included components. [ref]

5. Valve

***Figure 22**. Valve.*

The valve selected for the pumping water system is a 2-inch brass ball valve (Model 20002IBRL - PN25) manufactured by HYDROSFER. This shut-off valve features a durable brass body with a chrome-plated brass ball and PTFE seating, ensuring reliable performance and corrosion resistance in water distribution applications. The valve's 2-inch connection diameter and single-passage design make it suitable for controlling water flow in medium-pressure systems rated up to PN25. Its steel lever handle provides secure operation, while the brass construction offers longevity in potable water applications. As a unit-sold component, this ball valve represents a robust solution for flow regulation within the described water supply infrastructure, combining mechanical durability with standard industrial specifications for water system valves. The PTFE seating material ensures smooth operation and effective sealing during repeated use cycles.

6. UV filter

Figure 23. *UV filter. Taken from [ref]*

The UV filter incorporated into the pumping water system is the VIQUA VH200 UV disinfection unit, designed for point-of-entry water treatment. This compact system processes up to 9 gallons per minute (approximately 34 liters per minute), making it suitable for residential applications in homes with 1-3 bathrooms or light commercial use. The unit features high-output UV lamp technology that effectively eliminates microorganisms without chemicals, ensuring safe potable water. With versatile 3/4" female and 1" male pipe thread connections at both inlet and outlet, the system measures 17.75 inches in length with a 3.5-inch diameter. Operating on universal 100-240V power at 50-60Hz with 35W consumption, this UV filter provides reliable disinfection while maintaining energy efficiency. Its robust design integrates seamlessly into the water supply infrastructure, serving as a critical final treatment stage before distribution. The system meets typical residential flow demands while providing the necessary protection against waterborne pathogens in the described pumping configuration. [ref]

7. Tube pipe

***Figure 24**. Tube pipe. Taken from [ref].*

The tube pipe selected for the pumping water system is a 45.72-meter (150-foot) garden hose designed for water distribution applications. This flexible piping solution, originating from the United States, comes with a one-year product warranty and six-month general warranty, ensuring reliable performance in water transfer operations. While product images may show slight color variations from the actual item and do not include additional accessories, the hose itself provides a practical conduit for water movement within the system. Its extended length facilitates versatile routing options across the operational area. The inclusion of free shipping reduces overall procurement costs, though international customers should account for potential customs delays. As a fundamental component of the water distribution network, this hose serves to connect various elements of the pumping system while maintaining sufficient flexibility for installation and maintenance purposes. The product's classification as a standard garden hose suggests its suitability for moderate-pressure applications within the described water infrastructure. [ref]

1. Detailed Energy, Economic and Environmental Analysis

4.1 System Description

The proposed hybrid energy system consists of eight 320W solar panels and three 300W horizontal-axis wind turbines, complemented by fourteen parallel-connected lead-acid batteries maintaining a 24V system voltage. This configuration is designed to meet the power requirements of three beachfront restaurants, with all renewable energy components installed on the roof of one establishment. System protection incorporates a panel circuit breaker, while power conversion is achieved through an inverter transforming DC battery output to usable AC electricity. Notably, the design omits backup alternators based on the operational correlation between adverse weather conditions (resulting in insufficient solar/wind resources) and reduced restaurant demand during low beach visitation periods.

The electrical load distribution includes eight kitchen light bulbs and three bathroom lights per establishment, supplemented by two ceiling fans and one wall-mounted kitchen fan per restaurant (totaling six ceiling fans and three wall fans across all locations). To enhance customer appeal, each restaurant features a stereo system, decorative LED lighting (interior and exterior), one television, and two refrigerators (aggregating to six units system-wide).

The water purification system employs a dual-tank configuration (10,000L main tank and 3,000L secondary tank) sourcing water from a nearby river. A multi-stage filtration process begins with a coarse pre-filter protecting downstream components from large particulates, followed by a 100W pump delivering water through a sand filter to the main tank. Water then flows via gravity (with tanks positioned one meter above ground level) through a 35W UV purification system before reaching the secondary tank and distribution points. This design ensures both clean utility water and potable water while maintaining energy efficiency through gravitational distribution. The complete system architecture is presented in the accompanying schematic diagram.

4.*2 Economic Analysis*

4.2.1 Initial and OM cost

Firstly, the total system was divided into three subsystems for the initial cost estimation: the water system, the energy production system, and the restaurant equipment. For each subsystem, a list of components was created. Most of these components were found on the market, except for those related to the restaurant equipment. In that case, AI was used to estimate the costs, as restaurant managers often purchase such items directly from physical marketplaces, and their selection of products is hardly accessible on internet. The components for the water system are presented is Table 5.

Table 5. Cost of the components of the water system.

Component	Amount	Unit Cost [$USD]	Total [$USD]	Reference
coarse filter	1	30	30	[ref]
pump 100kW	1	67	67	[ref]
sand filter	1	202	202	[ref]
tank 10 m3	1	2200	2.200	[ref]
tank 3 m3	1	400	400	[ref]
valve	3	37	111	[ref]
UV filter	1	685	685	[ref]
Tube pipe (m)	1	1.5	149	[ref]

The total cost of the components was increased by 10% (multiplied by 1.1) to account for the necessary supports and connections between elements, resulting in an estimated total of 4,450 USD.

The installation cost was estimated based on the assumption that a Colombian technician would work two full 8-hour days. This results in an installation cost of approximately 370 USD.

For the annual operational and maintenance costs, it was considered that the sand in the filter must be replaced every five years and that a technician performs one annual inspection. Based on this, the annual operating cost is estimated at 200 USD per year.

The components for the energy production system are presented in the Table 6.

Table 6. Cost of the components of the energy system.

Component	Amount	Unit Cost [$USD]	Total [$USD]	Reference
Panel Circuit breakers	1	11.5	11.5	[ref]
manuel transfert switch	1	42	42	[ref]
charge controller	1	144	144	[ref]
Inverter	1	2100	2100	[ref]
battery	14	381	5334	[ref]
solar panel	8	89	712	[ref]
wind turbine	3	399	1197	[ref]

In order to include the wires and support costs, the cost of components has been multiplied by 1,1. Therefore, the components cost has been estimated at 9260 USD. For the installation cost it has been assumed that 2 operators will works for 3 days, and the base of the wind turbine has also been included. The cost amounts to 1460 USD. For the annual operational and maintenance cost, a battery lifetime of 10 years and one check per year by an operator have been considered. The OM cost has been estimated at 580 USD.

The components for the restaurants equipment are presented in Table 7.

Table 7. Cost of the assumed electrical devices.

Components list	Quantity	Unit cost [$USD]	Total [$USD]	Reference
Light bulb (kitchen)	9	2	18	[ref]
Light bulb (bathroom)	3	2	6	[ref]
Ceiling fan (indoor)	6	55	330	ref
Ceiling fan (kitchen)	3	60	180	ref
Wall fan (kitchen)	3	40	120	ref
Stereo system (indoor)	3	120	360	ref
LED strip light (indoor)	6	10	60	ref
LED strip light (outdoor)	6	12	72	ref
Refrigerator (kitchen)	6	450	2700	ref
TV	3	250	750	ref

The initial cost that has been estimated is 4600 USD. The total initial cost repartition has been estimated at 20140 USD and the OM cost at 781 USD/year.

4.2.2 Annual income

During weekends, the restaurants use up to 100 bags of ice per day, while the average daily consumption throughout the week is approximately 49 bags. With the integration of a refrigeration unit, it is estimated that at least 50% of the ice usage can be eliminated. This translates to an annual reduction of 8,939 bags. Given the unit price of 0.80 USD per bag, the total annual savings amount to approximately 7,151 USD/year.

In terms of food service, the restaurant currently serves around 20 meals per weekday and 70 meals during weekends, leading to a yearly total of 12,480 meals. By extending service hours past 6 PM with the use of lights -previously not feasible-, and improving the comfort of the place (fans and TV) an increase of at least 10% in meal sales is anticipated. This corresponds to an additional 1,248 meals per year. With an estimated profit margin of 1 USD per meal, the projected annual increase in revenue is 1,248 USD.

In conclusion, the total income due to the new system is estimated at 8399 USD/year.

4.2.3 Cost analysis

This analysis evaluates two scenarios for a renewable energy project combining solar panels and wind turbines. The assessment compares an Estimated Scenario (Scenario 1) with a Worst-Case Scenario (Scenario 2), where costs are 30% higher and annual income is 30% lower than in Scenario 1. The project lifetime is 20 years, with no residual value for the components at the end of this period.

The Table 8 below summarizes the initial investment, annual costs, and annual earnings for both scenarios:

- Scenario 1: Represents the estimated costs and income under normal conditions.
- Scenario 2: Reflects a 30% increase in initial and annual costs, and a 30% reduction in annual earnings, simulating a conservative outlook.

Table 8. Estimated cost for the system

Cost	Scenario 1	Scenario 2
Initial cost [$USD]	20142	26184
Annually cost [$USD]	781	1015
Earned annually [$USD]	7151	5501

The **Table 9** presents the Payback Period (PBP), Internal Rate of Return (IRR), Discount Rate (DR), and Levelized Cost of Energy (LCOE) for both scenarios. The results show that Scenario 1 recovers its initial investment in 3.16 years, while Scenario 2 takes 5.84 years. This indicates that Scenario 1 is significantly more attractive from a liquidity perspective. Scenario 1 has an IRR of 31%, well above the discount rate of 10%, suggesting high profitability. Scenario 2's IRR of 16% is still favorable but reflects the impact of higher costs and lower income. The LCOE for Scenario 1 is 0.35 USD/kWh, compared to 0.46 USD/kWh for Scenario 2. This metric confirms that Scenario 1 is more cost-effective in terms of energy production.

Table 9. Economic metrics for the system

Metric	Scenario 1	Scenario 2
PBP (years)	3.16	5.84
IRR	31%	16%
DR	10%	10%
LCOE (USD/kWh)	0.35	0.46

The LCOE was calculated using the Formula 1 and inputs:

- Initial Investment (I): 10,721.45 USD
- Discount Rate (r): 9.5%
- Annual O&M Costs: 581 USD
- Annual Energy Production (E): 4,588.05 kWh
- Project Lifetime (n): 20 years

The results, as shown in the table above, demonstrate that Scenario 1 offers a lower LCOE, making it more competitive in terms of energy cost.

$$LCOE = \frac{\sum_{i=0}^{n} \frac{It + OMt}{(1+r)^t}}{\sum_{i=0}^{n} \frac{Et}{(1+r)^t}} \tag{1}$$

Furthermore, in **Figure 25**, a cash flow of the economic assesment is presented.

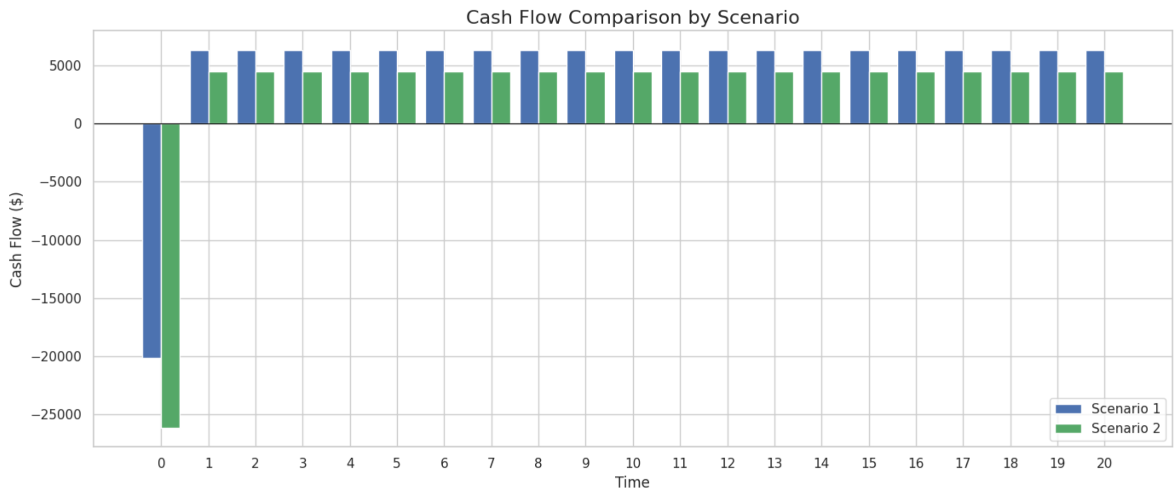


Figure 25. *Cash flow of the proposed system.*

4.3 Sustainability Analysis and Life cycle analysis

This project achieves complete elimination of Scope 2 emissions by relying exclusively on off-grid renewable energy sources. A thorough sustainability analysis requires evaluating the life cycle environmental impact of energy generation, encompassing the manufacturing, transportation, and end-of-life disposal of all major system components.

4.3.1 Renewable Generation Life Cycle Emissions

The Colombian hybrid solar and wind system life cycle emission factor is 0.677 kg CO_2 per kWh, according to the 2023 emission factor report published by UPME [ref].

The proposed system generates approximately 1,269.9 kWh annually, that means the emissions for this system are about 859.7 kg CO_2/year.

This calculation incorporates emissions associated with the manufacturing of panels and turbines, transport, installation, and ultimate disposal.

4.3.2 End-of-Life and Disposal Factors

- Solar Panels: Recycling plants for solar panels are not prevalent in Latin America, despite the fact that 80–90% of a panel's materials like aluminum and glass can be recycled. End-of-life strategies may involve sending used panels abroad to foreign facilities for recycling.

- Wind Turbines: The majority of components (steel, aluminum) are recyclable. Though, turbine blades constructed from fiberglass or composites can necessitate specialized disposal techniques.
- Lead-Acid Batteries: Up to 95% recyclable, these can be recycled locally. It is recommended to contract with haz-waste certified facilities or arrange take-back with battery vendors. [REF]

4.3.3 Sustainability Summary

Renewable system life cycle annual emissions are approximated at 3,106 kg CO_2. This figure represents all primary system components and life cycle impacts. Lacking emissions from operation and end-of-life disposal planning included, the system is still extremely sustainable relative to traditional grid or diesel-based options. Recycling and end-of-life processing of batteries and panels will further minimize the system's environmental impact in the end.

2. Recommendations

<u>Space Constraints</u>

With implementing the hybrid system, there are several challenges that may occur. The biggest concern is space, the system needs to fit within one of the four designated areas at Puerto Mocho that have been identified as suitable for installation. Out of these four spaces, the largest has an area of 329.68 m^2. The system must be able to fit comfortably within this space.

<u>Security</u>

Security is also going to be a major issue. The system will require a substantial initial investment to get set up, so it is important that everything is stored in a secure location. Items like solar panels, wind turbines, generators, and batteries all have a high resale value. One way the system’s safety can be ensured is by having proper security in place.

Since the beach was reopened in November 2024, the local government has deployed over 300 police officers to guard the area [2]. Once the system has been built, it is important that these officers are made aware of its location so they can routinely monitor the site. Additional safety measures can also be implemented. Along with the police presence, it is important to add physical security around the system such as fencing, lockable boxes to store batteries, generators, and other components [1].

Additionally motion detecting security cameras can be installed that begin recording as soon as any activity is detected. Along with these safety measures, it is important to encourage local beach vendors and lifeguards to help keep an eye on the system.

Involving officers and locals in helping protect the system will not significantly affect the project timeline. However, installing physical safety measures like fencing, lockboxes, and cameras will require extra time and additional funding to implement properly.

<u>Saltwater Corrosion</u>

Another challenge that the system will face is saltwater corrosion [4]. Saltwater corrosion can ruin the wiring and connectors, battery terminals, solar panels, and the frames used to hold them in place.

However, using some materials, like 5086 marine grade aluminum for the frame and weatherproof lock boxes, will cost more to implement. But they won’t require too much extra time to implement.

There are ways that effects of saltwater corrosion can be reduced. Using 5086 marine-grade aluminum for the frames will protect them [5]. The wires will also be coated with salt-resistant coatings. Additionally any lock boxes being used for the batteries, inverters, and other electronics must be weatherproof.

The solar panels must also be rinsed every week so any salt buildup can be removed. It is important to also try to make sure the panels and turbines aren’t directly facing the wind this will help reduce any mist from the sea hitting them [3].

<u>Heat Buildup</u>

It is also important to make sure that heat buildup does not occur within the system [6]. When solar panels overheat, their performance drops. If they are placed in spots with limited airflow and high temperatures, they can overheat.

Applying a reflective coating to the solar panels is another option to cut down on heat absorption. However, this will add more material costs and require extra labor and time. But in the long run, it'll reduce heat buildup and maximize panel efficiency.

Mounting the panels with a gap between them and the surface can help with airflow and heat dissipation. In addition, as mentioned earlier, regularly rinsing the solar panels helps reduce heat buildup by removing dust and debris. Applying a reflective coating to the solar panels is another option to cut down on heat absorption.

Water System Limitations

Another concern that had to be addressed was with the water system. Implementing a water system that harvests rainwater was not considered. This is because the structures of the restaurants at Puerto Mocho are not convenient for implementing these types of systems. Implementing an alternative system will increase time and cost.

As a result, alternative water systems had to be considered. While rainwater harvesting would have been the most convenient option, it is not feasible.

Educating Locals

The biggest challenge is educating locals on clean energy and explaining what the system actually does. It is not going to be easy to get the message across in a lot of cases, locals might prefer sticking with their current energy sources. That is why it is important to spend time with them, really educate them properly, and let them know that energy supply is limited. If they do not transition to clean energy, they could be jeopardizing their future by leaving nothing for future generations.

Locals might also be concerned about the cost of clean energy. However, being transparent about the costs and the savings can help prevent issues down the line. By taking the time to educate people about the system, it can actually become a part of the community. Once locals realize they rely on it for power, especially to run their businesses, they will make sure to take proper care of it, because it is something that’s helping run their business.

Educating locals will require additional time. An extra day may need to spend in Puerto Mocho explaining how the system runs and what it is doing. Nevertheless, long term, having locals involved is very important because they are the ones who will be relying on this system day to day.

<u>Profitability Limitation</u>

Another important challenge to consider is the lack of financial return, since implementing the system also adds an additional annual operating cost. There is no monthly savings cost to help cover your upfront cost for installing the system. So as a result, the money spent on setting up this hybrid system will not pay for itself through energy gains. Instead, the system's benefits are not financial. Implementing this system will help improve quality of life and provide a more reliable power source. As a result, this makes the decision to implement this hybrid system a harder one for restaurant owners to agree to.

This issue will not affect installation or setup time, but it can slow down the project's start time because it will be more difficult to get people to agree to implement a system that will not save them any money on a monthly basis.

To overcome the financial challenges that come with implementing a hybrid system, the focus should be on the benefits the system will have on the community, and how implementing a hybrid system will help us shift toward more reliable and sustainable energy sources.

Conclusions

The project comprises three distinct systems. Firstly, the water system includes a pump, a sand filter, a UV filter, and two separate tanks. This system requires an initial equipment cost of $4,288 along with an additional $370 for installation. Components such as the filters will need periodic replacement, increasing the annual operating cost by approximately $200.

Secondly, the energy system consists of lead-acid batteries, solar panels, and wind turbines. The total equipment cost for these components amounts to $6,734 with an additional $1,460 required for installation. Similar to the water system, certain components in this system will also require replacement over time. Ongoing operation contributes an additional annual operating cost of $700.

In addition to the core systems, modifications will be implemented within the restaurants to maximize the benefits of the new reliable power source. These modifications include the installation of additional light bulbs, ceiling fans, a stereo system, several televisions, and six refrigerators.

The total initial cost of the system is estimated at $17,388 with an additional annual operating cost of $900.

However, the implementation of this system presents several cost-saving opportunities for restaurant owners. On average, a restaurant owner uses 49 bags of ice per day, each costing $0.80. By implementing the proposed system and relying on fridges instead of ice, it was estimated that they can reduce their ice consumption by nearly 50%. This will help them save nearly $7,151 per year.

Furthermore, restaurant owners currently cease operations after 6 PM due to insufficient lighting. The introduction of light bulbs will eliminate this constraint, allowing restaurants to extend their operating hours. It is estimated that restaurants will be able to serve 10% more meals as a result of improved lighting.

Currently, restaurants serve an average of 20 meals per day on weekdays and 70 meals per day on weekends, totaling approximately 12,480 meals annually. A 10% increase in meals served would result in an additional 1,248 meals per year. Assuming an average profit of $1 per meal, this would generate an additional $1,248 in annual revenue for restaurant owners.

While the system entails a significant upfront cost and increases annual operating expenses by $900, it also has the potential to generate an additional $9,399 in annual revenue for restaurant owners. Within slightly over two years, the initial investment can be recovered, leaving restaurant owners with a net annual profit of $7,499 ($8,399 in additional revenue minus the $900 operating cost).

When evaluating this system, investors should consider not only the initial expenditure but also the long-term financial benefits, including cost savings and revenue growth. The project demonstrates clear sustainability and offers substantial value to potential investors. Beyond providing clean energy to restaurants, the initiative also serves an educational purpose by raising awareness in Colombia about sustainable energy alternatives and their practical applications. Additionally, it enhances tourism by improving the reliability and quality of services offered by local restaurants.

By replacing traditional ice boxes with refrigerators, food can be preserved more effectively, improving both freshness and kitchen sanitation. Moreover, the introduction of lighting enables restaurants to accommodate more tourists by extending their operating hours.

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