v. 5, n. 7, 2025

Journal of
Engineering
Research

OPTIMAL DESIGN OF AN ISOLATED HYBRID SYSTEM. A CONTRIBUTION TO SAN FRANCISCO DEL MAR PUEBLO VIEJO, OAXACA

Acceptance date: 04/08/2025

Minerva Elizabeth Hernández Santiago
Veracruz Institute of Technology

Miguel Ángel Quiroz García
Veracruz Institute of Technology

Olaya Pirene Castellanos Onorio
Veracruz Institute of Technology

Jorge Arturo Mendoza Sosa
Veracruz Institute of Technology

Francisco Javier Gómez González
Veracruz Institute of Technology

Oscar Omar Montalvo Pérez
Veracruz Institute of Technology

Abstract: This research presents the optimal design of an isolated hybrid renewable energy system applied to a rural community in the state of Oaxaca, Mexico. The study includes an analysis of the climatic conditions and consumption profile of the selected community, which allows the architecture of the hybrid system to be defined.

This study models a hybrid wind-solar system isolated from the electrical grid to meet the electricity needs of a rural community, promoting the use of renewable energy as a clean source in accordance with environmental preservation.

Through optimization with HOMER Pro software, a design is obtained that balances energy generation, economic efficiency, and long-term technical viability. The results demonstrate that the hybrid system is a viable alternative for improving the quality of life of the inhabitants, reducing costs, and minimizing environmental impact.

Thanks to this type of study, possibilities are being explored for supplying energy to communities that are difficult to access, thereby improving the quality of life and educational level of their inhabitants, providing energy security through systems such as the one proposed, guaranteeing universal access to affordable, reliable, and modern energy services, and facilitating access to research and non-polluting energy technologies.

INTRODUCTION

Over the years, energy demand has grown, but the amount of energy produced to meet this basic need has not increased. This is due to various causes, such as the high dispersion of the population due to the large distances between communities, the lack of infrastructure due to difficult access to land, and the rising costs of this infrastructure. Forbes magazine stated that, according to official data, electricity consumption in Mexico reached record levels this year, sometimes exceeding the generation and transmission capacity of its public service infrastructure (Reuters, 2024). In addition to this, the country has also paid the price for outdated and inadequate infrastructure. (Nava, 2021) More than 1 million people in Mexico, a country rich in resources but lacking in energy, live without electricity and without large-scale initiatives to solve this problem. Addressing this issue in figures becomes controversial, as to date there are no precise numbers on how many communities are without electricity, since only 1% of households in the country face this problem, according to the 2020 sociodemographic profile carried out by the National Institute of Statistics and Geography (INEGI, 2020). In figures, this represents a challenge of more than 352,000 households, or almost 1.2 million people, considering that, according to INEGI, an average of 3.6 people live in a household without electricity. Meanwhile, the Ministry of Energy (SENER), in its Sectoral Program (SENER, New National Electricity System Scheme, 2022), indicates a higher figure, with at least 2 million Mexicans without access to electricity in 2018. These figures are at odds with the Federal Electricity Commission, which in its 2020 business plan (CFE, 2020) states that 32,000 cities across the country were waiting to be electrified that year.

BACKGROUND

Mexico is committed to limiting electricity generation from fossil fuels to 65%—down from the current 80%—by 2024. Wind energy plays a fundamental role in achieving this goal, as in most countries with similar targets, this technology has been responsible for around two-thirds of the total target (Mexican Wind Energy Association). Oaxaca is a region with high renewable energy potential, mainly wind, according to the Wind Resource Atlas, which estimates that the state has good to ex-

Journal of Engineering Research ISSN 2764-1317 DOI https://doi.org/10.22533/at.ed.317572517076

cellent wind resources in approximately 6,600 km2 of land, with wind power classes ranging from 4 to 7, where 7 is the highest value. Windy terrain accounts for just over 7% of the state's total area. For this reason, this study focuses on some rural communities in the state of Oaxaca that face the main electrical infrastructure challenges mentioned above, coupled with the long distances between them and their difficult access.

RESEARCH QUESTION

Will the design of a hybrid wind-photovoltaic system, isolated from the electrical grid, be an optimal solution to meet the electrical energy needs of the municipal agency of San Francisco del Mar Pueblo Viejo, Oaxaca?

HYPOTHESIS

The implementation of a wind-photovoltaic system isolated from the electricity grid will provide a sustainable, cost-effective, and efficient energy solution to meet the community's electricity needs, while reducing dependence on fossil fuel sources and having a direct impact on the quality of life of the inhabitants, facilitating access to basic services such as drainage, improving health and education, and even stimulating the economic development of the locality.

RESEARCH OBJECTIVES

GENERAL OBJECTIVE

To design a hybrid wind-photovoltaic system, isolated from the electricity grid, to meet the electricity needs of the municipal agency of San Francisco del Mar Pueblo Viejo, Oaxaca.

SPECIFIC OBJECTIVES

- Compile the renewable resource and demand profile of the community under study.
- Propose the architecture of a renewable hybrid system that meets the community's electricity needs.
- Optimize the renewable hybrid system using specialized Homer Pro software.

JUSTIFICATION AND SCOPE OF THE RESEARCH

Oaxaca stands out for its remarkable potential for renewable energy generation, mainly wind power. It is important to note that this technology has a low impact on land use, as the base of a 1 MW wind turbine requires only 8 x 8 square meters of space, allowing agricultural activities to be carried out in the surrounding areas without major complications. A wind turbine of this capacity can generate enough electricity to meet the energy needs of approximately 850 households with characteristics similar to those in the country. In addition, modern wind turbines have the advantage of a modular design, which facilitates quick and efficient installation. For example, building a 100 MW power plant can take less than a year, a key benefit for economies that need to increase their energy capacity quickly.

Mexico also has exceptional solar radiation conditions, positioning solar energy as the best alternative even for the most isolated communities. It is worth noting that 85% of the national territory is suitable for photovoltaic projects, making Mexico a strong candidate for seventh place worldwide in solar energy generation. In this context, hybrid systems are emerging as an effective and accessible solution, reducing fossil fuel consumption in traditional generation systems while increasing sustainable access to electricity in rural and remote communities.

The hybrid off-grid system will be implemented in San Francisco del Mar Pueblo Viejo, also known simply as San Francisco Viejo, a town in the state of Oaxaca, located on the Isthmus of Tehuantepec and in the municipality of San Francisco del Mar, as can be seen in Figure 1.

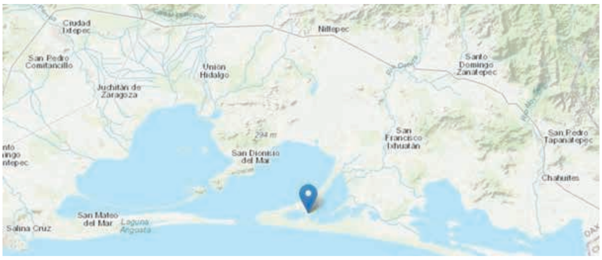

Figure 1. Relief map of San Francisco Viejo, Oaxaca (taken from Google Maps, 2023).

San Francisco del Mar Pueblo Viejo is located at an altitude of 32 meters above sea level, on the Barra de San Francisco, which divides the Laguna Inferior and the

Mar Muerto del Golfo de Tehuantepec, and in particular on the banks of the estuary known as Laguna El Carrizal (see Figure 2).

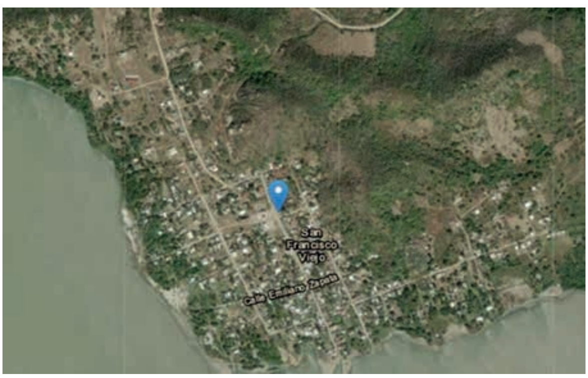

Figure 2. Land map of San Francisco Viejo, Oaxaca (taken from Google Maps, 2023).

Table 1, according to the results of the 2020 Population and Housing Census conducted by the National Institute of Statistics and Geography, shows that San Francisco del Mar Pueblo Viejo has a population of 931 inhabitants, of which 489 are men and 442 are women, with a total of 268 inhabited dwellings, of which only 28.36% have electricity.

Analysis of results

The analysis of results focused on the community of San Francisco del Mar Pueblo Viejo, Oaxaca, an area without access to the national electricity grid. Data on wind and solar resources were collected, as well as estimated energy consumption for a typical dwelling.

HOMER Pro software was used to determine the optimal combination of components, considering installation, operation, and maintenance costs. The best configuration was found to include:

- A photovoltaic system consisting of seven solar panels.
- A mini vertical axis wind turbine.
- Two deep-cycle batteries.
- A Sofar Solar inverter.

With this configuration, annual production of 7,240 kWh per dwelling was achieved, with an autonomy of 16.8 hours and an estimated monthly cost of $371.03 per household. These results demonstrate that the hybrid system is both technically and economically viable, providing a sustainable solution for the community.

COMPILATION OF RENEWABLE RESOURCE AND DEMAND PROFILE OF THE COMMUNITY STUDIED

- **Selecting the rural community**

The Universal Electricity Service Fund (FSUE) is a program administered by the Ministry of Energy (SENER). The objective of the FSUE is to finance the electrification of rural communities and marginalized urban areas. Thanks to data obtained from SENER, several communities were identified with a common characteristic: they do not have access to electricity. Table 2 shows the municipalities selected for study, as well as the percentage of homes without electricity in each one.

The community selected was San Francisco del Mar Pueblo Viejo, due to the easy access to information available, as it has official social media accounts through which communication was established to find out the current situation of the population with regard to access to electricity and the energy demand required by its inhabitants. Thanks to the research carried out, it was revealed that the population

POB TOTAL	POB FEM	POB MAS	TOTAL DE VIVIENDAS	VIVIENDAS HABITADAS	VIVIENDAS CON ELECTRICIDAD	VIVIENDAS SIN ELECTRICIDAD
931	442	489	347	268	76	192

Table 1. Population data for San Francisco del Mar Pueblo Viejo. (Data taken from (INEGI, 2020))

Relación de Localidades del Componente de Instalación de Sistemas Aislados de Electrificación 2022			
NO.	MUNICIPIO	LOCALIDAD	VIVIENDAS CON ELECTRICIDAD
1	Putla Villa de Guerrero	Tierra Colorada	86.44%
2	San Carlos Yautepec	San Miguel Chongos	85.71%
3	San Francisco del Mar	San Francisco del Mar Pueblo Viejo	28.36%
4	San Francisco del Mar	Puerto Estero	75.00%
5	San Mateo Rio Hondo	La Concepción	70%
6	Villa Sola de Vega	Guillaya (Arroyo de Guillaya)	0%
7	San Sebastián Río Hondo	Río Molino	14%
8	Santa María Chimalapa	Canaán	4.70%

Table 2. Localities included in the isolated electrification system installation component

had been cut off from the electricity supply, leaving them without an essential service, due to political problems. Several years after this event, a private company took on the task of restoring electricity to the area, limiting itself to reconnecting the power, but not restoring and expanding the service, achieving 50% coverage of the population, which leaves half of the community—approximately 135 homes—still without access to electricity, maintaining significant inequality in the supply of this basic resource.

CHARACTERIZE WIND SPEED IN THE COMMUNITY TO CALCULATE ITS WIND POTENTIAL

To determine the wind resource in the area under study, a 10-year analysis (2014 to 2023) of hourly wind speeds was carried out using NASA's Data Access Viewer program, which provides wind gusts at a height of 10 meters 24 hours a day. With this information – 8,760 data points – the average monthly wind speed of the community studied was estimated, and then the calculation was made at a height of 12 meters, since the proposed wind turbines are installed at that height. For this purpose, the formula in equation 1 was used:

$$Vreal = Vref \left[\frac{ln(z) \;\; \overline{zref^{zo}}}{ln(zo)} \right] \qquad (9)$$

Where Vref is the reference speed taken directly from the information provided by Data Access Viewer, which is the 8,760 historical wind speed data points collected over 10 years, 24 hours a day; z is the height at which the wind turbine will be installed, i.e., 12 meters; zo is a roughness index for which we will take a value of 1 meter, and zref is the reference height provided directly by the program, which in this case is 10 meters. By calculating the average speed at a height of 12 meters, the data can be better processed, as shown in Table 3.

Journal of Engineering Research ISSN 2764-1317 DOI https://doi.org/10.22533/at.ed.317572517076

	Velocidad promedio (m/s)
Enero	6.17
Febrero	6.14
Marzo	6.13
Abril	6.13
Mayo	6.10
Junio	6.09
Julio	6.10
Agosto	6.09
Septiembre	6.09
Octubre	6.11
Noviembre	6.14
Diciembre	6.13

Table 3. Average monthly wind speeds. Own work

Once the data from the community's 10-year history had been collected and sorted, and thanks to technological tools such as Excel, the annual speeds shown in illustration 24 were calculated, giving us an overview of the wind resource present in the study area, as can be seen in figure 3.

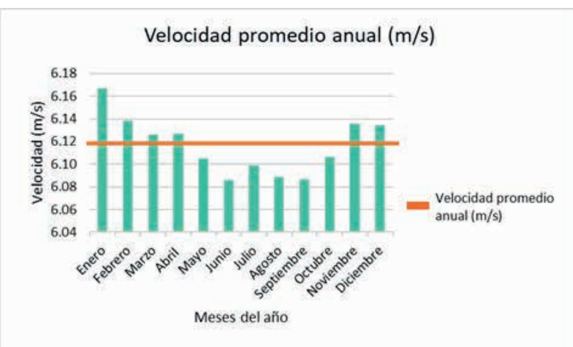

Figure 3. Average annual wind speed in the community. Own work

The processing and understanding of this data allowed us to select the appropriate turbine according to the technical data sheet provided by the manufacturer, such as the start-up speed and the nominal speed at which the wind turbine(s) to be installed will operate optimally according to the wind speeds in the communities and meet the proposed energy demand.

Characterize solar radiation in the community to obtain its solar potential To calculate the energy produced by a solar cell plant or model its evolution over time, it is necessary to obtain information on the radiation incident on the generator plane. If you want to predict the energy that a system will produce in the future, the problem is to estimate the radiation it will receive based on the available information about the behavior of radiation at the site (Nandwani, 2005).

Solar radiation data and the clarity index were obtained through NASA's Data Access Viewer program, which allowed for a comparison of a 10-year history—2014 to 2023—where an average solar radiation of 4.60 kW/h/m2 and a clarity index of 0.48 were obtained.

Figure 25 shows the monthly average solar resource over 10 years.

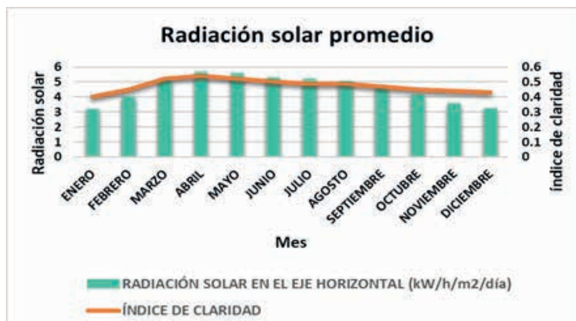

Figure 4. Average annual solar resource. Own work

Thanks to the solar radiation data for the area and the clarity index, among other factors, it is possible to design the ideal photovoltaic installation.

- **Calculate the energy demand of the population.**

To determine energy demand, it is necessary to understand the difference between the installed power in a home, which is the maximum electrical energy capacity that can be used by the devices and equipment connected to that home (Iberdrola Group, 2024), and the load profile or energy demand that characterizes power consumption over a period of time. This period can be daily, weekly, monthly, or annual depending on the objective of the study (Aravena, 2019).

Due to the conditions of the community and its population figures without access to energy, a model home with the basic components of a rural community was taken as a sample. Table 4 shows the equipment and total installed power (W).

ELECTRODOMÉSTICOS	POTENCIA (W)	TOTAL, DE APARATOS	POTENCIA INSTALADA (W)
FOCOS	15	4	60
VENTILADOR	70	1	70
REFRIGERADOR	200	1	200
RADIO	15	1	15
CARGADOR DE TELÉFONO	5	1	5
TOTAL			350

Table 4. Installed power in a model home. Own work

As can be seen, the installed power does not vary during the day—unless more appliances or equipment are installed—which is what differentiates it from the load profile, since the latter is based on the usage habits of each appliance in the home and therefore corresponds to the energy demand. To calculate this load profile, an estimate was made of how many hours per day the different appliances are used in the home. As can be seen in Figure 6, the graph is not constant, as energy demand varies over the course of 24 hours.

Figure 5. Load profile. Own work

RENEWABLE HYBRID SYSTEM ARCHITECTURE

- Characterize the possible combinations of the isolated wind-photovoltaic system using the selected software.

A. System components. To meet the electricity demand, different existing technologies are available, as can be seen in Figure 27.

This project considered the following components in the system: a photovoltaic array to harness solar radiation; a wind turbine to harness wind; and a lead-acid battery bank, which will come into action when there is intermittency in renewable resources. It is important to note that the hybrid system will provide direct current from the batteries, which is why an inverter must be integrated into the system (direct current to alternating current), as most household appliances need to be powered by alternating current.

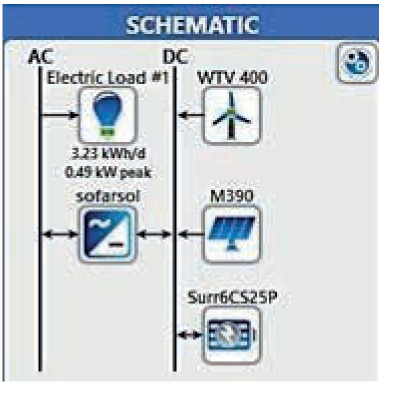

Figure 6 Electrical diagram of the isolated hybrid system.

➢ **Photovoltaic system.** The photovoltaic panel selected for this case was the M390-A1F model from MITREX, which is a monocrystalline solar cell with a maximum nominal power of 390 W and an efficiency of 19.2%, which is considered high. The price of this panel is $2,433.00 MX and its lifespan is the longest of all the components, with an estimated 25 years and an operating and maintenance cost of $121.65 MX per year.

➢ **Wind turbine.** The wind turbine chosen was a low-speed, 5-blade, vertical axis turbine from Mars Rock. Its power curve is shown in Figure 8.

Figure 7. Power curve of the selected turbine
https://www.researchgate.net/Curva-de-potencia-do-aerogerador-Fonte-Software-Homer-Energy-Pro_fig3_343062196

Based on the power curve, it is possible to determine how much power the turbine will develop at certain speeds. For this model, the start-up speed is 1.5 m/s and its nominal speed is 12 m/s, generating 400 W and withstanding speeds of up to 45 m/s. It should be noted that this wind turbine provides alternating current; however, in order for the energy generated to be stored in a h , it must be connected to an AC-DC converter, which is responsible for transmitting it directly to the batteries. This model is priced at $2,310.69 MX and has an annual operating and maintenance cost of $464.50 MX with a lifespan of 20 years.

➢ **Batteries.** The selected energy storage system is battery-based, as it is easy to size and more accessible during purchase. The batteries selected were Rolls 6 CS 25P deep cycle batteries with a lifespan of five years and a price of $9,071.35 MX, making them the most expensive component of the system. It should be noted that they do not require any financial investment for operation and maintenance. Figure 9 shows the life cycle versus depth of discharge.

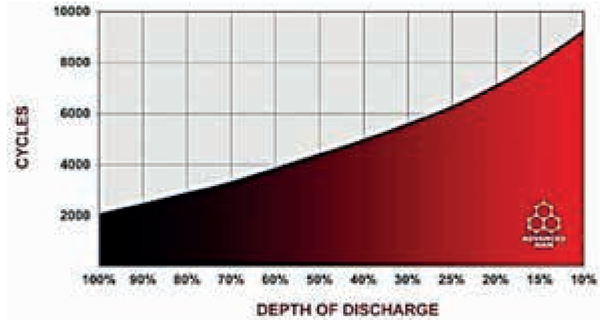

Figure 8. Life cycle vs. depth of discharge

Source: https://www.rollsbattery.com/battery/6-cs-25p/?pdf=7923

B. Optimization. Once the renewable resource data, load profile, and selected components have been entered, HOMER Pro will evaluate all the corresponding combinations to decide which system is technically and economically optimal. It should be noted that the estimate was made per dwelling, so the results of the simulation were individual and will have to be scaled up for the total number of dwellings in the community.

A sensitivity analysis was also performed for 20 and 25 years of project life to discover its effect on system optimization, mainly on the levelized cost of energy, annual operating cost, capital cost, and operating and maintenance cost. See Table 5.

Tiempo de vida del proyecto (años)	LCOE ($/kWh)	Costo de operación	Costo de capital	Costo O&M	Costo Presente Neto (NPC)
20	$4.84	$3,787.87	$2,520.78	$508.22	$84,425.71
25	$4.84	$4,064.55	$2,520.78	$508.22	$98,656.00

As can be seen, the costs do not vary significantly. however, it is necessary to consider that the lifespan of the components is more suited to a 20-year period, since the only component with a lifespan of approximately 25 years is the photovoltaic system. Therefore, it would be unfavorable to replace the wind turbine with a lifespan of 20 years for the remaining 5 years of the solar panels.

Journal of Engineering Research ISSN 2764-1317 DOI https://doi.org/10.22533/at.ed.317572517076

Componente	Capital ($)	Remplazo ($)	O&M ($)	Total ($)
Panel FV M390-A1F	$3,322	$0	$2,454.30	$5,413.57
Turbina eje vertical	$2,527.89	$0	$7,510	$10,038.18
Convertidor Sofar solar 2200TL-G3	$2,756.19	$2,036.34	$0	$4,792.53
Baterías Surrette 6CS 25P	$19,850.72	$44,336	$0.00	$64,186.93
Sistema	$28,457	$46,372.55	$9,964.59	$84,431.21

Table 6. Configuration costs Own work

Thanks to the optimization carried out by HOMER Pro, 61.6 hours of autonomy and an annual production of 1,890 kWh per dwelling were achieved. These are extremely important factors, considering that access to the community is very restricted, so that the intermittency of renewable resources will not affect the community thanks to the hours of autonomy that the system can cover.

OPTIMIZATION OF THE RENEWABLE HYBRID SYSTEM

• Determining the optimal system for the community

HOMER Pro evaluated all the corresponding combinations to decide which system is technically and economically optimal. It should be noted that the estimate was made in a model home, so the results of the simulation were individual and will have to be scaled up for the total number of homes in the community.

The results for the San Francisco del Mar Pueblo Viejo community are shown in Table 7, which analyzes capital, replacement, operating, and maintenance costs and total cost over a 20-year lifetime.

Componente	Capital ($)	Remplazo ($)	O&M ($)	Total ($)
Panel FV M390-A1F	$3,322	$0	$2,454.30	$5,413.57
Turbina eje vertical	$2,527.89	$0	$7,510	$10,038.18
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Baterías Surrette 6CS 25P	$19,850.72	$44,336	$0.00	$64,186.93
Sistema	$28,457	$46,372.55	$9,964.59	$84,431.21

Table 7. Configuration costs. Own work

On the other hand, the replacement cost is high because the batteries have a lifespan of only 5 years and the wind turbine has a lifespan of 20 years, so the storage system for the area must be replaced because it is an isolated configuration, a variable that also alters the operating and maintenance costs. It should be noted that, at first glance, the costs appear high; however, it is important to take into account that this is a 20-year investment.

CONCLUSIONS

The study determined that the design of a hybrid wind-solar system is a viable solution for the electrification of rural communities in Oaxaca. The specific objectives were achieved, optimizing the design with HOMER Pro and ensuring the technical and economic viability of the system. The proposed system offers a sustainable alternative with competitive energy costs and a significant reduction in CO2 emissions. The implementation of batteries ensures adequate autonomy, allowing for a constant power supply.

The study on the optimal design of an isolated hybrid system for San Francisco del Mar Pueblo Viejo, Oaxaca, shows the importance of renewable energy in the search for effective solutions for rural communities. This project not only addresses the problem of limited access to electricity in isolated regions, but also lays the foundations for a system that can be replicated in other communities around Mexico with similar characteristics.

Oaxaca, a region with high wind and solar potential, is an ideal setting for implementing a renewable hybrid system. The selected community faces challenges related to a lack of electrical infrastructure, poor economic conditions, and problems accessing the electrical grid. In this context, the design of an isolated wind-solar hybrid system not only guarantees that the population's energy demand will be met, but also contributes significantly to a fair and sustainable energy transition, in line with the sustainable development goals of the 2030 Agenda.

This research demonstrates that renewable energy solutions can be economically competitive and technically feasible, even in regions with challenging geographical characteristics. The simulation results indicate a competitive levelized cost of energy compared to traditional alternatives such as diesel generators or the restoration of the electricity grid infrastructure. This shows that hybrid systems are not only sustainable but also affordable for rural communities with limited resources. In addition, the incorporation of batteries for storage ensures energy autonomy, allowing the community to have access to electricity even in adverse weather conditions, such as cloudy or windless days. This design offers reliable coverage of 100% of the estimated energy demand, which is also projected to grow with population growth and increased use of electrical devices in the coming years. Access to electricity has a direct and positive impact on the quality of life of the inhabitants of San Francisco del Mar Pueblo Viejo. Among these benefits are:

1. **Education**: Adequate lighting
2. **Health**: Electricity in this community will enable the creation of a health center.
3. **Local economy**: Electrification allows for the refrigeration of products, strengthening its main economic activities such as fishing and food sales.
4. **Cost reduction**: It is estimated that families will save up to 40% compared to the costs associated with using diesel generators. One of the most significant achievements of the project is its contribution to sustainable development. By using renewable resources, the proposed hybrid system avoids the emission of tons of CO_2 annually, directly contributing to Mexico's climate change commitments. This design demonstrates that it is possible to meet the energy needs of vulnerable communities without compromising environmental balance.

It is recommended to continue with studies on the actual implementation of the system, considering aspects such as maintenance, financing, and social acceptance of the technology in the community.

In summary, this research not only offers a solution to an energy problem in a specific community, but also sets a precedent for the adoption of renewable hybrid systems in rural areas. By providing sustainable access to electricity, it improves the quality of life of residents, boosts local development, and contributes significantly to national energy transition goals. This approach demonstrates that renewable energy is not only viable but essential for building a more just, sustainable, and equitable future for all. Thanks to this type of research, awareness is raised about the importance of investing in new technologies and momentum is built towards a fair and affordable energy transition for all, promoting the implementation of renewable energy and fulfilling some of the sustainable development goals of the 2030 Agenda and its fundamental principle: leaving no one behind.

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