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MULTICRITERIA OPTIMIZATION OF THE ENERGY SUPPLY FOR A NORTHEAST BRAZIL HOSPITAL, CONSIDERING SOLAR PHOTOVOLTAIC ENERGY

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Abstract. *The introduction of new energy sources in an energy supply and conversion system can be analyzed through optimization projects and from information on energy demands and equipment utilized in a specific consumer center. This work proposes the utilization of mathematical programming to design a polygeneration system to be installed in a hospital located in João Pessoa, Northeast Brazil. Optimization will consider total annual costs and the annual carbon footprint simultaneously. In the energy system studied herein, the following energy demands were considered: electricity, heat (hot water), steam and cooling. Synthesis includes optimal configuration (commercially available equipment) and optimal operation throughout the year. Environmental information was obtained through Life Cycle Assessment, and was incorporated into a Mixed Integer Linear Programming (MILP) model. The contribution of this study is the innovative consideration of solar photovoltaic panels as a possibility to produce electricity, within the economic and legal scenarios established within the bicriteria optimization model, for the specific Brazilian scenario.*

Keywords: *mixed integer linear programming (MILP), multicriteria optimization, life cycle assessment, polygeneration, hospital.*

1. INTRODUCTION

The increase in world energy demands verified throughout the last decades has been mainly caused by increases in population and the consequent increase in consumption of energy. Environmental consciousness did not accompany industrialization and over the years, there has been a progressive increase in environmental degradation and resource depletion. However, recent years have introduced a gradual awareness and consequent change in habits referring to the way in which natural resources should be used, emphasizing the utilization of renewable resources, in such a way that consumerism (still increasing) has been timidly guided by environmental awareness (Carvalho, Freire, Brito, 2016). Since the Rio92 conference, the environmental impacts associated with consumption have emerged as a question related to sustainability proposals, and it has become increasingly clear that different lifestyles contribute differently to environmental degradation. Lifestyles that make intensive use of natural resources (populations of the most industrialized countries) have been contributing to a significant share of the current environmental crisis.

There are several ways to design an energy supply and conversion system, but that can be divided into the conventional manner, where individual energy conversions attend the energy demands of the consumer center, or through the application of energy integration concepts, using energy flows of different equipment in a combined way, such as polygeneration. Mathematical programming models based on Mixed Integer Linear Programming (MILP) have been widely applied to the optimization of energy supply systems (Yokoyama, Hasegawa, Ito, 2002; Carvalho, Melo, Carvalho, 2017).

Although polygeneration has been applied to the provision of energy services for the residential-commercial sector (Romero, Carvalho, Millar, 2014; Carvalho et al. 2013; Carvalho, Serra, Lozano, 2011; Lozano, 2009) detailed studies on multicriteria optimization are still scarce (Carvalho, Lozano, Serra, 2012). In multiobjective optimizations, the issue of conflicting objective functions (such as environmental and economic ones) is addressed, obtaining an optimal solution that meets a balance between the criteria analyzed. Although there are many projects where the main criterion analyzed is purely economic, environmental concerns have been increasingly adopted (Carvalho, Medeiros Neto, Carvalho, 2016;

Carvalho, Carvalho, 2016) and analyzed when planning energy supply systems, even being chosen as the only focus of optimization analyses (Delgado, Charcategui, Junior, Carvalho, 2015; Delgado, 2015).

Research on the optimal synthesis of energy supply systems, considering contradictory objectives simultaneously, could benefit from further research. In addition, the resilience of some configurations with respect to the interaction between economic and environmental performance is uncertain and should be investigated to a greater extent.

The objective of the study presented herein is to adapt and extend the methodology proposed by Delgado et al. (2015), considering simultaneously economic and environmental criteria in the synthesis of a polygeneration system to be installed in a hospital. This study goes a step further by considering photovoltaic solar energy in the polygeneration superstructure, and also the legal scenario established by the Brazilian Agency of Electricity (Brasil, 2012), which enables exports of self-generated electricity. Sugarcane bagasse was also considered as a locally available energy resource.

2. ENERGY SUPPLY SYSTEM

2.1 Energy demands

The consumer center under analysis is a university hospital, with 420 beds, located in the city of João Pessoa (Northeast Brazil). The energy demands considered were electricity, sanitary hot water, steam (laundry and sterilization) and cooling. The study encompassed one operational year, distributed in two representative days (week days and weekend/holidays) per month. Each day was divided into 24 hourly periods, yielding 576 different annual operation periods.

Real electricity data was available. The calculation of hot water, heating, and cooling demands utilized the degree-days method (Erbs, Klein & Beckman, 1983), climate data (Climaticus 4.2, 2005), occupation data (Nepote, Monteiro & Hardy, 2009) and energy audit data (Araújo, 2004). Table 1 shows the energy demands for the hospital, throughout the year, with final annual values.

Table 1. Energy demands of the university hospital (DELGADO et al., 2015).

Month Representative Day	n _d (days/year)	Electricity	Hot Water	Steam	Cooling
		Total MWh/day	Total MWh/day	Total MWh/day	Total MWh/day
Jan w*	20	8538	3543	0.465	5961
Jan h**	11	6315	3543	0.233	4360
Feb w	19	9696	6436	0.465	6472
Feb h	9	6247	6436	0.233	4290
Mar w	20	9861	6436	0.465	8013
Mar h	11	7474	6436	0.233	5443
Apr w	20	9949	6436	0.465	7071
Apr h	10	7348	6436	0.233	4737
May w	20	8901	6436	0.465	7895
May h	11	6383	6436	0.233	5534
Jun w	19	7489	5032	0.465	7768
Jun h	11	6832	5032	0.233	5259
Jul w	20	6568	3881	0.465	5186
Jul h	11	6045	3881	0.233	3760
Aug w	20	5954	3881	0.465	7343
Aug h	11	4681	3881	0.233	4941
Sep w	21	6686	3881	0.465	7483
Sep h	9	4755	3881	0.233	5046
Oct w	20	8041	5284	0.465	8834
Oct h	11	5969	5284	0.233	6057
Nov w	20	9309	6436	0.465	8260
Nov h	10	6022	6436	0.233	5627
Dec w	20	1036	6436	0.465	5912
Dec h	11	7389	6436	0.233	3879
Σ		MWh/year	MWh/year	MWh/year	MWh/year
Year	365	2791	1947	138	2309

*w = weekday; ** h = holiday/weekend

2.2 Superstructure

Figure 1 depicts the superstructure of the energy supply system for the hospital located in João Pessoa, following the scheme of Carvalho and Millar (2012). The optimization methodology followed herein requires the creation of a superstructure that must include all possible processes and connections. Equipment models and their connectivity, along

with operational constraints, are incorporated into a mathematical model, where the objective function is specified (herein a bicriteria objective function was considered). Once the system is optimized, this superstructure is reduced to an optimal configuration. Therefore, the superstructure must include all equipment and flows that may be part of an optimum configuration, allowing several redundant possible alternatives for each process.

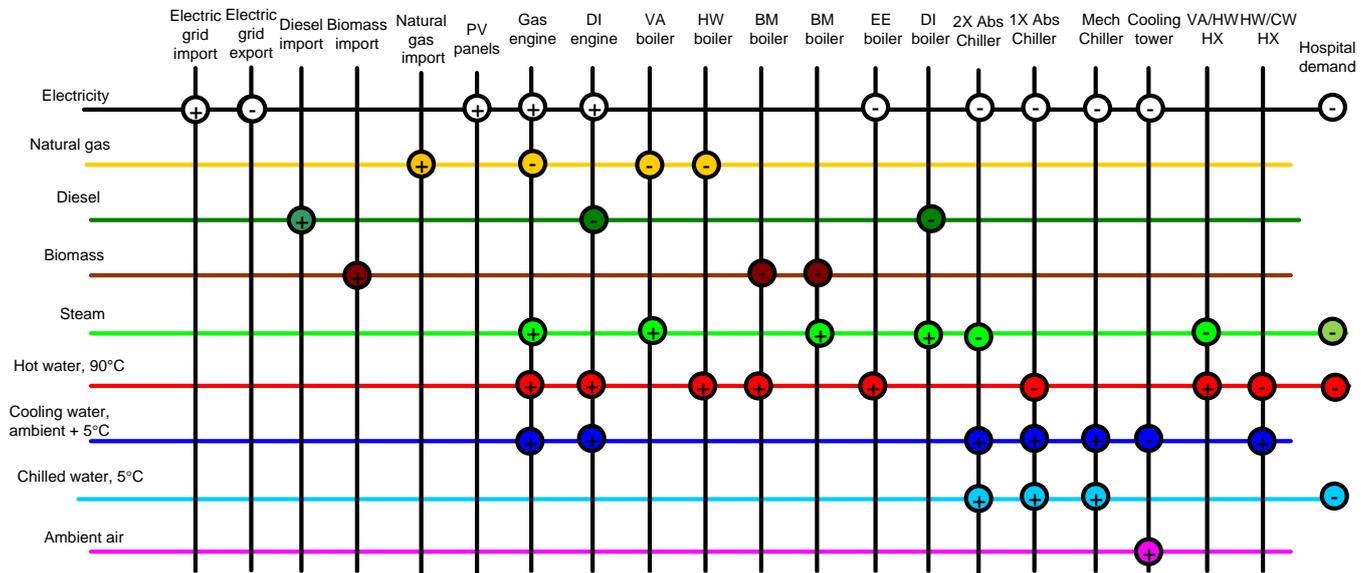


Figure 1. Superstructure illustrating all potential conversion pathways considered (adapted from DELGADO et al., 2015).

The available utilities were electricity (EE), diesel (DI), biomass (BM), Natural gas (NG), steam (VA, 180°C), hot water (HW, 90°C), cooling water (CW, $t_0 + 5^\circ\text{C}$), ambient air ($t_0^\circ\text{C}$), and chilled water (CO, 5°C). A positive node denotes supply/production of energy and a negative node denotes consumption. The horizontal lines represent the energy forms considered at the site, into which the equipment (vertical lines) are connected to consume or produce energy.

2.3 Technical, economic and environmental data.

Table 2 shows the technical, economic, and environmental characteristics of the equipment that belong to the superstructure (Figure 1). The rows indicate the technologies available, and the columns indicate the energy resources. The coefficient in bold indicates the flow that defines the productive capacity of the equipment, and positive and negative coefficients, indicate, respectively, that an energy flow is either produced or consumed. Table 2 includes the updated carbon footprints associated with each superstructure technology, utilizing data from Carvalho, Delgado and Chacartegui¹ (2016) and the most recent versions of Simapro 8.4.0.0 (PréConsultants, 2017) with Ecoinvent 3.3 (EcoInvent database, 2017).

¹carbon footprints were calculated as the sum of the partial emissions for each stage (construction, operation and maintenance, and dismantlement and disposal). Data on the material composition of each piece of equipment were obtained after exhaustive and extensive consultation of catalogues and manufacturers. The best available disposal scenario was considered for each material (recycling), and all waste flows (lubricating oil, wastewater, Li-Br, etc.) received adequate treatment before disposal. The reader is directed to Carvalho, Delgado and Chacartegui (2016) for more details on Life Cycle Assessment (LCA) for these equipment and energy services.

Table 2. Matrix of technical production coefficients and technology data (adapted from Carvalho, Romero and Millar, 2014 and Carvalho, Delgado and Chacartegui, 2016).

	Technical production coefficients									Equipment			
	GN	BM	DI	VA	AQ	AR	AA	AF	EE	Cost CI (10 ³ R\$)	Cost O&M (R\$/ MWh)	Nom. Power PNOM (MW)	Carbon footprint CFE kg CO ₂ - eq
Gas engine	-2.63				1.10	0.45			1	463.00	15.00	0.41	3.53 10 ²
Diesel engine			-2.66		0.80	0.50			1	227.00	15.00	0.36	6.97 10 ⁶
Steam boil (BM)		-1.40		1						47.90	2.00	0.25	2.73 10 ⁶
Steam boil (GN)	-1.18			1						51.00	8.00	0.30	2.22 10 ⁶
Steam boil (EE)				1				-1.15		42.50	2.00	0.15	2.22 10 ⁶
HX (VA-AQ)				-1.10	1					8.90	2.00	0.40	1.50 10 ³
Hot water boil (BM)		-1.25			1					49.30	2.00	0.17	2.73 10 ⁶
Hot water boil (GN)	-1.22				1					62.50	8.00	0.30	2.22 10 ⁶
Hot water boil (EE)					1			-1.11		28.20	2.00	0.15	2.22 10 ⁶
HX(AQ-AR)					-1.10	1				7.40	2.00	0.40	1.47 10 ³
Absorption chil (2x)			-0.77			1.77		1	-0.01	465.20	10.00	0.46	2.27 10 ⁵
Absorption chil (1x)				-1.32	2.32			1	-0.01	539.70	10.00	0.49	3.04 10 ⁵
Mechanical chiller						1.21		1	-0.21	145.00	4.00	0.28	5.23 10 ³
Cooling Tower						-1.00	1		-0.02	28.20	10.00	1.00	9.71 10 ³

The PV system is constituted by PV panels and inverters (electricity storage will not be considered). Information was obtained from consultation to PV panel (Kyocera, 2014) and inverter (Santermo, 2014) manufacturers. The cost of the system was R\$ 2202/m² (including the cost of panels, inverter, installation materials, transportation and assembly). The area of each panel is 1.64 m². The maintenance costs are R\$ 25/m² per year. Historic hourly radiation data (W/m²) were available from the Climaticus database (2005). Regarding the PV panels, the area available at the hospital facility is sufficient for the installation of 200 panels, and therefore priority is given to the installation of solar energy, which is then adjusted in function of the adjusted capacity.

Electricity presents different tariffs for peak (R\$ 298,00/MWh between 18h and 21h) and off-peak (R\$ 190,00/MWh) periods. For the electricity mix, a 2015 average was considered (ONS, 2017) for the state of Paraíba, considering all steps of the Power Electricity System: generation, transmission and distribution to the hospital. The electricity mix was based on the Daily Operation preliminary Report, issued by the Electricity System National Operator (ONS, 2017), utilizing the average percentage in three days (1, 15 and 30) for each month of 2015, yielding hydro 36.21%, thermoelectrical (oil) 40.85%, and wind 22.94%. Considering these percentages, the final carbon footprint associated with the consumption of 1 kWh of electricity from the electric grid was 0.605 kg CO₂-eq.

The tariff for natural gas (R\$ 293/MWh – PBGAS, 2017) does not include hourly or seasonal differentiation, as is the case of diesel (R\$ 290/MWh). For natural gas, the emissions were 0.254 kg CO₂-eq/kWh consumed, and for diesel, 0.333 kg CO₂-eq/kWh consumed.

Due to the location of João Pessoa, which counts with several sugarcane-ethanol plants, the biomass considered was sugarcane bagasse, at R\$ 52,00/MWh. LHV of bagasse (15.4 MJ/kg dry matter) and dry matter content (0.787kg DM/kg fresh bagasse) were considered along with the assumption that 1% of dry mass was converted into ash, resulting in 0.099 kg CO₂-eq/kWh.

The system was designed to interact with the electric grid also through the exports of self-generated electricity, considering the credit compensation scheme set out by BRASIL (2015). In this energy compensation system, surplus generated electricity can be fed into the distribution grid and registered as energy credits, which can be consumed in up to 60 months. This special regime for electricity exports applies to photovoltaic- and natural gas- produced electricity.

The self-generated electricity exported to the electric grid is evaluated at the same carbon footprint as the electricity imported from the grid, introducing the concept of avoided emissions (emissions avoided elsewhere by the production of electricity by the PV panels, i.e., avoiding the purchase of electricity from the grid).

3. OPTIMIZATION MODEL

The problem to be solved consists of two simultaneous tasks: selection of the combination of technologies (type and power installed) that are capable of meeting the energy demands of the hospital, and establishment of the operation mode for all equipment installed, for each time interval defined.

A combinatorial optimization method, based on mathematical programming (MILP), and its solution provides the means to select the most convenient configuration and operation modes for power systems. The optimization model was

implemented in LINGO 11.0 (2015), an optimization tool that uses the combination of branch and bound and simplex methods in its solution algorithm. The economic objective function considered the economic aspect of the energy supply system installed in terms of the total annual cost C_{tot} (in R\$/y), which minimized equipment and fuel costs as well as purchase/sale of energy services.

$$\text{Min } C_{tot} = C_{fix} + C_{ope} \quad (1)$$

The annual capital cost of the equipment C_{fix} was expressed by

$$C_{fix} = crf \cdot \sum_i [NEI(i) \cdot CI(i) + PV] \quad \text{Min } C_{tot} = C_{fix} + C_{ope} \quad (2)$$

$NEI(i)$ and $CI(i)$ were, respectively, the number of pieces of equipment installed and the capital cost of each piece of equipment installed for technology i . PV refers to the PV panels installed. A lifetime of 15 years was considered for the system, with an interest rate of 10% y^{-1} , obtaining a capital recovery factor $crf = 0.13 y^{-1}$. As aforementioned, due to the advantages regarding cost and direct electricity supply, the amount of PV panels that maximize results is given by the maximum capacity of the area available for installation (200 panels).

Considering that the year was divided into days, which were in turn subdivided into hours, (d,h) represented the h th hour of the d th day. The annual operation cost C_{ope} associated with the operation of the system was expressed by

$$C_{ope} = [P_{ng} \cdot F_{ng}(d,h) + P_{ee} \cdot E_i(d,h) - P_{ee} \cdot E_e(d,h) + P_{bm} \cdot F_{bm}(d,h) + P_{di} \cdot F_{di}(d,h)] \quad (3)$$

F_{ng} was the consumption of natural gas, and E_i and E_e referred to the electricity imported and exported, respectively. F_{bm} was the consumption of biomass, and F_{di} was the consumption of diesel. P referred to the price or tariff of the associated energy resource.

The environmental objective function was the minimization of the total annual carbon footprint (CF_{tot}):

$$\text{Min } CF_{tot} = CF_{fix} + CF_{ope} \quad (4)$$

Where CF_{fix} referred to the impact associated with the installation of equipment, and CF_{ope} referred to the consumption of energy utilities to satisfy the energy demands of the hospital. Then:

$$CF_{fix} = fam_e \cdot \sum_i [NEI(i) \cdot CFE(i) + PV] \quad (5)$$

The environmental amortization factor fam_e allocates the global emissions throughout the lifetime of the system, and was $0.10 y^{-1}$. The annual operation impact (CO_{ope}), associated with the operation of the system was expressed by:

$$CO_{ope} = \sum_d \sum_h [CO_{ng} \cdot F_{ng}(d,h) + CO_{ee} \cdot E_p(d,h) - CO_{ee} \cdot E_s(d,h) + CO_{bm} \cdot F_{bm}(d,h) + CO_{di} \cdot F_{di}(d,h)] \quad (6)$$

Where CO refers to the emissions associated with the consumption of the different utilities: ng (natural gas), ee (electricity), bm (biomass), and di (diesel). Operation was subject to capacity limits, production restrictions, and balance equations (the reader is directed to Carvalho, Delgado, Chacartegui, 2015 for more details).

3.1 Multiobjective optimization model

Herein the ϵ -constraint method was selected (the epsilon constraint method is rigorous for convex and non-convex problems (Gebreslassie et al., 2009), where the design task is posed as a bicriteria (economic and environmental) programming problem, which can be expressed as

$$\text{Min } \mathbf{f}(\mathbf{x}) = \{f_1(\mathbf{x}), f_2(\mathbf{x})\} \quad (7)$$

The solution to this problem is given by a set of Pareto optimal points representing alternative process designs, each achieving a unique combination of environmental and economic performances. The ϵ -constraint method is based on formulating an auxiliary model for the calculation of the Pareto points, which is obtained by transferring one of the objectives of the original problem to an additional constraint. This constraint imposes an upper limit on the value of the secondary objective. The problem is repeatedly solved for different values of ϵ to generate the entire Pareto set; it is a relatively simple technique, but computationally intensive (Ngatchou, Zarei, El-Sharkaw, 2005). The ϵ -constraint version of the bi-criteria problem can be mathematically expressed as

$$\text{Min } f_2(\mathbf{x}), \text{ subject to } f_1(\mathbf{x}) \leq \epsilon_j \text{ with } \epsilon_j = \epsilon_1, \epsilon_2, \dots \text{ and } \text{Lim}_{inf} \leq \epsilon_j \leq \text{Lim}_{sup} \quad (8)$$

$f_2(\mathbf{x})$ is the economic objective function and $f_1(\mathbf{x})$ is the environmental objective function. If the model is solved for all possible values of ϵ and the resulting solutions are unique, then these solutions represent the entire Pareto set of solutions of the original multiobjective problem. The extreme points of the interval $[\lim_{\inf}, \lim_{\sup}]$ within which ϵ should fall, can be determined by solving each single objective problem separately. Each point in the Pareto frontier represents a different optimal system (optimal configuration and operation, as both configuration and operational conditions may vary) which operates under a set of specific conditions.

4. RESULTS AND DISCUSSION

4.1 Economic and CO₂ emissions multiobjective optimization

Once the scenario was completely defined by the optimization model and conditions previously specified (energy demands, economic and environmental data), the following results were obtained. The model was solved by LINGO v11.0 (Lindo systems, 2017), with free selection of technologies and minimizing the different objective functions considered. Each single-objective MILP problem involved 130,272 total variables, 2333 integer variables and 86,441 constraints, with an average CPU solution time of 21 seconds on an Intel® Core™ i5 of 1700 MHz processor with a 4GB memory size.

Table 3. Optimal solutions for the hospital energy supply system, with 200 PV panels.

	Economic Optimal		CO ₂ -eq optimal	
Composition of system	Number (Installed Power)		Number (Installed Power)	
Gas engine	0 (0 MW)		1 (0.41 MW)	
Diesel engine	0 (0 MW)		0 (0 MW)	
Steam boiler (GN)	0 (0 MW)		1 (0.30 MW)	
Steam boiler (BM)	1 (0.250 MW)		0 (0 MW)	
Steam boiler (EE)	0 (0 MW)		0 (0 MW)	
Heat exchanger (VA-AQ)	1 (0.400 MW)		1 (0.40 MW)	
Hot water boiler (GN)	0 (0 MW)		0 (0 MW)	
Hot water boiler (BM)	3 (0.510 MW)		0 (0 MW)	
Hot water boiler (EE)	0 (0 MW)		0 (0 MW)	
Heat exchanger (AQ-AR)	0 (0 MW)		1 (0.40 MW)	
Double-effect absorption chiller	0 (0 MW)		0 (0 MW)	
Single-effect absorption chiller	0 (0 MW)		1 (490 MW)	
Mechanical chiller	3 (0.810 MW)		3 (0.810 MW)	
Cooling tower	1 (1.000 MW)		2 (2.00 MW)	
Photovoltaic panels	200 units		200 units	
Electricity imports	3226 MWh/year		297 MWh/year	
Electricity produced by PV panels	129 MWh/year		129 MWh/year	
Electricity credits	--		760 MWh/year	
Natural gas imports	--		9807 MWh/year	
Diesel imports	--		--	
Biomass imports	2635 MWh/year		--	
Initial investment in equipment	R\$ 1,507,167		R\$ 2,481,792	
Annual cost of electricity imports	R\$/year	663,451	R\$/year	56,495
Annual credit with electricity exports	R\$/year	--	R\$/year	161,289
Annual cost of natural gas imports	R\$/year	--	R\$/year	2,873,545
Annual cost of diesel imports	R\$/year	--	R\$/year	--
Annual cost of biomass imports	R\$/year	137,045	R\$/year	--
Operation and Maintenance costs	R\$/year	21,813	R\$/year	53,519
Annual cost of equipment**	R\$/year	54,170	R\$/year	132,976
TOTAL annual cost	R\$/year	1,050,598	R\$/year	3,224,085
CO ₂ emissions for equipment only	kg CO ₂ -eq/year	12,518,900	kg CO ₂ -eq/year	4,134,433
CO ₂ -eq emissions for electricity imports	kg CO ₂ -eq/year	1,951,900	kg CO ₂ -eq/year	179,645
CO ₂ -eq emissions for electricity exports	kg CO ₂ -eq/year	--	kg CO ₂ -eq/year	460,049
CO ₂ -eq emissions for natural gas imports	kg CO ₂ -eq/year	--	kg CO ₂ -eq/year	2,491,060
CO ₂ -eq emissions for diesel imports	kg CO ₂ -eq/year	--	kg CO ₂ -eq/year	--
CO ₂ -eq emissions for biomass imports	kg CO ₂ -eq/year	260,913	kg CO ₂ -eq/year	--
CO ₂ -eq emissions for equipment	kg CO ₂ -eq/year	1,251,890	kg CO ₂ -eq/year	413,443
TOTAL annual CO₂-eq emissions	kg CO₂-eq/year	3,464,703	kg CO₂-eq/year	2,624,099

The solution of each individual optimization problem provided the extreme limits: $\lim_{inf} = 2,624,099$ kg CO₂/year (environmental optimal) and $\lim_{sup} = 3,464,703$ kg CO₂/year (economic optimal). Table 3 shows the configurations obtained for these limits, in addition to the values of total cost, installed power and emission level of each configuration obtained. The number that accompanies the equipment indicates how many pieces of equipment are installed and their power.

The environmental optimal solution presented CO₂-eq emissions that were 24.3% lower than the economic optimal, but with annual costs that were 307% higher. A significant increase was required in the annual costs embedded to obtain a moderate reduction in the total annual emissions.

Table 4 shows some of the limits for ϵ , with the resulting configuration and primary and secondary objective values. For each configuration, E = gas engine, B = boiler (preceded by its fuel), A = single effect absorption chiller, and M = mechanical chiller. E* means that electricity is exported into the electric grid. The number accompanying the equipment indicates how many pieces of equipment are installed.

Table 4. ϵ -constraint method for the multiobjective consideration of CO₂-eq and costs.

	Lim _{sup} (ϵ) kg CO ₂ -eq/y	Carbon Footprint kg CO ₂ -eq/y	Minimal cost R\$/y	Configuration
	Optimal environmental	2,624,099	3,224,085	1E 1GNB 1A 3M E*
D	2,700,000	2,641,203	3,136,125	1E 1BMB 1A 2M E*
	2,800,000	2,711,820	3,120,719	1E 1BMB 3M E*
	2,900,000	2,711,820	3,120,719	1E 1BMB 3M E*
	3,000,000	2,711,820	3,120,719	1E 1BMB 3M E*
C	3,100,000	2,711,820	3,120,719	1E 1BMB 3M E*
B	3,200,000	3,187,922	1,095,422	1GNB 2BMB 3M
	3,300,000	3,246,853	1,073,399	3BMB 3M
A	3,400,000	3,246,853	1,073,399	3BMB 3M
	Optimal economic	3,464,703	1,050,598	4BMB 3M

Figure 2 shows the relationships between total cost and total emissions obtained for each of the four intermediate situations (represented in yellow), in addition to the environmental (shown in red) and economic (shown in green) optimals.

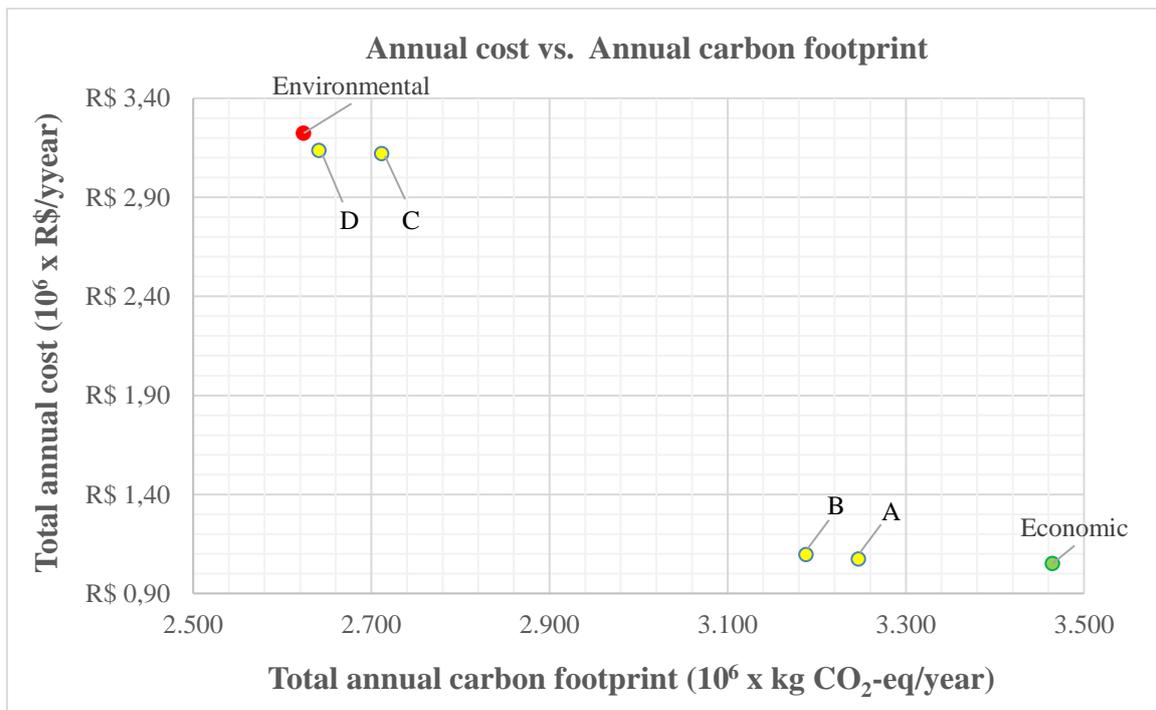


Figure 2. Annual cost vs. Annual carbon footprint

Table 5 shows the main characteristics of solutions A, B, C and D.

Table 5. Characteristics of solutions A, B, C and D

	A	B	C	D
System composition	Number	Number	Number	Number
Gas engine	0	0	1	1
Diesel engine	0	0	0	0
Steam boiler (GN)	0	0	0	0
Steam boiler (BM)	3	1	1	1
Steam boiler (EE)	0	0	0	0
Heat exchanger (VA-AQ)	2	1	1	1
Hot water boiler (GN)	0	1	0	0
Hot water boiler (BM)	0	1	0	0
Hot water boiler (EE)	0	0	0	0
Heat exchanger (AQ-AR)	0	0	1	1
Double-effect absorption chiller	0	0	0	0
Single-effect absorption chiller	0	0	0	1
Mechanical chiller	3	3	3	2
Cooling tower	1	1	2	2
Photovoltaic panels	200	200	200	200
Electricity imports	3,226	3,226	329	294
Electricity produced by PV panels	129	129	129	129
Electricity credits	---	---	624	760
Natural gas imports	---	191	9,554	9,554
Diesel imports	---	---	---	---
Biomass imports	3,191	2,622	301	330
Annual cost of electricity imports [R\$/y]	663,451	663,451	62,863	55,979
Annual credit with electricity exports	---	---	131,354	161,289
Annual cost of natural gas imports	---	56,035	2,799,221	2,799,221
Annual cost of diesel imports	---	---	---	---
Annual cost of biomass imports	165,934	136,332	15,650	171,76
Operation and Maintenance costs	59,534	54,989	131,928	134,442
Annual cost of equipment	184,480	184,615	242,411	290,595
TOTAL annual costs	1,073,399	1,095,422	3,120,719	3,136,125
CO ₂ -eq emissions for electricity imports	1,951,900	1,951,900	199,074	178,003
CO ₂ -eq emissions for electricity exports	---	---	377,721	460,049
CO ₂ -eq emissions for natural gas imports	---	48,577	2,426,629	2,426,629
CO ₂ -eq emissions for diesel imports	---	---	---	---
CO ₂ -eq emissions for biomass imports	315,913	259,555	29,795	32,700
CO ₂ -eq emissions for equipment	979,040	927,890	434,043	463,920
TOTAL annual CO₂-eq emissions	3,246,853	3,187,922	2,711,820	2,641,203

It was verified that multiobjective optimization techniques widen the perspective of single-objective energy system analyses and the determination of the complete spectrum of solutions that optimize the design according to more than one objective at a time. As in most practical problems, the multiple objectives herein analyzed competed with one another and a unique optimal could not be identified.

The uncertainties that affect investment decisions are related to future emission targets and policies, which imply that a method for optimizing not only economic criteria, but also environmental impacts, will provide better information for decision making, possibly resulting in a more robust solution (SVENSSON, BERNTSSON, 2010).

Significant reductions in costs can be attained if the decision-maker is willing to compromise the environmental performance of the system. The methodology presented herein was intended to promote a more sustainable design of energy supply systems by guiding the economic decision-makers towards the adoption of alternatives that caused less environmental impact.

5. CONCLUSIONS

Multiobjective optimization was addressed herein, with the development of a bicriteria optimization. The solution of the MILP model provided sets of Pareto optimal design alternatives, highlighting the trade-offs involved in its analysis and evaluation as well as the important role of decision makers in solving and using their specialized judgment in the multiobjective problem.

The energy supply system was optimized considering specific demands of a medium size hospital (420 beds) located in the city of João Pessoa, state of Paraíba, Brazil. The MILP model of single-objective optimization was adapted for application of the ϵ -constraint method, and it was observed that significant reductions in the environmental impact could be attained if the economic performance was compromised.

Comparison of economic and environmental optimals showed clearly different structures. Future work by the authors include resilience analyses to identify a range of operational feasibility for each configuration in the Pareto frontier. The selection of an ultimate global configuration considering economic and environmental viewpoints will lead to the selection of a specific configuration that performs in a wider range of adaptability. Current work by the authors also includes the consideration of electricity storage in the superstructure.

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8. RESPONSIBILITY NOTICE

The authors Bruno Campos, Caio Tácito, Jordan Nunes and Monica Carvalho are the only responsible for the printed material included in this paper.