Case Study: Optimization of Grid-Connected Photovoltaic Self-Consumption Systems for The Commercial Sector in Honduras

C Lara Monge¹, L Vásquez Márquez² and A M Reyes Duke³

1 Undergraduate student, Faculty of Engineering, Universidad Tecnológica Centroamericana UNITEC, San Pedro Sula, Honduras.
2 Undergraduate student, Faculty of Engineering, Universidad Tecnológica Centroamericana UNITEC, San Pedro Sula, Honduras.
3 Assistant Professor and corresponding author, Faculty of Engineering, Universidad Tecnológica Centroamericana UNITEC, San Pedro Sula, Honduras
E-mail: alicia.reyes@unitec.edu.hn

Abstract. It is common to see how the installation of photovoltaic systems is being used in the commercial sector to minimize costs on the electric bill, so if the aim is to obtain the greatest benefits from the photovoltaic system, it is necessary to carry out a correct sizing of its nominal DC capacity prior to installation. To achieve this in a more reliable way, the initiative was taken to develop a program with LabVIEW where it is possible to find the most profitable sizing based on the selection of the best scenario from a variety of simulations that it will carry out, this choice is based on the Net Present Cost (NPC) resulting from simulations. For the correct operation of the program, meteorological data of the hourly annual global irradiance were included. The data for the consumption analysis for each case was obtained from the load profiles of 8 selected banks. This research was carried out in the county of Santa Rosa de Copán, Honduras. The program developed in this research was able to determine the optimal result for each banking agency according to each scenario analyzed. The cases were categorized depending on their annual energy consumption, which are between 30 and 200 (MWh/year). Each bank was analyzed in 3 scenarios: no surplus compensation, net billing, and net metering. The development of this research determined the average nominal DC capacity required by an installation located in the proposed consumption categories and that with the current scheme that is managed in the country (without compensation of surpluses), it is economically attractive to optimize a grid-connected photovoltaic system for self-consumption, due to the significant amount of economic benefits it represents for the user, which in this research are between 28,000 and 165,000 (USD).

1. Introduction
Photovoltaic (PV) systems are constantly evolving allowing greater applicability in different sectors such as residential and commercial. Electrical power generation costs based on PV systems have decreased over time due to component improvements and increasing market competition. For a PV system that is connected to the electricity grid to be financially interesting it is necessary to optimize it to reduce the net present cost. The Honduran electricity tariff is higher than the cost of generating PV energy, so a reduction in consumption from the electricity grid would imply greater savings. One way to reduce grid consumption is by maximizing energy consumption from the connected PV system (maximizing self-consumption). It can be achieved by optimizing the design of a PV system adapting it to the electric load.
Honduran legislation contemplates self-consumption and the generation of surplus electricity by installed PV systems, however, no regulations have been established and rates have not been approved for the purchase of energy by distribution companies. This research seeks to develop a model that allows optimizing PV systems, adapting their nominal DC capacity, maximizing self-consumption and minimizing the net present cost, for the commercial banking sector, in which the supply of electrical energy is essential and the consumption pattern allows greater use of the solar resource.

2. Previous studies
Several studies of PV systems optimization have been carried out worldwide, as well as on the adaptation of power generation to the consumption profile for higher performance. Martín & Gómez developed a model that allows the optimization of PV systems connected to the grid without storage based on the orientation and optimal position of the PV array outside the facilities allowing a better adaptation to the demand curve[1]. Luthander et al., determined that self-consumption can be maximized in previously installed PV systems in two ways: using small capacity batteries for storage or a demand management system[2]. In Thailand, Tongsopit et al., they carried out a study in three economic scenarios for PV self-consumption. Evaluating non-compensation, net metering, and net billing of energy surpluses. Research results indicate that net metering is economically more attractive than net billing schemes[3]. In the city of San Pedro Sula, Honduras, an optimization study was carried out for the residential sector, analyzing the lowest net present cost in three economic scenarios[4].

3. Context
Honduran legislation contemplates self-consumption and the generation of surplus electricity by installed PV systems, however, no regulations have been established and rates have not been approved for the purchase of energy by distribution companies. The commercial sector is the second sector with the highest consumption of electricity in the country and most of the consumption comes from the national electricity grid being for the banking sector in Santa Rosa de Copán 1,663.37 (MWh) in 2019. The sector of buildings for residences, offices, businesses, and other commercial applications increases its energy demand annually around 1%[5]. The current method used for sizing PV systems does not guarantee that they are optimal and that they maximize self-consumption. The research is focused on the city of Santa Rosa de Copán located in the western part of Honduras. The working hours of the banking sector in the city of Santa Rosa de Copán are on average as well as the behavior of multiple facilities in the commercial sector, during the day which can be seen in Figure 1, providing an ideal period for the use of the solar resource for the generation of electrical energy through PV technology.

![Figure 1. Daily average load profile.](image-url)
4. Methodology

4.1. Research variables
For this research, the net present cost (NPC) of a PV system and the NPC of the local electricity grid supply were selected as the main variables. The NPC will determine the optimal sizing for the PV system. These variables will be affected by many other independent variables grouped in technical and financial variables.

4.2. Optimization model
The program requires data entry by the user, these are divided into technical and financial parameters and are necessary for operation, then the program can generate data autonomously without additional intervention by the user. The operation process is described in Figure 2, where are all entry and exit parameters are shown.

![Figure 2. Developed program operation concept.](image)

To determine the optimal sizing of the PV system, the lowest NPC of each of the simulations carried out will be chosen, for this a series of data accompanied by the discount factor is used, this is used to determine the discounted cash flow throughout the useful life of the project. The objective function which is the optimization model core is described in the following equation [6]:
\[
\min NPC = I_t + \sum_{i=1}^{n} \frac{O&M_i + S_t + C_{rep}}{(1+i)^t} + \sum_{i=1}^{n} \frac{E_{GS} p_{\text{elec}}}{(1+i)^t} g[1 + r_{\text{pen}}] - \sum_{i=1}^{n} \frac{E_{\text{surp}} p_{\text{surp}}}{(1+i)^t} g[1 + r_{\text{surp}}] - S
\]

Where \( I_t \) is the initial investment, \( O&M \) is the operation and maintenance annual cost, \( C_{rep} \) is the replacement cost, \( E_{GS} \) is the energy supplied from the grid, \( p_{\text{elec}} \) is the price of energy, \( E_{\text{surp}} \) is the energy surpluses, \( p_{\text{surp}} \) is the surpluses price, \( P_{\text{elec}} \) is the power demand, \( p_{\text{elec}} \) is the power price and \( S \) is the salvage value. All this equation terms must be \( \geq 0 \) and \( n=25 \).

### 4.3. Simulation

The simulation scenarios are as follows:

- **Scenario A**: The energy surpluses generated by the PV system are not compensated and are freely delivered to the electricity grid without receiving an economic benefit from them.
- **Scenario B**: The surplus energy generated by the PV system is economically compensated by the grid operating company according to the wholesale market prices (Net Billing).
- **Scenario C**: The energy surpluses generated by the PV system are injected into the electricity grid and are recognized by the grid operating company and are accumulated as credits to be used in subsequent billing periods (Net Metering).

### 5. Results

The technical parameters for the PV system are constant in all scenarios. The price of surpluses and the rate of increase in the price of surpluses are the only financial parameters that vary in the simulations. Table 1 shows the summary of the parameters entered in each simulation which were done in the developed program in LabVIEW.

#### Table 1. Principal parameters.

| Parameter                                  | Scenario A | Scenario B | Scenario C |
|--------------------------------------------|------------|------------|------------|
| Nominal PV module power                    | 10 (W)     | 10 (W)     | 10 (W)     |
| Performance ratio (PR)                     | 0.8 (-)    | 0.8 (-)    | 0.8 (-)    |
| DC/AC ratio                                | 1.2 (-)    | 1.2 (-)    | 1.2 (-)    |
| Annual degradation rate of the PV module   | 0.5 (%)    | 0.5 (%)    | 0.5 (%)    |
| Annual increase rate of consumed energy    | 1.07 (%)   | 1.07 (%)   | 1.07 (%)   |
| Specific capital costs                     |            |            |            |
| PV module                                  | 0.16 - 0.35 ($/kWp) | 0.07 ($/kWh) | 0.1749 ($/kWh) |
| Inverter                                   | 0.09 - 0.30 ($/kW)  |            |            |
| BOS                                        | 0.65 - 1.00 ($/kW)  |            |            |
| Annual O&M cost                            | 12 ($/kW – year)   |            |            |
| Annual insurance cost                      | 0.3 (%)      |            |            |
| Price of electric energy                   | 0.1749 ($/kWh)  |            |            |
| Price of electric power                    | 0 ($/kW)     |            |            |
| Increase rate in the price of energy       | 5.76 (%)     |            |            |
| Increase rate in the price of electric power| 0 (%)       |            |            |
| Discount rate                              | 10 (%)       |            |            |
| Inflation rate                             | 1 (%)        |            |            |
| Capacitor bank specific cost               | 0 ($/kVAR)    |            |            |
| Price of energy surpluses                  |            |            |            |
| Scenario A                                 | 0 ($/kWh)    |            |            |
| Scenario B                                 | 0.07 ($/kWh)  |            |            |
| Scenario C                                 | 0.1749 ($/kWh)|            |            |
| Increase rate in the price of energy surpluses | 0 (%)       |            | 5.76 (%)   |
5.1. Energy consumption
A load profile was elaborated for each case analyzed in this research; a typical annual load profile is shown in Figure 3. The peak of consumption varies from each case. The banks analyzed are ordered according to their annual consumption of electricity, with bank 1 being the one with the lowest consumption and bank 8 the highest. They are ordered in four categories: 30-49 (MWh/year), 50-60 (MWh), 100–150 (MWh/year) and 150-200 (MWh/year).

![Figure 3. Typical annual load profile for a bank.](image)

5.2. Energy surpluses no compensation
Table 2 shows that in most of the banking agencies analyzed in scenario A, the optimal DC nominal capacity remains between 20 and 100 (kW) and most maintain a self-consumption index (φsc) higher than 0.6. The PV NPC in all cases is lower than the local electricity grid NPC, reflecting significant savings over the 25-year useful life of the project.

| Bank | Optimal nom. DC capacity (kW) | PV NPC ($) | Grid NPC ($) | φsc (-) | φss (-) | LCOE ($/kWh) |
|------|-------------------------------|------------|--------------|---------|---------|--------------|
| 1    | 22.05                         | 87,450.57  | 116,369.20   | 0.66110 | 0.51890 | 0.03870      |
| 2    | 21.03                         | 94,991.93  | 124,867.35   | 0.68820 | 0.48020 | 0.03885      |
| 3    | 23.08                         | 117,104.03 | 148,938.82   | 0.67560 | 0.43370 | 0.03854      |
| 4    | 33.49                         | 139,666.47 | 186,316.17   | 0.65470 | 0.49500 | 0.03704      |
| 5    | 34.09                         | 145,814.23 | 192,963.24   | 0.65970 | 0.48350 | 0.03696      |
| 6    | 69.3                          | 263,430.12 | 365,452.66   | 0.64290 | 0.50500 | 0.03274      |
| 7    | 100.01                        | 310,335.69 | 425,582.68   | 0.54430 | 0.52990 | 0.03026      |
| 8    | 100.01                        | 391,245.84 | 556,327.00   | 0.66170 | 0.49280 | 0.03026      |

5.3. Net Billing
In table 3 the nominal DC capacity selected for each case increases significantly at values higher than 100 (kW), the highest being 250 (kW). The PV NPC decreases more in scenario B than in scenario A because the specific costs to larger installed capacities are lower and a monetary income is included for compensation of injected surpluses. The self-consumption index (φsc) decreases notably by increasing the amount of energy surplus generated and injected into the grid. The self-sufficiency index (φss) increases in scenario B for each case compared to scenario A.
Table 3. Scenario B results.

| Bank   | DC capacity (kW) | PV NPC ($)   | Grid NPC ($) | φsc (-)      | φss (-)      | LCOE ($/kWh) |
|--------|------------------|--------------|--------------|--------------|--------------|--------------|
| Bank 1 | 100.01           | $60,216.83   | $116,369.20  | 0.20380      | 0.72580      | 0.03026      |
| Bank 2 | 100.01           | $71,486.95   | $124,867.35  | 0.19510      | 0.64730      | 0.03026      |
| Bank 3 | 100.01           | $88,528.20   | $148,938.82  | 0.21720      | 0.60440      | 0.03026      |
| Bank 4 | 105.5            | $103,755.99  | $186,316.17  | 0.27350      | 0.64180      | 0.03026      |
| Bank 5 | 115.9            | $108,007.48  | $192,963.24  | 0.25722      | 0.64097      | 0.03026      |
| Bank 6 | 210.54           | $205,237.38  | $365,452.66  | 0.26670      | 0.63670      | 0.03026      |
| Bank 7 | 250              | $236,477.67  | $425,582.68  | 0.26530      | 0.64570      | 0.03026      |
| Bank 8 | 250              | $324,192.14  | $556,327.00  | 0.31960      | 0.59500      | 0.03026      |

5.4. Net Metering
This scenario presents the particularity of being the most optimistic in a scheme to compensate for surplus energy. For all banking agencies the optimal DC nominal capacity is the program limit, equivalent to 250 (kW). This is since the scenario promotes energy generation and the greater number of surpluses injected into the electricity grid.

The NPC for each case is negative because the income is so high during the 25 years of generation, however, these are not seen as a monetary income but as a credit for the user, which can be used in billings in further consumption periods.

The self-consumption index (φsc) for this scenario shows the lowest values due to the large amount of energy that is delivered and is not consumed by the load. Table 4 shows a summary of all results for this scenario.

Table 4. Scenario C results.

| Bank   | DC capacity (kW) | PV NPC [$]   | Grid NPC [$] | φsc [-]        | φss [-]        | LCOE [$/kWh] |
|--------|------------------|--------------|--------------|----------------|----------------|--------------|
| Bank 1 | 250              | -$706,754.30 | $116,369.20  | 0.08450        | 0.75230        | 0.03026      |
| Bank 2 | 250              | -$698,492.77 | $124,867.35  | 0.08030        | 0.66640        | 0.03026      |
| Bank 3 | 250              | -$673,777.58 | $148,938.82  | 0.09173        | 0.63790        | 0.03026      |
| Bank 4 | 250              | -$634,749.70 | $186,316.17  | 0.12090        | 0.67220        | 0.03026      |
| Bank 5 | 250              | -$628,137.88 | $192,963.24  | 0.12500        | 0.67232        | 0.03026      |
| Bank 6 | 250              | -$449,554.61 | $365,452.66  | 0.22800        | 0.64640        | 0.03026      |
| Bank 7 | 250              | -$387,318.75 | $425,582.68  | 0.26530        | 0.64570        | 0.03026      |
| Bank 8 | 250              | -$253,504.34 | $556,327.00  | 0.31960        | 0.59500        | 0.03026      |

5.5. NPC and indices
Figure 4 shows the behavior of the self-consumption (φsc) and self-sufficiency (φss) indices graph, which vary depending on the electricity demand of each of the banks analyzed and as the DC nominal capacity of the PV system increases, the SCI it tends to be lower and the SSI behaves in the opposite way, it tends to be higher.
Figure 4. Self-consumption and self-sufficiency indices behavior.

Figure 5 shows a summary of each of the banks analyzed in the research. It shows the behavior of the PV NPC for each of the scenarios and their respective index of self-consumption ($\phi_{sc}$) and self-sufficiency ($\phi_{ss}$). The graph is ordered from the lowest annual energy consumption which is bank 1 to the highest which is bank 8.

5.6. Optimal DC capacity

Figure 6 reflects the average nominal DC capacity of each scenario for the analyzed facilities located in the categories of electrical energy consumption established in this research.
6. Conclusions
The research presented has managed to meet the main objective of developing a program capable of optimizing the nominal DC capacity of a PV system connected to the electricity grid for the self-consumption of commercial sector facilities based on its lowest net present cost.

1. The behavior of the NPC FV has been shown in the results of each of the scenarios. For scenario A, the PV NPC increases significantly as the DC rating of the PV system increases. In scenario B, the increase in PV NPC as the DC nominal capacity of the PV system is increased is notable, however, it is much lower than in scenario A. In scenario C the PV NPC tends to decrease as the PV system size increases due to the significant number of economic benefits that this scenario represents for the customer.

2. The indices of self-consumption ($\phi_{sc}$) and self-sufficiency ($\phi_{ss}$) vary notably depending on the scenario in which it is found. In scenario A, the SCI remains at values above 0.6 and the SSI at lower values. In scenarios B and C, the SCI decreases significantly because the amount of energy that is injected into the grid in the form of surpluses is greater, thus taking values between 0.08 and 0.3.

3. This research was able to determine the average nominal DC capacity of PV system for a commercial facility standardizing it by its annual energy consumption, guaranteeing the costumer the maximization of self-consumption from the generated energy providing the most profitable economic scenario.

7. References
[1] Martín-Chivelet N, Montero-Gómez D. Optimizing photovoltaic self-consumption in office buildings. Energy Build. September 2017; 150:71-80.
[2] Luthander R, Widén J, Nilsson D, Palm J. Photovoltaic self-consumption in buildings: A review. Appl Energy. March 2015; 142:80-94.
[3] Tongsopit S, Junlakarn S, Wibulpolprasert W, Chaianong A, Kokchang P, Hoang NV. The economics of solar PV self-consumption in Thailand. Renew Energy. August 2019; 138:395-408.
[4] Deras-Pérez JF. Enfoque basado en el coste actual neto para optimizar la capacidad nominal DC de un sistema fotovoltaico de autoconsumo sin almacenamiento usando LabVIEW. San Pedro Sula, Honduras: Universidad Tecnológica Centroamericana; 2020
[5] REN21. Renewables 2020 Global Status Report. Paris: REN21 Secretariat; 2020.
[6] HOMER Energy, LLC. Net Present Cost. HOMER Grid. 2017. Available in: https://www.homerenergy.com/products/grid/docs/1.8/net_present_cost.html