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Techno-Economic Analysis of an Optimized Off-Grid Solar Photovoltaic System with Energy Storage for a Rural Residence in the Municipality of San Francisco de Yojoa, Cortés, Honduras

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***Abstract*– Honduras has one of the lowest electrification rates, standing at 86.6%. In contrast, the region boasts an electrification rate of 97.4%, according to OLADE reports in 2021. Currently, the rural areas of the country are the most affected by this issue, with an electricity coverage rate of 74.41%.**

The objective of this research is to evaluate an off-grid solar photovoltaic system, incorporating a technical-economic analysis that allowed for the optimization of the system and an assessment of the profitability of its installation in a rural house located in the municipality of San Francisco de Yojoa, Cortés. The results of the technical analysis, using the optimization tool HOMER Pro, indicate that the optimal power of the system, according to the energy demand, is 6.44 kWp, with an autonomy ranging between 16 and 12 hours. This presents a Levelized Cost of Energy (LCOE) of $0.179/kWh, which is lower than the cost of national electric energy at $0.23/kWh. Economically, the initial investment of $15,387.92 is recovered within a period of 8 years and 5 months.

Keywords-- Levelized Cost of Energy, Energy Storage, Optimal Desing, Off-grid solar photovoltaic system, Rural Electrification,

I. INTRODUCTION

A solar photovoltaic system represents an alternative power source that harnesses solar energy to generate electricity. It is also an effective, safe, economical, and cost-efficient way to meet household energy demands [1].

These systems save money considerably by eliminating dependence on the national power generation, transmission and distribution infrastructure. Considering that the national interconnected system of Honduras has 33.76% of electrical losses, supplying energy reliably in rural regions is essential to develop the quality of life of rural inhabitants.

Therefore, this study has designed an off-grid solar photovoltaic energy model to solve the electricity problems in rural households.

The study methodology is based on project evaluation, which requires an analysis of the market, namely, energy demand and the electricity tariff. A technical analysis using the Helioscope software will facilitate system sizing, as well as the use of HOMER Pro software, which will optimize it to achieve a low net present cost. Within the economic analysis, economic parameters such as NPV (Net Present Value) and

IRR (Internal Rate of Return) are considered, determining the economic profitability of the project, as well as the return on investment [2], [3].

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A. *Context*

Honduras, through the National Electric Power Company, known as ENEE, is currently the sole entity acquiring electricity from producers and transmitting it through the National Interconnected System (SIN) for delivery to end consumers. It aims to reduce the gap in the Electrical Coverage Index (ICE) between rural and urban communities.

Due to this issue, similar research has been conducted in Honduras [4], [5], evaluating the feasibility of isolated systems in the country.

Reyes Duke & Hernández, conducted an investigation aiming to determine the technical and economic viability of installing a hybrid generation system, incorporating photovoltaic solar energy and generators, in the Municipality of Puerto Lempira, Gracias a Dios, for the municipal company known as Local Electric Power Company S.A. (ELEESA).

The results obtained detailed the profitability of installing such a hybrid system, achieving an Internal Rate of Return (IRR) of 25.31%. Additionally, for the production cost, they determined a selling price of $0.55/kWh to achieve a return on investment in 8.38 years [4].

B. *Softwares and Tools*

The tools used for data acquisition included HOMER Pro software, Helioscope, Oracle Crystal Ball, and Meteonorm.

II. METHODOLOGY

In this section, we describe the study methodology that governs the research with the purpose of solving the research problem. The research is divided into three phases as shown in Fig. 1: market analysis, technical analysis, and finally, the economic analysis presenting the IRR and NPV value to determine the profitability of the project [6].

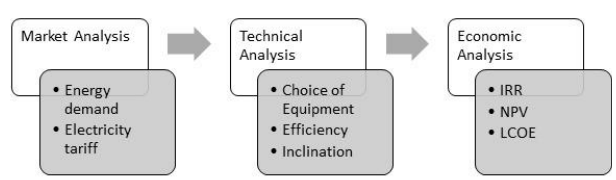

Fig. 1 Methodology

A. Market Analysis

This research focuses on evaluating the economic profitability of implementing off-grid photovoltaic systems in rural households, taking into account the average consumption data of a Honduran household. Based on this, the monthly consumption of a household in Honduras is utilized, subsequently optimizing the system according to the daily energy demand. For system sizing.

Regarding the estimated daily energy demand data in the research area, it is obtained using the HOMER Pro tool in order to acquire precise information about the daily load profile.

Demand is determined by various elements, including the actual need for electricity [7].

An analysis of the growth of the national electricity tariff for the coming quarters is carried out, determining the percentage of increase considering the previous periods, see Fig. 2.

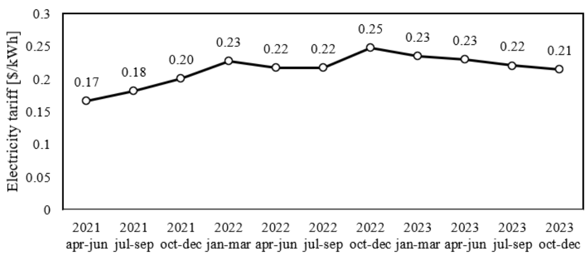

Fig. 2 Timeline of Honduran electricity tariff

B. Technical Analysis

After The technical analysis focuses on optimizing the installed capacity of the system and determining the components used for the power generation plant. This includes aspects such as panel orientation, annual generation, and factors influencing production, such as climate, solar radiation, panel tilt, azimuth, and equipment efficiency [3], [8].

The annual generation of the system will decrease over time due to the degradation of the photovoltaic modules and the performance of the components [9]. The most important parameter considered in a generation plant is the performance ratio and the losses in the system. These losses are usually associated with temperature, dirt, shadows, and the efficiency of the solar panels and the inverter [10], [11].

1. Research Location

For the design of the photovoltaic solar system, a residence located in San Francisco de Yojoa, Cortés, was selected. The residence is at 178 [m^2], situated at coordinates 15.014916, -87.952869.

The fig. 3 shown the location.

Fig. 3 Rural Home Location

2. Data Collection

The Table I presents meteorological data collected in San Francisco de Yojoa, Cortés, including global irradiance, diffuse radiation, temperature, and wind velocity.

This data provides insight into the solar energy potential and climatic conditions of the area, crucial for applications in renewable energy and environmental studies. Global irradiance measures the total solar energy received per unit area, while diffuse radiation accounts for the portion scattered by the atmosphere.

Temperature data indicates the thermal environment, and wind velocity information is essential for understanding wind patterns and their implications.

TABLE I
GLOBAL IRRADIANCE, DIFFUSE RADIATION, TEMPERATURE, AND WIND VELOCITY IN SAN FRANCISCO DE YOJOA, CORTÉS
.

Month	***Gh***	***Dh***	***Bn***	***Ta***	***Td***	***Wind Vel***
	kWh/m2]	***[kWh/m2]***	***[kWh/m2]***	***[°C]***	***[°C]***	***[m/s]***
January	127	61	113	23.5	209.0	1.9
February	136	63	112	24.8	21.4	2.2
March	176	69	153	26.1	21.6	2.5
April	182	74	153	28.0	22.6	2.7
May	181	83	137	28.6	23.7	2.6
June	166	81	117	28.3	24.0	2.4
July	185	87	137	27.8	24.1	2.4
August	179	83	137	27.9	24.2	2.4
September	164	63	145	28.0	24.2	2.2
October	145	70	115	26.7	23.5	1.9
November	117	59	100	24.8	22.1	1.7
December	122	61	105	24.1	215.0	1.8
Year	**1,881.00**	**855.00**	**1,523.00**	**26.60**	**22.80**	**2.20**

3. Off-grid solar photovoltaic system components

The main components of the solar energy system are solar panels, charge controller, batteries, and inverter [12].

The table II provides the technical specifications of a solar panel. It includes critical details such as the panel's maximum power output, efficiency, voltage and current at maximum power, open-circuit voltage, short-circuit current, and temperature coefficients

TABLE II

Model	*ZXM6-NHLD144 Series*
Cell Type	Monocrystaline
Peak Power per Module (Pmax)	460 W
Maximun Voltage at Peak Power (Vmp)	41.8 V
Maximun Power Curent (Imp)	11.01 A
Opeb Circuit Voltage (Voc)	50.3 V
Short Circut Current (Isc)	11.51 A

The table III details the technical specifications of an inverter. It includes key performance and operational parameters such as input and output voltage ranges, maximum power output.

TABLE III
INVERTER TECHNICAL SPECIFICATIONS

Model	*Inverter Huawei SUN2000-5KTL-L1*
Maximum DC Input Voltage	600
DC Start-up Voltage	100
Inverter Short Circuit Current (Isc)	12.5
Maximum Inverter Input Current (Imp)	18

C. Economic Analysis

The economic analysis aims to determine the profitability of implementing the isolated photovoltaic solar system [13]. It is important to highlight that the Internal Rate of Return (IRR) is a financial metric used to assess the profitability of an investment and financing project. The IRR is the rate of return that makes the Net Present Value (NPV) of a project equal to zero [14].

For the project acceptance criteria, the following are taken into account:

- If the IRR is greater than the discount rate, the project is viable.
- If the IRR is less than the discount rate, the project is not financially attractive, and it may be difficult for the project to cover expenses, resulting in no additional benefits, or conversely, the project may incur losses.
- If the IRR is equal to the discount rate, the project is indifferent.

The table IV below provides a percentage of the parameters used to project the economic profitability of the project.

TABLE IV
. INPUT PARAMETERS FOR ECONOMIC ANALYSIS

Parameter	*Value*
Bank Loan	70%
Local Loan	30%
Interest rate	9%
Discount rate	10%
Inflation	1.5%
Tariff growth	2.5%
Electricity price [$/kWh]	0.23

III RESULTS

A. Analysis of demand

For the market study, the average energy demand of a rural home was analyzed. Energy prices were also examined, and an analysis of the supply of off-grid photovoltaic systems was conducted in relation to the levelized cost of energy (LCOE) over the project's lifespan.

For this research, a synthetic load profile recommended by the HOMER Pro software was used. This profile takes into account the efficiency of appliances in a rural home, while also considering the average daily consumption of the load profile [kWh/day] [15].

The table V displays the most important parameters of the load profile extracted from HOMER Pro.

TABLE V
LOAD PROFILE PARAMETERS

Parameter	*Value*
Average daily consumption [kWh/day]	11.27
Average annual consumption [kWh/year]	4,113.55
Average peak demand in the day [kW]	0.55
Peak demand [kW]	2.39

Considering the information provided in TABLE IV, the daily load profile data at the study location can be visualized by a heat diagram that includes peak demand:

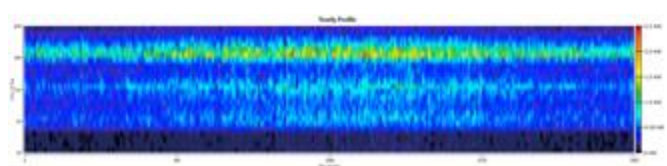

Fig. 4 Daily Load Profile

For the analysis of the electricity tariff growth in Honduras, a linear regression was conducted, as shown in the table VI:

TABLE VI
SUMMARY OF HOMER PRO RESULTS

Date	*Period*	*Tariff Projection*	*Growth*
2023 Oct-Dec	11	5.2423	-2.88%
2024 Jan-Mar	12	5.9482745	13.47%
2024 Apr-Jun	13	6.0641536	1.95%
2024 Jul-Sep	14	6.1800327	1.91%
2024 Oct-Dec	15	6.2959118	1.88%

For the economic analysis of the off-grid system with energy storage, the most pessimistic scenario was considered, where the tariff growth is 2.5% annually. The table VII summarizes the costs for the off-grid photovoltaic system.

The table VII presents key economic metrics for an energy system, including the levelized cost of energy (LCOE) for 12 and 16 hours of autonomy, unit cost per kilowatt peak (kWp), operation and maintenance (O&M) costs, and energy price per kilowatt-hour (kWh). To determine the LCOE, the HOMER Pro tool was used to simulate various scenarios, ultimately concluding that the system achieves the lowest costs with 12-16 hours of autonomy.

TABLE VII
SUMMARY OF HOMER PRO RESULTS

Summary	
LCOE 12 Hours of Autonomy [$/kWh]	0.179
LCOE 16 Hours of Autonomy [$/kWh]	0.22
Unit Cost [$/kWp]	2.39
O&M Cost [$]	25
Energy Price [$/kWh]	0.23

B. *Technical Analysis*

1. *Meteorological Analysis*

The Meteonorm database is used to access meteorological information for the area as shown in fig. 5.

Solar irradiation data in the area were:

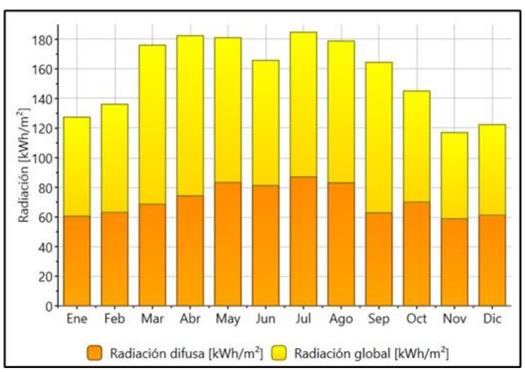

Fig. 5 Average Monthly Solar Radiation

2. *Design of the Photovoltaic Solar System*

For the optimization of the off-grid photovoltaic system with energy storage, various simulations were conducted in the HOMER Pro software with the aim of achieving the lowest levelized cost of energy.

The simulations were performed based on the system's autonomy hours, and the obtained results are shown in fig. 6.

6.44	2	5.00	CC	$13,125	$0.179
6.44	2	5.00	CC	$13,125	$0.232

Fig. 6 Scenarios where the LCOE is lower

The results of autonomy hours and the increase in LCOE are shown in Fig. 7, illustrating the relationship between the number of autonomy hours and the corresponding rise in LCOE.

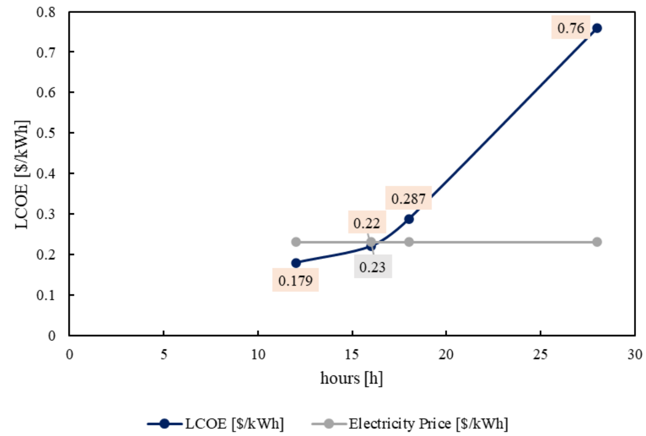

Fig. 7 LCOE vs Electricity Price

For the system sizing, a panel tilt angle of 7° is considered, adjusted for the roof inclination. As for the azimuth, two locations are taken into account due to roof slopes, one at 0° and the other at 270°.

The results obtained from the design and optimization of the offgrid photovoltaic solar system determined that to meet the energy demand during nighttime hours, the use of 2 batteries of 5 [kWh] each and a solar power of 6.44 [kWp] will be required.

The diagram of the off-grid photovoltaic solar system is shown below.

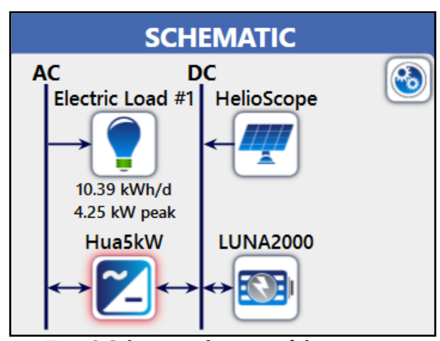

Fig. 8 Schematic diagram of the system

3. *Annual generation of the system*

In the system design to determine the annual energy generation, it is necessary to use monthly solar irradiation data throughout the year.

Therefore, the annual generation obtained from Helioscope was utilized, derived from the system design.

The results of the design are shown in fig. 9.

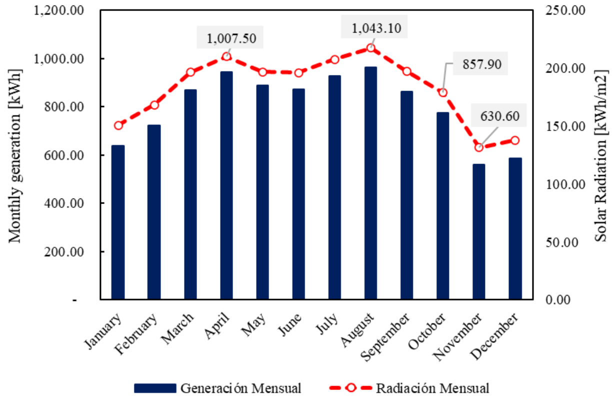

Fig. 9 Energy Generation versus Solar Resource

For the distribution of the photovoltaic modules, the available area on the roof of the house is taken into consideration. It's important to note that, due to cost considerations, it had to be adjusted to the natural slope of the roof, as shown in the fig. 10.

The design carried out in Helioscope is shown below:

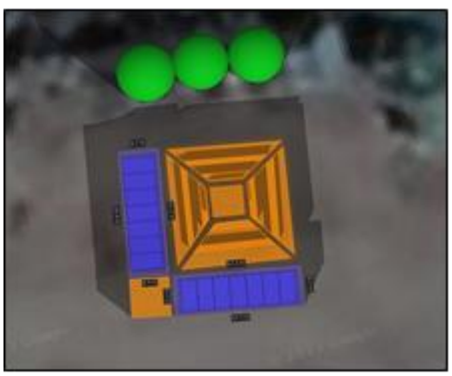

Fig. 10 Distribution of the solar modules

The summary for the technical analysis is shown in the table VIII.

TABLE VIII
TECHNICAL SUMMARY

Summary	
Inclination of the modules	7°
Orientation of the modules	Sur/Oeste
Number of modules	14
Peak power (kWp)	6.44
Specific production (kWh/kWp/year)	1628.3
Performance ratio (PR)	81%
Number of inverters	1
Nominal Power Inverters (kWac)	5
DC/AC ratio	1.28
Generation year 1	10,486.25

C. Economic Analysis

The results obtained from the technical analysis determined the initial investment required to carry out the installation of the off-grid solar photovoltaic system with energy storage.

The study considered the autonomy days, with the system ranging from 12 to 16 hours of autonomy without exceeding the cost of national electricity service.

TABLE IX
ECONOMIC SUMMARY

Parameter	*Value*
Unit Cost [$/kWp]	2,389.43
Budgeted Initial Investment [$]	15,387.92
O&M Costs [$]	25
Equipment Replacement	6761.7

The replacement of the equipment is being considered, and in this specific case, the battery replacement is planned for the 10th year. This decision is based on the number of cycles the battery can endure and the system's autonomy hours.

D. Sensitivity Analysis

For the sensitivity analysis, the Oracle Crystal Ball risk analysis tool was used to analyze 10,000 scenarios for the IRR and NPV.

This analysis allowed us to understand to what extent the IRR and NPV could be affected by certain variables considered in the project, including inflation, discount rate, tariff growth, and electricity price.

The results of the sensitivity analysis shown in the fig. 11 detailed that the Internal Rate of Return will be in a range between 11% to 19% with a certainty percentage of 62.12%

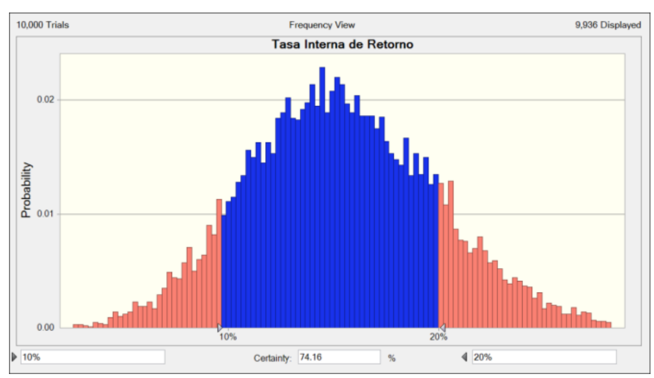

Fig. 11 Internal Rate of Return of the System**.**

The simulations conducted for the NPV, as shown in Figure 12, indicate that the NPV will be in the range of $178.09 to $5,324.10, with a certainty percentage of 70.94%.

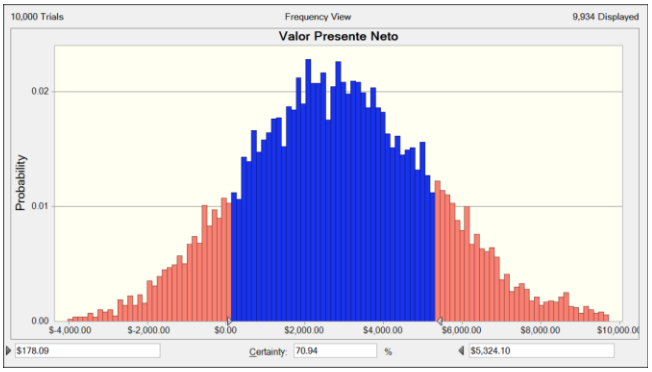

Fig. 12 Net Present Value of the system

The return on investment for the photovoltaic solar system based on the economic analysis is 8 years and 5 months.

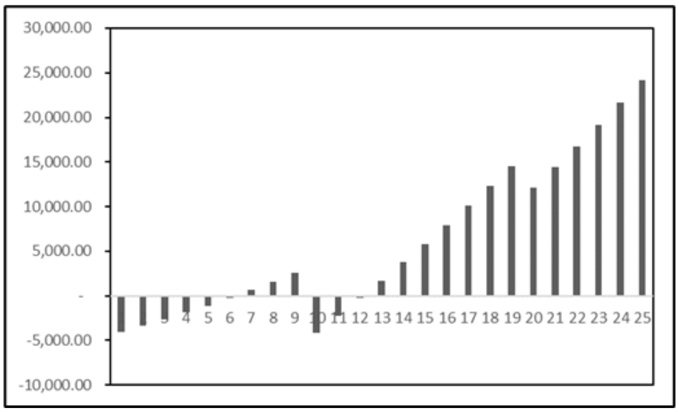

Fig. 13 Return on investment of the system.

III. Conclusions

The design and optimization of the isolated photovoltaic system with energy storage for a rural residence were successfully completed, leading to the project's installation.

The technical study determined that to meet the energy demand, a system with a power of 6.44 kW should be installed. Additionally, 2 battery modules of 5 kWh each will be required to cover the energy demand during the night.

The analysis of energy production costs determined that the optimal levelized cost of energy is $0.179/kWh with 12 hours of autonomy.

The economic analysis concluded that the implementation of a photovoltaic system with energy storage for a rural residence located in San Francisco de Yojoa is economically viable. The project generates an internal rate of return of 15%, rejecting the null hypothesis by exceeding the 10% discount rate.

The profitability analysis specified that the project has a return on investment of 8.40 years, concluding that the installation of isolated projects in rural areas is profitable.

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