Cost-benefit analysis of the implementation of off-grid photovoltaic systems in the Northwest residential sector of San Pedro Sula, Honduras

S Tinoco1 and A M Reyes Duke2

1 Undergraduate student, Faculty of Engineering, Universidad Tecnológica Centroamericana, Honduras
2 Assistant Professor and corresponding author, Faculty of Engineering, Universidad Tecnológica Centroamericana UNITEC, Honduras

E-mail: alicia.reyes@unitec.edu.hn

Abstract. This research analyzed the implementation, from a technical and financial point of view, of off-grid solar photovoltaic systems in the Northwest sector of San Pedro Sula, Honduras. The energy demand of the residential sector was studied, the monthly energy consumption data of 17 neighborhoods in the sector were processed and three main monthly energy consumption levels were determined. The sizing of the systems was carried out considering PV arrays connected to hybrid inverters. In addition, the nominal capacity of the battery banks of the three systems was defined based on 1 day of autonomy and a nominal voltage of the installation of 48V. PVsyst was used to approximate the energy that the photovoltaic array will potentially generate, and the specific yield value was used to project the energy to be generated throughout the life of the project. Homer Pro was used to determine the optimal configuration to find the lowest net present costs for each project. The financial analysis determined that the cost-benefit ratio is greater than 1 for systems with nominal DC capacity greater than 15.8kWp.

1. Introduction
Honduras is a country that has an excellent potential for solar energy, so since 2007 the government of the Republic has promoted the generation of electricity through this technology and since 2014 many companies have heeded the call and decided to bet for a clean energy generation. Currently, several buildings in the industrial and commercial sector of the city of San Pedro Sula have solar energy systems for self-consumption, however, in the residential area the number of homes that have opted for this technology is still minimal. Through this research, the relevant technical and economic aspects will be evaluated to determine whether it is feasible to install off-grid solar PV systems to satisfy the energy consumption of users belonging to this sector. The PVsyst software will be used to simulate off-grid systems with batteries and determine the energy that can be generated and the specific performance of this type of systems in the city. Additionally, Homer Pro software will be helpful in determining the optimal system rating to obtain the lowest possible LCOE.

The main tools of financial analysis will be used to determine the net present value, the internal rate of return and the levelized cost of electricity of this technology. Different ranges of typical electrical energy consumption in the sector will be chosen and a comparison will be made between the total cost that this type of installation would entail and the current cost of electrical energy in the residential tariff in Honduras.
2. Previous studies

Based on the development and advances in photovoltaic technology, various studies have been developed to evaluate the feasibility of off grid solar energy projects.

In 2014, Ghafoor and Munir analyzed the design and economics of a residential off grid PV installation in Faisalabad, Pakistan. The results showed that the unit cost of electricity produced using an off-grid photovoltaic system is less than the unit cost charged in the case of conventional electricity supplied to residential areas. [1]

In 2016, Zubi et al, concluded that off-grid photovoltaic energy can provide effective solutions for energy needs in developing regions with virtually no resource constraints and with very positive socioeconomic and environmental impacts. [2]

In Uganda, Mandelli et al, highlighted that attention is required when defining load profiles for sizing off-grid PV systems since, given the typical inputs for user’s electrical needs, various system configurations may be optimal. [3]

Duman and Güler, studied in 2018 the possibilities of implementing isolated renewable energy systems on the coasts of Turkey, concluding that the costs are higher than the costs off grid energy, however, they are lower than the costs from previous years. [4]

In 2019, Irfan et al, conducted a techno-economic analysis of off-grid PV systems in Pakistan, and found that electricity generation from solar photovoltaic energy costs $0.043/kWh and is much cheaper than conventional electricity, which costs $0.12/kWh. [5]

3. Context

The city of San Pedro Sula has an approximate land area of 898 km², is made up of 52 villages and 246 hamlets registered in the 2013 National Population and Housing Census. It has a population of 736,751 people in the urban area, and in the rural area of 41,126 people. [6]

Regarding the solar resource, the information provided by the World Bank’s Global Solar Atlas was taken into consideration. In which an annual direct normal irradiation of 1,352 kWh/m² and a specific yield of around 1,300 kWh/kWp stands out. [7]

The northwestern sector of the city of San Pedro Sula covers the colonies from the El Zapotal neighborhood, adjacent to Merendón, to part of the Guamilito neighborhood in the center of the city. It has a projected population of 140,142 inhabitants, according to data from the United Nations Population Fund. [8] At present, it is the sector with the highest capital gains in the city. Some of the characteristics that make it the sector with the highest growth and development are security, access to educational centers, commerce, and services.

Regarding electricity supply, the price of electricity in Honduras for the residential sector is 0.1326 $/kWh for consumptions less than 50 kWh/month and 0.1723 $/kWh for consumptions greater than 50 kWh/month.

4. Methodology

This research focuses on evaluating the cost benefit of the implementation of off grid photovoltaic systems in the residential sector of the Northwest region of the city of San Pedro Sula, considering the consumption data of 17 neighborhoods. Based on this, 3 typical monthly consumption levels are considered and 3 systems corresponding to each consumption level are dimensioned. For the sizing of each system, an angle of inclination of the panels of 15° and an azimuth of 0° is considered. In addition, PV modules with a nominal capacity of 400 W and an average above-plane irradiation of 1,800 kWh/m².

To find the capacity of the battery bank, it is necessary to know the daily energy demand, the days of autonomy for which the system is designed, the efficiency of the inverter, the system voltage, which in this case is 48 V and the depth of discharge of the selected battery, as shown in the following equation.

$$Q_{bat}[Ah] = \frac{Energy[Wh/day] \times Days\ of\ autonomy[-]}{\eta_{inv}[-] \times V_{sys}[V] \times DOD_{max}[-]}$$ (1)
To determine the quantity of photovoltaic modules required to satisfy the demand of the installation, the annual energy demanded is used, as observed in the following equation.

\[ mod = \frac{\text{Energy [kWh/year]}}{\text{Irradiance AM 1.5 [kW/m}^2\text{]} \times \text{Irradiation POA [kWh/m}^2\text{]} \times \text{Capacity PV module [kW]} \times \text{PR[–]}} \]  

Additionally, PVsyst is used to simulate PV systems and determine their specific performance and projected power generation for the first year. The typical residential load profile provided by the software is used and the daily energy consumption is specified in kWh.

HOMER PRO software is useful for determining the optimal configuration for which the system presents the lowest net current costs. To perform this analysis, the software downloads the meteorological information of the place and allows using the typical demand profile for the residential area, to select the average daily energy consumption. In addition, it allows selecting the components of the installation from its database. Based on this information the software determines the DC nominal capacity, the AC nominal capacity in inverters and the capacity of the battery bank to satisfy the demand at the lowest net present costs.

The financial analysis aims to determine the cost benefit of the implementation of each proposed system, making use of the following equation [9].

\[ CB = \frac{B}{C} = \frac{\text{Ahorros netos}}{\text{Inversión total}} \]  

From the above, 3 possible scenarios can result:

- CB > 1: This indicates that the Benefits are greater than the Costs, therefore, the implementation of the project would be convenient.
- CB = 1: The total costs are equal to the net benefits, which indicates that there would be no profit or economic benefit in the implementation of the project.
- CB < 1: The proposed project is discarded, as the costs will outweigh the savings or benefits.

In this case, the net savings are directly related to the amount of money that is not paid for electricity to the distribution company and the total investment includes the initial investment of each system plus the total costs of operation and maintenance and financial expenses in case of financing.

In addition, it is intended to find the LCOE of each system considering a useful life of 25 years, using the following equation [10].

\[ LCOE = \sum_{n=1}^{m} \frac{CC_n [$] + O&\text{M}_n [$] + \text{Fuel Cost}_n [$]}{\text{Energy Generated}_n \text{ [kWh]}} \]  

5. Analysis and results

5.1. Analysis of demand
Consumption information was collected for the months January to December 2019 of the selected sample. The monthly average values are shown in figure 1.
Based on the processed data, it was decided to consider 3 levels of consumption; 535 kWh, 971 kWh and 2000 kWh, to carry out the sizing of PV systems.

5.2. Technical analysis
5.2.1. Meteorological information. The Meteonorm database is used to access meteorological information for the area. The monthly solar radiation averages are shown in Figure 2.

5.2.2. Design of PV systems. Three isolated PV systems were dimensioned for the 3 corresponding consumption levels, leaving the characteristics shown in Table 1 as results.

Table 1. PV systems dimensions.

|                      | System 1   | System 2   | System 3   |
|----------------------|------------|------------|------------|
| Nominal DC capacity  | 6.4 kWp    | 10 kWp     | 19.2 kWp   |
| PV module            | CANADIAN SOLAR 400W – CS1U-400MS |
| AC rated capacity    | 5 kW       | 8 kW       | 15 kW      |
| Inverter             | INVERTER MPP SOLAR, LV5048 (5kW & 3.5kW) |
| Battery bank capacity| 900 Ah     | 1,500 Ah   | 1,800 Ah   |
| Battery              | HOPPECKE 6 OPzS | HOPPECKE 10 OPzS | HOPPECKE 12 OPzS |
5.2.3. **PVsyst results.** The design of the systems in PVsyst was carried out considering an inclination angle of 15 ° and an azimuth of 0 °. In addition, the option of designing isolated systems such as DC couplings is used to approximate the specific performance and the energy generated for each system. The results for each design are shown in Table 2.

| Parameter                        | System 1 | System 2 | System 3 |
|----------------------------------|----------|----------|----------|
| Annual production [kWh/year]     | 9,210    | 13,741   | 34.3     |
| Standardized production [kWh/kWp/day] | 2.77     | 3.25     | 2.74     |
| Specific performance [kWh/kWp/year] | 1439    | 1,431    | 1441     |
| Performance Ratio [%]            | 56.9     | 66.84    | 56.3     |
| Loss of the whole [kWh/kWp/day]  | 1.86     | 1.36     | 1.85     |
| System losses [kWh/kWhp/day]     | 0.23     | 0.25     | 0.27     |

5.2.4. **HOMER PRO results.** The software determined the optimal settings for each system that are presented below in Table 3.

| Parameter                        | System 1 | System 2 | System 3 |
|----------------------------------|----------|----------|----------|
| Demand [kWh/mes]                 | 535      | 971      | 2000     |
| DC capacity [kWp]                | 5.2      | 8.8      | 18       |
| AC capacity [kW]                 | 3.5      | 5        | 10       |
| Battery capacity [Ah]            | 900      | 1500     | 2000     |
| Generation year 1 [kWh]          | 7,774    | 13,156   | 26,909   |
| COE [$/kWh]                      | 0.14     | 0.13     | 0.11     |
| Operating costs [$/año]           | 239.51   | 477.55   | 1,244.00 |
| Initial capital [$]               | 9,713.00 | 15,573.00| 21,719.00|
| FV capital cost [$/kWp]           | 1,654.00 | 2,794.00 | 5,715.00 |
| Hours of battery autonomy [hr]    | 43.3     | 31.9     | 28.8     |

The results of the financial analysis performed by the software based on the previous configuration results and according to the prices of the investigated components, are shown below in Table 4.
5.3. Financial analysis
The initial investment required, for each system which is shown in Table 5, is derived from the prices of PV modules, inverters, batteries, cabling, structures, and labor for component installation.

| Parameter | System 1 | System 2 | System 3 |
|-----------|----------|----------|----------|
| DC capacity [kWp]: | 5.2 | 8.8 | 18 |
| Specific cost of capital [$/kWp] | 2460.87 | 2407.60 | 1696.27 |
| Total investment [$] | 12,796.50 | 21,186.88 | 30,532.80 |
| Specific Performance first year [kWh/kWp]: | 1495 | 1495 | 1494.94 |
| Annual degradation of PV modules [%] | 0.70% | 0.70% | 0.7% |
| Energy price [$/kWh]: | 0.1723 | 0.1723 | 0.1723 |
| Rate increase [%]: | 3% | 3% | 3% |
| Energy surpluses [%] | 6% | 6% | 6% |
| Annual O&M [$/kWp] | 5 | 5 | 5 |
| Annual Insurance [%] | 0.6% | 0.6% | 0.6% |
| Annual rate increase [$] | 3% | 3% | 3.0% |
| Current inflation rate [%] | 2.5% | 2.5% | 2.5% |
| Change of inverters [$] | 916.44 | 1,309.20 | 2,618.40 |
| Changing batteries [$] | 8,756.54 | 14,419.20 | 17,023.20 |
| Discount rate for NPV calculation [%] | 8.50% | 8.5% | 8.5% |
A projection of the cash flows of the project, as shown in Table 7, was carried out throughout its useful life, to later make the calculations of costs and net present savings, as well as the LCOE for each system.

Table 7. Financial analysis results.

|                      | System 1            | System 2            | System 3            |
|----------------------|---------------------|---------------------|---------------------|
| VPN Total Savings [$] | $ 5,614.48          | $ 26,424.51         | $ 54,048.12         |
| VPN Total Costs [$]  | $ 17,730.50         | $ 29,260.22         | $ 41,367.27         |
| Ratio B/C            | 0.88                | 0.90                | 1.31                |
| LCOE [$/kWh]         | 0.1306              | 0.1226              | 0.0860              |

As can be seen, the cost-benefit ratio becomes greater than 1 in system 3. And the LCOE is less than 0.17 $/kWh, the price of grid energy, in all cases.

Based on the configuration of the off-grid PV systems considered, Homer Pro and the financial analysis tools were used to determine the nominal capacity at which the cost-benefit ratio is equal to 1. Therefore, the point at which the cost-benefit ratio is equal to 1 corresponds to a nominal capacity of 15.8 kWp.

6. Conclusions
It was determined that the implementation of isolated photovoltaic systems with an energy storage system using batteries in the northwestern sector of the city of San Pedro Sula is feasible for nominal DC capacity values greater than 15.8 kWp.

The levelized cost of electricity generated from solar photovoltaic technology is less than the cost of energy provided by the grid.

The component that considerably increases the cost of photovoltaic installations without connection to the grid is the batteries, therefore, it is important to determine the type and nominal capacity of energy storage that best suits the needs of the installation.

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