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ANALYSIS OF THE ECONOMIC VIABILITY OF RENEWABLE ENERGY RESOURCES IN DISTRIBUTED GENERATION

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***Abstract**. Distributed generation is shown as an alternative to accommodate the expansion of the consumption of electricity in the world, besides providing benefits such as the reduction of transmission and distribution costs, enhanced reliability and generation of work positions. Renewable energy technologies can be considered as a "clean" form of distributed generation because there are no (or minimal) emissions of greenhouse gases during their operation. However, the competitiveness of these renewable energy sources in distributed generation is still questionable when compared to conventional forms of power generation. Thus, an economic viability study becomes necessary. This work carried out an economic viability analysis through an optimization of an energy system, based on linear programming methods, and considering renewable energy resources (solar energy and wind energy) as well as conventional resources (electric grid and fuel line), to meet the energy demands of a consumer center (electricity, steam and cooling). This study presents a methodology for the optimization of energy systems, considering renewable resources, and the results provide information about the economic impact on the use of renewable resources in energy systems, helping in the decision-making process.*

***Keywords**: Renewable energy, Optimization, Linear Programming.*

1. INTRODUCTION

According to Silva (2003), the Brazilian Northeast presents a privileged geographic position, with extensive coastal and mountain areas, and has become one of the most attractive regions for wind energy investments in the world (Abrahao and Carvalho, 2017). Wind power has been experiencing significant growth in recent years: production of electricity from wind power reached 33.489 GWh in 2016, equivalent to an increase of 54.9 % compared to 2017 (EPE, 2018). Wind power accounts for 5.4 % of Brazil's internal electricity supply, but despite its growth, it is still well below the contribution of hydro, 68.1 % (EPE, 2018). Also, the installed capacity is still much lower when compared to the leading countries in wind generation (Martins et al., 2008). Wind power is a temporal and seasonal energy source, which can vary throughout the day and year.

According to Salamoni and Ruther (2007), Brazil is situated in a latitude range where the incidence of solar radiation is much higher than most of the world. However, despite Brazil’s tremendous solarimetric potential, solar energy only represents 0.01% of the internal energy supply (EPE, 2018). The expansion of the utilization of solar resource for electricity and heating purposes is a recent trend. Like the wind, solar radiation is a temporal and seasonal resource, with zero values during a long period (at night).

Although there is clear potential for the utilization of renewable resources in Northeast Brazil, and despite the improvements achieved in energy conversion technologies, decentralized electricity from renewable sources is not a reality yet. Less than 8.5 % of Brazil's power originates from solar and wind resources (EPE, 2018). Any investments in energy projects should be preceded by an optimization study, which ideally considers all possible configurations of the system (different equipment) and also the operational strategy, as some technologies present temporal and seasonal use. The optimization process consists of maximizing or minimizing an objective function in a physical problem, providing a faster solution, with less effort when compared to the trial-and-error method. Linear programming can be employed in the optimization of energy systems, to determine optimal operating conditions and the configuration of an energy system.

In this context, a hospital located in Zaragoza, Spain, was the focus of several economic and environmental optimizations (Lozano et al., 2009; Carvalho et al., 2011;). Buoro et al. (2014) presented an optimization based on mixed integer linear programming (MILP), which optimized the energy to an industrial site located in Northeastern Italy. Energy demands were electricity, heating, and cooling, and the optimal solution integrated conventional energy technologies with renewable energy resources, including solar thermal for heat generation. The optimal synthesis of energy supply systems for remote open pit mines was studied by Romero et al. (2014) a polygeneration optimization technique to a hospital in Northern Ontario. Romero et al. (2016) employed MILP to optimize the design and control strategy of wind-diesel hybrid energy systems for remote Arctic mines, which was preceded by a comparison of the economic benefits of centralized and distributed model predictive control strategies for optimal and sub-optimal mine dewatering system designs (Romero et al., 2015).

Nogueira and Zurn (2005) optimized an energy system in a rural environment with linear programming (LP), considering only renewable energy technologies: photovoltaic panel, wind generator, microcentral hydroelectric, biodigestor, and battery bank. Dicorato et al. (2008) also employed LP to evaluate the contribution of distributed generation to energy efficiency. Araújo et al. (2009) simulated electricity production for several small wind turbines, for the location of Olinda (Northeast Brazil): local wind data presented average speed values of 10 m/s, but the rated wind speed of turbines was at least 12 m/s, and turbines were not able to generate electricity.

Delgado et al. (2018a) presented an analysis of biomass-fired boilers, to be included in the superstructure of a polygeneration system for a hospital in Northeast Brazil. The same location benefitted from an economic optimization that included photovoltaic solar energy for energy supply and conversion (Delgado et al., 2018b). More recently, a building located in João Pessoa (Northeast Brazil) underwent economic optimization to define its optimal configuration and operation (Melo and Carvalho, 2017).

In Brazil, the National Electric Energy Agency (ANEEL) established general conditions for microgeneration and minigeration access to electricity distribution systems and for the electric energy compensation system in Resolution N° 482 of 17 April 2012 (ANEEL, 2012). The electricity compensation system allows the consumer unit with microgeneration or minigeneration to export surplus electricity to the electric grid in exchange for an energy credit, which can be utilized in up to six months. Another consumer unit with the same owner can also benefit from these electricity credits. Consumer units can therefore import and export electricity, opening up new opportunities for benefit and for realized value in comparison to units that operate without connection to the electric grid.

The objective of the study presented here is to identify an optimal solution for a power system and its operation, taking into account the use of renewable resources, cogeneration and the electric energy compensation system.

2. METHODOLOGY

The base system for the study is presented in Figure 1, where: CS is a solar collector, LC is a fuel line, RD is the electric grid, PF refers to photovoltaic panels, EO is a wind generator, CG is a gas boiler, GMG is a motor generator, CRE is a recovery boiler, CA refers to absorption chillers, CC is a mechanical compression chiller, DEV is the steam demand, DAG is the cold water (cooling) demand, CEE refers to electricity credits exported into the electric grid and DEE is the electricity demand.

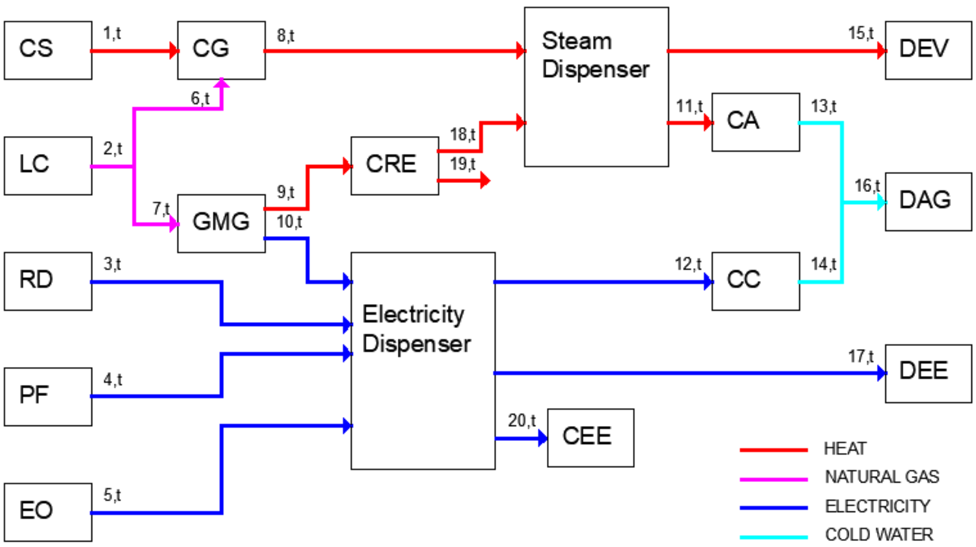

Figure 1. Base System

Due to the seasonality of the wind resource, four days were selected to represent an operational year: two weekdays and two weekend days. Each typical day was divided into eight periods (t) of three hours, totaling 32 periods. The seventh and twenty-third periods correspond to the peak period of the electricity grid. The energy demands vary across the time period, were obtained by Freitas (2016) and are presented in Table 1.

Table 1: Energy demands for the four representative days.

Energy demands for the 1st representative day (first weekday in the first semester) and the 3rd representative day (second weekday in the second semester)			
Time period t	DEV (kW)	DAG (kW)	DEE (kW)
t = 1 (0 to 3h)	0	0	1079
t = 2 (3 to 6h)	0	0	1079
t = 3 (6 to 9h)	1000	1000	1079
t = 4 (9 to12h)	3050	3050	1529
t = 5 (12 to 15h)	3050	3050	1529
t = 6 (15 to 18h)	3050	3050	1529
t = 7 (18 to 21h)	3346	3046	1759
t = 8 (21 to 24h)	2000	2000	1079
Energy demands for the 2nd representative day (first weekend day in the first semester) and the 4th representatives day (second weekend day in the second semester)			
Time period t	DEV(kW)	DAG (kW)	DEE (kW)
t = 1 (0 to 3h)	0	0	1090
t = 2 (3 to 6h)	0	0	1090
t = 3 (6 to 9h)	0	0	1090
t = 4 (9 to12h)	2000	2000	1543
t = 5 (12 to 15h)	3068	3068	1543
t = 6 (15 to 18h)	3068	3068	1543
t = 7 (18 to 21h)	3346	3346	1759
t = 8 (21 to 24h)	1000	1000	1090

The optimization procedure considers all possible scenarios of the energy system and determines the optimal configuration and operation by minimizing the objective function.

The objective function is expressed by Eq. (1), where NPV represents the net present value of the entire cash flow of the system, CI represents the capital cost of the project, CM refers to the monthly cost and μ is the present value factor that is expressed by Eq. (2), were *n* represents the lifetime of the system, 20 years, and *i* represents the interest rate, 0.9525 % a.m.

$$\text{NPV} = CI + \beta.\text{CM} \tag{1}$$

$$\beta = \frac{(1+i)^n - 1}{i(1+i)^n} \tag{2}$$

Multiplication of the present value factor by the monthly cost yields the present value for period *n* at an interest rate *i*. The capital cost (CI) is the overall sum of multiplying the nominal power (kW) of each equipment by its cost factor (R$ / kW), according to Eq. (3). P_X is the nominal power of each piece of equipment X, and K_X is the corresponding cost factor. A fixed set of available nominal power was utilized for the equipment, according to Table 2. For the solar collector, the available range covered area. Nominal power equal to zero was a possibility, which means that the equipment was not installed. Cost factors were obtained from França (2017) and are shown in Table 3.

$$CI = P_{CL}K_{CL} + P_{LC}K_{LC} + P_{RD}K_{RD} + P_{PF}K_{PF} + P_{EO}K_{EO} + P_{CG}K_{CG} + P_{GMG}K_{GM} + P_{CRE}K_{CRE} + P_{CA}K_{CA} + P_{CC}K_{CC} \tag{3}$$

Table 2: nominal power

Equipment	Nominal Power (except CL)					
CS (m²)	0	3200	6400	-	-	-
LC (kW)	∞	-	-	-	-	-
RD (kW)	∞	-	-	-	-	-
PF (kW)	0	5550	11000	-	-	-
EO (kW)	0	2400	4800	-	-	-
CG (kW)	0	734	1468	2202	2936	3670
GMG (kW)	0	2252	4504	-	-	-
CA (kW)	0	3500	-	-	-	-
CC (kW)	0	3500	-	-	-	-
CRE (kW)	0	2317	-	-	-	-

Table 3: Cost factors

Equipment (X)	Cost Factors (K_X)

CS (R$ / m²)	1000
LC (R$ / kW)	580
RD (R$ / kW)	164
PF (R$ / kW)	10610
EO (R$ / kW)	12000
CG (R$ / kW)	504
GMG (R$ / kW)	1652
CA (R$ / kW)	3452
CC (R$ / kW)	2820
CRE (R$ / kW)	880

The monthly cost represents the costs related to the consumption of natural gas and electricity (operation-related costs) and can be expressed by Eq. (4). Tariff data were obtained from Souza (2017) and are presented in Table 4. For simplicity purposes, the electricity tariff is a combination of the consumption and demand tariffs.

Kcomb represents the fuel tariff (R$ / kW), X_2 represents the power at 2, H (t) indicates a peak or off-peak period, K_{HP} is the peak electricity tariff, K_{FP} is the off-peak electricity tariff, and X_3 is the power at 3.

$$CM = (24 * 21 + 24 * 9)K_{comb}X_{2,t} + [(3 * 21)H(t)K_{HP} + (21 * 21 + 24 * 9)\big(1 - H(t)\big)K_{FP}]X_{3,t} \tag{4}$$

Table 4: Tariff data

Parameter	Tariff
Kcomb (R$ / kWh)	0.2025
K_{HP} (R$ / kWh)	1.8111
K_{FP} (R$ / kWh)	0.2304

The restrictions of the problem are obtained from energy balances at different points of the system. These restrictions are represented by Eq. (9), where: $X_{n,t}$ with n varying from 1 to 19 being the power points of the system in period t (according to Figure 1); η_{CG} is the efficiency of the gas boiler; η_{GMGel} is the electrical efficiency of the motor-generator group; η_{GMGter} is the thermal efficiency of the motor-generator group; COP_{CA} is the COP of the absorption chiller; COP_{CC} is the COP of the compression chiller, and η_{CRE} is the efficiency of the recovery boiler.

$$X_{8,t} + X_{18,t} - X_{15,t} - X_{11,t} = 0 \tag{9.a}$$

$$X_{2,t} - X_{6,t} - X_{7,t} = 0 \tag{9.b}$$

$$X_{3,t} + X_{4,t} + X_{5,t} + X_{10,t} - X_{12,t} - X_{17,t} - X_{20,t} = 0 \tag{9.c}$$

$$\eta_{CG}X_{6,t} + X_{1,t} - X_{8,t} = 0 \tag{9.d}$$

$$\eta_{GMGel}X_{7,t} - X_{10,t} = 0 \tag{9.e}$$

$$\eta_{GMGter}X_{7,t} - X_{9,t} = 0 \tag{9.f}$$

$$COP_{CA}X_{11,t} - X_{13,t} = 0 \tag{9.g}$$

$$COP_{CC}X_{12,t} - X_{14,t} = 0 \tag{9.h}$$

$$X_{13,t} + X_{14,t} - X_{16,t} = 0 \tag{9.i}$$

$$\eta_{CRE}X_{9,t} - X_{18,t} = 0 \tag{9.j}$$

$$(1 - \eta_{CRE})X_{9,t} - X_{19,t} = 0 \tag{9.l}$$

$$X_{15,t} = DEV \tag{9.m}$$

$$X_{16,t} = DAG \tag{9.n}$$

$$X_{17,t} = DEE \tag{9.o}$$

The restriction represented by Eq. 9.p limits the generation of electricity by the generator and the consumption by the network to, at a maximum, the demand plus the consumption of the refrigeration system. This restriction is essential to avoid surplus electricity originating from the grid or the generator, meeting legal restrictions (ANEEL, 2012; 2015).

$$X_{3,t} + X_{10,t} - X_{12,t} - X_{17,t} \leq 0 \tag{9.p}$$

There is another set of restrictions that refer to boundary restrictions. These constraints provide power limits at each point of the system (Eq. 10). The power must be greater than zero and lower than the nominal power of each equipment. For the power $X_{1,t}$, $X_{4,t}$ and $X_{5,t}$, as they depend on the natural conditions of wind speed and solar radiation, these must be lower than the hourly generation capacity of the corresponding equipment.

$$0 \leq X_{1,t} \leq P_1 \tag{10.a}$$

$$0 \leq X_{2,t} \leq \infty \tag{10.b}$$

$$0 \leq X_{3,t} \leq \infty \tag{10.c}$$

$$0 \leq X_{4,t} \leq P_4 \tag{10.d}$$

$$0 \leq X_{5,t} \leq P_5 \tag{10.e}$$

$$0 \leq X_{6,t} \leq \infty \tag{10.f}$$

$$0 \leq X_{7,t} \leq \infty \tag{10.g}$$

$$0 \leq X_{8,t} \leq P_{CG} \tag{10.h}$$

$$0 \leq X_{9,t} \leq \eta_{GMGter} P_{GMG} / \eta_{GMGel} \tag{10.i}$$

$$0 \leq X_{10,t} \leq P_{GMG} \tag{10.j}$$

$$0 \leq X_{11,t} \leq \infty \tag{10.l}$$

$$0 \leq X_{12,t} \leq \infty \tag{10.m}$$

$$0 \leq X_{13,t} \leq P_{CA} \tag{10.n}$$

$$0 \leq X_{14,t} \leq P_{CC} \tag{10.o}$$

$$0 \leq X_{15,t} \leq \infty \tag{10.p}$$

$$0 \leq X_{16,t} \leq \infty \tag{10.q}$$

$$0 \leq X_{17,t} \leq \infty \tag{10.r}$$

$$0 \leq X_{18,t} \leq P_{CRE} \tag{10.s}$$

$$0 \leq X_{19,t} \leq \infty \tag{10.t}$$

Meteorological data were obtained from the National Institute of Meteorology (INMET) for the study site, the city of Campina Grande, latitude -7.22° and longitude -35.9° (Northeast Brazil) (INMET, 2019). Maximum efficiency of the solar panel was a function of temperature, expressed by Eq. 11 (Duffie and Beckman, 2002):

$$\eta_{mp} = \eta_{mp,ref} + \mu_{mp}(T_c - T_{c,ref}) \tag{11}$$

For the specific SA275-60P solar panel employed herein, cell efficiency was $\eta_{mp,\,ref}$ = 0.196, reference temperature was $T_{c,\,ref}$ = 25 ° C, collector temperature T_c was obtained from climatic data and μ_{mp} was obtained from Eq. 12, where μ_{Voc} = -0.307 and V_{mp} = 31.22 V. For the solar collector, the efficiency was considered as 50%. The electricity output of the panel is given by multiplying the solar radiation by η_{mp}:

$$\mu_{mp} = \eta_{mp,ref} \frac{\mu_{Voc}}{V_{mp}} \quad (12)$$

Wind generation data were obtained from the power curve of the Eoltec Scirocco E5.6-6 wind turbine (Solarcity, 2019) meteorological data.

3. RESULTS AND DISCUSSIONS

The system optimization yields a subset of the base system (Fig. 1), shown in Figure 2, with the following equipment: solar collector that preheats the water entering the gas boiler, the fuel line that supplies fuel for the boiler and the generator set, a recovery boiler that recovers heat from exhaust gases for steam generation, the electric grid and a compression chiller.

Renewable energy generation technologies were not a part of the optimal economic solution, due to low power generation capacity in relation to nominal power (efficiency) and the seasonal and temporal regime of solar radiation and. Also, there are high capital costs associated with the installation of such equipment. The possibility of exporting surplus self-generated electricity in exchange for electricity credits was not sufficient for these technologies to be part of the optimal solution.

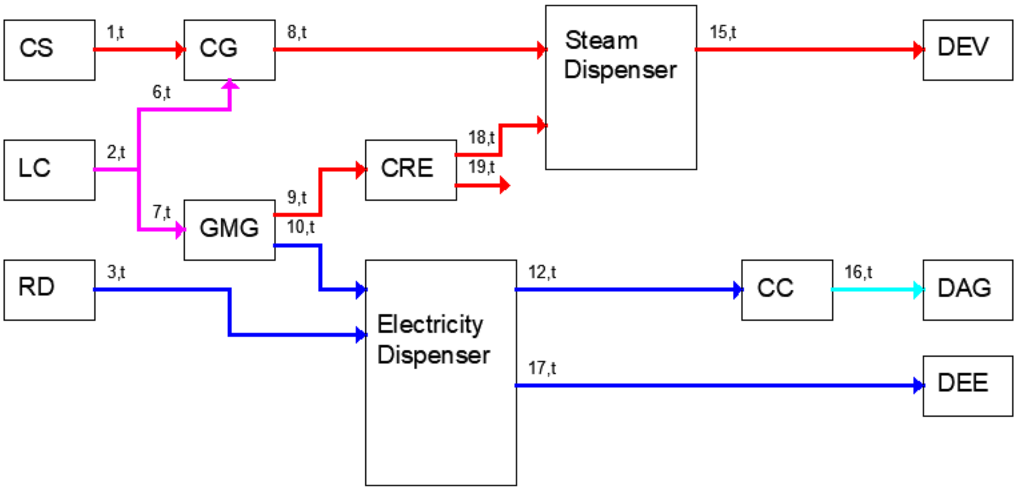

Figure 2. Optimal economic system.

Table 5 shows the nominal power for the equipment installed in the optimal solution. The maximum solar collector area available and the maximum nominal power of the generator set were chosen.

Table 5: Nominal power of the equipment included in the optimal economic solution.

Equipment	Nominal Power (except CL)
CS (m²)	6400
LC (kW)	∞
RD (kW)	∞
CG (kW)	3670
GMG (kW)	4504
CC (kW)	3500
CRE (kW)	2317

The optimization procedure also yields the optimal operation of equipment for each of the 32 representative time periods throughout the year. Part of this operation is being presented in Figures 3 to 10. $X_{1,\,t}$ represents energy flow in four time periods of each representative day due to the temporality of the solar radiation, being zero in some moments of the day. $X_{2,\,t}$, which represents the energy flow of the fuel line, shows a significant increase in period 7 and period 23 (peak period), where the engine operates to avoid electricity consumption from the electric grid at peak times. $X_{3,\,t}$, which represents the consumption of electricity from the grid, has a significant drop in period 7 and in period 23, which corresponds to the peak period, where the generator set is activated to meet the demand, avoiding consumption from the electric grid at peak times. $X_{6,\,t}$ represents the flow of energy entering the gas boiler, which is zero in the first two time periods, when steam demand is zero, and zero at the peak period when the steam demand is met by the generator set (cogeneration). $X_{8,\,t}$ has a profile similar to $X_{6,\,t}$. $X_{7,\,t}$, $X_{9,t}$ and $X_{10,\,t}$, which represent the input and output power flows of the generator set, and only shows flow at peak periods when this equipment is triggered to avoid consumption from the grid at peak times.

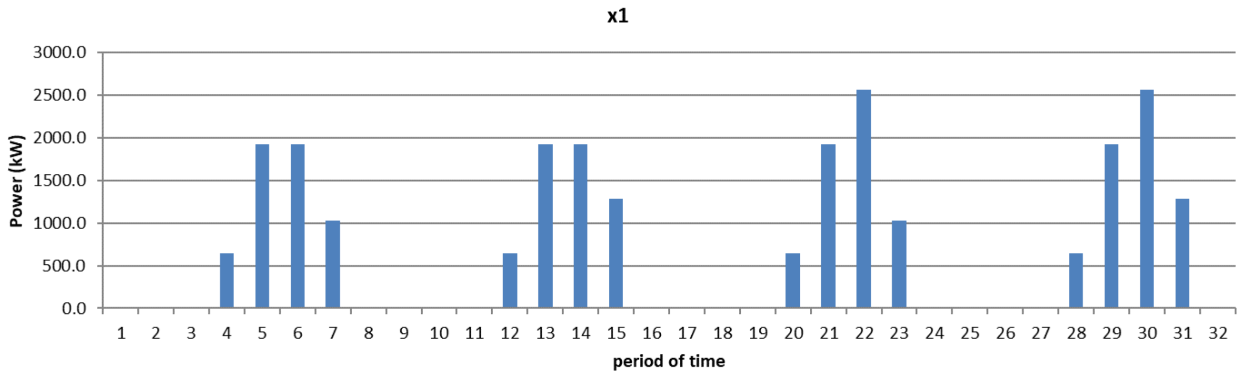

Figure 3. Operation at point 1: solar collector outlet.

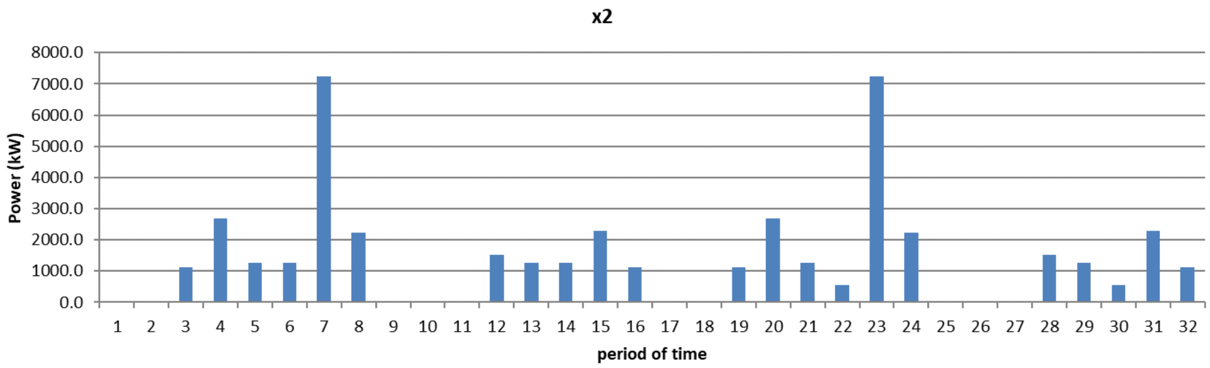

Figure 4. Operation at point 2: fuel line outlet.

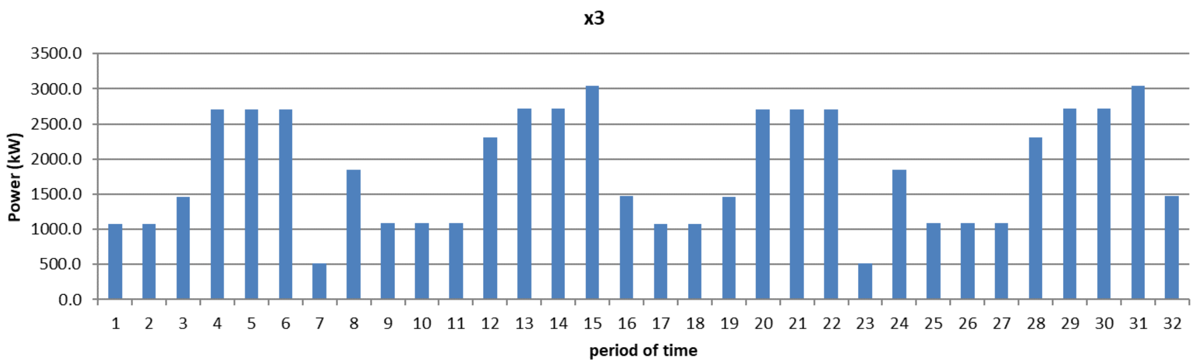

Figure 5. Operation at point 3: network outlet.

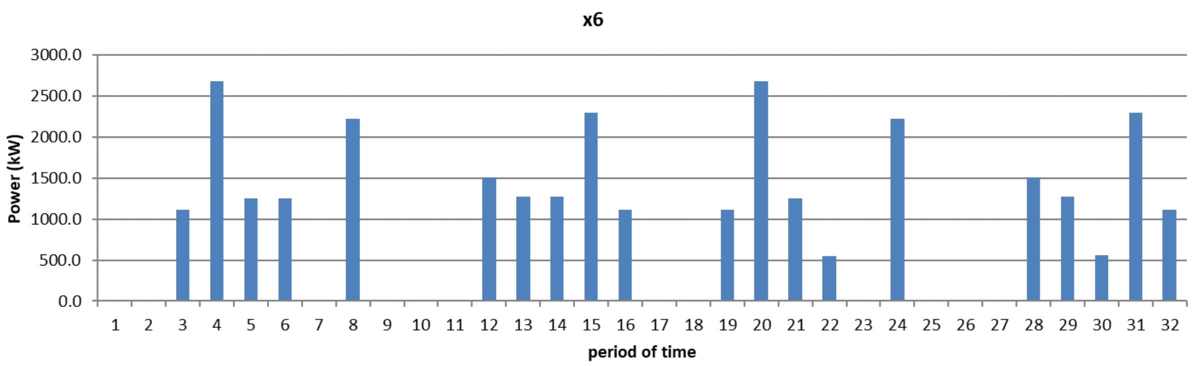

Figure 6. Operation at point 6: entry into the gas boiler.

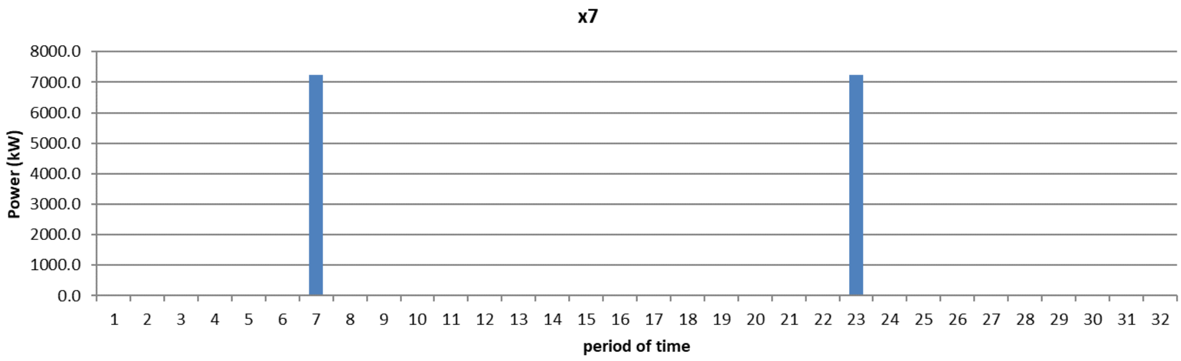

Figure 7. Operation at point 7: generator set input.

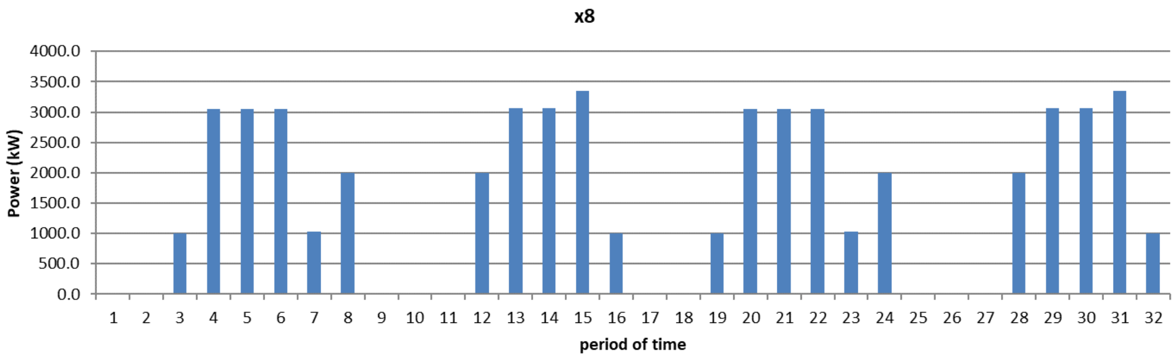

Figure 8. Operation at point 8: gas boiler outlet.

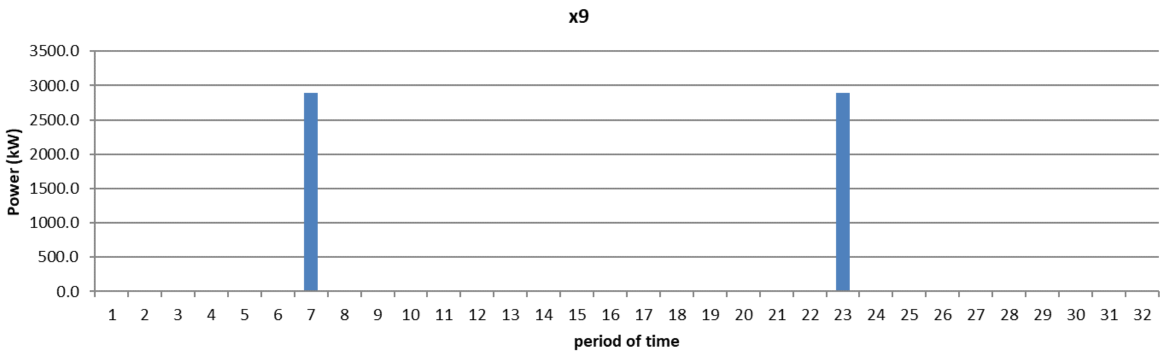

Figure 9. Operation at point 9: heat output in the generator set.

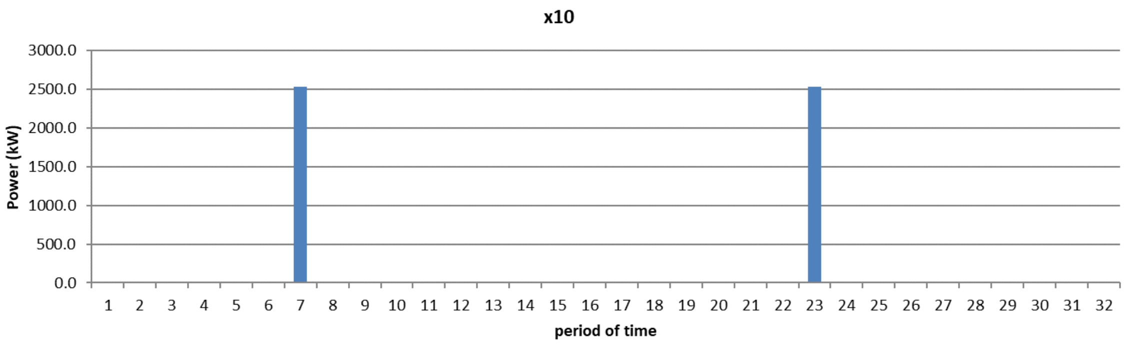

Figure 10. Operation at point 10: output of the generator set.

The results presented herein are similar to those obtained by Delgado et al. (2018b), with limited installation of photovoltaic panels at a hospital located 130 km from the study site considered herein. Abrahao, Peixoto and Carvalho (2017) also observed that not all commercially available wind turbines are applicable to the Paraiba state, which does not present high nominal speeds. The study by Melo, Carvalho, and Romero (2019) also presented little variability in the optimal solutions.

The optimization of energy systems is still a relevant subject nowadays, especially regarding the utilization of natural (energy) and economic resources, and the consequent effects on the environment. There is an important role to be played by energy system optimization in the transition away from fossil fuels, and due to the stochastic nature of solar and wind energy resources, the introduction of these elements within an optimization model has not been fully resolved yet. Energy storage also presents margins for improvement. Recognizing the fast progression of renewable energy markets, the importance of combining different energy resources includes the overcoming of limitations regarding individual technologies (efficiency, economics, reliability, and flexibility).

4. CONCLUSIONS

This study presented an optimization model that considers the availability of renewable energy conversion technologies (wind turbine, photovoltaic panel, and solar collector) as well as conventional equipment for generating electricity (generator set), gas steam generators, and compression and absorption chillers. There was the possibility of cogeneration and trigeneration, in addition to exporting surplus electricity generated by renewable energy technologies, and obtaining economic benefits with electricity credits, following Brazilian legal restrictions.

The overarching aim of this study, which is part of a PhD thesis, is to enhance design capability, performance, and sustainability of energy systems.

The optimal economic solution did not include the exports of self-generated electricity and the only renewable energy conversion technology installed were solar collectors, employed to preheat the water entering the boiler. Trigeneration was discarded due to the high capital costs of the absorption collector. The electric generator set operated during electric grid peak times, to avoid the consumption of electricity at higher tariffs, with the recovery of heat from exhaust gases (cogeneration).

5. ACKNOWLEDGMENTS

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