# Hybrid Power Generation System: A Case Study on the Colombian North Coast

# Sistema Híbrido de Generación de Energía Eléctrica: Un Caso de Estudio en la Costa Norte Colombiana

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**Margarita Gamarra Acosta**
Universidad de la Costa. Barranquilla (Colombia)
mgamarra3@cuc.edu.co

**Randy Granados**
Universidad del Norte. Barranquilla (Colombia)
randygranados@hotmail.com

**Juan Manuel Ariza**
Universidad del Norte. Barranquilla (Colombia)
ingjuanmanuelariza@hotmail.com

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**Resumen**

**Introducción—** El uso de fuentes de energía alternativas ha sido tema de gran interés a nivel mundial, tanto por beneficios ambientales como económicos. A pesar de ser un tema relativamente reciente, se han realizados varias investigaciones y proyectos al respecto. Se consideran híbridas las instalaciones que incorporan diferentes fuentes generadoras de electricidad. La finalidad es obtener el máximo aprovechamiento de los recursos energéticos para reducir la dependencia de las condiciones atmosféricas.

**Objetivo—** El objetivo de esta investigación es desarrollar un modelo de operación de una generación hibrida con componentes solar-eólico, con la finalidad de aprovechar al máximo estas fuentes de generación de energía.

**Metodología—** Se definió una topología para la conexión de los dispositivos. Para la realización de pruebas se han tomado dos prototipos, uno de generación eólica y otro de generación solar. Se realizaron mediciones del sistema híbrido y se comparó su rendimiento con los dos sistemas independientes.

**Resultados—** Se han realizado pruebas en laboratorio para verificar el correcto funcionamiento de los equipos utilizados (regulador, inversor y baterías) y pruebas en campo para tomar mediciones reales de generación de potencia del sistema híbrido. El sistema híbrido propuesto presentó un mayor desempeño frente a los otros dos sistemas independientes.

**Conclusiones—** En este estudio podemos concluir que el sistema híbrido cuenta con la ventaja de tener mayor independencia de las condiciones ambientales para la generación de energía. Teniendo en cuenta los resultados obtenidos en las pruebas de campo, la implementación de sistemas híbridos es adecuada en la costa atlántica.

**Palabras clave—** Sistema híbrido de generación; aerogenerador; panel solar; potencia eléctrica; energía alternativa

**Abstract**

**Introduction—** The use of alternative energy sources has been a topic of great interest worldwide, both for environmental and economic benefits. Despite being a relatively recent topic, several investigations and projects have been carried out about it. Installations that incorporate different sources of electricity are considered hybrids. The purpose is to obtain the maximum use of energy resources to reduce dependence on atmospheric conditions.

**Objective—** The objective of this research is to develop an operating model for a hybrid generation with solar-wind components, In order to take full advantages of these energy generation sources.

**Methodology—** A topology was defined for the connection of the devices. For testing, two prototypes have been taken, one for wind generation and the other for solar generation. Hybrid system measurements were made, and its performance was compared with the two independent systems.

**Results—** Laboratory tests have been carried out to verify the correct operation of the equipment used (regulator, inverter, and batteries) and field tests to take real measurements of the power generation of the hybrid system. The proposed hybrid system presented a higher performance compared to the other two independent systems.

**Conclusions—** In this study, we can conclude that the hybrid system has the advantage of having greater independence from environmental conditions for power generation. Considering the results obtained in the field tests, the implementation of hybrid systems is adequate on the Atlantic coast.

**Keywords—** Hybrid generation system; wind turbine; solar panel; electric power; alternative energy

## I. Introduction

The use of renewable energies, such as solar and wind energy, is not a new topic. Since ancient times these resources have been used for the benefit of man. Due to the limitation of the raw material used in the generation of energy and the negative environmental impact that these cause, the use of renewable energy in the generation of electricity has had great growth in recent years.

Territories located in coastal areas have a great advantage to implement generation systems with renewable energy sources: there is greater solar radiation during the year and coastal breezes are predominant.

In this way, we propose to develop a hybrid generation model that takes advantage of both solar energy and wind energy resources, considering the environmental conditions present on the Atlantic coast of Colombia. The implementation of the hybrid generation model allows feeding of small loads, with the wind and solar radiation conditions characteristic of this zone. The model was validated with data obtained from field measurements and simulated in software Matlab®, to verify the behavior of the model.

This document exposes the characterization of the model, the tests carried out, and the main results. The purpose of the project is to build a model of a hybrid generation system, to take advantage of renewable resources. For testing, two prototypes have been taken, one for wind generation and the other for solar generation.

## II. Related Works

The use of alternative energy sources has been a topic of great interest worldwide, both for environmental and economic benefits. Despite being a relatively recent topic, several investigations and projects have been carried out in this regard.

Installations that incorporate different sources of electricity are considered hybrids. The purpose is to obtain the maximum use of energy resources to reduce dependence on atmospheric conditions [1]. Regarding applied projects, those that have been implemented have had good results in terms of generated power and social development, as they are installed in remote areas. The main results of research and projects related to hybrid solar-wind generation systems are presented below.

The research developed in 2010 [2] presents an analysis and design of a hybrid solar-wind system for microgeneration for domestic purposes in rural areas of a country where the supply of energy has great problems and in some cases, it is not feasible to install distribution networks. The proposed hybrid system presents an alternative of generation without connection to the electricity grid and another with the connection. As in other research [3], [4], the design of the hybrid system is based on the load it must supply.

Authors in 2009 [5] studied the design of the structure and control system of a 3Kw solar-wind hybrid power system for a 3G base station. The proposed model was applied in Matlab-Simulink to simulate different conditions. The simulations and experimental results show that the architecture for the proposed system and the control strategy is effective.

The thesis developed in 2004 [6] integrates, in addition to the hybrid system, the power generation of small hydroelectric plants and presents a guide for pre-feasibility studies in the construction of the three electric power generation systems. This study expresses that the impact of the use of alternative or green energy sources is positive for environment an community.

The proposal of the study developed in 2005 [7] consists of developing a controller for Hybrid Power Generation Systems incorporating some advanced control techniques. Authors develop a control for an installed solar-wind-diesel hybrid system. The authors propose the models of each part of the system, considering previous research and empirical tests. The results show that fuzzy control is achieving the three operating objectives of the system: decrease fuel consumption of the backup system, reduce the depth of battery bank cycling and keep the battery bank as charged as possible.

Another approach of the solar-wind system was exposed in 2019 [8]. The proposal included forecasting strategies for load-related parameters and was tested on real data. The results demonstrated that, of the small independent hybrid power schemes considered, the hybrid photovoltaic-battery scheme is the most cost effective and reliable for meeting loads for the case study investigated.

In this study, we developed a hybrid generation model to support the system implementation in the feeding of small loads, with the wind and solar radiation conditions typical of the Atlantic coast of Colombia. The model will be validated with data obtained from field measurements and entered in the Matlab® simulation software, to verify the behavior of the model.

## III. Proposed Approach

A Hybrid Power Generation System (HPGS) is made up of different renewable energy technologies (solar, wind, biomass, microhydraulic, etc.) to meet energy requirements, like the conventional grid, at a competitive cost [9], [10].

HPGSs can be classified according to how generation systems are interconnected:

- Serial topology.
- Parallel topology:
  - Parallel topology with DC coupling
  - Parallel topology with AC coupling

*Serial topology* [7]: In this configuration, the renewable energy sources are connected in series to the DC bus. The power delivered to the battery can be controlled by incorporating a charge regulator in the power sources. The design is relatively simple to implement, but this system has the following disadvantage: low efficiency of the whole system due to the series configuration of the elements; a certain amount of energy is lost due to the low efficiency of the battery and the inverter.

*Parallel topology with AC coupling* [7]: This topology requires a dynamic control that takes into account the control of the voltage and frequency of the network, its stability, and its protection. In addition, each renewable generation source requires an inverter to match its voltage and frequency. This inverter must guarantee proper timing (Fig. 1).

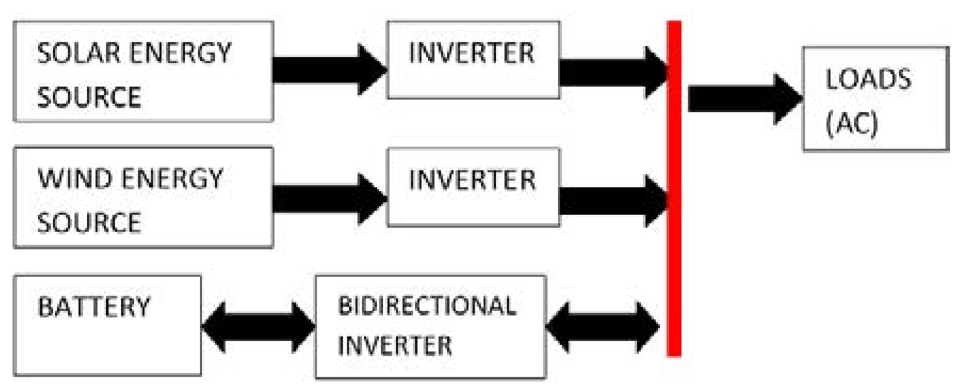


Fig. 1. Parallel topology with AC coupling.
**Source:** [7].

*Parallel topology with DC coupling* [7]: The system shown in Fig. 2 has the following advantages:

- The system load can be optimally powered.
- With this configuration it is possible to reduce the capacities of the battery and the renewable sources guaranteeing the supply of the peak demand of the system.
- It is possible to guarantee a continuous supply of energy less dependent on environmental and climatic conditions.

This topology has been chosen to develop the proposed hybrid generation system model, due to the advantages mentioned above and the ease of connections, compared to the two previous topologies. Considering this selected topology, a description of the model block diagram, the model parameters, and the input and output variables are considered below.

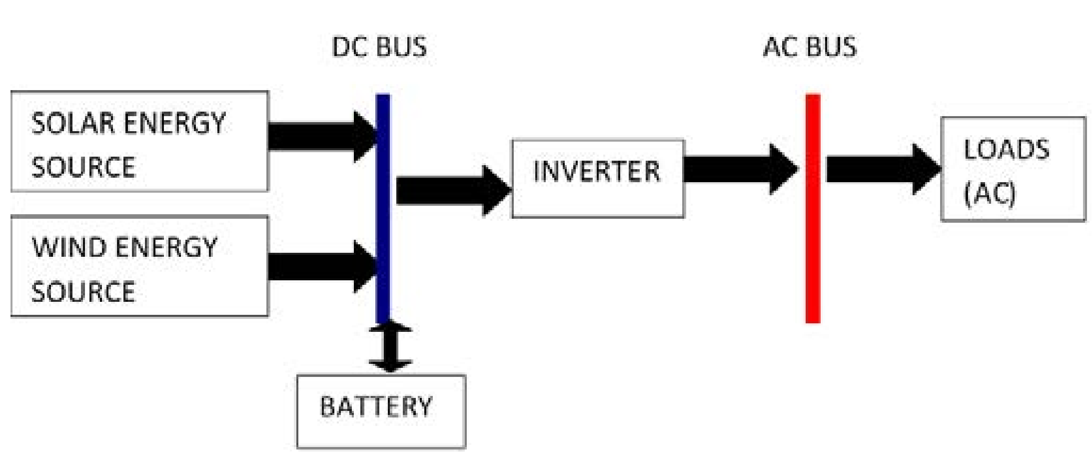


Fig. 2. Parallel topology with DC coupling.
**Source:** [7].

A. *Diagram of the model*

Considering that the hybrid system depends on two environmental conditions (wind speed and solar radiation) to be able to generate electrical energy, the proposed model can be summarized in the following scheme, showing the input and output variables and the parameters of the model (Fig. 3):

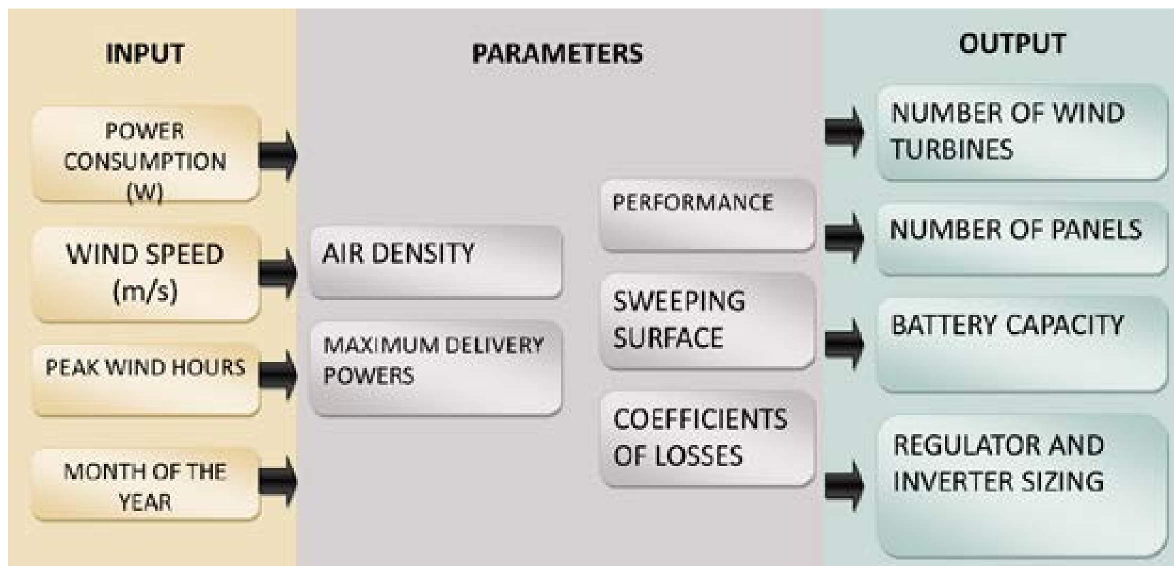


Fig. 3. Scheme of the hybrid generation system model.
**Source:** Authors.

The inputs of the model correspond to the consumption of electrical energy which must supply the hybrid system. This input data is essential to calculate the number of panels and wind turbines to be installed and the sizing of the electrical equipment of the system.

Considering that the power delivered by the generator depends on the wind speed to which it is subjected, then this value must be another input of the model. Similarly, the power generated by the panels depends on solar radiation.

As this value is related to the months of the year, then one of the months of the year has been taken as input, representative data of solar radiation, applied to the Atlantic coast. This information has been taken from the solar radiation maps of Colombia, month by month.

The parameters used in the model and how to relate them to the input variables to obtain the appropriate output values for the assembly of the hybrid system will be explained in detail below.

B. *Parameters of the model*

One of the inputs of the proposed model must be the energy consumption for the hybrid system, which corresponds to the real energy consumption. However, the Real Energy consumption $E_R$ includes some loss factors that are generated during the operation of the system (heating, accumulator, and inverter), and makes it different from the Theoretical Energy consumption $E_T$.

The actual energy consumption is determined from the expression (1):

$$E_R = \frac{E_T}{R} \quad (1)$$

Where $R$ is the overall performance parameter of the hybrid system, defined by the expression (2):

$$R = (1 - K_b - K_c - K_v)\left(1 - \frac{K_a N}{P_d}\right) \quad (2)$$

Where:

$K_b$: Coefficient of losses due to the accumulator's performance (battery).
$K_c$: Coefficient of losses in the investor.
$K_v$: Coefficient of miscellaneous losses.
$K_a$: Daily self-discharge coefficient.
$N$: Number of days of battery autonomy.
$P_d$: Depth of daily battery discharge.

To obtain the performance R, parameters with the following values are considered:

$$K_b = 0.1; K_c = 0.05; K_v = 0.1; K_a = 0.005; N = 1; P_d = 0.8.$$

The value of the daily self-discharge constant Ka considered is 0.02 because the batteries implemented in the system are Ni - Cd (Nickel - Cadmium).

The value of $R$ is considered an internal parameter of the model and the values selected for each of the constants involved were taken according to the physical characteristics of the test equipment (inverter and batteries). For this case study, according to the defined constants, the overall performance of the system is 0.748.

### C. *Dataset and test design*

Initially, laboratory tests were carried out on the system components: regulator, batteries, and inverter. In the development of the field tests, three different measurements were made: one for the independent solar system, another for the independent wind system, and another for the hybrid system. In addition, two test scenarios were taken: the campus of the Universidad del Norte and the surroundings of Castillo de Salgar (Puerto Colombia, Atlántico).

## IV. Results

### A. *Wind System*

In the test carried out at Castillo de Salgar, current and voltage data were taken at the wind turbine terminals. Fig. 4 shows a graph of the power measured at the wind turbine terminals, versus the wind speed.

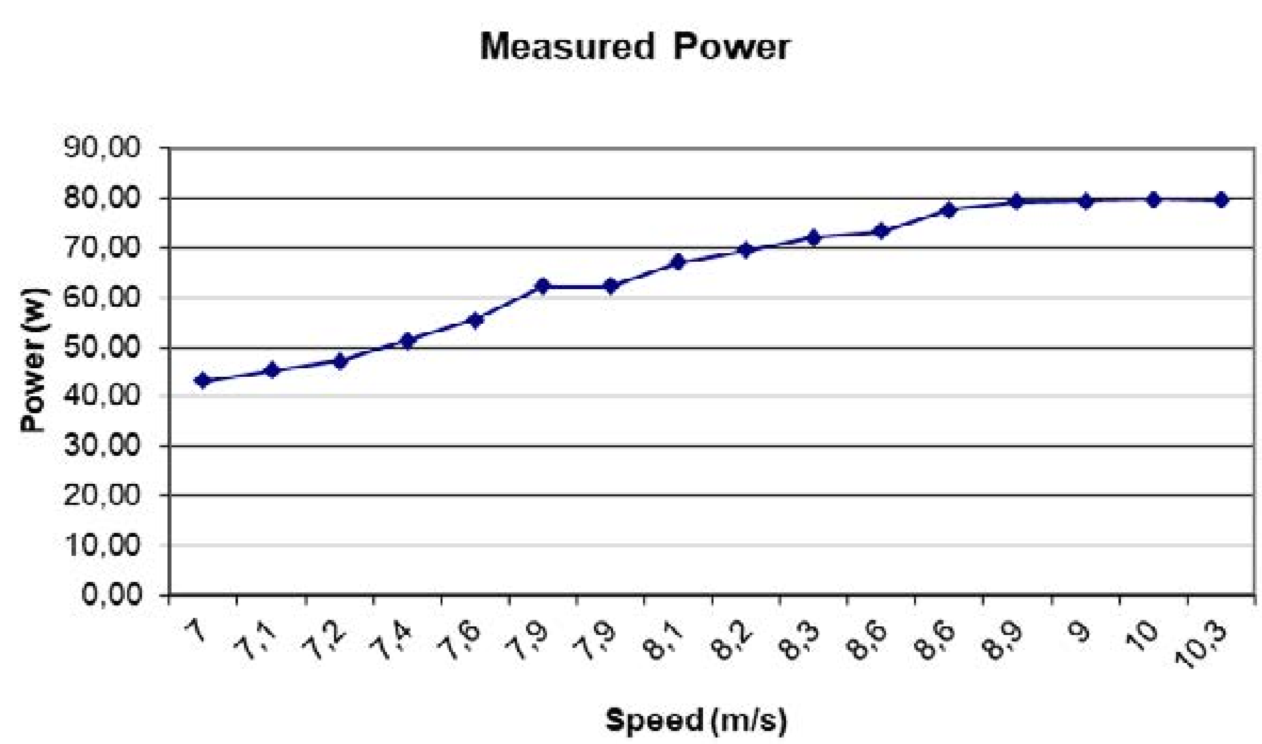


Fig. 4. Measured power vs wind speed.
**Source:** Authors.

A comparison between the calculated power and the measured power shows that the relationship between them is an almost constant value of 0.165. This constant corresponds to the wind turbine loss coefficient.

### B. *Photovoltaic system*

In this test we worked on the electric power generation process only with the photovoltaic system, using a single panel. The test with this independent system was carried out at the campus of the university since there was space available (without shadows) for the measurements.

According to the graph shown in Fig. 5, the power generated by a single solar panel ranges between 20 w and 35 w. The depressions in the graph are due to passing clouds that occurred on the days of the measurements.

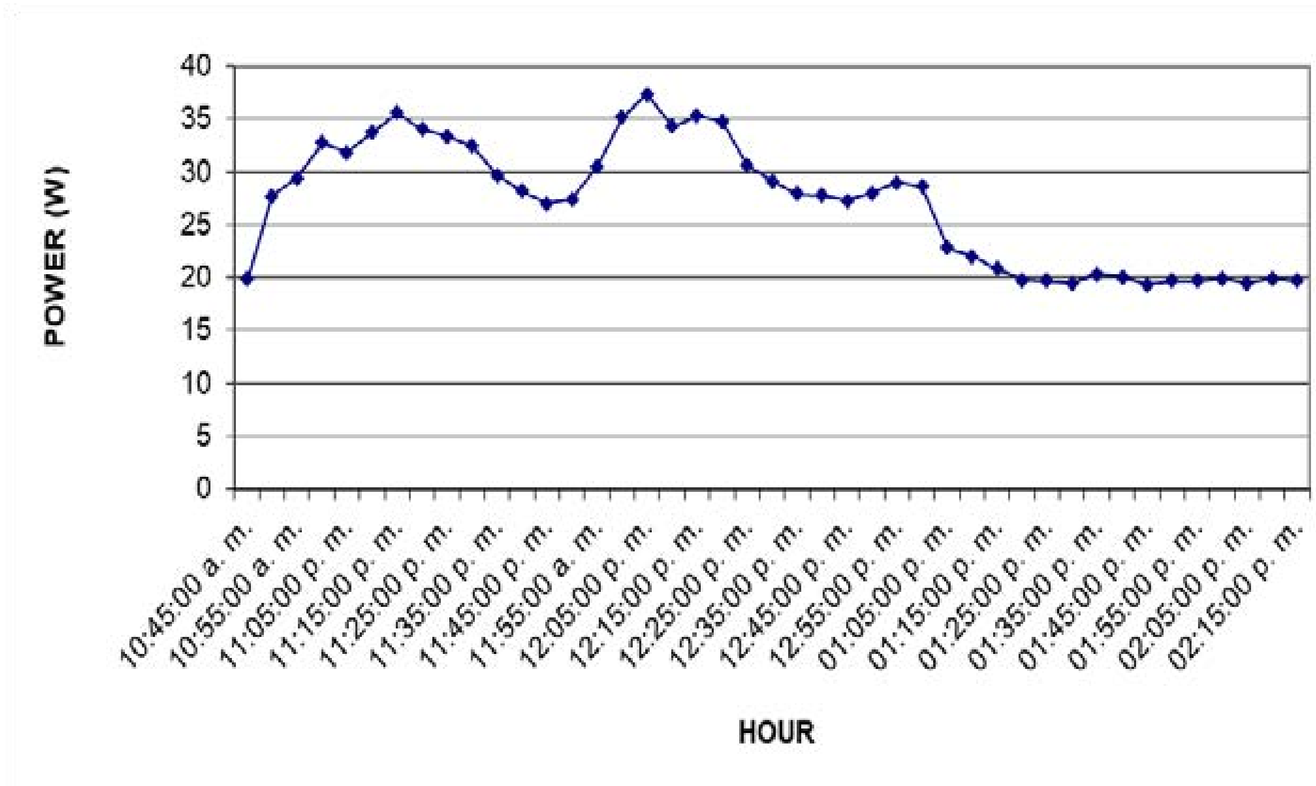


Fig. 5. Power measured in peak sun hours.
**Source:** Authors.

C. *Hybrid system*

For this test, we made the connections between the two independent systems: photovoltaic and wind. A single panel was used for the photovoltaic system, the same as for the test with the independent system. Two regulators, two batteries connected in parallel, and an inverter were used.

The results obtained in this test are shown in Fig. 6, the power delivered by the wind turbine, and Fig. 7, the power delivered by the solar panel.

According to the graph presented in Fig. 6, the average speed remained around 8 m/s, during the hours of the test. During this time, the power delivered by the wind turbine was between 45 w and 80 w.

Analyzing the results presented in Fig. 7, the photovoltaic system had a higher power delivery for the first hours of measurement (between 2:00 pm and 3:00 pm). In the afternoon hours, its power decreased around 20 w.

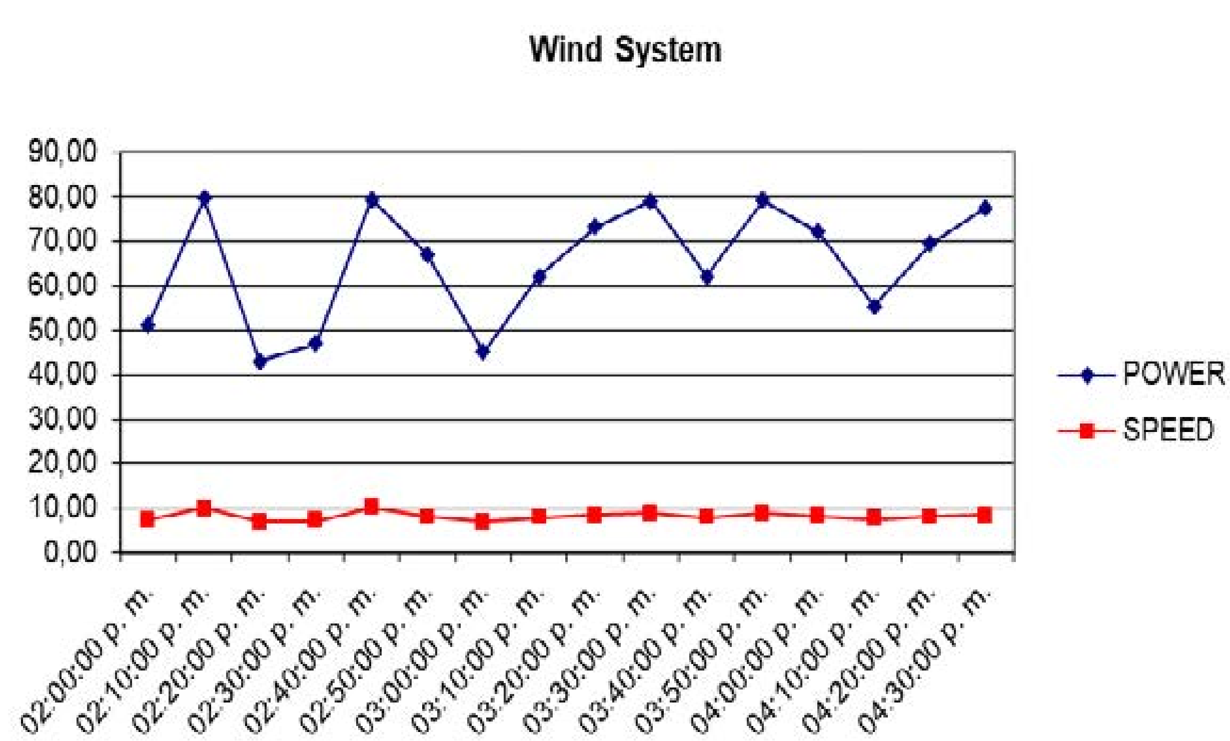


Fig. 6. Power generated by the wind turbine within the hybrid system and wind speed.
**Source:** Authors.

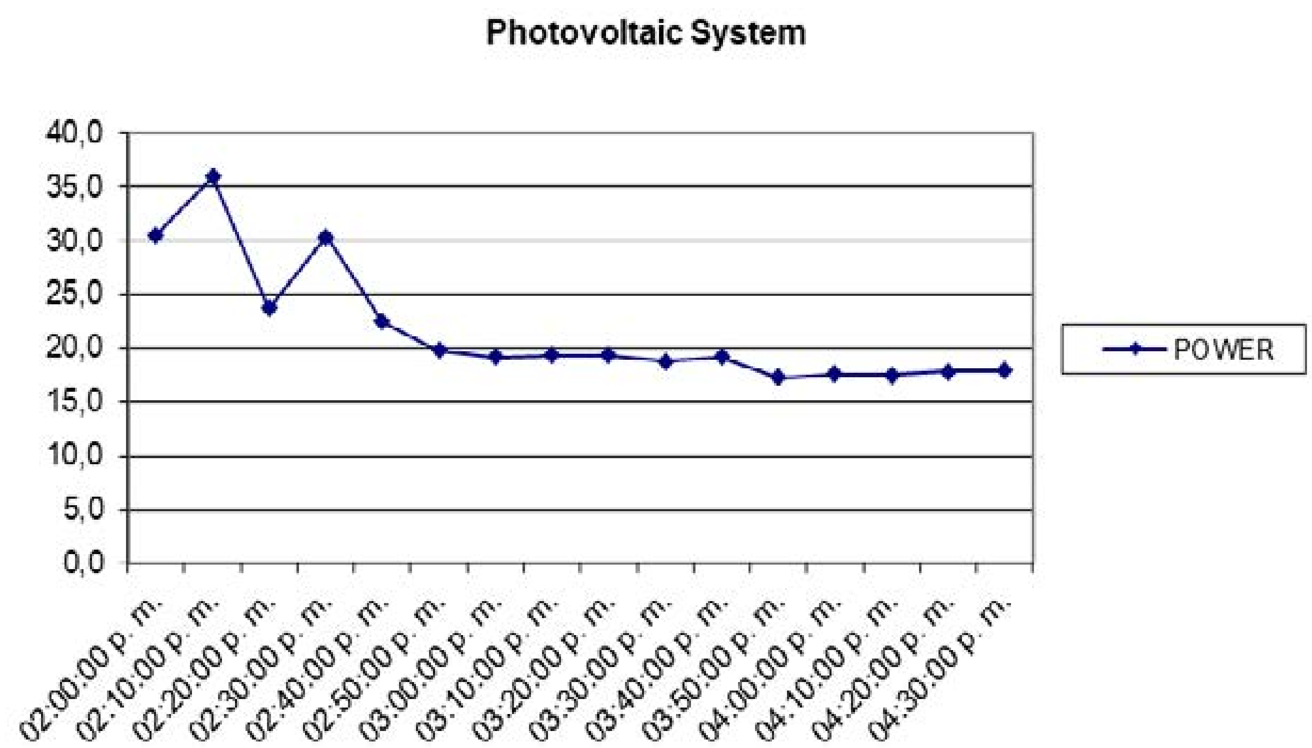


Fig. 7. Power generated by the solar panel within the hybrid system.
**Source:** Authors.

Table 1 exposes a comparison of the results obtained for the three systems analyzed (wind, photovoltaic and hybrid). This Table shows the advantage of the hybrid system regard to the performance of the generation and the independence of the environmental factors. Additionally, in the hybrid system, the time to charge the batteries is lower than the other two systems. A drawback is associated with the cost of the installation, as this hybrid system includes the cost of both the solar and the wind system.

Table 1.
Comparison of the three systems.

| | Wind System | Photovoltaic System | Hybrid |
|---|---|---|---|
| Dependence of the environmental factors. | Wind | Solar light | Major Independence |
| Peak hours of generation by day. | 15h | 5h | 20h |
| Availability of the generation system. | 15h+ battery discharge time | 5h+ battery discharge time | 20h+ battery discharge time |
| Time to charge the batteries. | Regular | Regular | Less time |
| The relative cost of the installation. | High-middle | Middle | High |

**Source:** Authors.

As a test run, two types of loads were connected to the hybrid system: resistive load and inductive load. The current required to keep the test motor running is not sufficient for this prototype. Then, the resistive load test was carried out in the field and the laboratory, and the inductive load test was only carried out in the laboratory.

Considering the proposed connections and the tests carried out, the following recommendations should be taken in a solar-wind power generation system:

- Before installing the equipment, a study of the area and the load to be supplied must be carried out and the data entered in the interface to size the system.
- The wind turbine must be installed at a minimum height of 3m above obstacles for maximum use of the wind.
- The mast for the wind turbine must have a support structure or place several retainers for greater stability.
- The solar panel must be placed with an inclination of approximately 30° directed towards the sunrise, for the maximum use of solar energy.

## Conclusions

During the development of the model of the hybrid generation system, we performed several tests in the lab and in the field, which allowed us to validate the proposed model, taking equations that related physical variables (such as wind speed and radiation) with the power that the hybrid system can deliver.

From the analysis of the tests and a review of the state of the art, we can state that the differences in the results between the theoretical and measured power values are due to the losses that exist in the equipment used.

Due to the geographical position, the implementation of hybrid systems is adequate on the Atlantic coast of Colombia. Additionally, the hybrid system has the advantage of having greater independence from environmental conditions for power generation.

Electronic equipment, such as a regulator and inverter, allow to have the desired output signal and maintain adequate voltage values for the loads and batteries. The accumulation equipment allows the availability of energy when the system is inactive.

For the installation of a hybrid generation system, a preliminary study of the area must be carried out, to locate the structure so that there is greater capture of wind and solar energy. The initial investment in a project with renewable energies is high, but the return on investment is seen in the long term.

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**Margarita Gamarra** received the M.Sc. degree in Electronic Engineering and the Ph.D. degree in System Engineering from the Universidad del Norte (Colombia). She was with Universidad del Norte, Universidad Autónoma del Caribe (Colombia) and Politécnico de la Costa Atlántica (Colombia). Since 2020, he has been with Universidad de la Costa (Colombia), where she is currently full-time professor and researcher. Her research interest is in digital image processing, machine learning and pattern recognition. https://orcid.org/0000-0003-1834-2984

**Randy Granados** received the degree in electric engineering from the Universidad del Norte (Colombia). Received a post-graduate degree in Efficient energy management at the Universidad del Atlántico (Colombia) and Engineering project management at the Universidad del Norte (Colombia). He currently is the project manager at the company Ingeniería Eléctrica Equipos y Servicios Sas (INGELEM).

**Juan Manuel Ariza** has a degree in electrical engineering and a postgraduate degree in engineering project management from Universidad del Norte (Colombia). Has experience in project formulation. At present works as a consultant in the state planning office with the Governor's Office of Cesar (Colombia).