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MULTICRITERIA OPTIMIZATION OF RENEWABLE-BASED POLYGENERATION SYSTEM FOR TERTIARY SECTOR BUILDINGS

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Abstract

This manuscript presents the bicriteria optimization of a polygeneration system to be installed in a tertiary sector building, considering economic and environmental objective functions. Electricity, hot water, steam, and cooling demands were considered. The bicriteria problem considered the annual costs and the annual carbon footprint. Updated environmental information was obtained through the application of the Life Cycle Assessment methodology and implemented within a Mixed Integer Linear Programming (MILP) model, along with economic and legal data. Solar photovoltaic energy and biomass were available, as well as natural gas and diesel. The energy system could import and export electricity to the electric grid. Individual optimal solutions were obtained from economic (annual costs) and environmental (annual carbon footprint) viewpoints were different, and the ε-constraint method was utilized to tackle these conflicting objectives. It was verified that significant reductions in annual costs could be obtained if the annual carbon footprint was partially compromised. A configuration based on one gas engine, two biomass boilers and three mechanical chillers was recommended, with an annual carbon footprint of 2,895,909 kg CO_2-eq/year (approximately 570,000 kg CO_2-eq/year less each year in comparison with the economic optimal) at a total annual cost of R$ 1,429,435.
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Key words: economics, life cycle assessment, mixed integer linear programming, multicriteria optimization, polygeneration

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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 the 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 et al., 2016). Since the Rio 92 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 different strategies for the design of energy supply and conversion systems. The conventional manner employs individual energy

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conversions (e.g., boilers, mechanical chillers) to meet the energy demands of a consumer center. However, more exotic technologies (such as absorption chillers or Fischer-Tropsch units) can be installed with the utilization of energy integration concepts - energy flows of different equipment are combined, such as in polygeneration. Also, less conventional energy resources can be taken into consideration, such as landfill gas (Chacartegui et al., 2015; Nascimento et al., 2019) and urban pruning waste (Araújo et al., 2018; Palander and Hietanen, 2018). The primary motivation for the consideration of polygeneration herein is to help ensure reduced costs through improvements in the efficiency of energy resource consumption while also achieving low carbon footprints.

Mathematical programming models based on Mixed Integer Linear Programming (MILP) have been widely applied to energy system optimization (Carvalho et al., 2017; Pina et al., 2017a; Yokoyama et al., 2015; Zatti et al., 2018). Although polygeneration has been applied to the provision of energy services for the residential-commercial sector (Carvalho et al., 2011; Carvalho et al., 2013; Carvalho et al., 2014; Lozano et al., 2009) detailed studies on multi-objective optimization (MOO) are still scarce (Carvalho et al., 2012). Whereas in single-objective functions the optimal corresponds to extreme solutions (minimum or maximum) of the objective function of the problem, the consideration of a multiobjective function allows different points of view to be considered simultaneously, which is especially interesting in the case of individually divergent solutions. A multiobjective framework for the sustainable design of polygeneration systems was presented by Pina et al. (2018), and a review of multi-criteria decision making towards sustainable renewable energy development was reported by Kumar et al. (2017). The limits and potentials of MILP-based methods for the optimization of polygeneration energy systems were reviewed by Urbanucci (2018).

In MOO, 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 employed is purely economic (Romero et al., 2014), environmental concerns have been increasingly adopted and analyzed when planning energy supply systems, even being chosen as the only focus of optimization (Carvalho et al., 2011; Carvalho, et al., 2016). Theodosiou et al. (2015) discussed how to integrate the environmental management aspect in the optimization of energy systems.

Besides MILP, other approaches, such as genetic algorithms, can be employed to address the issue of MOO in different energy systems: *e.g.*, Shahsavar and Khanmohammadi (2019), who optimized energy and exergy assessments, and Khanmohammadi et al. (2018a), who optimized cooling capacity and annual costs. A two-stage stochastic optimization algorithm was developed by Urbanucci and Testi (2018), adopting the Monte Carlo method for the definition of a multi-objective optimization problem applied to an Italian hospital. An operational optimization method based on the moving average of real-time measurements of energy demands and ambient conditions was proposed by Urbanucci et al. (2018), and applied to a district heating and cooling network located in Spain.

Research on the optimal synthesis of energy supply systems could benefit from further research; more concretely, the consideration of sometimes contradictory objective functions simultaneously. The behavior of optimal configurations regarding the dynamics of economic and environmental performances is uncertain and should be further investigated. Unique difficulties arise in the design of energy supply systems for buildings due to the variability of energy loads throughout the day and throughout the year (seasonal behavior), different energy utility tariffs with on- and off-peak values, and wide variability of technology options for equipment. However, these characteristics offer potential for innovation and are not seen as insurmountable.

The study presented herein builds upon research developed by Carvalho et al. (2016) and Delgado et al. (2018a) by considering economic and environmental objective functions in the optimization of an energy supply system. Also, since Aquila et al. (2017) discussed that Brazil still underexploits renewable energy sources, with utilization/installation incompatible with the potential of the country, photovoltaic solar energy and sugarcane bagasse (biomass) were considered herein as available energy utilities, along with the legal scenario established by the Brazilian Agency of Electricity (Brazil, 2015).

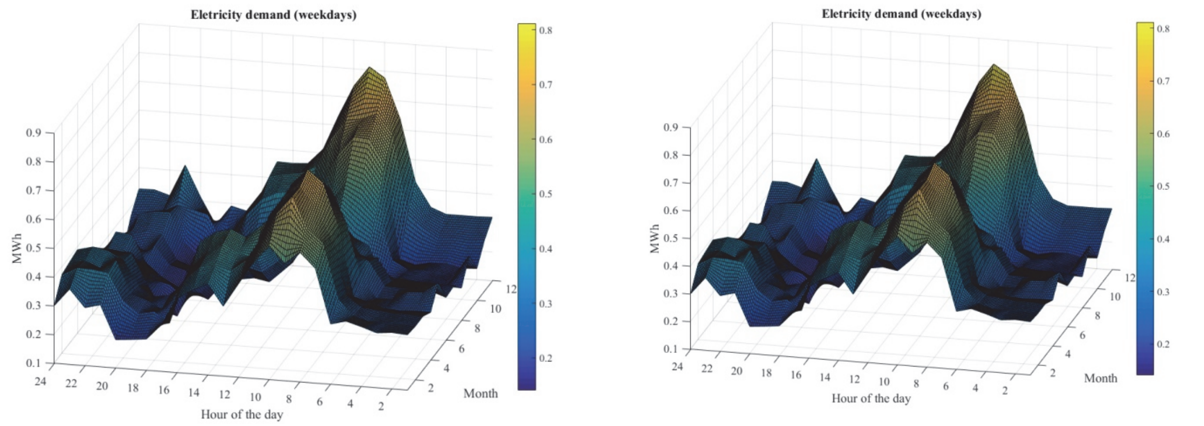
The objective of the study presented herein is to implement bicriteria consideration within an optimization model. Environmental information, obtained from the application of the Life Cycle Assessment methodology, was introduced in an optimization model based on MILP. The bicriteria optimization considers carbon footprint data and economic costs. This study considers solar energy (photovoltaic solar panels) and biomass as indigenous resources available on site, besides more traditional energy sources such as natural gas and diesel.

2. Material and methods

2.1. Energy demands, equipment and energy utilities

A medium-sized (420 beds) university hospital was considered herein, located in João Pessoa (Northeast Brazil GPS-coordinates 7° 7' 10" S, 34° 50' 42" W). The energy demands considered are electricity, sanitary hot water, steam (for laundry and sterilization purposes) and cooling. As the operation of hospitals is regular throughout the year, two days were selected to represent each month of the year (weekday and weekend/holidays), yielding 24 representative days.

Electricity demands are obtained from energy reports provided by the electrical engineering staff of the university. Sanitary hot water and cooling demands are obtained from the application of the degree-days approach (Erbs et al., 1983), utilizing climate (Climaticus 4.2, 2005) and occupation data (Nepote et al., 2009). Daily energy demands are available in hourly intervals (24h) for each day and shown in Figs. 1-3. Steam demands are calculated in accordance with the schedules of the laundry and sterilization facilities within the hospital: steam demand is constant during 6 and 20 h (operation of the sterilization central) to which the contribution of the steam demand of the hospital restaurant is added during lunch and supper times. The hot water demand presents two contributions: laundry (between 8 and 18 h) and regular, non-stop internal use of the hospital.



(a) (b)

Fig. 1. Electricity demands of the hospital (a) weekdays (b) weekend days

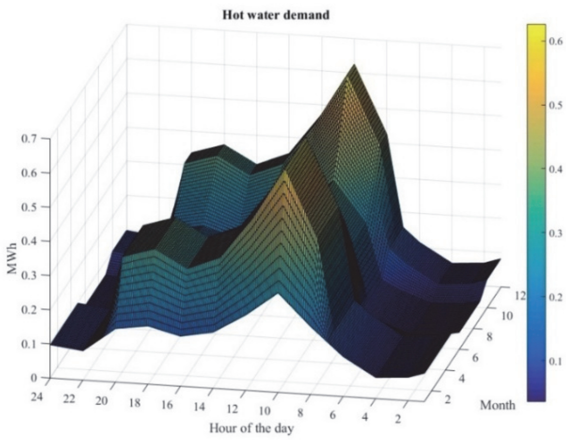
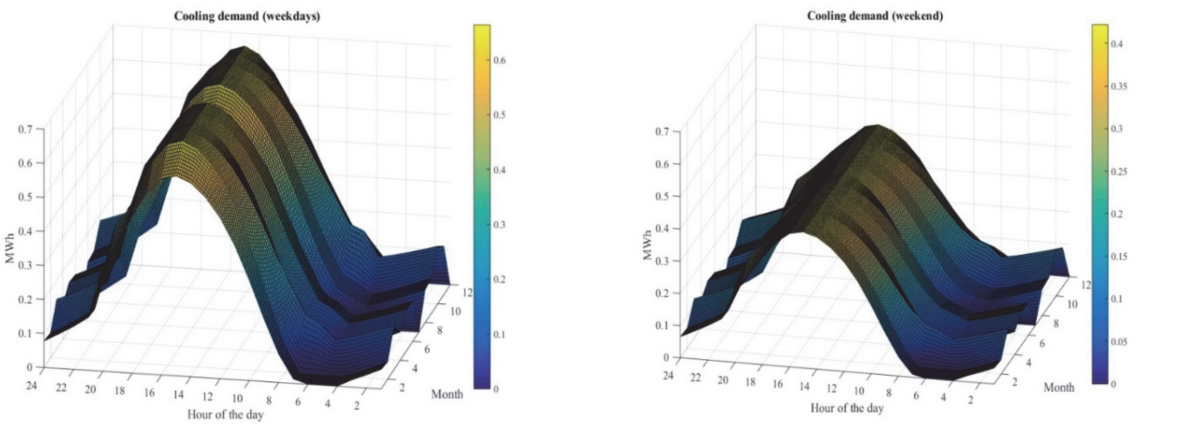


Fig. 2. Hot water demands of the hospital



(a) (b)

Fig. 3. Cooling demands of the hospital (a) weekdays (b) weekend days

Regarding the equipment and energy resources, a representation of alternatives available on site should encompass all possible alternatives for satisfying the energy demands of the consumer center. Solution of the mathematical program will extract the optimal solution from this representation, which includes all operations (imports, exports, energy conversions), and energy utility units and flows, embedded in such a way that all alternatives can be analyzed (Fig. 4).

The available energy resources are electricity (EE), diesel (DI), biomass (BM), and natural gas (NG). These resources can be utilized in single- or multiple- energy conversions, yielding the energy services steam (VA), sanitary hot water (HW), cooling water (CW), and chilled water (CO). Surplus heat can be evacuated into ambient air (AA). Fig. 5 shows a representation of the energy resources available (lines) and technologies (columns), and how they interact with each other. HX refers to heat exchanger.

2.2. Technical, economic and environmental data

Table 2 shows the technical, economic, and environmental characteristics of the commercially available equipment considered herein. The lines indicate the equipment available, and the columns indicate the energy utilities. The productive capacity of the equipment is indicated by a bold number, followed by coefficients that indicate whether an energy flow is produced (+) or consumed (-). Table 2 includes the updated carbon footprints associated with each superstructure technology, utilizing data from Carvalho et al. (2016) that was introduced into Simapro 8.4.0.0 (PréConsultants, 2017) with Ecoinvent 3.3 (Wernet et al., 2016).

Carbon footprints were calculated considering all stages: construction (extraction of raw materials, processing, and transportation), operation, maintenance, dismantlement and disposal. Following Carvalho et al. (2016), recycling was considered for all equipment and all waste flows (lubricating oil, wastewater, Li-Br etc.) received adequate treatment before disposal. The reader is directed to Carvalho et al. (2016) for more details on Life Cycle Assessment (LCA) for these equipment and energy services. CI refers to the capital cost of each technology, and O&M costs correspond to operation and maintenance costs. P_{nom} is the nominal power, and CFE is the carbon footprint associated with each technology.

The photovoltaic (PV) system includes PV panels and inverters. Data are obtained from PV panel (Kyocera, 2014) and inverter (Santerno, 2014) manufacturers. The capital cost is R$2202/m^2 and includes panels, inverter, installation equipment, transportation and assembly. The photovoltaic panel area is 1.64 m^2 and presents an average efficiency of 15%. The annual maintenance costs are R$25/m^2. Hourly radiation information (in W/m^2) is available from the Climaticus database (2005).

The tariffs for grid-imported electricity (*mix*) is R$ 298/MWh for peak periods (between 18 h and 21 h) and R$ 190/MWh for off-peak periods. The electricity mix considered the 2015 average (ONS, 2017) for the state of Paraíba, for the supply for low voltage electricity to the final user (hydro 36.21%, oil 40.85%, and wind 22.94%).

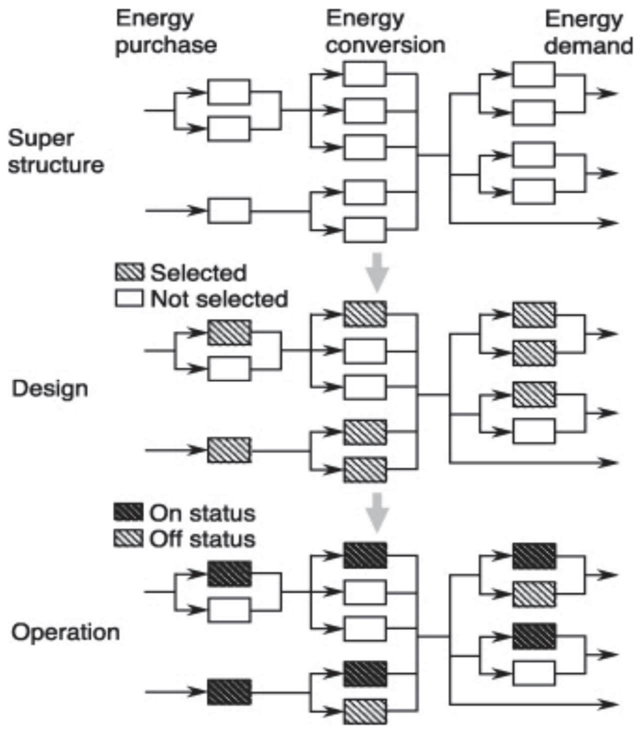


Fig. 4. Concept of superstructure (Yokoyama et al., 2015)

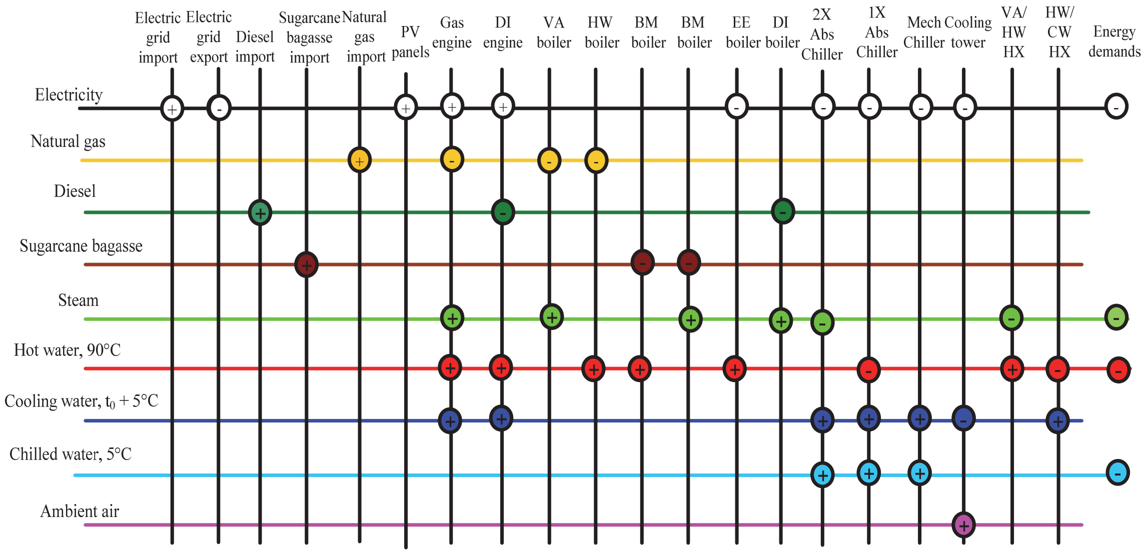


Fig. 5. Representation of available energy utilities and equipment

Table 2. Updated matrix of technical production coefficients and technologies

	Technical production coefficients						***Equipment***						
	NG	***BM***	***DI***	***VA***	***HW***	***CW***	***AA***	***CO***	***EE***	***Cost CI (10^3 R$)***	***Cost O&M (R$/ MWh)***	***PNOM (MW)***	***CFE (kg CO_2-eq)***
Gas engine	-2.66				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	0.40	6.97 (10^6)
Steam boiler		-1.40		1						51.00	8.00	0.25	2.73 (10^6)
Steam boiler	-1.18			1						47.90	2.00	0.30	2.22 (10^6)
Steam boil				1					-1.15	42.50	2.00	0.15	2.22 (10^6)
HX 1				-1.10	1					8.90	2.00	0.40	1.50 (10^3)
Hot water boiler		-1.25			1					62.50	8.00	0.17	2.73 (10^6)
Hot water boiler	-1.22				1					49.30	2.00	0.30	2.22 (10^6)
Hot water boiler					1				-1.11	28.20	2.00	0.15	2.22 (10^6)
HX 2					-1.10	1				7.40	2.00	0.40	1.47 (10^3)
Absorption chiller (2x)				-0.77		1.77		1	-0.01	465.20	10.00	0.45	2.27 (10^5)
Absorption chiller (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	217.40	4.00	0.27	5.23 (10^3)
Cooling Tower						-1.00	1		-0.02	28.00	10.00	1.00	9.71 (10^3)

The carbon footprint (CF) associated with the consumption of 1 kWh of electricity from the electric grid is 0.605 kg CO_2-eq. For natural gas and diesel, there are no variations in tariff according to the time of consumption. The tariffs are, respectively, R$ 293/MWh (PBGAS, 2017) and R$ 290/MWh. The carbon footprints are, respectively, 0.254 kg CO_2-eq/kWh and 0.333 kg CO_2-eq/kWh.

Sugarcane bagasse is considered herein, at R$ 52/MWh (Delgado et al., 2018a; 2018b) and 0.099 kg CO_2-eq/kWh. The LHV of bagasse is 15.4 MJ/kg dry matter (DM) and dry matter content is 0.787kg DM/kg fresh bagasse, and it is considered that 1% of dry mass is converted into ash.

The system is allowed to export self-generated surplus electricity to the electric grid, considering the credit compensation scheme set out by the Brazilian electricity agency (Brazil, 2015). This compensation scheme awards energy credits that are valid for up to 60 months. This special condition applies to photovoltaic- and natural gas- generated electricity (also covering cogeneration schemes, which could be a possibility). The electricity exported to the electric grid is evaluated at the same carbon footprint as the electricity imported from the grid, leading to the concept of avoided carbon footprint: electricity generated by the PV panels is consumed (lower CF), instead of importing electricity from the grid (higher CF).

2.3. Optimization model

The optimization model addresses two aspects: the configuration of the system and how it should operate throughout an operational year. The optimization model (based on MILP) is implemented in LINGO 11.0 (2015), a solver that combines branch and bound and simplex methods in its solution algorithm. The economic objective function considers the total annual cost C_{tot} (in R$/y), which minimized fixed and operational costs (Eq. 1):

$$Min\ C_{tot} = C_{fix} + C_{ope} \tag{1}$$

The annual capital cost of the equipment, C_{fix}, can be expressed as (Eq. 2):

$$C_{fix} = CRF \cdot FIC \left\{ \sum \left[NEI(i) \cdot CI(i) \right] + \left[CPV \cdot NPV \right] \right\} \tag{2}$$

Where *NEI (i)* and *CI(i)* are the number of pieces of installed equipment and the capital cost of each installed equipment for technology *i*. NPV indicates the number of installed PV panels, and CPV indicates the individual capital cost. Lifetime is considered 15 years for the system, with an interest rate of 10%, obtaining a capital recovery factor CRF = 0.13. FIC refers to a factor of indirect costs, which agglutinates engineering and supervision expenses, legal expenses, contractor's fees and contingencies, assumed to be equal to 15% of the equipment investment costs (FIC = 0.15). The annual operation cost C_{ope} relates to the operation of the system and can be expressed as (Eq. 3):

$$C_{ope} = \sum_d \sum_h \begin{bmatrix} P_{ng}F_{ng}(d,h) + P_{ee}E_i(d,h) - P_{ee}E_e(d,h) + \\ + P_{bm}F_{bm}(d,h) + P_{di}F_{di}(d,h) \end{bmatrix} \tag{3}$$

F_{ng} is the consumption of natural gas, and E_i and E_e refers to the imported and exported electricity from the national electric grid, respectively. F_{bm} is the consumption of biomass, and F_{di} is the consumption of diesel. P corresponds to the price or tariff of the associated energy resource. For each time interval considered, the production of energy is restricted to the installed capacity of equipment and an energy balance must be fulfilled for each utility (Eq. 4):

$$\text{Production} - \text{Consumption} + \text{Imports} - \text{Demand} = 0 \tag{4}$$

Equation (4) is modified only for electricity, because of the possibility of self-generating electricity in the PV panels (EEPV) and exporting electricity to the grid, as shown by Equation (5):

For electricity, and for each hour, and each day:

$$\text{Production} - \text{Consumption} + Imports - Exports - Demand + EPPV = 0 \tag{5}$$

$$EEEPV = NPS \cdot A \cdot (Rad / 1000) \cdot ef \tag{6}$$

$$\text{N}PS <= NPV \tag{7}$$

Equation (6) defines the electricity produced by the PV panels, as a consequence of the radiation absorbed during each hour, for each day. A represents the surface of each panel (m^2), eff is the efficiency of each panel (manufacturer data), Rad is the global radiation per surface unit in horizontal plane (Wh/m^2, J/m^2), due to the geographic location. NPV is the number of PV panels installed, and NPS is the number of active PV panels for each time interval considered in the balance equations. NPS represents the degree of utilization of the panels. Operation is subject to capacity restrictions, production limitations, and balance equations (the reader is directed to Carvalho et al. (2016) for more details).

Regarding the environmental aspect, the total annual carbon footprint (CF_{tot}) is considered within the environmental objective function (Eq. 8):

$$Min\ CF_{tot} = CF_{fix} + CF_{ope} \tag{8}$$

where CF_{fix} denotes the carbon footprint associated with equipment and CF_{ope} indicates the carbon footprint associated with the consumption of energy resources (Eq. 9):

$$CF_{fix} = fam_e \cdot \left\{ \sum \begin{matrix} \left[NEI(i) \cdot CFE(i) \right] + \\ + \left[COPV \cdot NPV \right] \end{matrix} \right\} \tag{9}$$

The environmental amortization factor fam_e is considered as 0.10 y^{-1}, and COPV refers to the carbon footprint associated with a PV panel. The annual operation carbon footprint (CF_{ope}) is associated with the operation of the system and imports/exports of the different energy utilities (Eq. 10):

$$CF_{ope} = \sum_d \sum_h \begin{bmatrix} CF_{ng}F_{ng}(d,h) + CF_{ee}E_i(d,h) - CF_{ee}E_e(d,h) + \\ + CF_{bm}F_{bm}(d,h) + CF_{di}F_{di}(d,h) \end{bmatrix} \tag{10}$$

where *CF* refers to the carbon footprints associated with the consumption of the different energy utilities.

2.3.1. Multiobjective optimization model

The method selected to address the issue of bicriteria optimization is the ε -constraint, which is probably the best-known technique to solve multicriteria optimization problems (Ehrgott, 2013). The optimization model is solved separately for each objective, and then one objective is minimized, while the others are converted into constraints (Bérubé et al., 2009; Chircop and Zammit-Mangion, 2013; Marler and Arora, 2004; Mavrotas, 2009; Pirouz and Khorran, 2016; Yang et al., 2014).

Herein the economic objective was minimized, represented by (Eq. 1), subject to the constraints of the environmental objective, as shown in (Eq. 11).

Minimize total annual costs, subject to:

$$\begin{cases} CF_{tot} \le \varepsilon_i \quad \therefore i = 2,3,..q \\ Lim\,CF_{inf} \le \varepsilon_i \le Lim\,CF_{sup} \end{cases} \tag{11}$$

The original individual optimization problems are solved separately *a priori* to obtain the minimal economic and minimal environmental solutions, providing, respectively, Lim CF_{sup} and Lim CF_{inf}. The range [Lim CF_{inf}; Lim CF_{sup}] is divided into intervals, and the problem is repeatedly solved for different values of ε to generate the entire set of solutions. Along [Lim CF_{inf}; Lim CF_{sup}], different solutions can be obtained, with different configurations and installed capacities. Each value found at the solution frontier will represent an ideal solution for that proposed constraint, including optimal configuration and operation, which can vary for each separate analysis.

3. Results and discussion

Based on the energy demands of the consumer center and on the economic, legal and environmental data available, the optimization model is solved by LINGO v11.0 (Lindo Systems, 2017). 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.

The solution of each individual optimization problem provided the extreme limits: Lim_{inf}= 2,568,833 kg CO_2-eq/year (environmental optimal) and Lim_{sup}= 3,464,703 kg CO_2-eq/year (economic optimal). Table 3 shows environmental and economic optima solutions. The number that accompanies the equipment indicates the number of installed sets and the power.

The environmental optimal solution presents carbon footprint 26% lower than the economic optimal, while its annual costs are 283% higher. A significant increase is required in the annual costs to obtain a moderate reduction in the total annual emissions.

Table 4 represents the CF limitations for ε, and for each configuration, E = gas engine, B = boiler (preceded by its fuel), SA = single effect absorption chiller, and M = mechanical chiller. E* means that electricity is exported into the electric grid. The number before the component indicates the number of installed components.

Fig. 6 illustrates the relationships between total cost and total emissions obtained for each intermediate situation (blue circles), in addition to the environmental (green squares) and economic (red diamonds) optima. Table 5 represents the main characteristics of solutions A, B, C and D.

Table 3. Optimal solutions for the hospital energy supply system

		Economic Optimal	***CF optimal***
	Composition of system	***Number (Installed Power)***	***Number (Installed Power)***
	Gas engine	0 (0 MW)	2 (0.820 MW)
	Diesel engine	0 (0 MW)	0 (0 MW)
	Steam boiler (NG)	0 (0 MW)	0 (0 MW)
	Steam boiler (BM)	1 (0.250 MW)	1 (0.250 MW)
	Steam boiler (EE)	0 (0 MW)	0 (0 MW)
	Heat exchanger (VA-HW)	1 (0.400 MW)	1 (0.400 MW)
	Hot water boiler (NG)	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 (HW-CW)	0 (0 MW)	1 (0.400 MW)
	Double-effect absorption chiller	0 (0 MW)	0 (0 MW)
	Single-effect absorption chiller	0 (0 MW)	1 (0.490 MW)
	Mechanical chiller	3 (0.810 MW)	1 (0.270 MW)
	Cooling tower	1 (1.000 MW)	2 (2.000 MW)
	Photovoltaic panels	200 units	200 units
MWh/year	Imported electricity	3226	1,142
	PV electricity	129	129
	Electricity credits	--	1,552
	Natural gas imports	--	9,031
	Diesel imports	--	--

	Biomass imports	2635	599
R$/year	Cost of electricity imports	663,451	221,739
	Credit with electricity exports	--	330,413
	Cost of natural gas imports	--	2,646,159
	Cost of diesel imports	--	--
	Cost of biomass imports	137,045	31,165
	Operation and Maintenance costs	54,170	133,733
	Annual cost of equipment	195,932	270,057
	TOTAL annual cost	1,050,598	2,972,440
kg CO_2-eq/year	CF for electricity imports	1,951,900	691,123
	CF for electricity exports	--	-938,995
	CF for natural gas imports	--	2,293,940
	CF for diesel imports	--	--
	CF for biomass imports	260,913	59,333
	CF for equipment	1,251,890	463,433
	TOTAL annual CF	3,464,703	2,568,833

Table 4. ε -constraint approach based on carbon footprint and costs.

Solutions	*$Lim_{sup}(\varepsilon)$ kg CO_2-eq/y*	*Carbon Footprint kg CO_2-eq/y*	*Minimal cost R$/y*	*Configuration*
	Optimal environmental	**2,568,833**	2,972,440	2E 1BMB 1SA 1M E*
D	2,600,000	2,599,974	2,109,694	1E 1BMB 1SA 2M E*
C	2,700,000	2,616,478	2,002,849	1E 1BMB 3M E*
C	2,800,000	2,616,478	2,002,849	1E 1BMB 3M E*
C	2,900,000	2,895,909	1,429,435	1E 2BMB 3M E*
C	3,000,000	2,942,745	1,310,980	1E 2BMB 3M E*
C	3,100,000	2,942,745	1,310,980	1E 2BMB 3M E*
B	3,200,000	3,187,922	1,095,422	1GNB 2BMB 3M
A	3,300,000	3,246,853	1,073,399	3BMB 3M
	Optimal economic	3,463,703	**1,050,598**	4BMB 3M

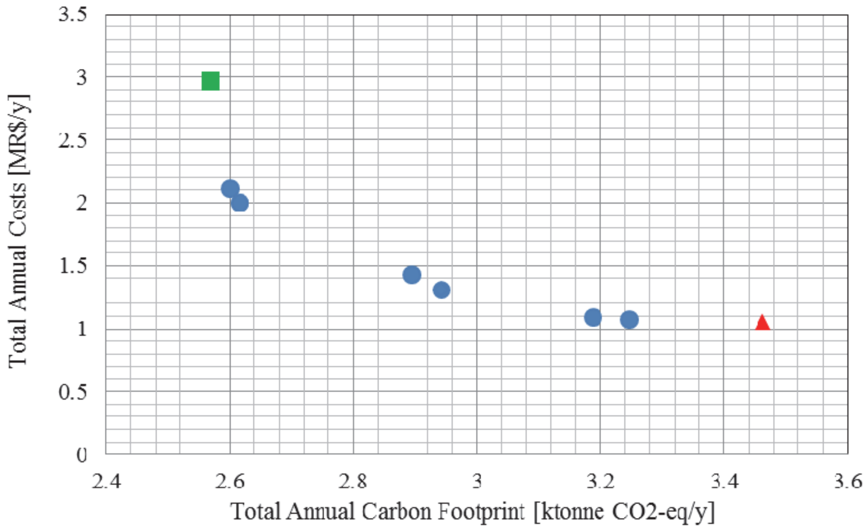


Fig. 6. Annual cost vs. annual carbon footprint

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 (NG)	0	0	0	0
	Steam boiler (BM)	3	1	1	1
	Steam boiler (EE)	0	0	0	0
	Heat exchanger (VA-HW)	2	1	1	1
	Hot water boiler (NG)	0	1	0	0
	Hot water boiler (BM)	0	1	0	0

	Hot water boiler (EE)	0	0	0	0
	Heat exchanger (HW-CW)	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
MWh/year	Imported electricity	3.226	3.226	1763	1640
	PV electricity	129	129	129	129
	Electricity credits	---	---	210	311
	Natural gas imports	---	191	4513	4891
	Diesel imports	---	---	---	---
	Biomass imports	3,191	2,622	977	908
R$/year	Cost of electricity imports	663,451	663,451	353,922	325,551
	Credit with electricity exports	---	---	- 38,342	- 73,142
	Cost of natural gas imports	---	56,035	1,322,281	1,433,163
	Cost of diesel imports	---	---	---	---
	Cost of biomass imports	165,934	136,332	50,811	47,209
	Operation and Maintenance costs	59,534	54,989	81,767	86,318
	Annual cost of equipment	184,480	184,615	840,411	290,595
	TOTAL annual cost	1,073,399	1,095,422	2,002,849	2,109,694
kg CO_2-eq/year	CF for electricity imports	1,951,900	1,951,900	1,066,712	992,190
	CF for electricity exports	---	---	- 127,290	- 188,417
	CF for natural gas imports	---	48,577	1,146,277	1,242,401
	CF for diesel imports	---	---	---	---
	CF for biomass imports	315,913	259,555	96,735	89,879
	CF for equipment	979,040	927,890	434,043	463,920
	TOTAL annual CF	3,246,853	3,187,922	2,616,478	2,599,974

Due to the large gap between the purely environmental and economic optimal solutions, the recommendation of a *balanced* situation would be the most appropriate in this case, as energy demands would be met still at a considerably low cost with lower carbon footprint throughout the year, without individually affecting one aspect.

Considering a good trade-off between annual carbon footprint and annual cost, and after verifying how the carbon footprint decreased with increases in costs versus an increase in cost for each point of the interval, configuration C is recommended, with Lim_{sup} = 2,900,000 kg CO_2-eq/year. Point C (configuration 1E 2BMB 3M E*) represented the preferred solution in the interval [Lim_{inf}, Lim_{sup}], with an annual carbon footprint of 2,895,909 kg CO_2-eq/year (approximately 570,000 kg CO_2-eq/year less each year in comparison with the economic optimal) at a total annual cost of R$ 1,429,435.

Further sensitivity analysis can be carried out to explore economic or policy-related actions and is very useful to verify the impacts associated with a change in a specific variable if it differs from what was previously assumed. Price sensitivity can be assessed by the solution map depicted by Fig. 7. As mentioned by Carvalho et al. (2013), the term resilience expresses the ability of the system to withstand expected changes (flexibility) as well as unexpected changes (robustness). Biomass and natural gas prices are varied to verify the resilience of a specific design to changes in the economic scenario. The total annual cost of the explored solutions is presented in Fig. 8 and the corresponding configurations numbered in Fig. 7 are described in Table 6. In order to show different topologies, the price range for biomass has been chosen well above the nominal price (R$ 52/MWh). As shown in Fig. 7, there exist price regions with a dominant topology, smoothly separated one from each other. For the range of prices selected, the main driver for the total annual cost increase is the price of biomass (Fig. 8), while the most robust topology is solution 1 (Table 6).

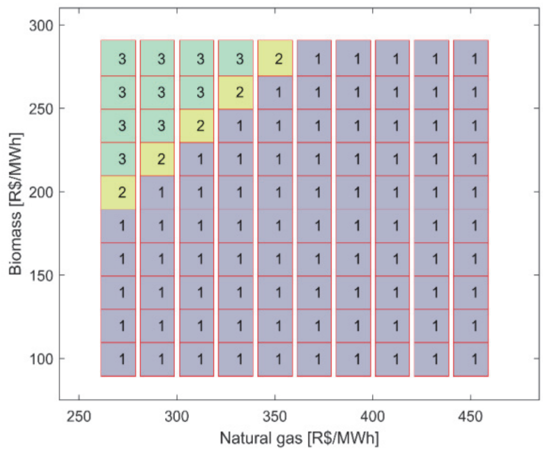


Fig. 7. Sensitivity analysis: resilience map

The uncertainties that affect investment decisions are mainly related to future emission targets and policies, which imply that the optimization of the system not only depends on the economic criterion but also on environmental impacts. These issues will provide better information for decision-making, possibly resulting in a more robust solution (Svensson and Berntsson, 2005). Also, uncertainties in energy demands can also have a significant effect, as mentioned by Urbanucci and Testi (2018).

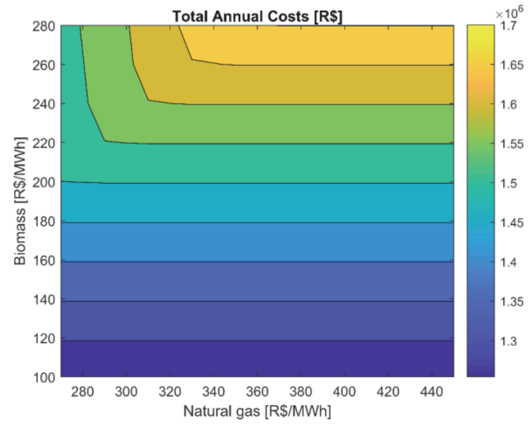


Fig. 8. Sensitivity analysis: total annual cost map

Table 6. Optimal solutions obtained by the sensitivity analysis: configurations

Solution	***1***	***2***	***3***
System composition			
Gas engine	0	0	0
Diesel engine	0	0	0
Steam boiler (NG)	0	0	0
Steam boiler (BM)	1	1	1
Steam boiler (EE)	0	0	0
Heat exchanger (VA-HW)	1	0	1
Hot water boiler (NG)	0	1	2
Hot water boiler (BM)	3	2	0
Hot water boiler (EE)	0	0	0
Heat exchanger (HW-CW)	0	0	0
Double-effect absorption chiller	0	0	0
Single-effect absorption chiller	0	0	0
Mechanical chiller	3	3	3
Cooling tower	1	1	1

MOO techniques can provide valuable information that is required for detailed analyses of design trade-offs between different, conflicting objectives. For example, if the energy system installed must present both low costs and low emissions, a range of optimal options will be provided, from the lowest cost (but highest emissions) alternative to the highest cost (but lowest emissions), along with a range of designs in between these extreme - these are the most interesting to the decision-maker.

As mentioned by Antipova et al. (2013), MOO has been progressively employed in a wide variety of applications, including the energy sector, which is not an exception to this trend. Although the purpose is to identify alternatives that balance several criteria, economic aspects are usually one of the objectives considered in MOO. Khanmohammadi et al. (2018b, 2018c) consider that the inclusion of economic aspects can provide a more realistic design of energy systems, further than environmental analysis on its own.

Brazilian studies utilizing MOO include the contracting of wind-photovoltaic projects connected to the Brazilian electric system (Aquila et al., 2018). The Brazilian government can determine that the wind-PV projects participating in lower-priced auctions are optimally configured to meet the objective of maximizing the socioeconomic well-being produced by the electricity sector.

Future work by the authors includes the consideration of hourly emission data associated with the consumption of electricity from the Brazilian electric grid (herein a constant annual average factor was considered). From an economic viewpoint, hourly electricity prices are well-established, as mentioned by Pina et al. (2017b), who have already raised awareness on the lack of hourly CO_2 emission data associated with the Spanish electric grid. Also, following Fernández et al. (2019), energy storage with integration of solar energy is being further investigated. Different indigenous energy sources can be considered to diversify the superstructure, such as bioelectricity (Carvalho et al., 2019; Melo et al., 2019).

Finally, it was verified that a considerable decrease in costs can be attained if the environmental performance of the system can be compromised. Consideration of more than one objective at a time targets a more sustainable design of energy supply systems, by guiding decision-makers towards the adoption of alternatives that cause less environmental effects. Perhaps still not a reality for Brazilian settings, but limitation or reductions in emissions are already being enforced by some countries, even if this means an increase in costs. Mitigation of climate change could, at some point, require the implementation of stricter cap-and-trade regulations, and further research on MOO could contribute to help solve the issue. A resilience map, such as the one shown in Fig. 7, can provide a wider perspective on the range of adaptability of a specific configuration.

As mentioned by Carvalho et al. (2013), further research is required on efficiency, flexibility, and robustness, rather than utilizing traditional methods for analyzing cost, benefits, and risk. Design of energy systems should nowadays consider not only technical but also economic and environmental uncertainties (*i.e.*, we cannot predict how the future will unfold).

4. Conclusions

This study addresses the issue of MOO, through the development of bicriteria optimization of an energy system for a tertiary sector building. With the use of MILP, sets of Pareto optimal design alternatives are provided, highlighting the trade-offs involved in its analysis and evaluation as well as the important role of decision makers.

The energy supply system is optimized regarding the specific energy demands of a hospital located in the city of João Pessoa, Northeast Brazil. The single-objective optimization model was adapted to the ε-constraint method, and it is observed that significant decrements in the carbon footprint can be achieved if the economic performance is compromised.

Comparison of the economic and environmental optimal solutions represents clearly different structures. Significant cost reductions can be achieved if the designer is willing to compromise the system's environmental performance. The methodology presented here aimed to improve the sustainable design of energy supply systems, guiding traditional, *purely economic* decision makers to the adoption of alternatives that would cause less environmental effects, while still meeting the energy demands of the consumer center.

A configuration based on one gas engine, two biomass boilers and three mechanical chillers was recommended. The operational mode included electricity exports to the grid. The annual carbon footprint was 2,895,909 kg CO_2-eq/year (approximately 570,000 kg CO_2-eq/year less each year in comparison with the economic optimal) at a total annual cost of R$ 1,429,435.

MOO techniques widen the perspective single-objective optimal energy systems, establishing a variety of solutions that optimize the project according to more than one objective at a time. As in most practical problems, the objective functions discussed here competed with each other and a global optimal solution could not be identified.

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