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ECONOMIC OPTIMIZATION APPLIED TO A COMBINED GENERATION SYSTEM FOR A HOTEL IN JOÃO PESSOA

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Abstract

In this study, an economic optimization analysis is conducted for a combined generation system focused on meeting the electricity, heating, and cooling demands of a hotel located in João Pessoa, in northeastern Brazil, a region characterized by high solar energy availability throughout the year. The proposed system integrates an internal combustion engine, photovoltaic panels, a combustion heater, a chilled-water storage tank, and both electric and absorption chillers. For comparison purposes, a reference system was considered in which all electricity is purchased from the public grid, heating is supplied by a natural gas heater, and cooling is provided by a conventional vapor-compression system. The total annual cost of this arrangement is R$ 685,516.84, whereas the economically optimized solution resulted in a cost of R$ 515,053.00. The results indicate that integrating different technologies allows greater operational flexibility, efficient use of waste heat, and better utilization of solar energy. Additionally, the findings provide technical and financial insights for funding agencies and policymakers, encouraging the adoption of sustainable technologies in hotel buildings within the region.

Keywords: Solar energy, combined generation, optimization, hotel sector.

1. Introduction

The commercial building sector in tropical regions faces significant challenges related to energy consumption, especially due to high cooling demands (Mazzone, 2020). According to Singh and Khullar (2019), in cities with high solar irradiation rates and elevated annual average temperatures, air-conditioning systems account for a substantial share of electricity consumption in hotels, hospitals, and commercial centers.

Tropical regions offer high potential for the use of solar energy; however, the variability of solar radiation requires hybrid solutions and storage systems. In buildings, notable applications include photovoltaic systems for electricity generation combined with electric chillers, as well as solar thermal collectors coupled with absorption chillers in some cases (Sakti et al., 2023; Zhang et al., 2022). Hybrid technologies, such as heat pumps integrated with thermal energy storage, also show great potential for reducing emissions in hotels (Reddy et al., 2024).

In this context, Khosla et al. (2020) point out that the integration of photovoltaic and thermal systems emerges as a complementary alternative, utilizing waste heat for heating and driving absorption chillers, thereby increasing efficiency and reducing costs. Long-term studies conducted in hotels also indicate that heat recovery in chillers can lower costs and reduce pollutant emissions associated with cooling systems (Wing Yu et al., 2024).

According to Hoang et al. (2021), combined generation using internal combustion engines emerges as an alternative for the simultaneous production of electricity and heat. Karthikeyan and Kumar (2023) emphasize that the waste heat from these engines can be utilized to operate absorption chillers, directly contributing to meeting cooling demands, especially during periods of high thermal load. Khani et al. (2021) highlight that the combination of these technologies in combined generation systems represents an opportunity to reduce pollutant emissions in hot and sunny countries such as Brazil. However, as noted by Farzaneh et al. (2022),

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the technical and economic feasibility of these systems depends on detailed analyses that consider local factors such as load profile, energy costs, existing subsidies, and climatic conditions.

In this context, optimization studies are frequently employed to identify the most suitable systems for a given energy demand (Park et al., 2023). According to Zhang et al. (2023), the application of optimization techniques in combined generation systems offers significant advantages, allowing the identification of the most appropriate equipment configurations by considering variables such as generator size, chillers, and storage units, as well as determining optimal operating regimes based on demand profiles and local climatic conditions.

Given this context, the objective of this study is to conduct an economic optimization analysis applied to a combined generation system that utilizes renewable inputs, proposed for a hotel located in João Pessoa, in northeastern Brazil, aiming to integrally meet the demands for electricity, heating, and cooling. In addition to analyzing the integration of different energy technologies under real operating conditions, this work contributes technical and financial data that can support funding institutions and government agencies in the development of public policies and incentive mechanisms. By comparing the performance of the proposed system with that of a conventional plant, which relies exclusively on grid electricity and natural gas to meet heating demand, the results allow for the economic quantification of the differences between the two evaluated scenarios. Thus, this study seeks to support the adoption of sustainable energy solutions in commercial buildings in the region, promoting greater efficiency in energy consumption and low-impact energy generation.

2. Material and methods

2.1. Case Study Description

The energy demands of the hotel considered in the study include electricity, heating (hot water between 45 °C and 50 °C at the points of use), and cooling (chilled water between 7 °C and 10 °C at the supply), as reported in Reddy et al. (2024) and Wing Yu et al. (2024), respectively. The demand profile was modeled based on twelve representative days, one for each month, with an hourly discretization of 24 periods, totaling 288 operational periods over the year. The representative days consider only typical energy demand values, following the methodology proposed by Pina et al. (2020). A representative day corresponds to a typical profile selected to characterize the average conditions of a given period in terms of energy demand. This approach reduces the amount of data to be processed in simulations while maintaining fidelity to consumption patterns.

The hotel is located in the city of João Pessoa, Paraíba, in northeastern Brazil, which features a humid tropical climate and a high annual average temperature. According to INMET data (2024), in March, João Pessoa recorded an average maximum temperature of 32.3 °C. These climatic conditions directly influence the energy consumption profile, with particularly high cooling demand throughout the year.

The hotel’s annual electricity consumption was 13.73 MWh, the adopted cooling demand was 18.73 MWh, and the heating requirement was 14.53 MWh. These values were adapted from the study by Lima (2021). The adaptation involved adjusting the demand values by applying a correction factor proportional to the built area of the hotel, in order to represent a facility with greater accommodation capacity compared to Lima (2021). For the energy demand data in this study, a hotel with an area approximately 40% larger than that in Lima (2021) was considered.

This procedure allowed for the estimation of energy loads compatible with the size of the building under consideration. The adjustment was made to ensure greater consistency between the energy supply potential of the proposed system and the demand required by the hotel.

Tab. 1: Hotel energy demand

Month	Day Frequency in the year	Electricity (kWh/day)	Heating (kWh/day)	Cooling (kWh/day)	Occupancy rate (%)
January	31	1114.9	1225.4	1545.8	100
February	28	1064.5	789	1508	90
March	31	807.3	689.8	1132.4	70
April	30	1100.4	1075.7	1504.6	100
May	31	1013.1	1204.1	1416.9	100
June	30	1013.1	1337.5	1320.9	100
July	31	674.8	1005.4	882.3	70
August	31	497.9	700.2	657.5	50
September	30	792.7	1003.6	1119	80
October	31	874.2	898.1	1186.1	80
November	30	1010.5	810.5	1228.7	80
December	31	920.4	728.6	1280.2	80
-	-	MWh/year	MWh/year	MWh/year	-
Total	365	13.8	14.5	18.7	-

Figure 1 shows the hourly energy demand for the representative day of July, when the hotel occupancy was 70%. The hourly energy demand profile varies for each representative day, depending mainly on climatic conditions.

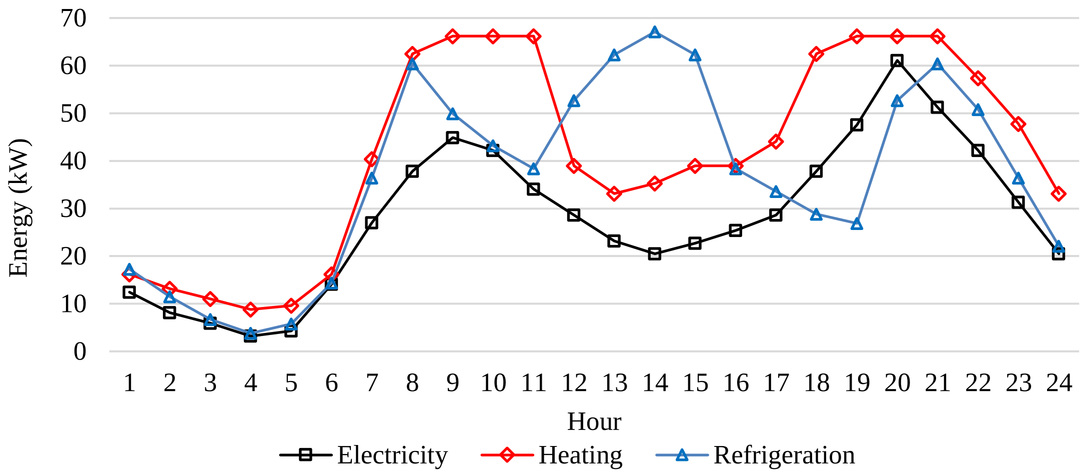

Fig. 1: Hourly energy demand (representative day of July)

The representative day of July was chosen for presenting the results, as under this occupancy condition there is greater integration and contribution of the different energy sources in meeting the hotel's demand.

Figure 2 shows the solar radiation (the energy source for the panels and collectors) in João Pessoa for a representative day in June and November 2024, corresponding to the days with the highest and lowest solar incidence, respectively. For the hotel, a solar-exposed area of 250 m² was considered.

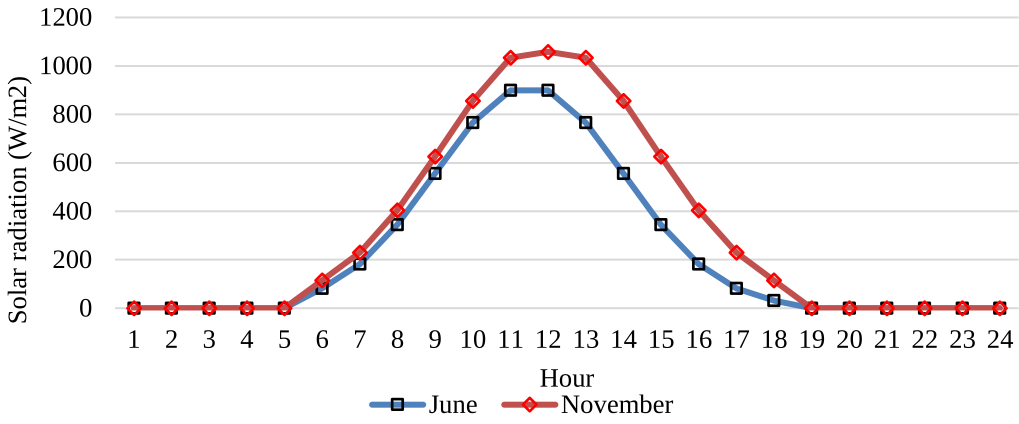

Fig. 2: Solar radiation in João Pessoa, Paraíba. Source: INMET (2024).

2.2. Superstructure

The superstructure is a representation of the space of possible solutions. This configuration includes all feasible options, technologies, their connections, and flows. In this way, the optimization model can determine the best possible configuration for a given criterion. Figure 3 shows the proposed superstructure designed to meet the hotel's required energy demands.

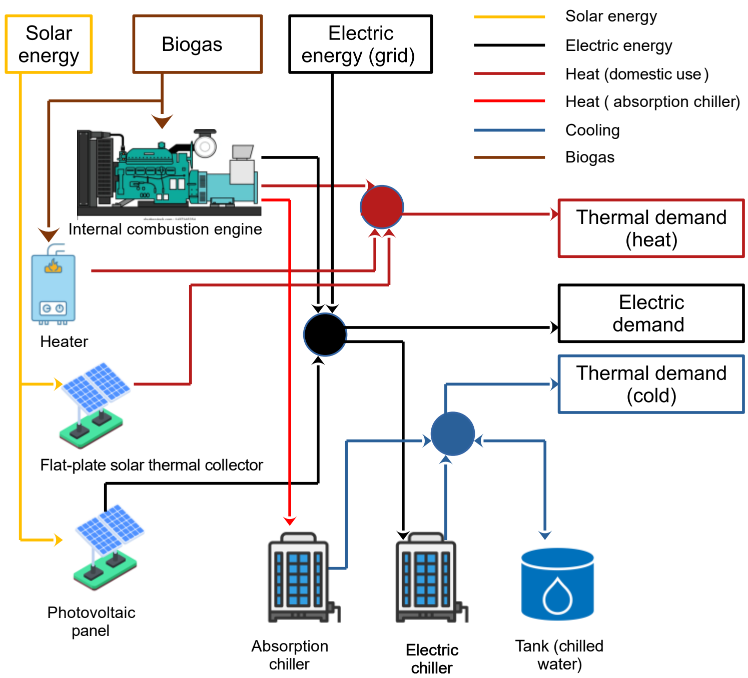

Fig. 3: Proposed superstructure

The superstructure includes photovoltaic panels (for electricity generation), solar collectors (for hot water production), an internal combustion engine (powered by biogas, providing electricity and heat), single-effect absorption chillers (driven by the waste heat from the engine's exhaust gases, producing chilled water for cooling), an electric chiller (capable of meeting the cooling demands), a chilled-water storage tank, and a biogas-fired heater (for heat production).The system is connected to the electrical grid, with the possibility of purchasing electricity only. The biogas used in the plant comes from an urban biodigestion system; for this application, treated biogas ready for use in the internal combustion engine (ICE) and the heater was considered. Thermal losses through the exhaust gases and the ICE cooling fluid were not taken into account, and a constant heat transfer factor was adopted to represent the system's thermal energy recovery.

2.3. Equipment

Table 2 presents the main technical data, including the nominal power and energy conversion efficiency of the equipment that composes the superstructure.

Tab. 2: Technical and economic data of the superstructure equipment.

Equipment	Unit cost (R$/kW)	Efficiency	Reference
MCI (electric power generator)	6000	0.35 (electric) 0.38 (thermal)	(Yağli et al., 2016)
Biogas heater	1000	0.60	Adapted from (Melo et al., 2022)
Solar collector (flat plate)	1000	0.70	Adapted from Lima, 2021
Photovoltaic panel	2800	0.15	Adapted from Lima, 2021
Single-effect absorption chiller	8000	0.63*	Adapted from (Melo et al., 2022)
Electric chiller	6600	5*	Adapted from (Pina et al., 2018)

* Values associated with the COP (Coefficient of Performance) of the chillers.

The equipment considered in the optimization process corresponds to commercially available technologies. The data presented in Table 1 were obtained considering installation and operation in locations with climatic conditions similar to those of João Pessoa, which is characterized by high average annual temperatures and high solar radiation levels throughout the year.

2.3. Optimization Model

The objective function consists of minimizing the annual system costs, including equipment, operation, and maintenance costs (Equation 1).

$$\text{Min } CTE_{tot} = CTE_{fix} + CTE_{var} \qquad \text{(eq. 1)}$$

The therm CTE_{tot} (R$/year), represents the total annual cost. Fixed costs, denoted as CTE_{fix} (R$/year), cover the purchase and maintenance of equipment, while variable costs, CTE_{var} (R$/year) include energy costs (electricity imported from the grid and biogas purchase).

$$CTE_{fix} = f_{am} \cdot (f_{ic} + 1) \cdot \sum_t CI(t) \cdot PIN(t) \qquad \text{(eq. 2)}$$

The fixed cost is calculated based on the amortization and maintenance factor f_{am} and the indirect cost factor f_{ic}, the investment cost per functional unit of the equipment CI(t) (as indicated in Table 2), and the installed capacity of the equipment PIN(t). In the summation of Equation 2, the indices t of the terms CI(t) and PIN(t) refer to each of the equipment units included in the plant.

$$CTE_{var} = \sum_{d,h} NRY(d) \cdot (CTE_{bio}(d,h) + CTE_{ele}(d,h)) \qquad \text{(eq. 3)}$$

This cost is calculated from the following parameters: the representative number of days NRY(d) (as indicated in Table 1), the biogas acquisition cost CTE_{bio} and the electricity acquisition cost $CTE_{ele}(d, h)$. In the summation of the variable cost, the indices d and h represent the representative days and hours, respectively.

Table 3 compiles the input data used in the economic optimization assessment.

Tab. 3: Input data for economic evaluation.

Description	Value	Unit	Reference
System lifetime	20	Year	Pina et al. (2020)
Amortization and maintenance factor	0.16	1/h	Adapted from (Pina et al., 2020)
Indirect cost factor	0.1	-	Adapted from (Pina et al., 2020)
Electricity purchase price	0.7	R$/ kWh	Adapted from Energisa. (2024)
Fuel purchase price	0.7	R$/ kWh	Adapted from ANEEL 2025

The mathematical formulation of the optimization problem was implemented in the AMPL environment (A Mathematical Programming Language, AMPL, 2023). The solver used is CBC (Coin-or Branch and Cut), an open-source tool capable of solving Mixed-Integer Linear Programming (MILP) problems.

3. Results

The main results of the economic optimization are presented in Table 4. The following subsections provide a detailed explanation of these results.

Tab. 4: Main results of economic optimization by technology.

Technology	Capacity PIN, kW	Load factor	Investment, R$/year
MCI	43.5	0.36	4501.5
Heater	74.5	0.74	1296.4
Photovoltaic panel	48.2	0.80	2340.7
Electric chiller	60.0	1.0	6842.2
Absorption chiller	21.7	0.43	3061.0

The optimal total cost solution considered the installation of the internal combustion engine (ICE), biogas-fired heater, photovoltaic panels, absorption chiller, and electric chiller. To meet the energy demand, the hotel relies heavily on the electric chiller and the biogas-fired heater, both with a load factor above 70%. The equipment with the highest investment-related costs were the electric chiller and the ICE.

3.1. Reference system solution

For the purpose of comparison and to represent a configuration commonly used in hotel installations, a reference system was established in which all electricity is purchased from the public grid, the heat demand is supplied by a natural gas-fired heater, and cooling is provided by a vapor compression system. The total annual cost of this arrangement was estimated at R$ 685,516.84, with R$ 12,568.53 corresponding to fixed costs and R$ 672,948.31 to operational costs.

3.1. Optimal total annual cost solution

The software recorded 9,078 variables in the problem resolution: 1,728 binary variables and 7,350 linear variables. A total of 10,331 constraints were recorded, all linear, including 5,036 equality constraints and 5,295 inequality constraints. The data were generated for a single linear objective: minimizing the annual economic cost.

The optimal solution for the economic optimization problem indicated a total annual cost of R$ 515,053.00, with R$ 496,973.00 corresponding to operational costs and R$ 18,080.00 to fixed costs.

Figure 4 shows the plant configuration after the economic optimization process. The figure also indicates the annual values associated with the energy flows.

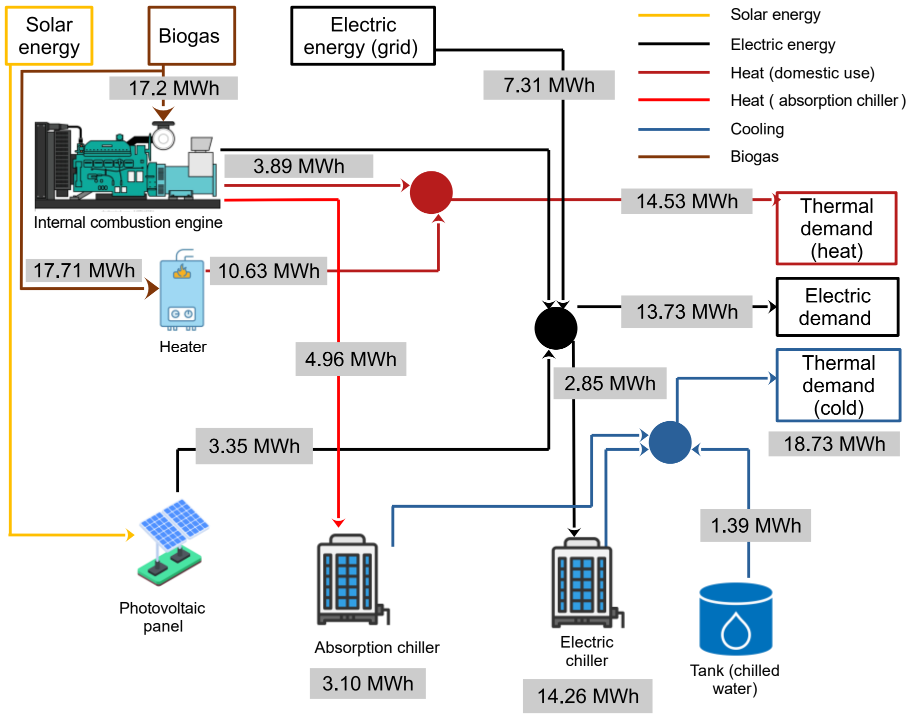

Fig. 4: Energy flows of the optimal total annual cost solution.

From an economic standpoint, the optimal configuration excludes the use of solar collectors for water heating. The area exposed to solar radiation is fully utilized for photovoltaic panels.

The electricity demand is mainly met by purchasing energy from the grid, 7.31 MWh (44% of the total). This is followed by the internal combustion engine (ICE) with a production of 6.02 MWh and the photovoltaic panels contributing 3.35 MWh, approximately 36% and 20% of the total, respectively. In the optimal economic cost solution, the system produced more energy than it purchased from the grid, helping to reduce dependence on grid electricity.

The heat demand is primarily met by the biogas-fired heater, supplying 9.90 MWh, followed by the engine's waste heat at 3.63 MWh, corresponding to 68% and 32% of the total, respectively. The energy wasted by the internal combustion engine, mainly associated with heat dissipation, amounted to 2.58 MWh.

Regarding the cooling demand, which represents the building's largest energy consumption at 18.73 MWh, most of the supply comes from the electric chiller at 14.26 MWh, accounting for 76% of the total. The contributions from the absorption chiller and the storage tank are 3.10 MWh and 1.39 MWh, corresponding to 16% and 8% of the demand, respectively.

Figures 5 to 7 show the optimal hourly production of electricity, heat, and cooling, considering the representative day of July, when the hotel occupancy rate is 70%.

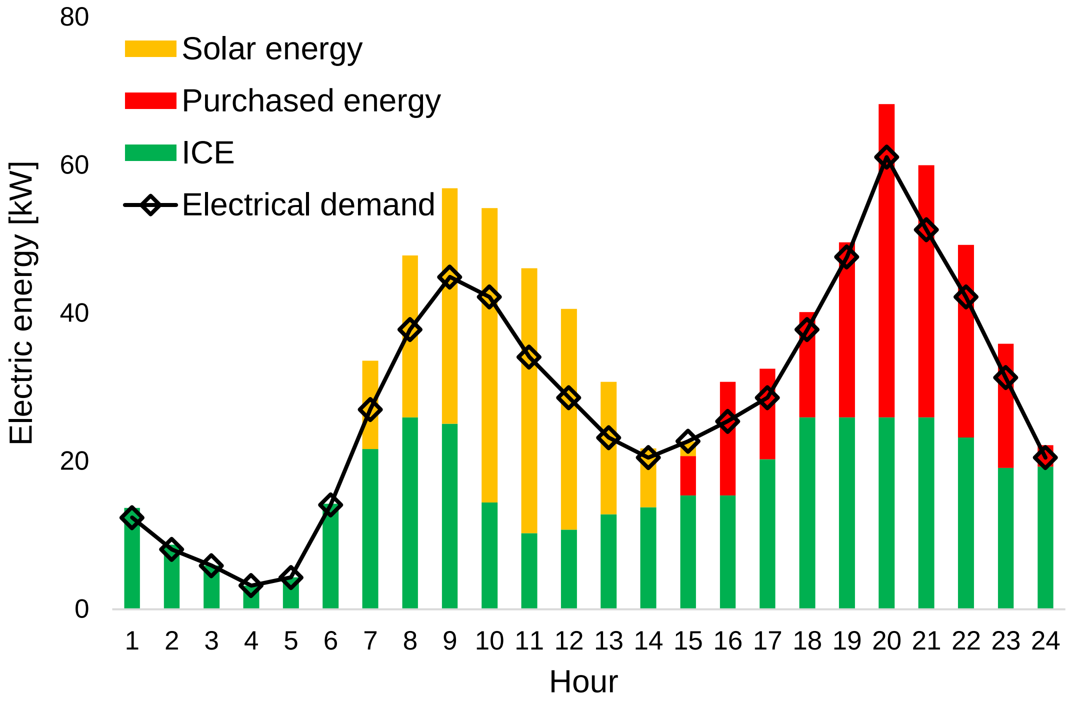

Fig. 5: Hourly electricity flows in July

The electricity demand exhibits two main peaks: one in the morning between 8:00 and 10:00, and another in the evening between 18:00 and 22:00. These periods correspond to high hotel occupancy, which explains the elevated energy consumption. During the night, the demand is low (average value below 20 kW), gradually increasing from 6:00 onwards.

Electricity purchases begin at 15:00, increasing until the second demand peak. Between 16:00 and 23:00, activity from the internal combustion engine and electricity purchases is observed, with average values of 23 kW and 22 kW, respectively.

Energy generation from the photovoltaic panels occurs during hours of highest solar radiation. This period is characterized by energy production exceeding the demand, with the surplus energy being used by the electric chiller to store chilled water in the tank.

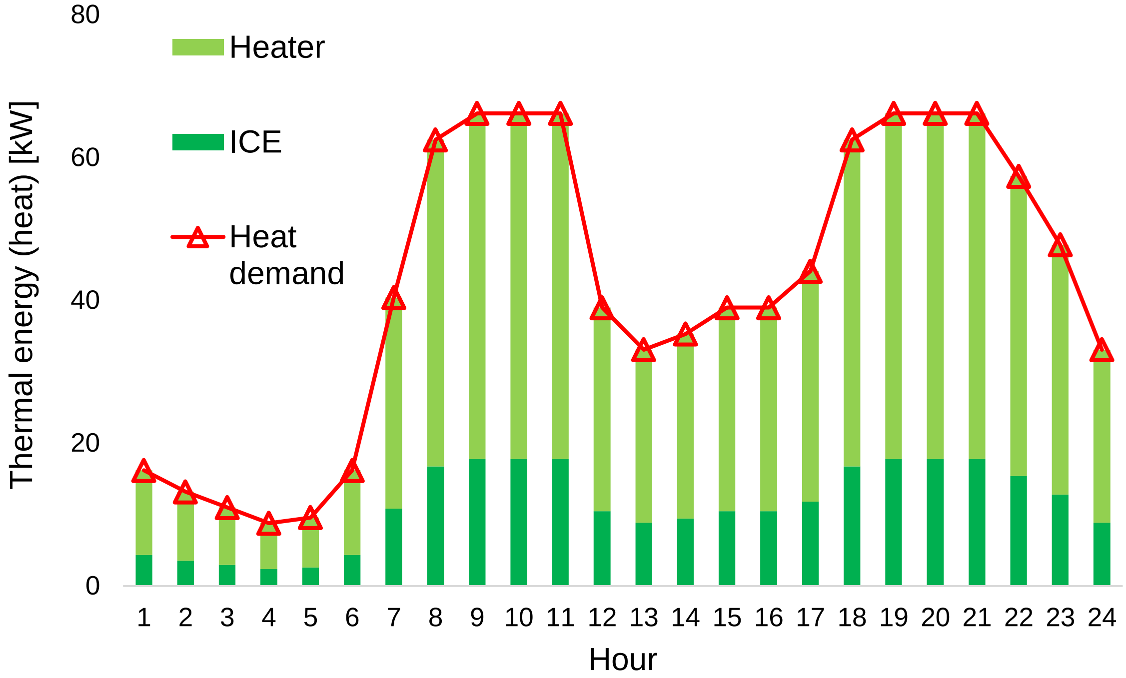

Fig. 6: Hourly thermal (heat) energy flows in July

The heater remains active throughout the period, operating at maximum capacity between 07:00–09:00 and 18:00–21:00. During the other hours, the heater provides an average of 22 kW.

The internal combustion engine (ICE) contributes heat throughout the day, with higher thermal generation during peak demand hours, supplying an average of 16 kW in these periods. The ICE's thermal energy contribution is low during off-peak hours, approximately 9 kW. For economic analysis, the engine's operation is driven by electricity production, given that its value is higher than the cost of purchasing electricity when compared to the expense of generating heat.

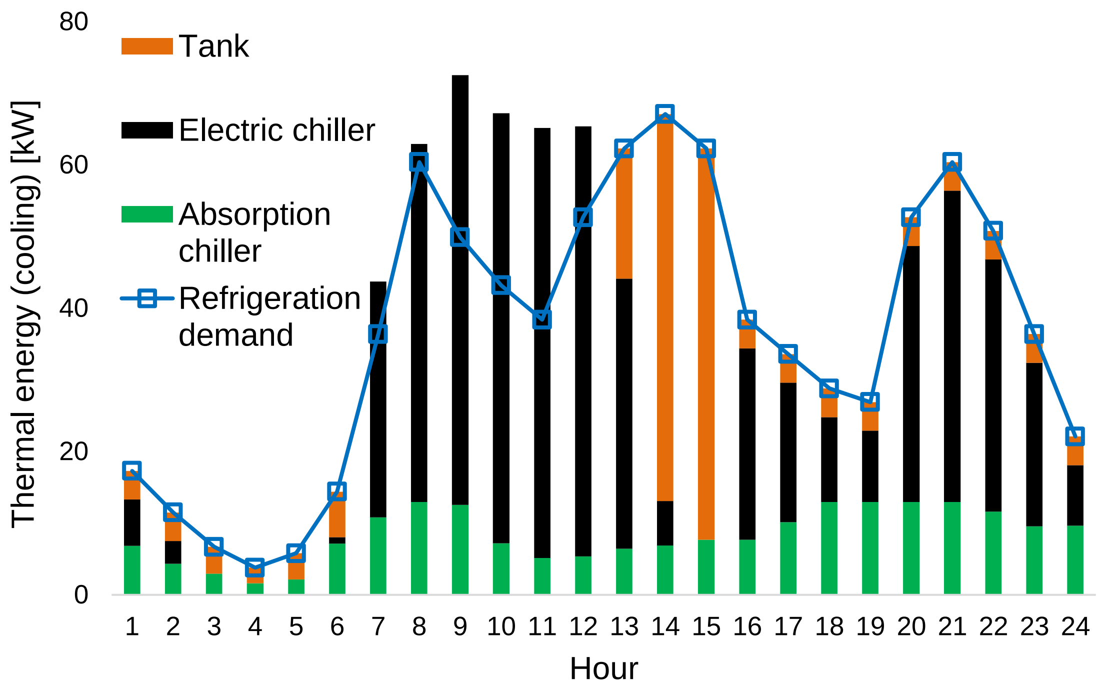

Fig. 7: Hourly thermal (cooling) energy flows in July

The electric chiller operates continuously from 07:00 to 12:00. For most of this period, the equipment produces more energy than the demand, and this excess production is used to store chilled water in the tank. Between 01:00 and 05:00, the operation is reduced, with an average output of approximately 2 kW. From 16:00 to 24:00, the energy produced follows the same profile as the demand, with an average of about 24 kW.

The storage tank supplies energy during the early afternoon demand peak, reaching a maximum of 54 kW at 15:00. Between 07:00 and 12:00, there is no energy supply from the tank. During the rest of the day, the tank provides a reduced energy output, averaging 8 kW.

The results indicate that the integration of different technologies allows for greater operational flexibility, utilization of waste heat, and use of solar energy, contributing to the sustainability of the facility. Although the reference system presents a lower annual cost than the optimized solution, the proposed configuration offers significant benefits in terms of energy matrix diversification, reduced dependence on the electricity grid, and emissions mitigation, factors that are strategic for hotels seeking alignment with decarbonization targets and greater resilience to energy price fluctuations. Furthermore, changes in input economic parameters, such as the cost of raw materials or the annual interest rate on investment, may render the proposed solution competitive in terms of total cost, reinforcing its attractiveness under more favorable market scenarios.

3. Conclusion

In this study, an economic optimization analysis was conducted for a combined generation system designed to meet the energy demands of a hotel located in João Pessoa, in northeastern Brazil. The system under study integrates different technologies: an internal combustion engine (ICE), photovoltaic panels, a solar collector, an electric chiller, an absorption chiller, a biogas-fired heater, and a thermal storage tank. The analysis was carried out within a mixed-integer linear programming (MILP) optimization framework. This approach allowed for the identification of the system’s most economical configuration, considering both hourly operation and fixed and variable costs.

The optimal economic solution prioritizes the use of photovoltaic panels for electricity generation, excluding the option of solar collectors for water heating. Most of the electricity is purchased from the grid (44%), followed by production from the internal combustion engine (36%) and photovoltaic generation (20%). Heat is predominantly supplied by the biogas-fired heater (68%). Cooling, the hotel’s main energy demand, is mostly met by the electric chiller (76%), complemented by the absorption chiller (16%) and the storage tank (8%). Hourly analysis revealed distinct consumption and production patterns, highlighting the role of storage in managing peak demand periods.

In addition to the technical and economic analysis, this study provides support for the formulation of public policies and financial incentive mechanisms aimed at promoting the adoption of combined generation technologies with low environmental impact. By highlighting the potential for reducing operational costs, decreasing greenhouse gas emissions, and improving the efficiency of energy resource use, the study identifies factors that can guide incentive programs and support the deployment of environmentally friendly combined generation technologies. The identification of conditions under which such systems become viable can inform investment decisions, increase the share of renewable energy sources, and reduce the environmental impact associated with energy consumption in the hotel sector. The results presented may serve as a basis for government support strategies, fostering not only environmental sustainability but also the economic competitiveness of the tourism sector.

For future studies, it is recommended:

- Analysis of the environmental impact of the proposed superstructure;
- Sensitivity analysis related to variations in energy tariffs, fuel costs, and subsidies;
- Evaluate the performance of concentrated solar collectors as an option to meet the thermal energy demand.

These extensions are expected to strengthen the study’s contribution to the development of sustainable energy policies tailored to the specific conditions of tropical regions.

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