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Energy Planning: On-Grid Photovoltaic System in the Brazilian Semi-Arid

Augusto Arcela
Wesly Jean
Antonio C. P. Brasil Júnior
Laboratory of Renewable Energy, Faculty of Technology, University of Brasília, Brasília, Brazil
augusto.arcela@gmail.com, weslyjean999@gmail.com, brasiljr@unb.br

Rudi van Els
Energy Engineering, Faculty of Gama, University of Brasília, Brasília, Brazil
rudi@unb.br

Abstract. Jacaré-Curituba *is one of the biggest settlement made in Latin America with land reform in mind. It is in the middle of* Caatinga *Biome, a semiarid vegetation that suffers from drought and climate change. Localized in* Sergipe *state, it hosts 720 families living from agriculture besides a cooperative (COOPAC) that processes cassava products harvested by the local farmers. As is, the costs from their energy bills consume a good amount of their profits. The energy comes from the National Grid with high cost of energy, mainly supplied by hydro powers in* São Francisco *River. It primarily serves for the processing of products and irrigation of the crops. Local resources, infrastructure and demand were analyzed in two states in Northeastern Brazil (*Sergipe *and* Alagoas*) through QGIS and ran the OnSSET model to identify the most viable electrification solutions for the region. Because of the high solar potential in the area, photovoltaic systems were demonstrated to be adequate. Furthermore, the design and simulation of an On-Grid Photovoltaic System for COOPAC is carried out using HOMER software. The results demonstrate relevant savings in energy consumption, which could be invested in other development sectors locally.*

Keywords: *Photovoltaic, OnSSET, HOMER,* Sergipe*,* Alagoas

1. INTRODUCTION

Energy is an unquestionable vector in the process of socioeconomic development of a region. The way it is generated and used are crucial to ensure that future generations are able to exploit energy resources, as is currently possible (EPE, 2007). The UN established Sustainable Development Goals (SDG) and the 7th guarantees universal access to electric services until 2030 (Nam, 2015; Le Blanc, 2015; Mentis *et al.*, 2017a). Like other countries in the world, Brazil has a history of adopting energy policies seeking to ensure access to the population at fair prices, respecting environmental commitments and sustainable management of natural resources, although those are currently threatened (Rochedo *et al.*, 2018).

Energy planning is a way to identify the most appropriate technologies to attend electric demands of a given society (Silva and Bermann, 2002). This form of analysis identifies alternative energy sources, such as wind and hydro power turbines, thermoelectric generators or solar panels. It also determines configurations such as stand-alone, mini-grid or on-grid. Geographic Information System support this planning (Resch *et al.*, 2014) and OnSSET - QGIS is a suitable software framework.The model identifies the most appropriate electrification alternatives spatially, assuming the lowest cost one as the most suitable to a region (Mentis *et al.*, 2017b).

Based on this, the objectives of the present research are to identify the most adequate energy solutions in the vicinity of *Jacaré-Curituba* settlement in *Sergipe* and *Alagoas* states through the OnSSET Model. Along with it an On-Grid Photovoltaic System was designed and simulated using HOMER (Hybrid Optimization Model for Energy Resources) software to COOPAC, a cassava processing cooperative within the settlement. A reduction of energy costs for the cooperative is expected so that there is money to develop other sectors in the area. Photovoltaic On-Grid Systems are already a reality in other parts of the world, some examples have been hugely successful by reducing 68 % of costs (Ajan and Kumar, 2015) or by completely satisfying the energy demands (Moury and Ahshan, 2009). Throughout the work the results of simulations and economic viability of adopting such solutions are discussed.

2. METHODOLOGY

2.1 Study Area

The Brazilian Semi-arid is situated on the Northeastern region of the country. Its Köeppen climatic classification is primarily BShw, which means a low annual rainfall with mean temperature higher than 18°C and a dry season in the winter (Sparovek *et al.*, 2007). *Caatinga* is the main biome of the region, a harsh environment to live and climate change is making it even rougher. Since the middle 1990s events of severe drought have occurred in the region, and between 1990 and 2016, 16 out of 25 these years had lower rainfall than expected (Marengo *et al.*, 2018). This resulted in 72,000 km^2 of degraded land in 2016 (Tomasella *et al.*, 2018), with big implications on water, energy and agriculture security - which comprises the Nexus interconnection (Bazilian *et al.*, 2011).

The *Caatinga* Biome is the fourth biggest and one of the most unique Brazilian Biomes, totaling about 734,000 km^2, this represents nearly 50 % of the Northeastern territory and 10 % of the national one (Lucena *et al.*, 2007; Souza *et al.*, 2015). Composed by a vegetation characterized by low and scattered deciduous trees and shrubs, along with different species of cacti, adapted to store water (Souza *et al.*, 2015).

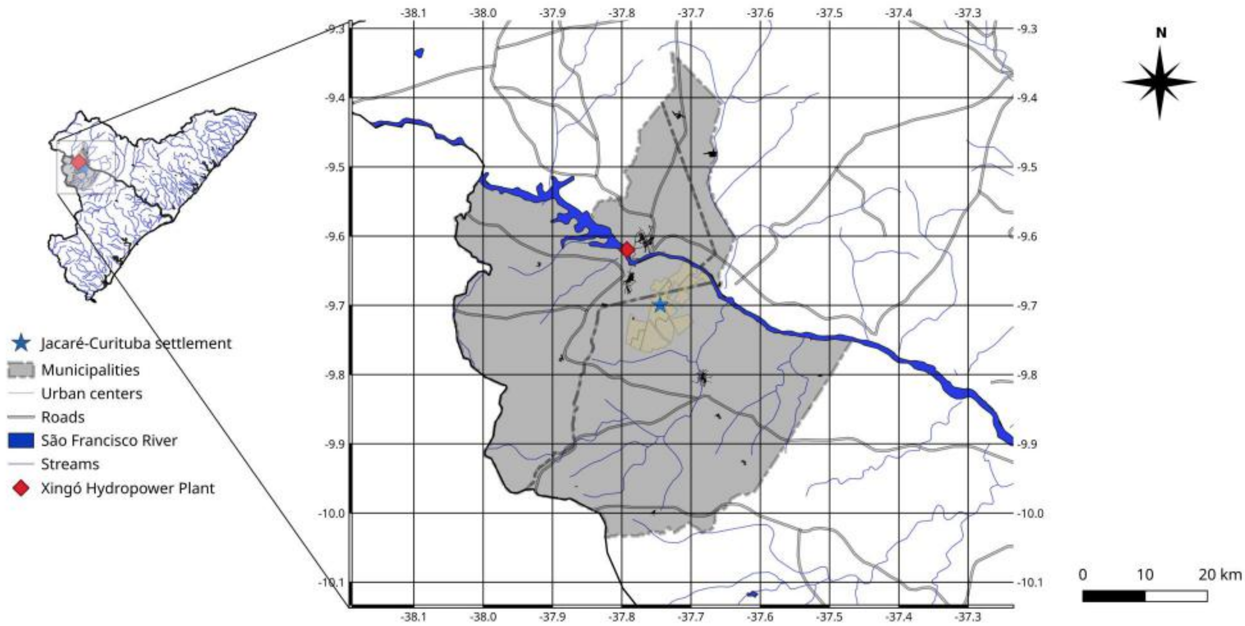

Figure 1: Study area. The location of the settlement is marked with a star. The surrounding municipalities from both states are highlighted.

2.1.1 *Jacaré-Curituba* Settlement

Jacaré-Curituba settlement is located at northwestern *Sergipe* state, between *Poço-Redondo* and *Canindé de São Francisco* municipalities (Fig. 1). It is considered to be the largest irrigated settlement made for land reform in Latin America, with 3,105 ha of which 1,860 are irrigated. There are 720 families living there, and 686 have access to irrigation. The utilized systems are drip and micro sprinkler irrigation, which have been implemented since 2002 (Barros et al., 2017). The water comes from Xingó Dam, which is pumped to a reservoir. It is then distributed to the farmers through a channel and smaller pumps.

The electricity is provided by its hydroelectric plant. The energy that powers the major pumps to supply the reservoir is paid by the government, but the energy consumption of the smaller pumps and the cooperative is responsibility of the local residents. The water provides for a variety of crops, such as cassava, corn, beans, okra, banana, guava and acerola cherry. Conventional crops using pesticide and fertilizer use are the most common in the region. Temporary crops, such as cassava, corn and beans are planted using crop rotation. Livestock representatives breeded in the region are sheep, goat, chicken and cattle.

2.1.2 COOPAC

COOPAC (Agroindustrial Production and Commercialization Cooperative of *Sergipe* State) is a cassava processing cooperative inside the settlement and is composed of a factory, an office and a market (Fig. 2). The factory has a capacity to maintain three tons of cassava roots in its cold room (working at 5 - 10^{o}C), it also has other electric equipment to peel, liquefy, seal, bake and make ice. They have three trucks, one of which is refrigerated and fueled by CNG. Its main products are peeled cassava roots ready to cook and flour, but other products such as cakes and fruit juices are also made by order.

They are responsible for processing 15 tons of cassava roots monthly to supply the market, restaurants, hospitals and schools. The cooperative's energy consumption is near 1,450 kWh per month, with an energy cost of $ 0.75 BRL per kWh, which is considered high for the local living standards.

(a) COOPAC Factory (b) Cassava and Maize crops

(c) Settlement reservoir (d) *Xingó* Dam

Figure 2: *Jacaré-Curituba* Infrastructure and *Xingó* Hydropower.

2.2 On-Grid Solar System

Solar energy is a renewable and clean source of electricity, which makes it a good sustainable technology to adopt where the irradiation is sufficient. Solar systems are able to directly capture solar irradiance and transform it into electricity through Photovoltaic (PV) panels. Other parts of the world are using this technology with variable success in minimizing expenditures (Moury and Ahshan, 2009; Ajan and Kumar, 2015). The conversion efficiency is measured by the proportion of solar irradiation incident on the surface of a cell that is converted into electrical energy. The photovoltaic module is formed by several photovoltaic cells, the smallest component that is sold commercially.

The Solar On-Grid system's representation is illustrated in Fig. 3.

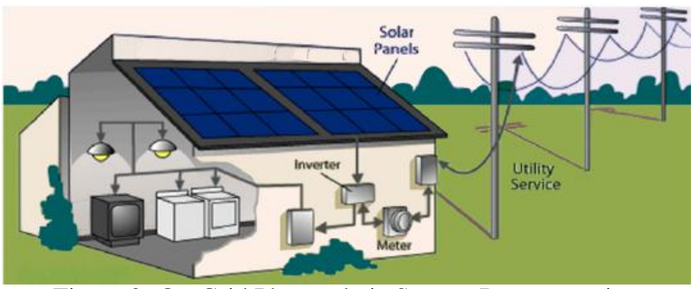

Figure 3: On-Grid Photovoltaic System Representation

The Solar On-Grid system has the following components: Photovoltaic modules connected to an inverter. Inverter (Grid-Tie) that converts direct current (DC) electricity from the PV system of the system to alternating current (AC) and vice versa.

2.2.1 Solar Energy Resources

The map shown in Fig. 4 represents the global horizontal irradiation at the settlement. A great solar potential was found in the locality, ranging from 1,900 to 2,100 W/m^2, thus energy could be produced efficiently using PV panels.

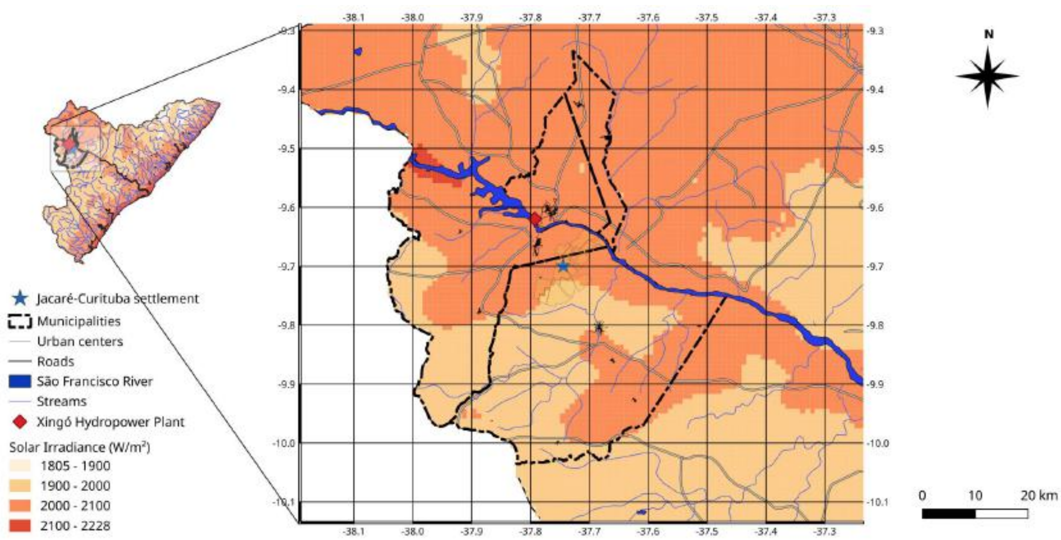

Figure 4: Solar irradiance *Jacaré-Curituba* settlement and vicinity, which represents the power potential for photovoltaic panels.

Solar irradiation and clearness index within the *Jacaré-Curituba* settlement are shown in Fig. 5. The monthly average solar radiation at the settlement is 5.5 kWh / m^2 / day. The index of clearness in the locality ranges from 0.5 to 0.6, considering that this index serves as an indication of the atmospheric conditions, showing with greater clarity the variations of the global radiation in function of several climatic factors.

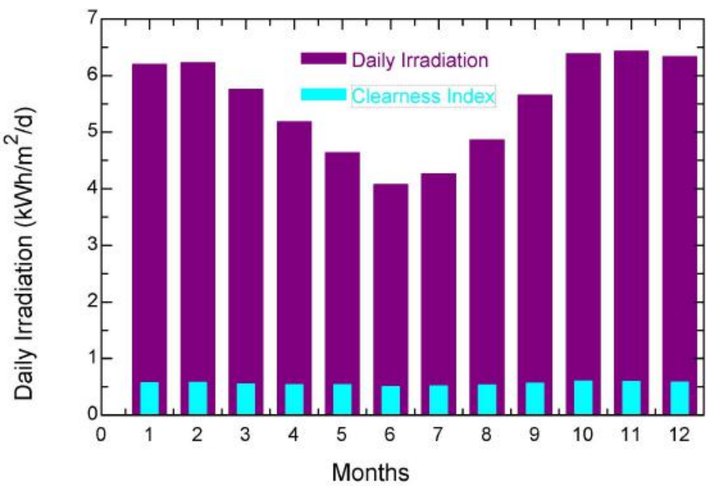

Figure 5: Solar irradiation and clearness index within *Jacaré-Curituba* settlement.

2.3 Modelling Tools

2.3.1 OnSSET Model

The dESA team from KTH Royal Institute of Technology developed a model written in Python, namely OnSSET (Open Source Spatial Electrification Tool), which offers integration with QGIS. Through PyQGIS, transformation of GIS layers data to a table, serving as input for OnSSET model and the given results can be visualized in QGIS. The model identifies the most appropriate electrification alternatives spatially, assuming the lowest cost one as the most suitable to a region. Costs depend on local resources, topography, infrastructure, electrified population and power demand (Mentis *et al.*, 2017b; Moksnes *et al.*, 2017). The OnSSET - QGIS framework was used to evaluate the most viable power sources spatially in the municipalities located at the vicinity of the settlement in *Alagoas* and *Sergipe* states.

This model takes into account the target level and quality of energy access, categorized in "tiers" defined in SE4ALL (Tab. 1) - Sustainable Energy For All - which is a theoretical framework that justified SDG 7 (WBG, 2015). Population density, local electrification infrastructure, planned transmission network and night light are used to classify between electrified and unconnected households. Population data is also estimated to the year 2030 in order to calculate future energy demands to be supplied. Geospatial factors such as topography, proximity to land cover, roads and substations affect the initial investment costs, especially in the network extension. Local availability of energy resources also affects the Levelized Cost of Electricity (LCOE).

Table 1: Levels of consumption based on the Multi-Tier Framework of energy access, in kWh per capita and year adapted from Mentis *et al.* (2017b).

Level of Access	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Consumption	8	44	160	423	598

As the model output both LCOE and total cost per connection of each cell in the grid are calculated, which determines the least cost generating technology assumed to be the most adequate to adopt (Mentis *et al.*, 2015; Nerini *et al.*, 2016).

2.3.2 HOMER Model

The HOMER (Hybrid Renewable Energy Optimization Model) is a computational model developed to design microenergy systems. It models the physical behavior of a microenergy system and its lifecycle cost, which is the total cost of installing and operating the system over its lifetime. It also determines several other types of system costs, such as Net Present Cost (NPC) and Cost of Energy (Bhatt *et al.*, 2016).

It can model microenergy systems connected or not to the network that meet electrical and / or thermal loads, and comprising any combination of photovoltaic modules, wind turbines, biomass energy, alternating motor generators, and other sources.

2.4 Designing the Photovoltaic System

Figure 6 describes the proposed system for COOPAC, consisting of photovoltaic panels, grid-tie inverter, power grid, inputs loads and solar irradiation. The project was designed to meet the cooperative's electrical needs, such as lighting, refrigeration and work equipment. The electrical load is 25 kWh/d and its power peak 3.7 kW. Total system power is calculated with Eq. (1), the designed system power is 17,1 kW:

$$P = \frac{[I_s * A * \eta_m * L] * N_m}{NHS} \quad (1)$$

Where I_s is Daily Irradiation (kWh / m^2 / d), *A* is the Module Area (m^2), η is the Module Efficiency, *L* are the System Losses, N_m refers to the Number of Modules and *NHS* means the Number of Solar Hours.

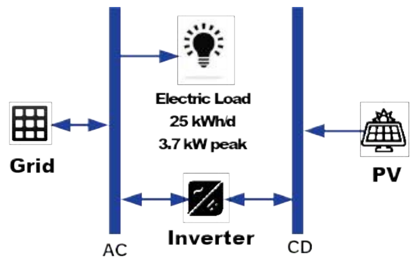

Figure 6: On-Grid Photovoltaic System Design.

2.4.1 Electrical Load

In order to simulate the most adequate configuration for the system we estimated COOPAC's usual energy consumption data through equipment load and time of use. A load profile that represents the energy consumption during the twenty-four hours of a normal day of work in the cooperative was considered (Fig. 7). Consumption is estimated at 10 kWh / day and with a peak of 1.18 kW.

During the period from 7:00 p.m. to 5:00 p.m., when the cooperative is not yet in operation, consumption varies from 0.22 kW to 0.15 kW due to the operation of the cold room, mainly. In the period from 06:00 to 18:00 the load increases considerably due to the use of equipment, lighting and cold chamber opening.

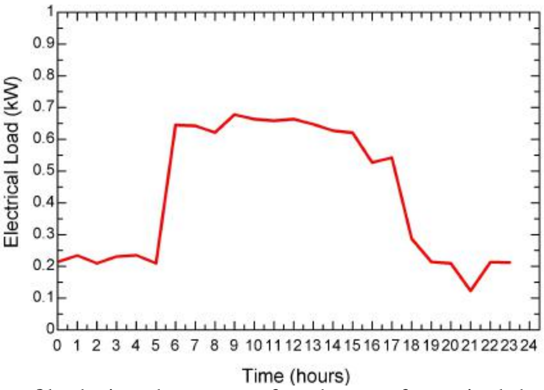

Figure 7: Energy consumption profile during the twenty-four hours of a typical day of work at COOPAC's factory.

2.4.2 Payback Analysis

The economic viability of the project was evaluated by using the Payback Analysis using HOMER results as input. This method calculates the difference between Cumulative Benefits from Costs.

Calculating the costs involves summing Initial Costs (IC), occasional Replacement of equipment (R), regular Operation and Maintenance (O & M) and Fuel (F) for every part of the system - PV Panels, Inverter and Grid consumption. As solar panels don't need paid fuel, this cost is zero. The benefits come from energy savings each month and the salvage cost at the last year of the life cycle of the system. These calculations are done for each year until the end of the life cycle of the system and then cumulatively summed.

Then we can calculate the Net Cumulative Balance or Cash Flow by subtracting costs from benefits. When the difference between benefits and costs is zero, we know when that the system has paid itself, which is called Payback Period. The unit of money is in year-zero USD (07/04/2019), without any discount rate.

3. RESULTS

3.1 Optimal Technology Split

Figure 8 shows the least cost electrification solutions for each cell. As expected by the high solar potential and low energy demands, autonomous photovoltaic generation is a good alternative for the region, especially for locations far from urban centers of the municipalities. Other parts of the settlement are appropriate for this technology as well, and could be implemented to mitigate energy costs.

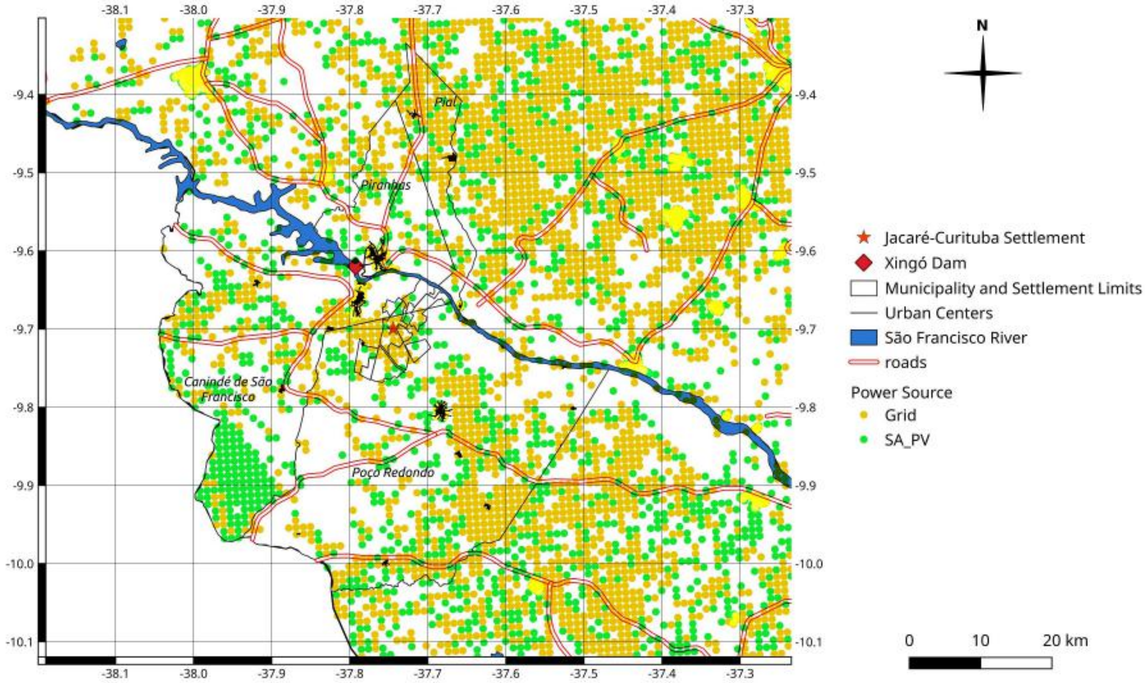

Figure 8: Optimal split for the highest rural and urban demands for *Jacaré-Curituba* settlement and vicinity.

3.1.1 Economic Viability Analysis

The optimized results of the economic viability analysis of this simulation are shown in Tab.2. The HOMER computational tool compared between different configurations and considered the first to be the most viable due to its lower starting capital cost.

Table 2: HOMER simulations output of the costs and load fraction attended by different configurations of PV systems. A grid of 25 kW was considered.

PV Power (kW)	Inverter Power (kW)	Initial Cost (USD)	Annual Operation Cost (USD)	Net Present Cost (USD)	Cost of Energy (USD/kWh)	Load Attended (%)
5	2	5,362	129	7,011	0.15	0.86
5	4	7,628	132	9,310	0.2	0.86
10	2	8,457	107	9,824	0.211	0.93
10	4	10,723	3	10,757	0.231	0.93
5	6	9,895	188	12,303	0.264	0.86
10	6	12,990	-25	12,670	0.272	0.93
5	8	12,162	245	15,299	0.328	0.86
10	8	15,257	8	15,355	0.329	0.93

The most feasible configuration has a 5 kW power photovoltaic panel and a 2 kW grid-tie inverter. Its initial cost is 5,362 USD. The attended fraction of the load is 86 %, while the remaining would be supplied by the grid. This means a 86 % of COOPAC's annual direct savings in electricity. The electricity produced generates an excess that represents 17.6 % of the load needed to be met. The excess of 2,080 kWh per year could be injected into the grid.

The net balance is positive within two years after the adoption of the PV system (Fig.9). This means that by investing on the system, COOPAC would save more money than depending on the current grid. As the system's life cycle is 25 years, it is expected to have saved more than $ 200,000 BRL in 2019 money, enough to invest in a more efficient system in the future.

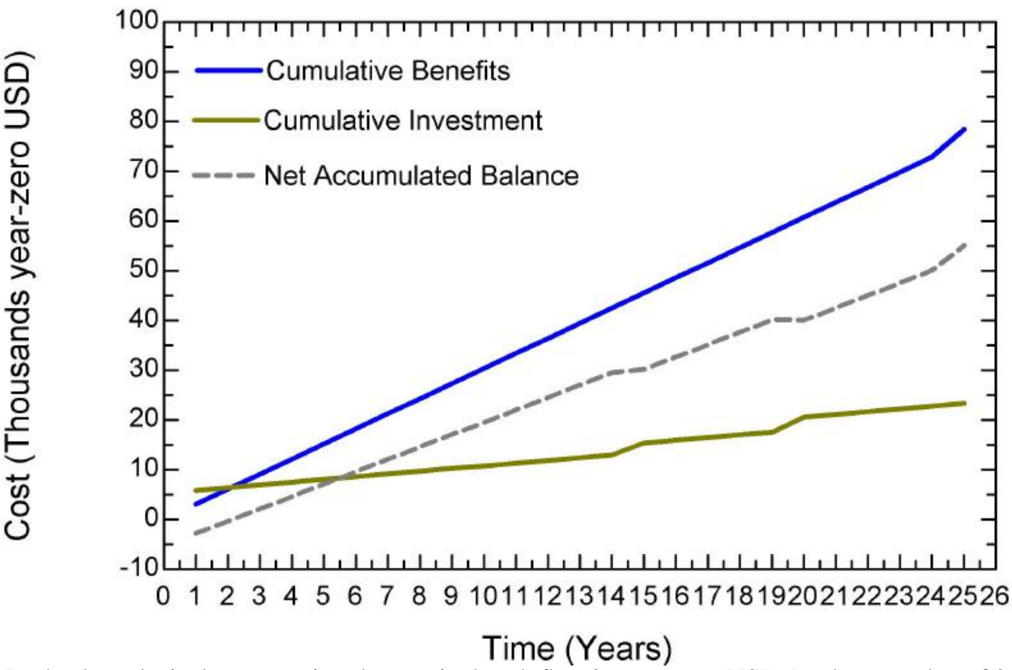

Figure 9: Payback analysis demonstrating the nominal cash flow in year-zero USD (exchange value of 3.8 BRL to 1 USD - from 07/04/2019).

This analysis takes into account the total investment of the PV system and the remaining 14 % of the load supplied by the grid. The investment includes initial, O&M and replacement cost. Benefits come from grid savings along with salvage revenue. After two years and a few months the investment will have been paid.

Besides, this configuration would stop the 1,314 kg / year and 5.7 kg / year emissions in CO_2 and in SO_2, respectively. Other configurations had superior load compared to this configuration, but in terms of costs they might not be feasible since it is a small business and in a low-income location.

4. CONCLUSION

This research presented an energy plan coupled with economic viability analysis for a clean-energy generating system based on photovoltaic panels for COOPAC. It would cost 5,362 USD to implement in order to attend 86 % of the demanding load.

Considering the local reality, the initial cost is high. Even so, when accounting for the 25 years lifespan of the system, it becomes more affordable than depending only on the grid. This way, it is possible to recover the investment in under two years by adopting this solution. The photovoltaic panels generates energy intermittently because it works only when the sun is shining on them. This is not a problem for photovoltaic systems connected to the grid, because any additional required demand is automatically delivered to the consumer by the utility. In the case of autonomous systems, batteries are used and these could be acquired to store the excess energy for later use.

According to our simulations, the proposed photovoltaic system is capable of attending 86 % of the energy demand, while the rest would be supplied by the grid when solar irradiation is low (at night or because of bad weather conditions). There is a positive net balance after just two years and a half of the adoption. As the lifespan of the system is estimated to be 25 years, the amount saved would be above $ 200,000 BRL. This would make investments possible in other sectors and in a newer and more efficient system in the future.

Finally, unlike the electricity purchased monthly from an electric company, photovoltaic energy requires an initial investment that is usually high for the region standards. Tax incentives may include an exemption from sales tax on the purchase of the photovoltaic system, property tax or personal income tax. These incentives provide an economic benefit to consumers by reducing the capital costs and enabling sustainable clean energy mainly in areas of low income.

Besides, there are environmental gains as well. The system would reduce GHG emissions in 1.314 ton of CO_2 and 5.7 kg of SO_2 per year if compared to the actual source of energy for the same consumption. Regarding social gains, the settlement population would have energy to irrigate their crops and process their products without heavy energy costs.

5. ACKNOWLEDGEMENTS

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