

Model for energy management of a hybrid generation system connected to the grid

Modelo para la gestión energética de un sistema de generación híbrido conectado a la red

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Abstract

Given the need to provide electrical power services in places such as isolated communities where it is not feasible to build an electrical substation, a solution was developed through the design and implementation of two load profiles: residential and industrial. These were organized as resistive loads within a hybrid system composed of two solar modules, a vertical-axis wind turbine, two lead-acid batteries, and the electrical grid. Secondly, a methodology was applied based primarily on the implementation, development, and integration of a stationary autoregressive model derived from the prior characterization of the equipment, in order to represent the behavior of each renewable energy source—in this case, solar panels and a vertical-axis wind turbine. Finally, with the help of the software tools HOMER Energy and RETScreen, a financial and economic analysis of the hybrid system's performance was conducted, identifying the variables that determine return on investment, as well as the project's revenues and costs according to its geographic location.

Keywords: renewable resources, model predictive control, load profile, load flow, Internal Rate of Return (IRR), Cost of energy (COE), Net Present Cost (NPC), Cost of Inversion (CI), Return of Investment (ROI).

Resumen

Ante la necesidad de brindar el servicio de energía eléctrica en lugares como comunidades aisladas donde no se puede construir una subestación eléctrica, para lograr el objetivo se utilizó la deducción e implementación de dos perfiles de carga: residencial e industrial, los cuales se organizarían como carga resistiva para un sistema híbrido formado por dos módulos solares, un aerogenerador de eje vertical, dos baterías de plomo-ácido y la red eléctrica. En segundo lugar, se llevó a cabo una metodología basada principalmente en la aplicación, desarrollo y articulación de un modelo autorregresivo estacionario basado en la caracterización del equipo previamente establecido para representar el comportamiento de cada fuente de energía renovable, que en este caso se utilizaron paneles solares y un aerogenerador de eje vertical. Finalmente, con la ayuda de los softwares HOMER energy y RETScreen, se realizó el análisis financiero y económico del comportamiento del sistema híbrido, mostrando las variables que determinan el retorno de la inversión, los ingresos y los gastos del proyecto de acuerdo con su ubicación geográfica.

Palabras claves: recursos renovables, control predictivo de modelos, perfil de carga, flujo de carga, tasa interna de retorno (TIR), costo de la energía (COE), costo presente neto (CPN), costo de inversión (CI), retorno de la inversión (ROI).

INTRODUCTION

Nowadays there are multiple technological advances such as those inventions that generate energy through renewable resources and in turn are capable of bringing electric power service to some non-interconnected zones of the country. Its purpose is to convert the solar energy provided by the sun and the kinetic energy of the wind into an electrical resource. These technologies are known as photovoltaic solar panels and wind towers, which when used in the same set, this is called a hybrid generation system (HS).

One definition of a hybrid system is: an electricity distribution system containing distributed energy resources and loads (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled and coordinated manner, either while connected to the main power grid or while isolated (Marnay, 2016). Hybrid systems are designed to feed electrical, and heat loads for small communities, such as urbanization, universities, commercial areas, facilities and industrial parks, among others. These are essentially active distribution networks, because distributed generation systems and different loads in distribution voltage levels are conglomerated.

The reason why we are thinking of implementing these systems, and it is also a consequence of a need, is to be able to supply non-interconnected zones with the electric power service. With this solution, which some countries such as Brazil, Chile and Mexico (Osorio, 2012) are already taking advantage of, those municipalities, townships, localities and hamlets that are not connected to the National Interconnected System will benefit from electricity. Where the idea is to take advantage of the generation of non-Conventional Renewable Energy Sources (NCRES) to be consumed by the loads, and also, anticipating a failure of the HS in one or more of its circuits, the network will supply the missing energy if you have access to it, otherwise, a battery bank will function as a backup.

The inclusion of the NCRES brings with it a challenge in terms of the operation and management of the energy resource of the HS itself. This challenge requires managing a model that indicates the estimated generation of each source given a specific demand in the place where the system is implemented so that it works reliably, continuously and avoiding supply problems.

RESOURCE AVAILABILITY



Figure 1. Place of installation.

The project is located north of the city of Bogotá (Figure 1), on the roof of the laboratories of the Escuela Colombiana de Ingeniería Julio Garavito university. Through IDEAM's interactive atlas (IDEAM, 2005), it was possible to establish the availability of resources, both solar and wind, since the hybrid system is made up of two solar panels and a vertical axis wind turbine. A great advantage of this interactive tool is that historical information of three main variables that were used to develop this study can be found easily and quickly: temperature, irradiance and wind speed in the location where the project is located.

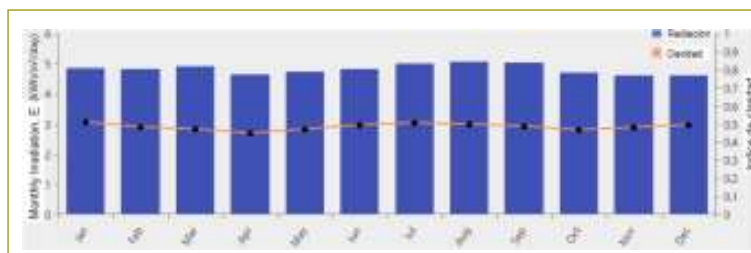


Figure 2. Monthly average irradiation.

To proceed with the monthly economic analysis of the HS, the irradiance and wind speed data for 2019 were taken in the city of Bogotá, which are shown in Figure 2 and Figure 3, from a meteorological station located next to the equipment. According to the global solar radiation parameter, between the months of January to March, there is an increase in this variable, where its historical average is recorded at 4821 [J per day (XM, s.f.). The clarity index recorded is approximately 0,5 because the data does not show a significant deviation.



Figure 3. Monthly average wind speed.

Between the months from June to September, average wind speeds of 2,5 [m/s] could be recorded, this is due to the fact that the Sabana de Bogotá, the site where the HS is installed, is located at a high altitude and that receives the impact of winds with speeds higher than the annual average speed.

LOAD PROFILES

The changes in the generation of the sources that make up the HS are also a consequence of the variation in the magnitude of the load on an hourly basis, also considering the meteorological conditions. To achieve the objective of evaluating energy management, it was decided to carry out computer simulations of electrical variables to be measured, such as voltage, energy demand, active power. Based on this information, the same for all the days on which climatic information was obtained, a model was implemented that characterizes the behavior of each source hourly.

A residential load profile and an industrial load profile were implemented in order to have knowledge of the behavior of the system's generation under certain load and weather conditions.

Residential profile

Figure 4 shows the chosen profile, which roughly describes residential behavior. The guide form for this profile was taken from the public information of XM-Expertos en Mercados company website (Cruz Lazo, 2010). This curve could describe the energy demand of a house, and to accurately predict its electricity consumption, it is essential to understand the determining factors that affect it, such as the most common devices used in the home, the consumption habits of its users. inhabitants, the place where they live, among other

factors (Hernandez and Carrillo, 2017). The graph was sized according to the installed capacity of the system, leaving an estimated clearance of 20% below and thus obtaining a maximum power value of 280 W.

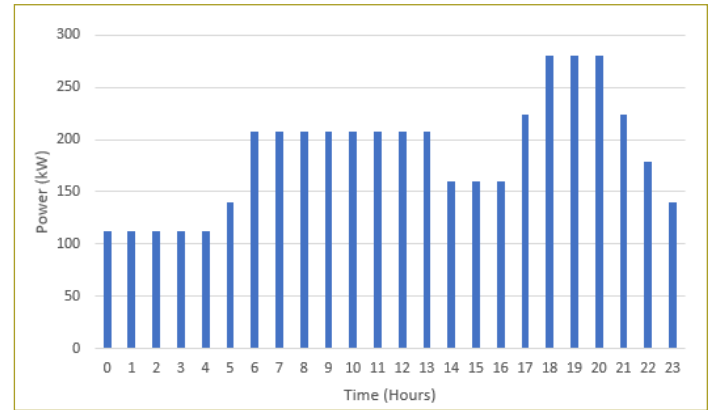


Figure 4. Residential profile.

Residential profiles are distributed in eight resistance values, as shown in Table I, in order to observe drastic changes in demand as well as in generation behavior.

Table I
Resistance and power values

Hour	0-4	5	6-13	14-16	17	18-20	21	22	23
R[Ω]	25,7	20,5	13,8	18	12,8	10,2	12,8	16	20,5
P[W]	112	140	207	159	224	280	224	179	140

Industrial profile

In general terms, when we talk about industry we refer to large processes with multiple generation, transformation and loading equipment in the production chains in order to obtain a final product that will be sold to the company's clients. Based on the above, the choice of electrical load (Electric Load Management or LM) can be defined as the actions carried out to change its profile in order to achieve a peak load of the total system. The objective is for the profile to be as uniform as possible as shown in Figure 5 with the purpose of planning its production, storing energy, introducing energy efficiency measures specifically focused on the moment of peak consumption and thus reducing reactive power and correcting the power factor.

It was decided to study and take this profile into account in the analyzes carried out, since these types

of profiles are the most common and the most used in large processes where a large amount of energy is consumed, therefore, the system must respond differently under the presence of this profile than if it were connected to the profile of residential demand. The system must give priority and guarantee the energy demanded by the load at a certain time instead of storing it, increasing the amount of energy fluid taken from the network, although at that time the project works as a way of saving.

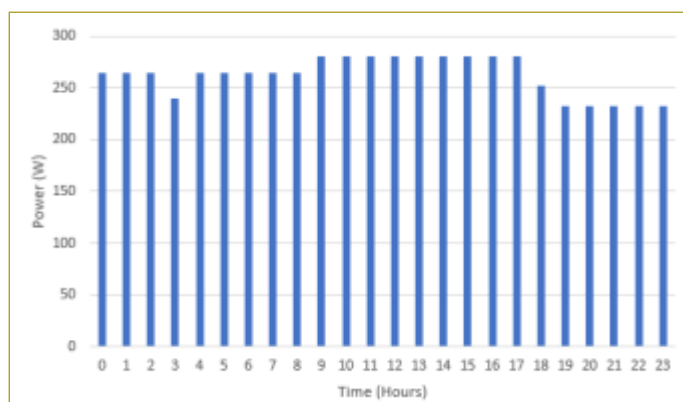


Figure 5. Industrial profile.

Similar to the previous profile, Figure 5 was sized according to the installed capacity of the system, leaving an estimated clearance of 20% below and thus obtaining a maximum power value of 280 W, as shown in Table II.

Table II
Resistance and power values

Hour	0-2	3	4-8	9-17	18	19-23
R[Ω]	10,91	12	10,91	10,3	11,43	12,41
P[W]	264	240	264	280	252	232

Description of obtaining load profiles

The electrical demand of a system is the intensity of current, or electrical power, relative to a specific time interval, that absorbs its load to function. This period is called the demand interval, and its indication is mandatory in order to interpret a certain demand value (Espina, 2017). In order to have an approximate value of the electrical variables of the HS during the day, the characterization of the equipment that makes up the

system was carried out, taking their nominal power from there. The following are going to be used: two 340 Wp photovoltaic solar panels Brand Sunset, a 400W wind turbine Brand Aleko and two 12V 48 Ah Hoppecke batteries connected in series. Table III presents the installed capacity of the hybrid generation system under nominal equipment manufacturing conditions.

Table III
Installed capacity of HS

Source	Units	Power per source [W]	Total power [W]
Photovoltaic modules	2	340	680
Wind turbine	1	400	400
Batteries	2	261,815	523,63
Total			1603,63

MODEL PREDICTIVE CONTROL

A predictive control model (MPC) is an advanced process control method that has been used by industry in numerous processes since the 1980s, in recent years it has also been used in stability models for electrical power systems. The main advantage of the MPC is the fact that it allows the immediate time slot to be optimized, while also taking into account future time slots or intervals. The MPC is based on the optimization of processes and finite horizon based on a plant model. At time t the current state of the plant is sampled and a control strategy that minimizes cost is computed for a relatively short future time horizon: $[t, t+T]$ (Zambrano and González, 2013).

Based on the previous explanation, the objective of the MPC is to find a future trajectory of the variable that was chosen to be manipulated, u . A prediction horizon N is set for which future outputs will be predicted at every instant. This is possible by implementing a prediction model that describes the behavior of the process variables to control, and which resides in the controller. Predictions depend on the known values until the moment and future control signals. The solution to the problem results in a vector containing the future control actions whose dimension depends on the control horizon, however, only the first element of this new vector must be sent to the plant.

It should be clarified, there is always a disturbance that cannot be measured, it represents all the unknown and unpredictable events that disturb the operation of the plant. The MPC model uses powerful linear dynamic modeling tools found in control systems and system identification. The model consists of:

- A plant model to be controlled, whose inputs are variables that can be manipulated, disturbances that can be measured, and disturbances that cannot be measured.
- A model that allows unmanageable disturbances.

Plant model is a time invariant linear system described by the following equations (1) to (3):

$$\mathbf{x}(k+1) = A\mathbf{x}(k) + B_u \mathbf{u}(k) + B_v \mathbf{v}(k) + B_d \mathbf{d}(k) \quad (1)$$

$$y_m(k) = C_m x(k) + D_{vm} v(k) + D_{dm} d(k) \quad (2)$$

$$y_u(k) = C_u x(k) + D_{yu} v(k) + D_{du} d(k) + D_{uu} u(k) \quad (3)$$

where x is the state vector of the plant, u is the vector of the manipulated variables (MV), d is the vector of the measurable disturbances (MD), u_d is the vector of the disturbances that cannot be measurable (UD) entering the plant, y_m is the vector of the outputs that are measurable (MO), and y_{um} is the vector of the outputs that are not measurable (UO). Therefore, due to the above, the general output vector, y , collects the information of y_m and y_{um} (Bemporad, Morari and Ricker 2005).

On the one hand, the model is made up of two fundamental structures for its correct operation: an MPC block in charge of making the generation forecast by source for the next day and a plant block, in which the system is graphically displayed taking into account all the elements that make up the same and connections between them. It is to clarify that the data used in Figure 6 were measured and used in the present simulation.

On the other hand, the plant model is the one shown in Figure 7, where each component that makes up it will be explained later. Each element was arranged in such a way that when the simulation is compiled, each energy source acts under the proposed prediction model, thus obtaining generation results in the short term and in the stipulated time.

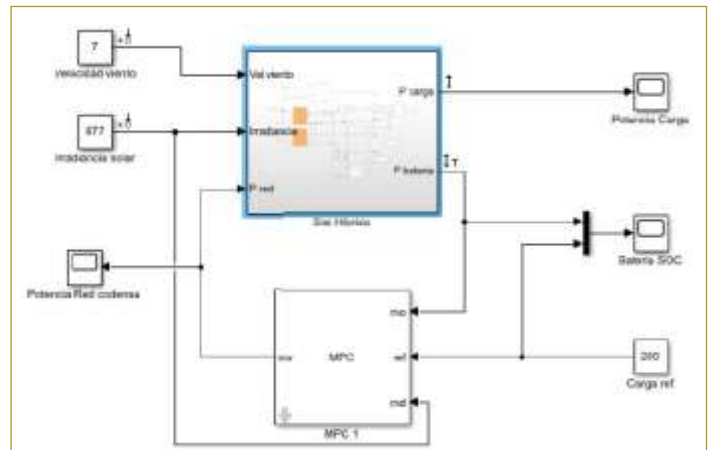


Figure 6. Block diagram of the MPC model in Simulink.

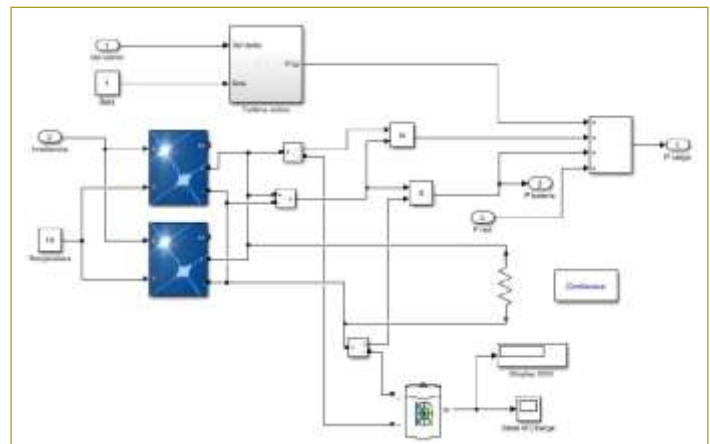


Figure 7. Block diagram of the plant model in Simulink.

ELECTRIC MODEL

HS is also known as an electrical energy source that can operate in two main scenarios: island mode or interconnected to the grid. The first is when the cluster is separated from the main electrical system and in this way, it can function autonomously according to the conditions of its operating infrastructure. The second case is the one that this document will deal with, where the grouping of the equipment is connected to the local distribution system (SDL) in order to consider a more efficient and safe distribution structure (Andrango, 2018). Figure 8 shows the one-way diagram captured in the corresponding software with the n of running a load flow at time $t = 0$, that is, on the day the measurement was made at 9:00 in the morning. Every day for later the information provided by the software is entered into the energy management model

and the prediction of the next day of power generation is evaluated.

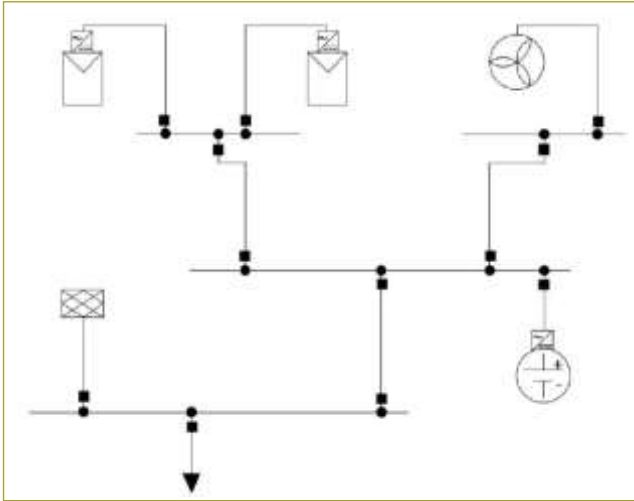


Figure 8. One-way diagram in DigSilent software.

DigSilent software can be programmed so that said power flow is carried out by the Newton-Raphson method since it is desired to find out the solution to a system of non-linear equations at a specific moment of the day. Equations (4) and (5) are used in order to find out the calculated values of the real power and the total reactive power that enters the HS through the bus AC in which it is called typical bar i , and which in turn is the network connected:

$$P_i = \sum_{n=1}^N |Y_{in} V_i V_n| \cos(\theta_{in} + \delta_n - \delta_i) \quad (4)$$

$$Q_i = -\sum_{n=1}^N |Y_{in} V_i V_n| \sin(\theta_{in} + \delta_n - \delta_i) \quad (5)$$

Then, equations (6) and (7) name the calculated value of P_i as a calculated value and the definition of the error is reached as the programmed value minus the calculated value,

$$\Delta P_i = P_{i,prog} - P_{i,calc} \quad (6)$$

$$\Delta Q_i = Q_{i,prog} - Q_{i,calc} \quad (7)$$

The resulting power will be found varying since the conditions of the solar and wind resources are not

constant over a previously established period. That generated energy will also vary as the load varies, which is why an estimate of the fluid that will be consumed is made in order to provide possible contingencies if the meteorological conditions are not favorable. Solar irradiance and wind speed data were taken from the website of the *Instituto de Hidrología, Meteorología y Estudios Ambientales* (IDEAM). These data were collected with monthly resolution in order to have a more general concept of the behavior of HS throughout the year (IDEAM, 2016).

ECONOMIC AND FINANCIAL ANALYSIS

For the economic modeling of the SH, the HOMER energy software was used, a tool that allows the design of renewable energy projects, oriented to SH's, which as a result shows a viable system for all possible combinations of the system to be considered.

This means that the calculations are made according to the equipment that makes up the system, but it does not give us the possibility of including a new one with the purpose of increasing both electricity generation and the profitability of the HS. HOMER energy uses net current cost (NPC) to represent the life cycle cost of a given system. The total NPC unites all costs and revenues that occur over the life of the project, with future cash flows discounted to the present using the discount rate.

The income is made up of the sale of energy to the network, plus any salvage value that the system may produce at the end of its useful life. To calculate the salvage value of each component at the end of the exercise, the software uses the equation (8).

$$S = C_{rep} \frac{R_{rem}}{R_{comp}} \quad (8)$$

where S is the salvage value, the replacement cost of each component, the remaining useful life of the component and the useful life of the component. HOMER uses the equation (9) to calculate net present cost.

$$C_{NPC} = \frac{C_{an,tot}}{CRF_{i,N}} \quad (9)$$

where C is total annualized cost, i is the discount rate, N is the Project Life, and CFR is the capital recovery factor, calculated by equation (10).

$$CFR(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \quad (10)$$

Nevertheless, HOMER calculates cost of energy by equation (11).

$$COE = \frac{C_{an,tot}}{E_{prim} + E_{def} + E_{sales\ to\ the\ grid}} \quad (11)$$

where E_{prim} and E_{def} are the total amounts of primary and deferrable load, respectively, that the system serves per year, and E_{sales} is the energy that was sold to the grid (Lambert, Gilman and Lilienthal 2006).

Since a unimodal study is carried out, the corresponding block diagram of the set of equipment is the one shown in figure 9.

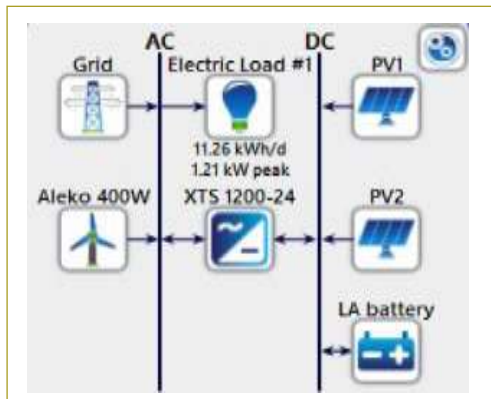


Figure 9. Block diagram in HOMER energy software.

For the financial modeling of the HS, the *RETScreen* expert software, developed by the Government of Canada, was used. It allows modeling and analyzing all that project that involves clean energy. Thus, a set of analyses can be carried out: energy, cost, emissions, financial and sensitivity and risk. *RETScreen* allows you to select the location of the project from among a variety of cities in the country, and associates meteorological data extracted from the NASA database with each one, so it is possible to perform the pertinent calculations to adapt the energy demands of the place selected.

Photovoltaic systems have few components, and their behavior is not linear, so it becomes a little more complicated to model. However, *RETScreen* uses simplified algorithms to minimize data requirements and to speed up calculations, while maintaining an acceptable level of precision. In turn, wind systems are another complex technology to model since they have more parts and are the reason why the project can make the initial capex more expensive.

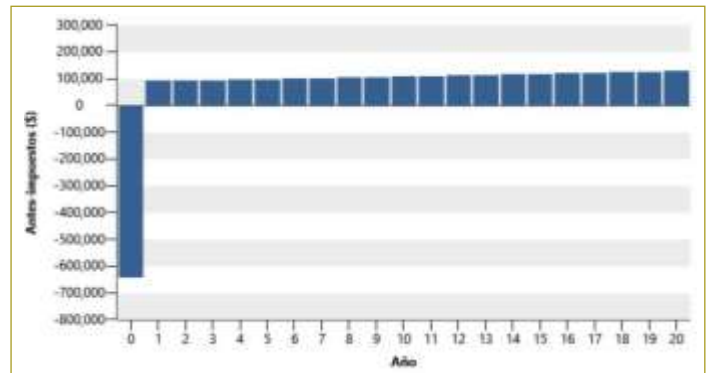


Figure 10. Annual cash flow of the project before taxes.

On the horizon of the twenty years that were considered as the useful life of the project, figure 10 shows indicators that account for the exceeding of the zero margin, that is, the abscissa line. Consequently, either the cost structure of the business is not out of date with respect to the realities of the market or the financing by the shareholders has been sufficient. It is an indicator of the result of a company when taking into account the interests and financial costs, which depend on the way in which the project is financed and therefore, the interest rates.

If we refer to the accumulated flow of the effect during the year, figure 11, an increase in cash flow is observed, proportional to that shown in the distribution before taxes, which is derived from the savings generated by the system over the horizon of stipulated time. It is evident that the annual distribution of the net present value is positive all the time, this is because the load demanded the energy generated from renewable sources and there was no need to take electricity from the grid, thus generating savings in monthly billing.

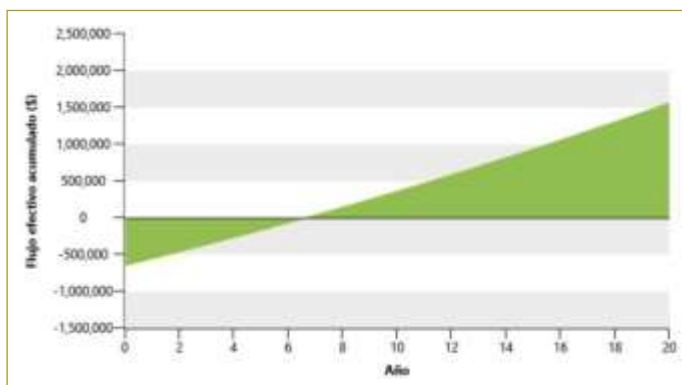


Figure 11. Accumulated cash flow of the project.

For the purposes of simplifying the calculations, only the results obtained for the residential profile will be shown. Table IV shows three main metrics that describe the viability of the project. Internal rate of return shows us a relative measure of profitability, the main problem is that based on the number of periods, the order of the equation to be solved would correspond, the higher this percentage, in less time the initial investment is recovered. It is a viable project since, based on the initial investment, the IRR is high enough to recover the total amount initially invested in a period of less than 5.7 years. The return on investment (ROI) variable is located at an important value since 0.121 pesos of profit is being recovered for each peso invested in the project.

Table IV
Economic metrics of the project

Economic metrics	Value
IRR	16.3 %
ROI	12.1 %
Retribution	5.7 years

CONCLUSIONS

MPC control gives the possibility of having knowledge of the value that the variables will take in the short term, giving a vision to the user of how the sources that make up the system will behave and therefore if, under said prediction, it is possible to meet the previously established demand.

Hybrid systems are currently implemented and taken into account to provide energy to those vulnerable areas where a transmission line does not have access. At the

same time, it is important to have control over energy to use it correctly and not misuse it.

Economic and financial results showed that under the residential profile scenario both the IRR and the return of investment (ROI) (16.3% and 12.1% respectively) are higher than if we consider the case of the industrial profile (9.8% and 6.6% respectively), cause in the residential profile there are hours that can be covered only with renewable generation, also depending if considered important weather conditions.

Finally, results obtained for both load or demand profiles indicate that the SH cannot be working in island mode or disconnected from the grid for a considerable time and especially at the moment when the load demands a greater amount of energy since the contributions of the sources would not be enough to supply said consumption of the end user. In contrast to the above, this SH, as described in this document, is reduced only to a project that can generate significant savings at the time of implementation, and as an alternative in case the generation of the SH does not be enough, the network would be used as a backup.

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