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OPTIMIZATION OF A STANDALONE PV-WIND-DIESEL-BATTERY HYBRID SYSTEM FEASIBLE FOR A UNIVERSITY RESTAURANT IN RECIFE, BRAZIL

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Abstract. This paper presents a feasible study to determine the best configuration of a standalone hybrid renewable energy system (HRES) for the University Restaurant (RU) of the Federal University of Pernambuco (UFPE). The proposed work utilizes a hybrid solar-wind system with diesel generator and/or battery backup. The solar radiation and wind data were obtained from NASA surface meteorology and solar energy database. The Hybrid Optimization Model for Electric Renewable (HOMER) software was used to do the simulations and techno-economic evaluation. Many different cases have been carried out to find the optimal configuration based on the net present cost (NPC) and cost of electricity (COE). Results indicated that a system with PV panel, diesel generator, and battery is the most economically viable option. However, the second option was selected, since it is more environmentally correct, with a renewable fraction of 54% of power production, and 16.3% of excess of electricity. The system contains PV panels, wind turbines, diesel generator and a battery bank for backup. It is also economically viable with the NPC of \$1,173,037 and a COE of \$0.5/kWh. In addition, the result shows that this system reduces the emission of pollutants such as CO₂ when compared with the system without wind turbines.

Keywords: University restaurant (RU); hybrid system; HOMER software.

1. INTRODUCTION

In recent years, global warming which is caused by emissions of greenhouse gases along with other air pollutants has become a significant concern for humanity (Fazelpour, *et al.*, 2014). Due to these environmental concerns, implementing sustainable energy strategies is one of the most important aspects for a sustainable world (Akyuz, *et al.*, 2011). With the increasing knowledge in new sources of energy supply, many people and companies around the world have seen the usage of renewable energies as something friendly and environmentally correct. Recent developments in renewable generation technologies allows the use of natural resources (wind, hydro, or photovoltaic (PV)) as alternative energy sources, but their intermittency typically results in inadequate energy supply for a substantial proportion of the year (Gan, *et al.*, 2015). According to Bentouba and Bourouis (2016), the lack of solar energy during the night and the lack of wind energy for a few hours during the day makes hybrid configurations more attractive for electricity supplies,

which rely on renewable energy sources. HES (hybrid energy systems) are becoming energy systems of choice for stand-alone applications due to ever increasing fuel costs and global concern on GHG (Green House Gas) emissions (Perera, *et al.*, 2013). In addition, choosing this type of systems usually implies lower costs and demonstrates higher reliability than photovoltaic (PV) or wind systems. The most commonly used systems are PV–Wind–Battery and PV–Diesel–Battery (Bernal-Agustín and Dufo-López, 2009). Therefore, the combination of one source of energy generation with a different one overcomes the weakness of each source working individually due to their intermittency during the seasons of the year.

Researchers have been using softwares to find the best combination of HES. In order to develop a HES model to identify the economic configuration of PV and Wind energy with Diesel generation and batteries' banks, the Hybrid Optimization Model for Electric Renewables (HOMER) has been used (Sandeep and Vakula, 2016). HOMER is a tool developed by National Renewable Energy Laboratory, USA, in 1992, which is the most used tool for the system optimization by the researchers (Khan and Iqba, 2005; Bernal-Agustín, *et al.*, 2006; Bekele and Palm, 2010). It is an optimization software package, which can handle different technologies (including PV, wind, hydro, fuel cells, and boilers) and evaluate design options for both off-grid and grid-connected power systems for remote, stand-alone, and diesel generation applications (Mamaghani, *et al.*, 2016). The program simulates the operation of thousands of different system designs, with and without a backup generator. It is then able to identify the least cost system as a function of load size and other variables (Lilienthal and Givler, 2005). HOMER models the physical behavior of the power system and its life-cycle cost, which is the total cost of installing and operating the system over its life span. The variable, which HOMER uses to represent the life-cycle cost of the system, is the total net present cost (NPC). This single value includes all costs and revenues that occur within the project lifetime, with future cash flows discounted to the present. The total net present cost includes the initial capital cost of the system components, the cost of any component replacements that occur within the project lifetime, the cost of maintenance and fuel, and the cost of purchasing power from the grid (Lambert, *et al.*, 2006).

In this paper, we are interested in determining the feasibility of implementing a stand-alone renewable energy system for the University Restaurant (RU) of the Federal University of Pernambuco (UFPE). The optimization of a RES with different scenarios was considered, which includes the utilization of photovoltaic panels, wind turbine, generator, and battery. The main objective is to obtain a deeply understanding in the application of renewable energy resources in governmental/public buildings. During the investigation, solar and wind data were collected from NASA, and a load model for the restaurant was created based on in the historical consumption and list of equipment utilized. To obtain the optimum configuration, HOMER is used to simulate and find the best option with low cost to implement, based on the net present cost (NPC) and the cost of electricity (COE).

2. METHODOLOGY

2.1 Location and description

The University Restaurant of the Federal University of Pernambuco was selected in this study. As shown in Fig. 1, its geographical location is 8°03'03.6"S 34°57'10.8"W. This restaurant was established in 2011 with an area of 1,292 m², and it has a capacity of serving up to 550-seated people. Daily, from Monday to Friday, meals are served in the breakfast (up to 500), lunch (up to 3,000), and dinner (up to 1,500) (UFPE, 2017; Santos, *et al.*, 2015).

2.2 Electrical load

Although there is equipment that requires a certain thermal demand, the main equipment at the University Restaurant requires electrical demand. A private company called CELPE (Energy Company of Pernambuco) provides electricity for the entire university as well as for the restaurant. Electrical appliances and their parameters were obtained based on data collected by interviews on the site (Lamp: 154 units; Air conditioning: 4 units; Desktop computer: 8 units; Cold room: 5 unit; Mixer: 1 unit; Blender: 3 units). These equipments consume the major part of the electrical load, with an additional consumption of some small equipment like electric mixer (1 unit) and blender (3 units). It is important to mention that the cold rooms and the air conditioning work 24 hours, 7 days a week, in such way that it keeps the perishable foods like meats, well preserved.

Based on the list of equipment mentioned above and on the historical consumption, Table 1, the load profile for one year was obtained as one can see in the Fig. 2. RU has an electrical load, which varies monthly, with more important variations, especially at the beginning, the middle, and the end of the year, for some reasons. At the beginning of the semesters (Jan-Feb, Aug-Sep), the university receives new students (freshman) and they want to have the experience of having meals in this place. At the end of the semesters (Jun-Jul, Nov-Dec), most of the students have tests, so they stay in the university during the entire day. Therefore, the consumption once again increases more than the usual. In this paper, it was not considered the future expansion of the RU and this can be subject for a future work.



Figure 1. Geographical location - University Restaurant (RU).

Table 1. Historical consumption of a year - University Restaurant (RU).

Month	Electrical consumption	
	kWh/mo.	kWh/d
Jul/15	19,283.15	622.04
Aug/15	17,266.51	556.98
Sep/15	16,013.50	533.78
Oct/15	20,129.30	649.33
Nov/15	21,264.14	708.80
Dec/15	20,812.50	671.37
Jan/16	13,739.30	443.20
Feb/16	15,262.80	545.10
Mar/16	16,350.23	527.43
Apr/16	18,374.36	612.48
May/16	19,415.07	626.29
Jun/16	19,947.01	664.90

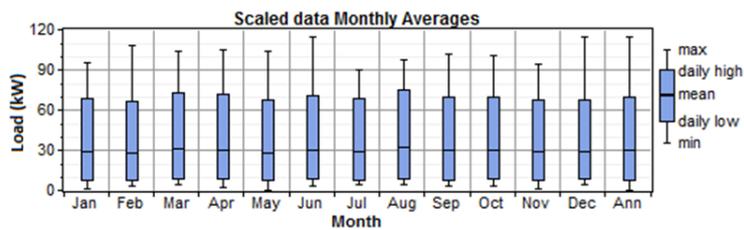


Figure 2. Load profile for one year - University Restaurant (RU).

2.3 Energy sources

Although there is considerable information about solar and wind data for Pernambuco, which is the state where the city of Recife and the university restaurant are located, studies that shows specific values for the location of the restaurant have not been conducted yet. Therefore, the following sub-sections presents in details how these data was collected.

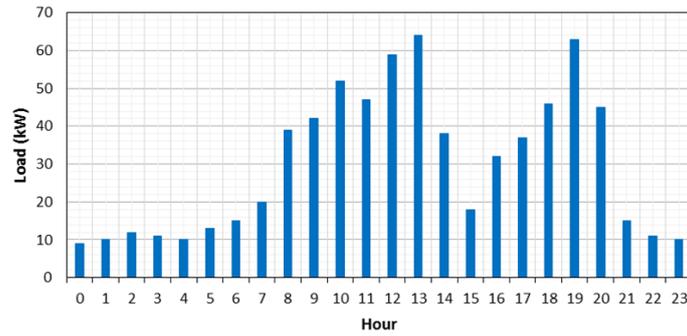


Figure 3. Hourly load data during a year - University Restaurant (RU).

2.3.1 Solar and wind resource assessment

The raw solar resource data input to the HOMER software are the monthly average global horizontal radiation obtained from Atmospheric Science Data Center (ASDC)-NASA surface meteorology and solar energy database for the restaurant location (NASA/SEE, 2016). The data are obtained online by entering the latitude (8°03'S) and longitude (34°57'W), where the restaurant is located. Fig. 4 illustrates Recife's monthly average of two solar parameters (daily radiation and clearness index), which presents the good availability of solar energy throughout the year. The annual average solar radiation for the site where the restaurant is located is 5.89 kWh/m²/day. This value confirms how this place qualifies as a producer of energy.

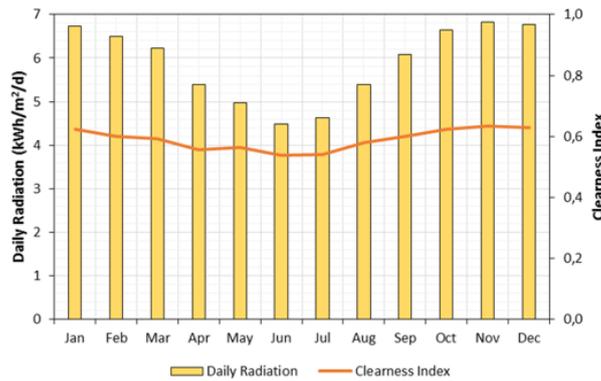


Figure 4. Averaged solar irradiance for Recife.

The electrical energy generation as an output of a photovoltaic system can be estimated as follows (Abdilahi, *et al.*, 2014; Abdilahi, *et al.*, 2016):

$$E = A \cdot r \cdot H \cdot PR \quad (1)$$

where, E = Energy (kWh), A = Total Solar panel area (m²), r = Solar panel yield (%), H = Annual average solar radiation on tilted panels (shadings not included) and PR = Performance ratio, coefficient for losses.

The maximum power from a solar panel can be calculated as (Abdilahi, *et al.*, 2014; Abdilahi, *et al.*, 2016):

$$P_{mp} = \eta_{PV} \cdot G_{\beta} \cdot A \quad (2)$$

where, A is the surface area of a PV module, P_{mp} is the maximum power from a solar panel, η_{PV} is the efficiency of silicon based PV cell and G_{β} is the global horizontal solar irradiance.

Similarly to the data obtained for solar resource, the data for wind resource were obtained from the NASA surface Meteorology and Solar Energy website (NASA/SEE, 2016). Data are collected at 10m height, and the 10 year averaged annual wind speed for the latitude and longitude of the restaurant is 4.15 m/s. This value has a poor resolution probably due to the vegetation and buildings near the restaurant. Fig. 5 illustrates the monthly averaged wind speed at the specific location. As said before, the wind speed is measured at 10m height. From the figure, the months of September and October have the maximum measured wind speed of 4.5 m/s, and the lowest value is measured in March, which is 3.51 m/s.



Figure 5. Monthly averaged wind speed at Recife.

2.4 Economic model

The economic model for HOMER simulation is developed using the net present cost (NPC) which is the total cost of installing and operating the system over its lifetime. HOMER models each individual system by performing an hourly time-step simulation for one year (NREL, 2005). In addition, economic analysis is very essential to suggest an optimal combination of components in the HRES. Ramli, *et al.* (2016) calculates the total NPC of a system by:

$$C_{NPC,tot} = \frac{C_{ann,tot}}{CRF(i, R_{proj})} \quad (3)$$

where, $C_{ann,tot}$ is the total annualized cost (\$/year), i is the annual real interest rate (%), R_{proj} is the project lifetime (year), CRF represents capital recovery factor. CRF is a ratio given by:

$$CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \quad (4)$$

where N and i are number of years and annual real interest rate respectively.

HOMER uses an annual real interest rate rather than a nominal interest rate in computations (Hossaina, *et al.*, 2017). The annual real interest rate can be obtained from the nominal rate by using (Sinha and Chandel, 2015):

$$i = \frac{i' - f}{1 + f}$$

where i is the annual real interest rate, i' is the annual nominal interest rate, and f is the annual inflation rate.

The average cost per kWh of electricity is called cost of energy (COE). The COE is calculated by dividing total annualized cost by annual electricity supplied to the load, which is defined as follows (Ramli, *et al.*, 2016):

$$COE = \frac{C_{ann,tot}}{E_{served}} \quad (6)$$

CO_2 emissions from the HRES can be calculated according to the following equation (Sinha and Chandel, 2015):

$$t_{CO_2} = 3.667 \cdot m_f \cdot HV_f \cdot CEF_f \cdot X_c \quad (7)$$

where t_{CO_2} is the amount of CO_2 emissions, m_f is the fuel quantity (liter), HV_f is the fuel heating value (MJ/L), CEF_f is the carbon emission factor (ton-carbon/TJ) and X_c is the oxidized carbon fraction.

An important information according to Sinha and Chandel (2015) is that in 3.667g of CO_2 there is 1g of carbon.

2.5 Hybrid System Components

The main system components chosen in this study have been selected based on research in the literature, the availability of products and their prices for the Brazilian market. The criteria used to select those components were the cost of investment, replacement, operation & maintenance (O&M), and lifetime. Additional information about the components used in HOMER are shown in Table 2.

Table 2. The input data of the various components in HOMER (Hossaina, *et al.*, 2017; Ramli, *et al.*, 2016).

	Cost of investment	Cost of replacement	Cost of O&M	Lifetime
PV array	\$ 2000/kW	\$ 1200/kW	\$ 30/kW/yr	30 yr
Wind turbine	\$ 3000/kW	\$ 1500/kW	\$ 40/kW/yr	20 yr
Generator	\$ 220/kW	\$ 200/kW	\$ 0.03/h	15000 h
Inverter	\$ 400/kW	\$ 375/kW	\$ 20/kW/yr	30 yr
Battery	\$ 1200/unit	\$ 1200/unit	\$ 60/unit/yr	12 r

2.5.1 PV modules

Photovoltaic modules produces direct current electricity directly from solar sources and they can charge batteries of 12V. To this work, were selected PV panels from Canadian Solar, which has its PV models certified by the Brazilian accreditation agencies. The model Canadian Solar's Quartech CS6P-265P has a rated power of 265W and 16.47% of efficiency based on stand test condition (STC).

In this study, it was assumed an investment cost of \$2/Wp (including PV panel and installation costs). The cost of replacement and O&M were of \$1.2/Wp and \$0.03/Wp, respectively (Table 2) (Ramli, *et al.*, 2016). A derating factor of 80% was employed in this study (Lambert, *et al.*, 2006). The lifetime of the PV modules was estimated to be 30 years and no tracking system was used.

2.5.2 Wind Turbines

Unlike windmills, which are used directly to produce work such as water pumping or grain grinding, wind turbines are used to convert wind energy to electricity (Tong, 2010). The wind turbine selected in this simulation is obtained from the Ennera Energy and Mobility S.L, a company established in Spain. The Windera S model is a 3 blade, horizontal axis with a rated capacity of 3.2 kW (Enera energy, 2017). The power coefficient and the wind turbine power curve, which has the cut-in and cut-out wind speed of 3 m/s and 25 m/s, respectively. The costs associated with investment (all parts of the wind turbine and installation), replacement, O&M were considered as \$3/Wp, \$1.5/Wp, and \$0.04/Wp respectively (Table 2) (Ramli, *et al.*, 2016). Manufacturer estimates the lifetime of 20 years for the wind turbine.

2.5.3 Diesel generator

Diesel generators have been widely employed along with renewable sources in RES to increase the reliability of such systems (Mamaghani, *et al.*, 2016). A diesel generator, model Cummins, is used in this study. The initial capital cost of the generator was assumed to be \$220/kW, and the replacement cost and O&M are \$200/kW and \$0.03/h respectively (Table 2). The cost of diesel per liter is assumed to be \$0.8. The operating lifetime of the generator was considered to be 15,000 h, and it has a minimum load ratio of 25% (Hossaina, *et al.*, 2017).

2.5.4 Batteries

To this study, it was selected a L16P Trojan Battery (Trojan battery, 2017). HOMER has this model, which become easier to work with, and which is found in the market. The capital cost and replacement for Trojan L16P is \$1200/unit, and the cost of O&M is \$60/unit/yr (Table 2) (Hossaina, *et al.*, 2017).

2.5.5 Inverters

A converter is a device that converts electric power from DC to AC in a process called inversion (Lambert, *et al.*, 2006). The inverter is one of the key components of the system as it converts the DC electricity produced by the PV modules into AC electricity (wind turbines are not considered since they already have the inverter included in the capital cost and the diesel generator produces AC voltage) (Mamaghani, *et al.*, 2016). The inverter used in this work was selected from Ramli, *et al.* (2016), with the capital cost of \$400/kW, the replacement cost of \$375/kW, and the cost of O&M of \$20/kW/yr. The lifetime was assumed to be 30 years (Table 2).

2.6 HOMER model design

The general scenario of the hybrid renewable energy system was firstly designed with photovoltaic panels, wind turbine, diesel generator, battery, converter and an AC load profile as shown in Fig. 7. The hourly load data of one year based on the historical consumption, the monthly average wind speed and the solar irradiance are the input data to HOMER. The project lifetime is assumed to be 25 years and the annual interest rate is taken as 10% with an inflation rate of 2%. All this data was presented previously. The values attributed in HOMER need to be in US dollar, then, those values in Table 2 are consistent with the Brazilian market and the literature.

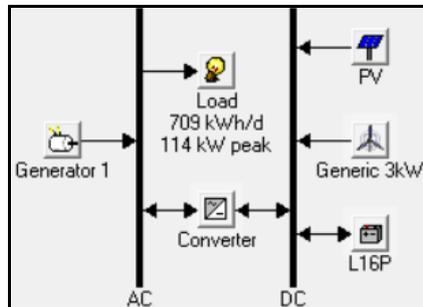


Figure 7. Schematic diagram of the proposed system.

To optimize each combination, HOMER sets all possible system configurations based on the data attributed by the user, specifying the range that each component can vary, and then, it simulates the best configuration by the net present cost. The user can add or remove these values in an appropriate window. For this simulation, Table 3 presents the sizes of equipment considered in the optimization.

Table 3. Equipment's sizes considered in the optimization.

PV array (kW)	0-120 (step of 10)
Wind Tur. 3kW (unit)	0-24 (step of 2)
Generator (kW)	0-100 (step of 20)
Battery L16P (unit)	0-84 (step of 12)
Converter (kW)	0-84 (step of 12)

3. RESULTS AND DISCUSSION

3.1 Optimization results

According to the HOMER software, 64896 simulations were run with different configurations. Based on the net present cost (NPC), the software found eight best configuration, changing the utilized equipment and its quantities. Fig. 8 shows the optimization results in the categorized form, which includes the best optimal system configurations, from lowest NPC to highest NPC.

	PV (kW)	G3 (kW)	Label (kW)	L16P (unit)	Conv. (kW)	Initial Capital (\$)	Operating Cost (\$/yr)	Total NPC (\$)	COE (\$/kWh)	Ren. Frac.	Diesel (L)	Label (hrs)
	100	60	48	72	\$ 299,600	82,246	\$ 1,046,152	0.445	0.53	66,729	5,803	
	100	2	60	48	\$ 419,600	83,005	\$ 1,173,037	0.500	0.54	64,888	5,649	
			80	36	\$ 70,400	136,454	\$ 1,309,001	0.557	0.00	123,631	7,905	
		2	80	36	\$ 190,400	137,135	\$ 1,435,176	0.611	0.02	121,230	7,774	
			100		\$ 22,000	160,938	\$ 1,482,838	0.631	0.00	154,469	8,760	
	120		100		\$ 290,800	131,789	\$ 1,487,056	0.633	0.46	119,501	7,261	
	120	2	100		\$ 410,800	133,174	\$ 1,619,621	0.690	0.47	118,752	7,229	
		2	100		\$ 144,400	162,630	\$ 1,620,602	0.690	0.02	153,719	8,759	

Figure 8. Optimization results in the categorized form for the proposed system.

From the simulation, as one can see in the above figure, the optimal solution based on the NPC is compound by 100kW PV panel, 60kW diesel generator, 48 batteries and 72kW converter. In this first case, the NPC of the system is \$ 1,046,152; in addition, the COE is \$ 0.445/kWh with a renewable fraction of 53%. The generator needs 66,729 liters per year of fuel consumption, and this can be a disadvantage when the environmental concern is considered.

Fig. 9 shows the cash flow summary, where the diesel generator (label) presents the highest cost of \$ 630,489 while the converter has the lowest cost of \$ 47,504. The reason is the high consumption of diesel, corresponding to \$ 484,563, which is 76.86% of all the cost associated with the generator.

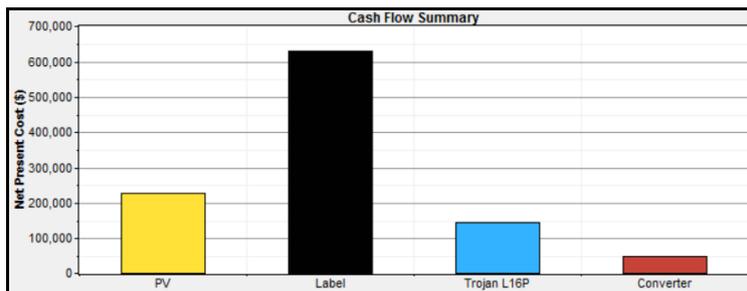


Figure 9. Cash flow breakdown by components for the 1st case.

Fig. 10 illustrates the monthly average electric production for the first case. In this case, the PV array provides 53% of electricity, which is 171,876 kWh/yr, and the generator provides the complement of 47%, that is 155,492 kWh/yr. The total annual production of electricity is equal to 327,369 kWh. The annual consumption of AC primary load is equivalent to 258,715 kWh/yr. At the end of the year, this configuration produces 52,589 kWh in excess of electricity, which represents 16.1%.

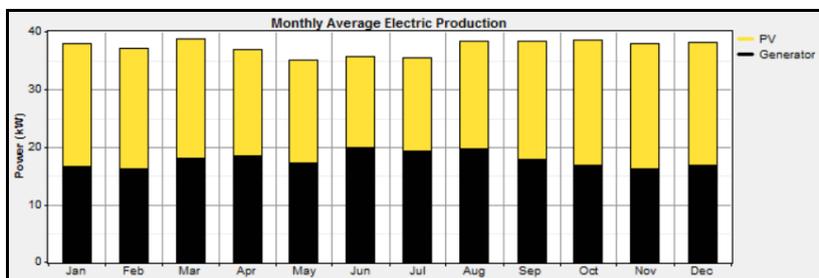


Figure 10. Monthly power production from different sources for the 1st case

The second case differs from the first case due to the addition of wind turbines. The configuration in this second case is compound by 100kW PV panels, 2 wind turbines, 60kW diesel generator, 48 batteries and 72kW converter.

From Fig. 8, the NPC for this second case is equal to \$ 1,173,037, an increase of \$ 126,885 when compared to the first case. This is because of the high initial cost of \$ 419,600. The levelized cost of electricity (COE) and the operating cost are a little bit more expensive, with \$ 0.5/kWh and \$ 83,005/yr respectively. However, this system has a renewable fraction of 54%, which is bigger than the renewable fraction of the first case. Additionally, the fuel consumption is lower for this case, with the annual consumption of 64,888 liters.

For the second optimized system yet, Fig. 11 shows the cash flow summary, where the diesel generator (label) still presents the highest cost of \$ 613,442 and the converter still has the lowest cost of \$ 47,504, which is the same of the first case. The reason is still due to the high consumption of diesel, corresponding to \$ 471,196, which is 76.81% of all the cost associated with the generator.

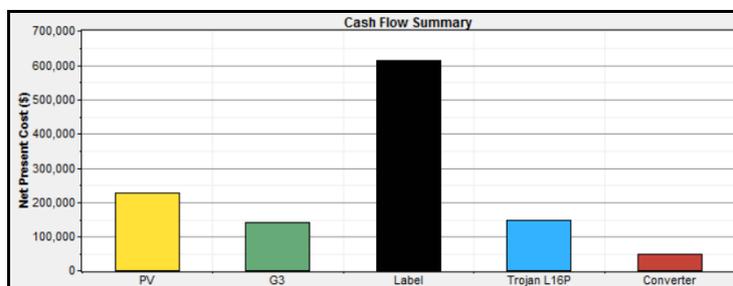


Figure 11. Cash flow breakdown by components for the 2nd case.

The advantage of the second case is the increasing in the renewable energy percentage. Fig. 12 illustrates the monthly average electric production for the second case. The PV array and the wind turbines produces 171,876 kWh/yr (52%) and 5,787kWh/yr (2%) respectively. This represents a production of 54% of renewable energy. The diesel generator produces 151,085 kWh/yr of electricity. Then, the total annual electricity production is equal to 328,749 kWh/yr. The annual consumption of AC primary load is equivalent to 258,716 kWh/yr, which is the same for both cases. At the end

of the year, this configuration produces 53,707 kWh in excess of electricity, which represents 16.3% and it is a bit more than in the first case.

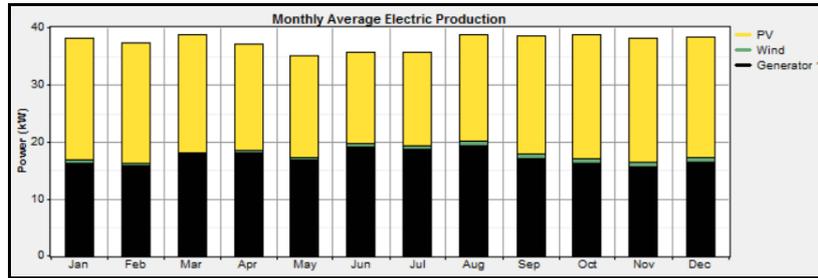


Figure 12. Monthly power production from different sources for the 2nd case.

Table 4 shows the amount of harmful emissions including CO₂, CO, unburned hydrocarbon (UHC), particulate matter (PM), sulfur dioxide (SO₂) and nitrogen oxides (NO) for the first and second optimized system. The CO₂ is the biggest pollutant, with 175,720 kg/yr and 170,873 kg/yr of emissions for the first and second system respectively, while the lowest emissions is due to PM, which represents the amount of 32.7 and 31.8 kg/yr respectively.

Table 4. Harmful emissions

System	Emissions (kg/yr)					
	CO ₂	CO	UHC	PM	SO ₂	NO
1 st case	175,720	434	48	32.7	353	3,870
2 nd case	170,873	422	46.7	31.8	343	3,764

4. CONCLUSIONS

In this paper, an optimization study for the University restaurant (RU) of the Federal University of Pernambuco (UFPE) was conducted to include renewable energy in the actual system. The combination of sources such as solar and wind energy, with diesel generator and battery storage in a standalone system can supply the energy needs to the restaurant without using electricity of private companies. The results obtained by HOMER showed that the best option comprises 100kW PV array, 60kW diesel generator, 48 batteries and a 72kW converter. In this case, 53% of the load is covered by the PV array while the generator covers 47%. However, the best choice is the second option, since it comprises 100kW PV panels, 2 wind turbines, 60kW diesel generator, 48 batteries and a 72kW converter. In this case, there is a reduction in fuel consumption due to the addition of the wind turbines, which contributes with the production of electricity and the reduction of pollutant emissions. To future works, one can use different equipment of others brands to see how the system will performance. As other suggestion, one can make the system grid-connected, and then, make a comparasion.

The proposed system showed by the results presents a cost-effective solution to add a renewable source of electricity for the restaurant. This system has a NPC of \$ 1,173,037 and a cost of electricity of \$ 0.5/kWh. The operating cost is \$ 83,005/yr. The energy produced is enough to supply the needs and generates an excess of 16.3%, which is within the security range. In addition, in this case, 54% of the electricity is provided by renewable sources, where 52% of the load is from the PV array and 2% from the 2 wind turbines. It is important to mention that in the second case the emission of CO₂ is less than in the first case as well as the emission of other pollutants. Then, it is expected that in the future, the rapid development in technologies increase, as well the reduction of taxes by governments for products related with production of renewable energy. Soon, the usage of generators could be reduced by the penetration of renewable products such as photovoltaic panels and wind turbines.

5. ACKNOWLEDGEMENTS

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