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Solar Energy and Biomass within Distributed Generation for a Northeast Brazil Hotel

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Abstract: Besides satisfying the energy demands of buildings, distributed generation can contribute toward environmental conservation. However, determining the best configuration and operational strategy for these systems is a complex task due to the available technology options and the dynamic operating conditions of buildings and their surroundings. This work addressed the synthesis and optimization of an energy system for a commercial building (hotel). Electricity, hot water, and cooling demands were established for a hotel located in Northeast Brazil. The optimization problem was based on mixed-integer linear programming and included conventional equipment, solar energy resource (photovoltaic and thermal technologies), and biomass. The objective function of the optimization was to minimize annual economic costs, which involved considering the capital and operation costs. A reference system was established for comparison purposes, where energy demands were met conventionally (without cogeneration or renewable energy), whose annual cost was BRL 80,799. Although the optimal solution did not rely on cogeneration, it benefited from the high degree of energy integration and had a total annual cost of BRL 24,358 (70% lower). The optimal solution suggested the installation of 70 photovoltaic panels and used biomass (sugarcane bagasse) to operate a hot water boiler. Solar collectors for hot water production were not part of the optimal solution. Sensitivity analyses were also carried out, varying the electricity and natural gas tariffs, and the type of biomass employed, but the configuration of the system did not change compared with the optimal economic solution.

Keywords: distributed generation; polygeneration; tertiary sector; MILP; SDG 12

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1. Introduction

Due to population growth, energy demands have increased. The limitation of traditional (fossil) energy resources has become a concern, and hence, the need for alternative energy resources has gained ground in recent years. A search for quality accompanies the increase in energy demands, and the continuity of energy supply is also an essential issue. Furthermore, environmental conservation is an important issue that must be tackled when planning energy supply and conversion systems.

In this sense, a paradigm shift is currently taking place at two levels in the energy sector: on the one hand, there is a shift from single-fuel, single-product energy systems to multi-fuel energy systems; on the other hand, there is a shift from conventional centralized energy systems to distributed generation (DG) [1].

DG is energy generation carried out at or near the final consumer location, in opposition to conventional energy generation systems. DG has technical and environmental advantages in the electric power system, both for the final consumer and for society as a whole, such as independence regarding the quality of supply from the energy distributor, high efficiency regarding the use of primary energy sources, system reliability, reduction of greenhouse gas emissions, and reduction in energy consumption and costs, when compared to conventional systems (separate production of energy services).

The increased efficiency in energy use is the main advantage of producing different energy services (e.g., heat, cooling, and electricity) from the same energy source, contributing to environmental conservation goals. These polygeneration (also called multigeneration) schemes allow for many configurations and thus enable project design flexibility, encompassing a variety of specific regional conditions. The adequate design of a polygeneration system is a conditioning factor for its success: undersized systems cannot exploit the full potential of energy integration, and if the system is oversized, there will be little or no primary energy savings at all.

There are no data related to polygeneration within the Brazilian energy matrix; there is, however, data related to cogeneration: until October 2019, the Brazilian electricity system had 18.5 GW of cogeneration installed, which is equivalent to just over 11% of the entire national generation total [2]. Most of these cogeneration units used sugarcane biomass, while the second source that most contributed to cogeneration in the country was natural gas, with a capacity of just over 3 GW.

Polygeneration systems have been a reality in the industrial sector for decades, but there is minimal implementation in the building sector [3]. Among buildings, the highest energy demands are associated with hospitals, followed by hotels, with the latter characterized by highly variable demands, both daily and annually [4,5]. Hotel buildings are unique compared to other public and commercial buildings; according to Kresteniti [4], this is due to their variable size and seasonal occupancy.

The energy demands of hotels are primarily associated with air conditioning needs and water heating. Energy demands are influenced by the hotel design, location, operation, type of service, occupancy patterns, and efficiency of air conditioning systems, where 30 to 50% of energy can be consumed [6]. Walnum et al. [7] mentioned that the importance of the energy for hot water increases when there is a lower need for space heating. Hot water corresponds to high operating expenses in a hotel facility, and although site-dependent, can represent up to 22% of total energy consumption [8].

Optimization techniques can be employed to reduce costs while extracting the maximum thermodynamic potential of the energy resources involved (this leads to important primary energy savings and environmental advantages). Mixed-integer linear programming (MILP) is often used to analyze and optimize industrial systems. MILP is sufficiently flexible to solve large and complex problems, such as process integration and industrial symbiosis, and presents a fast conversion and a global optimum using well-defined solution methods [9]. In other words, the MILP framework identifies the best conditions in a system, seeking to achieve maximum resource efficiency, minimum environmental impact, and minimum total costs, to name a few objectives.

Focusing on recent hotel optimization studies, Wu et al. [10] used MILP to obtain the optimal combination of equipment and its operation by considering three different trigeneration systems. The results indicated that the system coupled to the solar collector presented better economic performance, while the system that used biomass presented better environmental benefits. Yang and Zhai [11] developed a mathematical model of a combined cooling, heating, and power (CCHP) system hybridized with photovoltaic (PV) panels and solar thermal collectors. The particle swarm optimization algorithm was adopted to find the optimal values of the design parameters. The hybrid CCHP system achieved better performance in energy savings and CO_2 reduction when compared to a conventional CCHP system; however, it presented higher total annual costs due to the elevated capital costs. Zhang et al. [12] optimized the capacity and electrical cooling rate of a multigeneration system for a hotel located in Beijing. A Matlab stochastic model was used for the optimization, which considered annual cost savings, primary energy, and carbon dioxide emissions. Zeng et al. [13] studied a hotel building in Changsha that was equipped with a CCHP system coupled with an underground heat pump, a photovoltaic system, and a solar thermal system. The optimization model was based on the multi-population genetic algorithm, and the optimal operation followed the total electric demand, obtaining 31.59% lower costs and 52.37% fewer emissions. Li et al. [14] optimized a CCHP system that included a PV generation unit, thermal storage tank, and batteries. The chaos-mutation-whale optimization algorithm was employed, and the results demonstrated savings in the imports of electricity from the grid and in primary energy. Yan et al. [15] proposed a multi-objective stochastic optimization model of an integrated energy system with a gas turbine, thermal and PV collectors, absorption chiller, underground source heat pump, battery, and water tank storage devices. The method considered the uncertainties of solar irradiance and the loads of a hotel building located in Beijing. The annual cost reduction rate was more sensitive to the natural gas price, and the investment in solar collectors had a more substantial impact than the gas turbine.

Despite the economic and environmental benefits, polygeneration systems have been underexplored in residential and commercial buildings. This is mainly due to the considerable complexity of the design problem for building applications, which requires new interdisciplinary approaches that consider the multifaceted nature of the issues (characterized by multiple energy resources, multiple energy products, multiple technology options, and multiple operating periods).

The overarching aim of this study was to minimize the annual costs associated with the configuration and operation of an energy system to be installed in a Northeast Brazil hotel. First, the energy demands were established (electricity, hot water, and air conditioning), and then a superstructure was created with all equipment and energy resources that were locally available. Second, a MILP-based optimization problem was built that included solar energy (PV and thermal) and biomass. Then, a reference system was established for comparison purposes (no cogeneration, no renewables), and sensitivity analyses were carried out to verify the resilience of the optimal economic solution. By taking advantage of highly integrated energy conversion processes, energy efficiency was achieved, along with economic savings and sparing of the environment (environmental conservation).

2. Materials and Methods

2.1. Energy Demand

The hotel was located in the city of Conde, on the south coast of Paraíba (tropical climate), Northeast Brazil (−7.286025° S, −34.801113° W). The hotel had two levels, with a total of 29 apartments and leisure areas.

The energy demands considered were electricity (lighting and electrical equipment), hot water (showers), and air conditioning (chilled water). These energy demands varied due to the weather (seasonality) and the hotel operating mode (according to the occupancy rate). The annual operation of the hotel was characterized by two representative day types (working day and weekend) per month, with 24 hourly periods each.

The electricity demands were established following the Unified Distribution Standard NDU 001 version 6.3 [16]. For the hot water demands, the Brazilian Association of Technical Standards (better known by its acronym in Portuguese—ABNT) was followed (ABNT NBR 15569/2020 [17]). Climate data (monthly average temperature) were also employed [18]. Finally, two air conditioning units were used to characterize the cooling demand (evaluated for workdays and weekends of each month, based on the equipment technical specifications, load utilization factor, and occupancy rate).

Table 1 compiles energy data regarding electricity, hot water, and cooling for the hotel in kWh/day. The energy demands considered the hotel occupancy rate, which was based on the flow of guests (provided by the hotel management). The annual demands of the hotel were 40.36 MWh electricity, 48.13 MWh hot water, and 71.62 MWh cooling.

Table 1. Energy demands for the hotel.

Month/ Representative Day	Days per Year	Electricity	Hot Water	Cooling	Occupancy Rate
		Total (kWh/day)	Total (kWh/day)	Total (kWh/day)	(%)
Jan workday	20	166.79	173.22	295.94	90
Jan weekend	11	185.32	203.65	328.82	100
Feb workday	19	166.79	175.63	295.94	90
Feb weekend	9	166.79	187.49	295.938	90
Mar workday	20	92.66	107.29	164.41	50
Mar weekend	11	129.72	148.74	230.174	70
Apr workday	20	74.13	88.19	131.53	40
Apr weekend	10	185.32	219.21	328.82	100
May workday	20	74.13	93.31	131.53	40
May weekend	11	185.32	231.93	328.82	100
Jun workday	19	74.13	98.43	131.53	40
Jun weekend	11	185.32	244.66	328.82	100
Jul workday	20	74.13	101.27	131.53	40
Jul weekend	11	129.72	176.5	230.174	70
Aug workday	20	55.6	77.25	98.65	30
Aug weekend	11	92.66	125.88	164.41	50
Sep workday	21	55.6	72.42	98.65	30
Sep weekend	9	148.26	187.75	263.056	80
Oct workday	20	55.6	67.59	98.65	30
Oct weekend	11	148.26	175.23	263.056	80
Nov workday	20	55.6	64.96	98.65	30
Nov weekend	10	148.26	168.41	263.056	80
Dec workday	20	111.19	124.92	197.29	60
Dec weekend	11	148.26	164.99	263.056	80
Σ		MWh/year	MWh/year	MWh/year	
Year	365	40.36	48.13	71.62	

2.2. Superstructure

After the energy demands were established, the research focused on commercially available technologies and local energy resources (conventional and renewable). A superstructure was built to encompass the technically possible combinations that could be part of the energy system (Figure 1).

P represents the utilities purchased from the market (imports) and S represents the sale to the market (exports). D represents the demands of the consumer center and L represents the losses to the environment (evacuated heat to ambient air (AA)). The utilities available in this superstructure were electricity (EE) (which can be purchased (P) or exported (S) from the electric grid), as well as sugarcane biomass (BM) and natural gas (NG), which were available for purchase (P). The solar resource could be used by PV modules and solar collectors (for hot water (HW)). Other energy services included hot water (HW), refrigeration/cooling water (RW), ambient air (AA), and chilled water (CW) for air-conditioning purposes.

Each piece of equipment could interact with energy resources and other pieces of equipment, e.g., the gas engine with heat recovery consumed natural gas and produced electricity and hot water.

The use of solar energy is motivated by its intensity in the Brazilian Northeast and can be used to generate electricity and produce hot water. The energy system could be designed to operate autonomously (as an island), but the connection to the electricity grid can be very advantageous in the case of self-generated electricity exports (herein associated with PV panels and the natural gas engine).

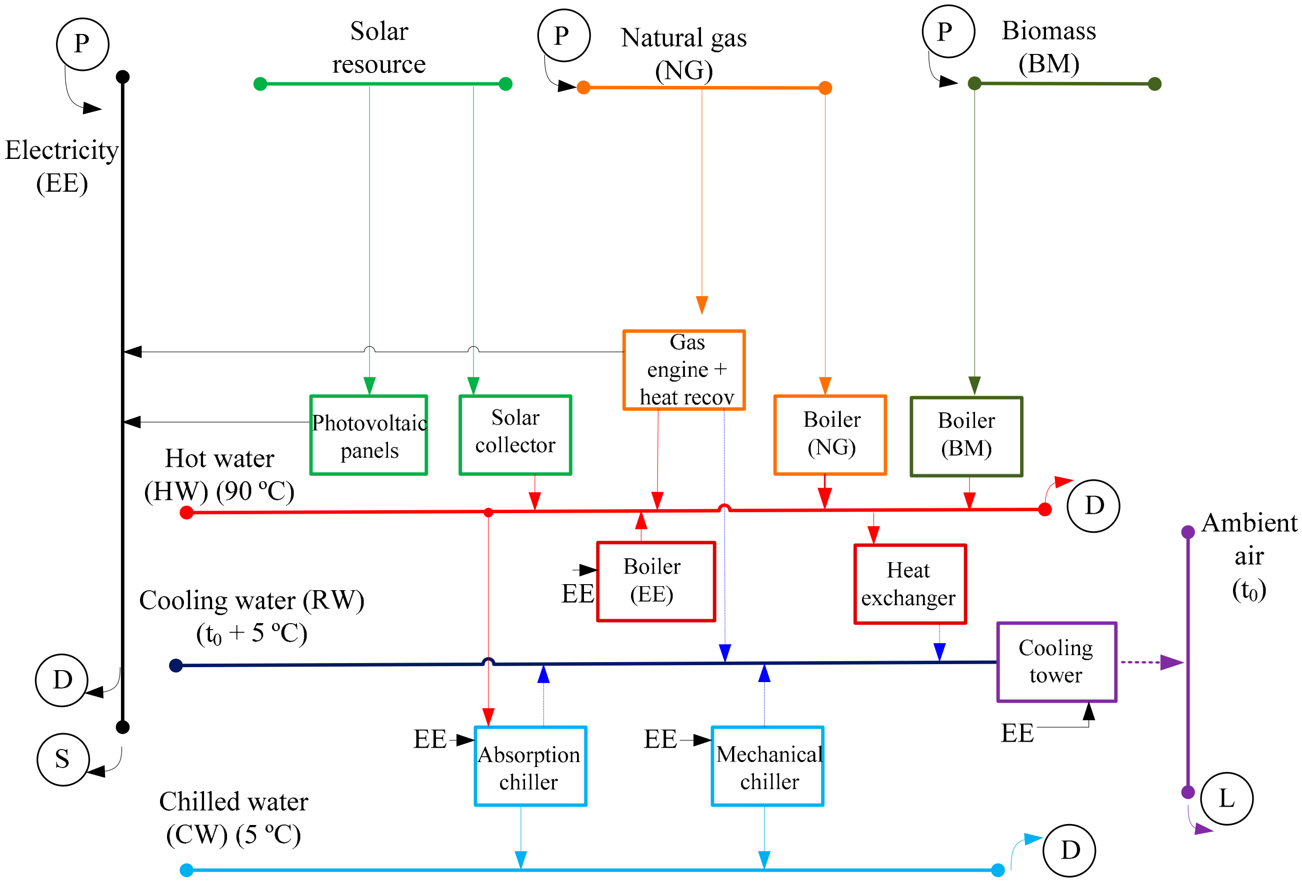

Figure 1. Superstructure of the energy supply system for the hotel.

Table 2 shows the selected equipment and the technical production coefficients for the superstructure. The rows contain the potential technologies to install and the columns contain the utilities available. Positive coefficients indicate that the utility can be produced, while negative coefficients indicate the consumption of that utility. The numbers in bold define the energy flow that characterizes the equipment (to which the other coefficients were normalized). Data presented in Table 2 were obtained from equipment catalogs and consultations with manufacturers.

Table 2. Matrix of technical production coefficients.

	Selected Equipment			**Utility** ***j***						
Technology ***i***	**Cost (10^3 BRL)**	**Nominal Power** P_{nom} **(kW)**	**O&M Cost (BRL/MWh)**	**NG**	**HW**	**RW**	**AA**	**CW**	**EE**	**BM**
NG engine	24.17	16	15.00	−4.7	+0.58	+0.61			**+1**	
Hot water NG boiler	54.00	125	2.00	−1.23	**+1**					
Hot water EE boiler	31.12	150	2.00		**+1**				−1.11	
Hot water BM boiler	56.17	149	8.00		**+1**					−1.33
Heat exchanger	3.3	150	2.00		−1.10	**+1**				
Absorption chiller	150	105	10.00		−1.27	+2.25		**+1**	−0.01	
Mechanical chiller	60	51.4	4.00				+1.32	**+1**	−0.32	
Cooling tower	5.52	180	10.00			−1	**+1**		−0.02	

The costs in Table 2 refer to the capital cost and consider transportation and installation. O&M refers to operation and maintenance costs, which were considered dependent on the production of each piece of equipment [19,20].

The PV system considered herein was restricted to electricity production. In this way, the system could also interact with the grid through exports of self-generated electricity.

The available roof area of the hotel was approximately 924 m^2, which allowed for the installation of 455 photovoltaic panels (2.03 m^2 per panel). However, upon consultation with a renewable energy consultant, it was verified that 70 panels were sufficient to meet the electricity demands (as shown in Table 2) at BRL 598.52/m^2 (including costs regarding modules, inverters, installation materials, transport, and assembly). The installation of more panels would change the status of the hotel with the electric concessionaire (leading to a more complex connection scheme and costs), and therefore the optimization considered a limit of 70 panels available for installation.

For the hot water solar collectors, the roof area would allow for the installation of 398 collectors (2.32 m^2 per unit). In consultation with the manufacturer and considering the hot water demand, 45 collectors were considered sufficient at BRL 67.57/m^2 per year (including equipment, transportation, and assembly). Thus, the number of solar collectors in the optimization was limited to 45 units.

The electricity tariff considered was the B3 group, which is associated with the conventional "commercial, services, and others" modality, at 0.56211 BRL/kWh [21]. PBGÁS is the company responsible for the commercialization and distribution of natural gas, and the tariff considered was 3.7448 BRL/m^3 [22]. For biomass, sugarcane bagasse was considered following Delgado et al. [23] at 51 BRL/MWh.

2.3. Optimization Problem

The proposed optimization problem, based on MILP, was implemented in LINGO 11.0 [24], which is an optimization modeling software that employs a branch-and-bound strategy. The objective of the optimization problem was to minimize the total annual cost C_{tot} (in BRL/year), shown in Equation (1).

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

where C_{fix} are the fixed costs (initial investment in equipment) and C_{ope} are the operation costs (purchase of energy resources to meet the demands and costs of operation and maintenance). Equation (2) represents the fixed costs, where NIP_i represents the number of installed equipment and $C_{inv,i}$ represents the capital cost for the ith technology. PM refers to the installed photovoltaic modules and SC refers to solar collectors.

$$C_{fix} = crf\ (1 + icf) \sum_i [NIP_i C_{inv,i} + PM + SC] \tag{2}$$

In Equation (2), crf is the capital recovery factor (a ratio used to calculate the present value of an annuity [25]). There was also an indirect cost factor encompassing engineering, transportation, installation, supervision, service, and contingency costs, resulting in 15% of the capital costs (icf = 0.15 [19]). Assuming that the interest rate (iyr) and the equipment life (nyr) were the same for all types of equipment, the capital recovery factor was given by Equation (3).

$$crf = \frac{iyr(1 + iyr)^{nyr}}{(1 + iyr)^{nyr} - 1} \tag{3}$$

For the current economic and financial Brazilian scenario, considering a lifetime of 15 years for the system and an interest rate of 10% per year, a capital recovery factor of 0.13/year was obtained.

For the operation costs (represented by Equation (4)), $p(d,h)$ expresses the costs with the purchase of electricity or fuel, and $t(d,h)$ expresses the number of operation hours, for the period h of the representative day d.

$$C_{ope} = \sum_d \sum_h p(d,h)t(d,h) \tag{4}$$

The annual operating cost (C_{ope}) was defined by Equation (5).

$$C_{ope} = P_{ng}\, F_{ng}(d,h) + P_{ee}E_i(d,h) - P_{ee}E_e(d,h) + P_{bm}F_{bm}(d,h) \tag{5}$$

P is the price or tariff associated with an energy source in BRL/MWh and F is the energy consumption in MWh. E_i and E_e refer to the imports and exports of electricity in MWh.

The installed power for each piece of equipment is presented in Equation (6).

$$INP(i) = NIP(i)P_{nom}(i) \tag{6}$$

where $NIP(i)$ is the number of pieces of equipment for ith technology and $P_{nom}(i)$ is the nominal power of each piece of equipment.

A binary matrix (0 = no, 1 = yes) can represent the possibilities of interaction of the energy system with the economic environment, with indicators for the possibilities of purchase ($INDPUR$), demand ($INDDEM$), sale ($INDSAL$), and waste ($INDWAS$, e.g., in the case which excess heat is evacuated) for each of the j energy resources available (Table 3). For each time interval, the production of energy is restricted to the installed capacity of equipment, and thus, an energy balance must be fulfilled for the jth utility (energy resource).

Table 3. System interaction matrix.

Utility (*j*)	***INDPUR***	***INDDEM***	***INDSAL***	***INDWAS***
Natural gas (NG)	1	0	0	0
Hot water (HW)	0	1	0	0
Refrigeration water (RW)	0	0	0	0
Ambient air (AA)	0	0	0	1
Chilled water (CW)	0	1	0	0
Electricity (EE)	1	1	1	0
Biomass (BM)	1	1	0	0

For each time interval, the energy production for each equipment i, on a given day d and given time h is restricted to the installed capacity of the equipment, as shown by Equation (7).

$$PROD(d,h,i) \le INP(i) \tag{7}$$

The production constraint is presented in Equation (8), where X represents the energy flow of the jth utility, produced or consumed by the ith technology, while K is the absolute value of the production coefficients (shown in Table 2).

$$X(i,\ j,\ d,\ h) = K(i,j)PROD(d,h,i) \tag{8}$$

The system must satisfy energy balance equations for each utility j and for each period (d,h), as represented by Equations (9)–(15).

$$PROD(j,kd,kh) - CONS(j,d,h) + P(j,d,h) - S(j,d,h) - D(j,d,h) - L(j,d,h) = 0 \tag{9}$$

$$PROD(j,d,h) = \textstyle\sum_{\mathrm{i}} X(i,j,d,h)YTUP(i,j),\ \text{with } YTUP(i,j) \in \{0,1\} \tag{10}$$

$$CONS(j,kd,kh) = \textstyle\sum_{\mathrm{i}} X(i,j,d,h)YTUC(i,j),\ \text{with } YTUC(i,j) \in \{0,1\} \tag{11}$$

$$C(j,d,h) \le INDPUR(j).[CONS(j,d,h) + D(j,d,h)],\ \text{with } INDPUR(j) \in \{0,1\} \tag{12}$$

$$P(j,d,h) \le INDWAS(j)PROD(j,d,h),\ \text{with } INDWAS(j) \in \{0,1\} \tag{13}$$

$$L(j,d,h) \le INDSAL(j)PROD(j,d,h),\ \text{with } INDSAL(j) \in \{0,1\} \tag{14}$$

$$D(j,d,h) \le INDDEM(j)\cdot[PROD(j,d,h) + C(j,d,h)],\ \text{with } INDDEM(j) \in \{0,1\} \tag{15}$$

where $PROD(j,d,h)$, $CONS(j,d,h)$, $P(j,d,h)$, $S(j,d,h)$, $L(j,d,h)$, and $D(j,d,h)$ refer to the production, consumption, purchase, export, waste, and demand of utility j in period (d,h), respectively. $YTUP(i,j)$ was 1 when the production coefficient given in Table 2 is positive, i.e., when the ith technology produced the jth utility. $YTUC(i,j)$ was 1 when the production coefficient given in Table 3 was negative, i.e., when the ith technology consumed the jth utility. Production ($PROD$) and consumption ($CONS$) corresponded to internal utility flows, whereas purchase (P), sale (S), waste (L), and demand (D) are the interchanges of utilities between the energy supply system and the environment. The binary variables $YUP(j)$, $YUS(j)$, $YUW(j)$, and $YUD(j)$ indicated, respectively, the possibility of such interchanges.

Equation (16) expresses the utilization of electricity from the PV modules (for j = 6 in Table 2, and for each period and day).

$$PROD(j) - CONS(j) + P(j) - S(j) - D(j) - L(j) + EPMH = 0 \tag{16}$$

$$EPMH = NAPM * A * \left(\frac{Rad}{1000}\right) * eff \tag{17}$$

$$NAPM \leq NPMI \tag{18}$$

Equation (16) defines the electricity produced by PV modules that originated from the radiation absorbed during each hour for each day, where $EPMH$ is the electricity exported (Wh/h), A (m^2) represents the surface area of each module, eff is the efficiency of each module (manufacturer data—15.1%), and Rad (Wh/m^2, J/m^2) is the global radiation per surface unit on a horizontal plane due to the geographic location. $NPMI$ is the number of PV modules installed and $NAPM$ is the number of active PV modules for each time interval considered in the balance equations. $NAPM$ was used as a restriction in Equation (18) to represent the degree of utilization for the modules.

Finally, Equation (19) shows the energy balance for each hour and day for the hot water production by the solar collectors (j = 2 in Table 2).

$$PROD(j) - CONS(j) + P(j) - S(j) - D(j) - L(j) + SCHH = 0 \tag{19}$$

$$SCHH = NASC * A * \left(\frac{Rad}{1000}\right) * eff \tag{20}$$

$$NASC \leq NSCI \tag{21}$$

In Equation (20), $SCHH$ defines the hot water produced by each solar collector unit from the radiation absorbed during each hour for each day. $NSCI$ is the number of solar collectors installed and $NASC$ is the number of active solar collectors in each time interval considered in the energy balance.

The optimization model compares all possible ways (within the superstructure) to meet the energy demands of the hotel, either directly or through single or multiple energy conversions hour by hour throughout the year. Thus, the optimization procedure compared all possible configurations contained in the superstructure and their operations.

3. Results

A reference system was established for comparison purposes in which all demands were met traditionally (without cogeneration, biomass, or solar energy). This is indicated by the symbol "–" in Table 4. Then, the optimization problem was freely solved, with no restrictions, leading to the optimal economic solution. In this case, a value of zero means that the optimization resulted in a null value for this amount. The optimization results are shown in Table 4.

Table 4. Reference system vs. optimal economic solution.

	Reference System		Economic Optimum	
Equipment	**Equipment Quantity**	**Installed Power**	**Equipment Quantity**	**Installed Power**
Gas engine with heat recovery	-	-	0	0
Hot water boiler (natural gas)	1	125 kW	0	0
Hot water boiler (electricity)	0	0	0	0
Hot water boiler (biomass)	-	-	1	149 kW
Heat exchanger	0	0	0	0
Absorption chiller	-	-	0	0
Mechanical chiller	1	51 kW	1	51 kW
Water cooling tower	0	0	0	0
Photovoltaic modules	-	-	70	17.33 kW_e
Solar collectors	-	-	0	0
	Annual energy flows (MWh/year)		Annual energy flows (MWh/year)	
Imported electricity	64		36	
Natural gas purchase	60		0	
Biomass purchase	-		42	
Exported electricity	-		46	
Electricity from PV modules	-		74	
Initial investment in equipment	BRL 131,100		BRL 218,646	
	Annual costs (BRL/year)		Annual costs (BRL/year)	
Imported electricity	43,014		24,327	
Natural gas purchase	20,355		0	
Biomass purchase	-		2136	
Exported electricity	-		−31,207	
Operation and maintenance	387		679	
Annual cost of equipment	17,043		28,424	
Total annual cost	BRL 80,799		BRL 24,358	

For the reference system, the problem presented 52,766 constraints and 66,019 variables, of which 586 were integers. The model performed a total of 28 iterations, with a solution time of 10 s, on a 2500 MHz Intel® Core i7 processor with 8 GB of memory. For this system, the minimum annual costs were achieved by installing a natural gas hot water boiler to meet the heating demand, a mechanical chiller to meet the cooling demand, and purchasing electricity directly from the grid to meet the electricity demand.

When the model was freely solved (without restrictions) there were 56,242 constraints and 69,501 variables, of which 1170 were integers. The model performed 2684 iterations over a solution time of 14 s.

In the optimal economic solution, the minimum annual cost was associated with the installation of a biomass boiler (heating demand), a mechanical chiller (cooling demand), and electricity generated by photovoltaic modules plus direct purchase of electricity from the grid (electricity demand).

The optimal economic solution did not install cogeneration but relied on solar PV energy. The impossibility of cogeneration can be explained by the low demand for heat (restricted to hot water and related to the local climate) in the hotel. In addition, the high capital cost of the absorption chiller also made trigeneration unfeasible. No solar collectors were installed to produce hot water and the maximum allowed number of PV panels were installed.

Although the capital costs increased in the optimal economic system, there was a considerable annual benefit. With the free choice of technologies and possibilities of using PV solar energy and biomass, yearly savings of BRL 56,441 were achieved. This represented approximately 69.8% lower costs compared to the reference system.

4. Sensitivity Analysis

4.1. Electricity Tariff

In this case, the electricity tariff was changed to consider the time of use (peak time between 6 and 9 pm, BRL 1335/MWh; shoulder time 5–6 pm and 9–10 pm, BRL 829/MWh; and off-peak times for all other times, BRL 460/MWh).

The optimization results did not present any changes in the configuration or operation, only in the costs. Table 5 shows the optimal solution found for the optimization model when the time-of-use tariff was employed. The initial investment in equipment totaled BRL 218,646 (the same as the optimal economic solution).

Table 5. Annual costs: time of use vs. optimal economic solution.

	Time-of-Use Annual Costs (BRL/year)	Optimal Economic Annual Costs (BRL/year)
Biomass purchase	2135	2135
Electricity purchase	22,046	24,327
Exported electricity	−21,338	−31,207
Operation and maintenance	679	679
Annual cost of equipment	28,424	28,424
Total annual cost	31,945	24,358

The total annual cost was about 31.15% higher than the optimal economic system (BRL 7587/year), leading to an unfavorable scenario. Dantas and Pompermayer [26] mentioned that when the time-of-use tariff is employed along with a photovoltaic system within the same consumer center, there are no advantages in using this time-of-use tariff because when PV generation is at its peak (roughly between 6 am and 6 pm), the time-of-use tariff presents its lowest value (off-peak). Therefore, at peak hours, electricity is more expensive and PV generation is too low to meet the demands; therefore, the consumer has to purchase electricity at a higher price than was sold/exported.

Although the change from the conventional tariff to the time-of-use tariff with the distributed generation system was not favorable, it should be noted that electricity and thermal storage were not evaluated herein. The use of storage resulted in better use of an intermittent renewable energy resource, which could alleviate the problem of incompatibility between energy production and energy consumption services [27].

4.2. Natural Gas Tariff

The sensitivity analysis of the natural gas tariff was performed, varying the tariff between −20% and +20% relative to the base case value (340 BRL/MWh). For all scenarios, no system configuration change occurred. The base case configuration met the demands for the natural gas tariff value ranging from −20% to +20%, indicating the good performance of the optimal solution in the face of the uncertainties related to the natural gas tariff. It was verified that natural gas generator sets were only installed when the natural gas tariff decreased to 106 BRL/MWh, a 69% decrease in its base value (and rather improbable).

4.3. Biomass Types

Sugarcane bagasse biomass (51 BRL/MWh, 2130 kcal/kg) was chosen for the superstructure and its feasibility was compared with the use of firewood (78 BRL/MWh, 3100 kcal/kg) and pellets (114 BRL/MWh, 4000 kcal/kg), as these are two types of biomass that are allowed for the specified hot water boiler.

The assessments considered the different energy tariffs for biomass, along with their lower heating value. It was found that pellets were the most expensive biomass resource, while firewood presented the second-best result after considering the purchase cost and total annual cost. Although firewood presented an attractive purchase cost, sugarcane bagasse remained the best biomass option due to its lower input and transport costs.

The result corroborates those of Delgado et al. [23]. Among different biomass options, sugarcane bagasse was also found to be the most suitable option in the optimization of a polygeneration system in a hospital.

4.4. Electricity Tariff

It was observed that solar thermal collectors were never installed. This fact demonstrated that, for this hotel and its hot water demands, there was no need to install solar collectors. There was no variation in the system configuration when the electricity tariff was varied between −20% and +20% of the base case value (562 BRL/MWh).

Finally, when evaluating the installation of distributed microgeneration within an optimal economic system and considering the current Brazilian scenario, it is possible to compare results with Delgado et al. [28]. The study proposed a MILP-based environmental and economic optimization in which the superstructure included PV panels and biomass. The optimal economic solution relied on biomass for hot water boilers. However, the optimal environmental solution indicated trigeneration (natural gas cogeneration module plus a single-effect absorption chiller) to minimize the environmental impacts associated with the energy system. In Delgado et al. [28], the cost of the photovoltaic modules was BRL 2280, which was 87.7% higher than the value employed herein (BRL 1215). Such a difference was due to the evolution of distributed generation, specifically regarding the expansion of solar energy companies of this sector in Brazil, leading to a decrease in equipment costs. Brazil has advanced positively in its incentive policies for the dissemination of distributed generation, and these systems have become economically viable for the consumer units.

5. Conclusions

This study used mixed-integer linear programming to optimize the configuration and operation of an energy system that supplied electricity, hot water, and cooling for a hotel in Northeast Brazil.

The results demonstrated the financial savings related to incorporating renewable energy sources (solar energy and biomass) in an optimal economic system. The optimal solution, which minimized the hotel's total annual costs, did not install cogeneration but was supported by photovoltaic solar energy.

The optimal economic system met the electricity demand by installing 70 photovoltaic modules and purchasing electricity from the grid. The hot water demand was satisfied by a biomass boiler and the cooling demand by a mechanical chiller. When comparing the optimal economic solution with a reference system (an optimal solution in which cogeneration and renewable resources were not allowed), it was verified that the former benefitted from the use of photovoltaic panels and biomass. Although the optimal economic solution presented higher capital costs, its total annual cost was 69.8% lower than the reference system (based on conventional equipment).

Sensitivity analyses evaluated the change in electricity and natural gas tariffs and types of biomass. When the electricity tariff was changed to a time-of-use modality, there were no financial advantages. No changes were observed when the natural gas tariffs varied; moreover, a gas engine was only installed when the tariff dropped by almost 70%. When different types of biomass were evaluated (sugarcane bagasse, pellets, and firewood), sugarcane bagasse was the most appropriate choice, as it suited the energy demands of the hotel. When natural gas and electricity tariffs varied from −20% to +20%, no changes were observed in the optimal configurations, indicating the good performance of the optimal solution against the uncertainties related to these tariffs.

Since the formulation and enforcement of legislation that encourages renewable energy resources, several factors have contributed to the economic feasibility of these systems over the years. Some of these factors include incentives by state governments; tax exemptions (ICMS, Brazilian tax on the circulation of goods and services); implementation of incentive policies for the financing of distributed generation systems; energy policy measures, such as the energy compensation scheme; and the growth of companies, which has led to more competitive and accessible equipment to the consumers and favored the distributed generation market.

A continuation of this study can consider thermal and electrical energy storage. Integration of storage technologies into the energy supply optimization procedure might introduce fewer constraints into the resulting system and lower costs. Many of the technical challenges in reformulating the mathematical optimization procedures to accommodate intermittent and variable renewable energy supply utilities may be reapplied by considering energy stores acting as energy supply components. Moreover, this could permit the investigation of the potential benefits of storage technologies regarding improving power quality and stability (voltage, frequency, and power factor maintenance) by introducing additional power quality constraints on the design optimization search.

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Nomenclature

A	Surface area (m^2)
AA	Ambient air
BM	Biomass
CCHP	Combined cooling, heat, and power
C	Cost
CONS (j, d, h)	Energy consumption
CW	Chilled water
crf	Capital recovery factor
d	Day
D	Demand
DG	Distributed generation
EE	Electricity
E_e(d, h)	Export of electricity to the grid (MWh)
E_i(d, h)	Consumption of electricity from the grid (MWh)
eff	Efficiency (%)
EPMH	Electricity exported (Wh/h)
F_{bm}(d, h)	Consumption of biomass (MWh)
F_{ng}(d, h)	Consumption of natural gas (MWh)
h	Hour
HW	Hot water
icf	Indirect cost factor
INDDEM	Binary indicator for energy demand

INDPUR	Binary indicator for energy purchase
INDSAL	Binary indicator for energy exports
INDWAS	Binary indicator for energy waste
INP	Installed power
iyr	Interest rate (y^{-1})
j	Energy utility (energy resource)
k (i, j)	Absolute value of production coefficient
L	Losses
MILP	Mixed-integer linear programming
NAPM	Number of active PV modules
NASC	Number of active SC
NIP	Number of installed equipment
NG	Natural gas
NPMI	Number of PV modules installed
NSCI	Number of SC installed
nyr	Lifetime (y)
O&M	Operation and maintenance
P	Purchase
p (d, h)	Costs with the purchase of electricity or fuel
P_{bm}	Tariff of biomass (BRL/MWh)
P_{ee}	Tariff of electricity (BRL/MWh)
P_{ng}	Tariff of natural gas (BRL/MWh)
P_{nom}	Nominal power (kW)
PM	Photovoltaic modules
PROD (d, h, i)	Energy production
PV	Photovoltaic
Rad	Radiation (Wh/m^2)
RW	Cooling water
S	Sale/exports
SC	Solar collectors
SCHH	Hot water produced by each solar collector unit
t (d, h)	Number of operation hours
X (I, j, d, h)	Energy flow
YTUC(i,j)	Binary variable 1/0 indicating that technology i consumes/does not consume utility j
YTUP(i,j)	Binary variable 1/0 indicating that technology i produces/does not produce utility j
YUD(j)	Binary variable 1/0 indicating the possibility of demand of utility j
YUP(j)	Binary variable 1/0 indicating the possibility of purchase of utility j
YUS(j)	Binary variable 1/0 indicating the possibility of sale of utility j
	Subscripts
fix	Fixed
i	Technology
inv	Refers to capital costs
ope	Operational
tot	Total

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