

Article

Energy Optimization in Hotels: Strategies for Efficiency in Hot Water Systems

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Abstract: This paper presents a procedure for the energy optimization of domestic hot water (DHW) systems in hotels located in tropical climates that use centralized air conditioning systems. The study aims to maximize heat recovery from chillers and reduce the fuel consumption of auxiliary heaters by optimizing operational variables such as water mass flow in the primary and secondary DHW circuits and outlet temperature of the backup system. The optimization is implemented using genetic algorithms (GA), which enable the identification of the most efficient flow configurations under variable thermal demand conditions. The proposed methodology integrates a thermoenergetic model validated with real operational data and considers the dynamic behavior of hotel occupancy and water demand. The results show that the optimized strategy reduces auxiliary heating use by up to 75%, achieving annual energy savings of 8244 kWh, equivalent to 2.3 tons of fuel, and preventing the emission of 10.5 tons of CO₂. This study contributes to the design of sustainable energy systems in the hospitality sector and provides replicable strategies for similar climatic and operational contexts.

Keywords: energy optimization; heat recovery; domestic hot water systems; energy efficiency



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1. Introduction

Global economic and social development has increased energy demand in all sectors, leading to a greater focus on energy efficiency, especially in the context of the economic crisis and global warming. The need to improve international competitiveness and mitigate the environmental impact of various technologies underscores the importance of optimizing the use of energy resources [1–3].

As more people gain access to modern technologies, there is a significant increase in the use of air conditioning systems, particularly in hot regions. According to the International Energy Agency (IEA), air conditioning accounts for one-fifth of total electricity consumption in buildings worldwide and 10 percent of global electricity consumption. Over the next three decades, the use of these systems is expected to increase rapidly, becoming a critical factor

influencing energy demand. By 2030, global energy efficiency standards are expected to be implemented, improving the energy performance of HVAC systems by more than 50% [4,5].

In this context, the tourism sector, especially hotels in tropical climates, faces a significant challenge, as air conditioning and domestic hot water (DHW) systems both account for 60% to 70% of their total energy consumption [6]. Various energy-saving alternatives in thermal systems exist to address this high consumption, such as reducing demand, reusing residual energy through heat recovery, installing high-efficiency motors, and improving thermal insulation. Renewable technologies and the automation of operational processes can complement these strategies [7,8].

The recovery of heat generated during the compression cycle in centralized air conditioning systems is presented as an effective solution to optimize DHW production in hotels [9,10]. As the use of these systems increases, it is crucial to implement strategies that reduce energy consumption and pollutant emissions and maintain user comfort. Integrating efficient technologies and sound operational practices is critical to ensure a sustainable and cost-effective energy supply in hotel facilities.

In hotels, hot water production must be constantly maintained, with temperatures above 50 °C at the furthest points and the ability to rise to 70 °C periodically to prevent the growth of bacteria such as *Legionella*. During the winter, recovered heat may be insufficient due to the part-load operation of chillers, requiring an additional backup source to ensure a hot water supply. Fluctuations in demand and part-load operation affect energy efficiency, creating the need for large volumes of thermal storage and energy-consuming backup systems such as gas or electricity [11–13].

The existing literature focuses mainly on the sizing and optimal configuration of energy systems, leaving a significant gap in operational optimization based on integral thermoenergetic models. This limitation is especially relevant in contexts where operating conditions vary considerably, such as in high tourism seasons in Cuba, where the energy demand for water heating increases due to the almost permanent use of auxiliary heaters. Despite the importance of these scenarios for energy efficiency and operating cost reduction, few studies address the mathematical modeling of chillers within a scheme to maximize heat recovery in domestic hot water (DHW) systems. This lack of research limits the development of efficient operational strategies that, in addition to optimizing energy performance, contribute to environmental sustainability by reducing resource consumption and pollutant emissions. The work aims to establish an energy optimization procedure and propose strategies for energy efficiency in domestic hot water systems in hotels.

The main contributions of this research are detailed below:

- The development of mathematical models that describe the behavior of heat recovery in chillers, allowing its integration with the simultaneous production of domestic hot water, using operational data and associated environmental variables;
- The methodology for the modeling of the installation that integrates the components of the domestic hot water (DHW) system, facilitating the proposal of parameters that ensure an efficient operation according to the hot water demand conditions;
- The procedure for energy optimization of the sanitary hot water production system, obtaining the most efficient operation strategy with the lowest consumption and environmental impact;
- Given the importance of the tourism sector and its environmental impact, this article explores the opportunities and challenges associated with energy optimization in domestic hot water systems in the hotel context.

This paper is organized as follows: Section 1, the Introduction, presents the background and motivation for the study, highlighting key challenges in the modeling, operation, and optimization of domestic hot water (DHW) systems in hotel facilities. Section 2,

State of the Art, provides a review of recent literature, methodological foundations, and technological approaches related to energy optimization and heat recovery systems in hotels. Section 3, Materials and Methods, describes the proposed methodology, which includes the development of a thermoenergetic model based on real operational data, as well as the implementation of an optimization procedure using genetic algorithms. The case study is also introduced. Section 4, Results and Discussion, presents the thermodynamic evaluation of the system, analyzes the optimization results, and discusses economic, environmental, and comparative findings with respect to other studies. Finally, Section 5, Conclusions, summarizes the main contributions of the study, including the quantified energy savings, life cycle cost evaluation, environmental benefits, and the potential applicability of the proposed strategy in similar tropical environments.

2. State of the Art

The search focused on studies addressing energy optimization, heat recovery, and operational strategies in centralized air conditioning and domestic hot water systems, with a special interest in hotel facilities. The selection criteria included peer-reviewed articles, publications in relevant conferences, and technical studies applied to real contexts.

2.1. Literature Review

To develop the materials and methods section of this study, an exhaustive analysis of the scientific literature was carried out using a systematic search in recognized academic databases. The focus of the analysis was structured under the following search strategy: TITLE-ABS-KEY (“energy optimization” OR “energy efficiency” OR “energy savings”) AND TITLE-ABS-KEY (“heat recovery” OR “domestic hot water systems” OR “modeling of hot water systems” OR “hot water systems”) AND TITLE-ABS-KEY (“centralized air conditioning” OR “hotel installations” OR “operational strategies”) AND PUBYEAR > 2015 AND PUBYEAR < 2025. This temporal filter allowed us to limit the results to research published between 2016 and 2024, ensuring the incorporation of the most recent and relevant advances in the field.

2.2. Methodological Context and Literature Integration

The analysis identified the most commonly used methodological approaches to system optimization, such as thermal modeling, computational simulations, and the development of operational strategies to maximize energy efficiency. These methodological elements were integrated into the study’s development, adopting procedures tested in the literature and adjusting them to the specific conditions of the case study.

In this context, operational data from air conditioning and domestic hot water systems, including demand variables, energy flows, and thermal profiles, similar to those described in the literature, were used. The methodological implementation was developed using advanced computational tools and energy modeling software, following reproducible guidelines to facilitate future comparisons and validations in different industrial applications.

As a result, the novelty of our research topic was confirmed since it covers a group of variables and indicators that have been little worked on in the literature, highlighting its novelty and importance. Figure 1 shows the main variables, optimization methods, and energy efficiency. The trend indicates operational work, air conditioning, good use of energy, regenerative cycles, and sustainability in the processes, which are the same approaches our research has.

Typical DHW systems in Caribbean hotels with centralized air conditioning are composed of three pumping circuits, as shown in Figure 2.

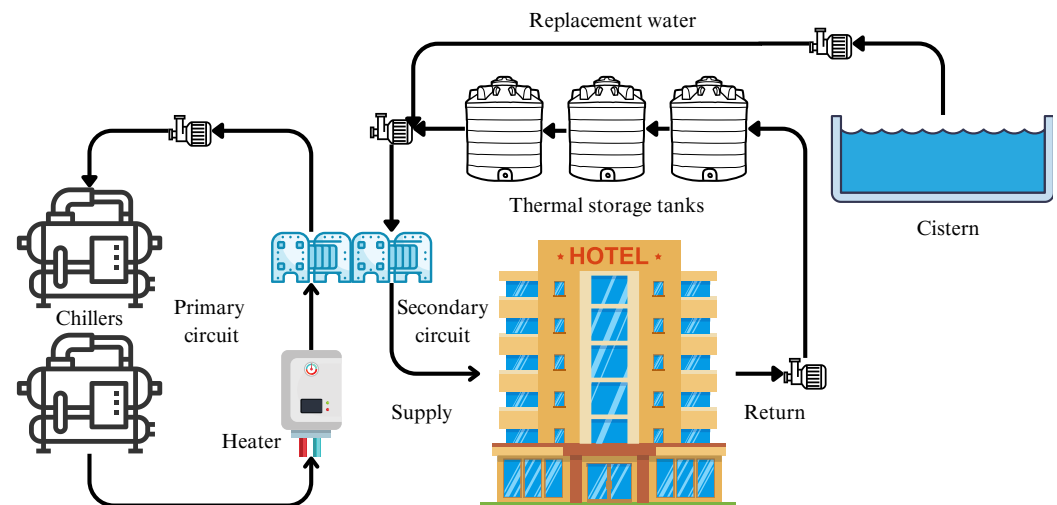


Figure 2. Physical and functional diagram of the installation with heat recovery and thermal storage tanks for domestic hot water.

Primary hot water circuit (PHWC): by recirculating a certain volume of water, heat is partially recovered in the recuperator before passing to the condensation process. This volume of water passes as a hot fluid through a plate heat exchanger until it returns to the heat recovery unit of the chillers. In case the water temperature in the DHW circuit does not guarantee the set hot water temperature ($60\text{ }^{\circ}\text{C}$), the water temperature in the DHW circuit itself is increased by means of a backup heater. **Secondary hot water circuit (SHWC):** a counterflow volume of water circulates through the plate heat exchanger from the room temperature water (AWT) that is replenished in the DHW system (equal to that consumed), plus the volume of service water that is not consumed and returns. Once the water gains heat in the plate heat exchanger, it is sent to the users for consumption. The return is stored in storage tanks. **Recirculation circuit (RC):** promotes the circulation of hot water through the network of service pipes distributed throughout the hotel.

3. Materials and Methods

The availability of domestic hot water (DHW) is a fundamental requirement for comfort in the hotel sector, where its consumption represents a significant part of the energy expenditure. This consumption varies according to factors such as climate, hotel category, and occupancy level. In this context, it is crucial to address energy efficiency in air conditioning and water heating systems, as their optimization can significantly reduce both energy consumption and operating costs and environmental impact [19].

Studies indicate that air conditioning loads in hotels are variable throughout the year; in the case of hot water demand, in addition to seasonal variation, there are daily peaks, mainly in the morning and afternoon [20]. This requires heating and storage systems to be adequately sized. However, a common problem is the oversizing of these systems, where the installed capacity exceeds the actual demand, resulting in inefficient operation [21].

Hot water demand is influenced by cultural and social norms, as well as region-specific climatic conditions, making generalization across countries difficult [22]. In addition, current regulations on hot water demand in non-residential buildings are outdated and do not adequately address the selection of necessary equipment [23,24].

Despite the fact that in tropical countries the need for air conditioning and hot water is always present, there is limited research on the simultaneous optimization of both systems

in hotels. Understanding consumption patterns is essential for designing efficient systems. A recent study has compiled information on DHW consumption profiles in different types of buildings, providing tools to accurately estimate the energy consumption associated with these systems [19].

The implementation of more efficient technologies and a proper design that considers peak demand are essential to ensure an adequate supply of domestic hot water without incurring unnecessary costs.

3.1. Methodology for the Development of the Energy Model

The proposed methodology is based on a real installation and consists of experimental field work that includes the measurement of various operating parameters of the water chillers, such as electrical power, chilled water supply and return temperatures, as well as refrigeration cycle parameters. These measurements allow estimating the thermal load profile of the installation and the heat recovery potential.

In the domestic hot water (DHW), measurements of mass flows and temperatures in the supply and return are made to determine the hot water consumption profile, in addition to recording the temperatures in the primary DHW circuit.

By modeling the system, all the processes that describe its operation are integrated, which facilitates the estimation of the behavior of the temperature profiles in the event of variations in operating conditions.

The methodology (Figure 3) also identifies the decision variables necessary for the optimization procedure, proposing specific strategies for each operating condition or system set point. This includes considering the optimal ratio of flows and temperatures in the primary circuit, as well as the operating range of the chillers to maximize heat recovery. Finally, the objective function will be defined, along with the decision variables and system constraints, to carry out an optimization procedure that minimizes operating costs and the associated environmental impact.

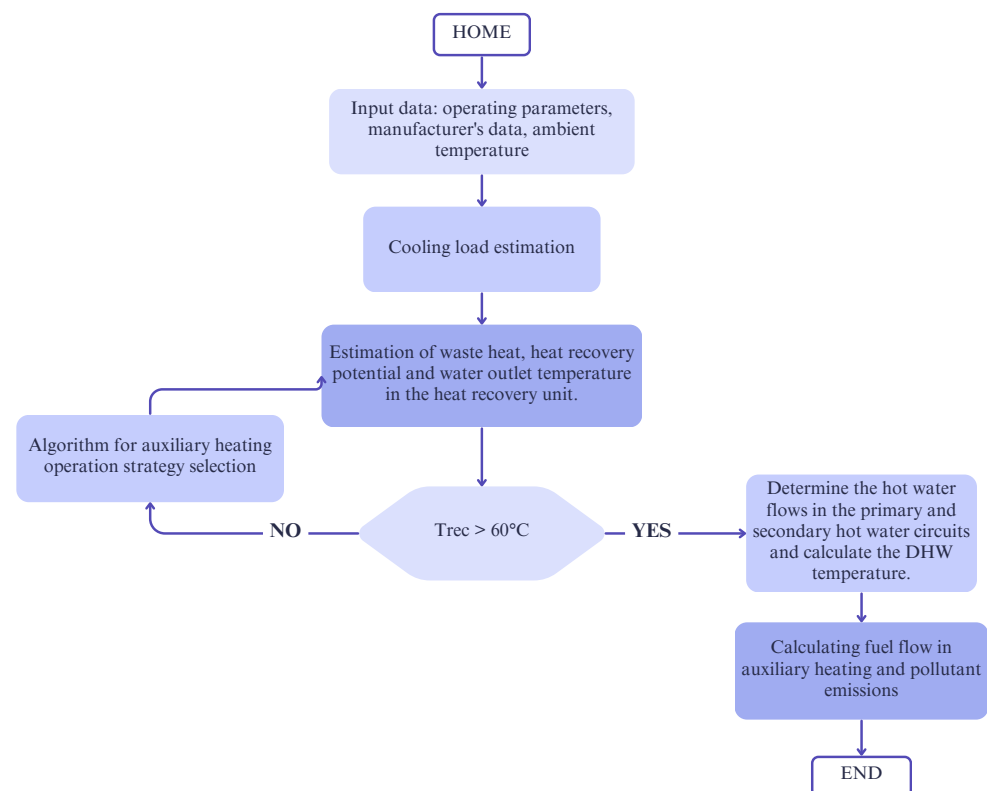


Figure 3. Block diagram with the development of the methodology.

Considerations for the development of the energy model:

- Stationary operating conditions exist;
- Heat losses between the heat exchangers and the surroundings are neglected;
- Heat losses between the hot water supply and return in the insulated pipes are considered to be less than 5 °C;
- Pressure drops in the heat exchangers are neglected;
- Heat losses to the medium in the water chillers are neglected (the rejected heat is the sum of the cooling capacity and the compressor power);
- The system works at constant flow.

3.2. Case Study: Hotel Facility

The facility under study consists of two water chillers arranged in parallel with a cooling capacity of 363 and 505 kW, respectively, using the refrigerant R134a as the working substance. The chillers contain air-cooled condensers, which are equipped with constant-speed fans.

Each chiller operates with a refrigeration circuit that includes expansion valves and screw compressors. The installation is designed to recover the condensation heat generated in both chillers through a heat exchanger, which is connected in series with the condenser of each unit.

The heat recovery is integrated into a system for the production of domestic hot water (DHW), which consists of two circuits interconnected through a plate heat exchanger. A general schematic of the system is shown in Figure 2, which illustrates the layout and operation of the system.

The heat recovered from the chillers is transferred to the primary hot water circuit, where it reaches temperatures of up to 65 °C under nominal operating conditions. However, when the system operates at low cooling loads, an backup heater is required to raise the temperature of the primary circuit to 60 °C. This ensures that the water sent to consumers reaches the established value of 55 °C, in accordance with the standards required for hotels in Cuba.

The most critical situation occurs during the winter months, when chiller activity decreases. During this period, the auxiliary heater must remain on most of the time, since the heat generated by the chillers is not enough to meet the thermal demand of hot water. It is important to note that the high tourist season in Cuba coincides with these winter months, which creates a scenario in which high occupancy, maximum demand for hot water, and low ambient temperatures are combined. These variables have a significant impact on the operation and efficiency of the domestic hot water production system.

The backup system consists of a direct-fired heater, model Pegasus-F2-102, with a useful power of 99 kW and a water flow rate of 1.25 kg/s. The heater operates with liquefied petroleum gas (LPG), reaching temperatures between 60 and 80 °C and an efficiency of 85%. However, the hotel lacks a control strategy for the auxiliary heater, resulting in its activation only during peak hot water demand. During the rest of the time, the heater remains off, causing a decrease in temperature and generating instability in the system. In addition, LPG consumption is not recorded separately for the cooking services and the domestic hot water system. Figure 4 illustrates the average monthly LPG consumption, with November to March being the months with the highest demand.

The current operation of the system presents deficiencies that affect both the stability of the required temperatures and the efficiency of the heat exchange processes in the production of hot water. Although the current operating strategy allows energy savings through a limited use of the auxiliary heater, it is not the most adequate to maintain a constant hot water supply temperature.

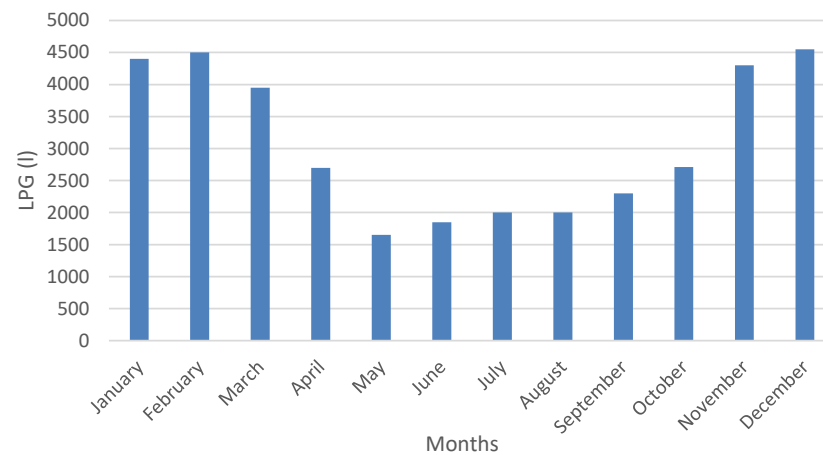


Figure 4. Average monthly LPG consumption of the case study hotel.

Therefore, it is essential to study the variables that influence the behavior of temperatures in order to propose a strategy that guarantees stability in the hot water supply and, at the same time, minimizes fuel consumption in the auxiliary heater. It is suggested to implement a new strategy that adjusts the water mass flow ratios in the hot water circuits and optimizes the use of the backup system during peak consumption times.

3.3. Energy Optimization Procedure

In hotel domestic hot water systems, operation is inherently dynamic, resulting in significant changes in optimal operating points from day to day or even within the same day. To address these challenges, periodic adjustments to operating conditions are necessary to adapt to fluctuations in demand. The technological advances allows for one to implement real-time optimization (RTO), which allows for maximizing benefits or minimizing costs while meeting operational constraints. Although steady-state models are generally used due to the design of the process to operate in steady state except during significant changes, this optimization offers effective solutions to improve performance [25,26].

The main objective of this optimization problem is to determine the optimal ratio of flows in the primary and secondary circuits to maximize heat recovery in the chillers, ensuring that the system maintains a stable temperature at 55 °C according to established hotel standards. In addition, it seeks to optimize the energy performance of the system to maximize its overall efficiency and minimize fuel consumption in the auxiliary heater.

3.3.1. Target Function

The proposed objective function seeks to minimize the energy consumed by guaranteeing the minimum temperature difference between the heat recovery temperature (T_{9c}) and the auxiliary heating temperature (T_{ca}); see Equation (1).

$$FO = \min \sum_{k=0}^{24} Q_{ca} = m_{cp} \cdot C_p [T_{ca}(k) - T_{9c}(k)] \quad (1)$$

The decision variables are defined as those that can be operationally modified:

- m_{cp} : hot water flow in the primary circuit, kg/s;
- m_{cs} : hot water flow in the secondary circuit, kg/s;
- T_{ca} : temperature at the outlet of the auxiliary heater, °C;
- T_{9c} : the heat recovery temperature, °C.

The expression describing the behavior of the supply temperature as a function of the independent variables is given by Equation (2):

$$T_{\text{sum}} = \frac{m_{\text{cp}}}{m_{\text{cs}}} (T_{\text{ca}} - T_6) + \left(\frac{m_{\text{ret}} + m_{\text{cs}}}{m_{\text{ret}} + m_{\text{rep}}} \right) T_k + \left(\frac{m_{\text{rep}}}{m_{\text{ret}} + m_{\text{rep}}} \right) T_{\text{rep}} \quad (2)$$

where

- T_{sum} : hot water supply temperature, °C;
- T_k : temperature of the storage tanks, °C;
- T_{rep} : temperature of the replenishment water, °C;
- T_6 : water temperature at heat recovery, °C;
- m_{ret} : return water flow, kg/s;
- m_{rep} : replenishment water flow, kg/s.

Optimization with Genetic Algorithms

Energy systems with fluctuating demand, such as domestic hot water systems in hotels, require adaptive optimization methods to balance efficiency, cost, and stability. In this context, GA emerge as an effective tool due to their ability to solve complex problems by simulating natural selection. GA are particularly suitable for multi-objective problems, where their ability to explore multiple solutions simultaneously is valuable. Their structure, based on evolutionary principles, allows them to adapt effectively to problems with nonlinear constraints and interdependent variables. In addition, they are often more robust than other optimization methods in scenarios with multiple local optima and complex constraints, making them ideal for dynamic energy systems. In practice, GA offer balanced solutions between sustainability, efficiency, and operational resilience, making them a versatile tool for optimizing energy systems with variable demand [27].

GA are implemented as an optimization tool to minimize the costs of domestic hot water (DHW) production in the facility. This approach considers the operating constraints inherent to the system model. GA, recognized for their ease of implementation and computational efficiency, offer a robust solution for complex problems involving the management of operational variables in thermal systems, especially those subject to variable demand. The optimization procedure following the GA approach is as follows (Figure 5):

Main Program

1. Initial configurations

- Read data from a set of measurements taken every 10 min, stored in the file `Datos.mat`. These include:
 - Total Power (P_{total})
 - Inlet water temperature to the heat recovery system (T_6)
 - Chilled water temperature (T_{ah})
 - Ambient temperature (T_{amb})
 - Sanitary water return flow (m_{ret})
 - Sanitary water supply flow (m_{sum})
 - Time vector (t_{tiempo})

2. Calculate cooling load (Q_{ch}) for each compressor using the equation

$$Q_{\text{ch}} = A_1 + A_2 \cdot P_{\text{total}} + A_3 \cdot T_{\text{amb}} + A_4 \cdot T_{\text{ah}} + A_5 \cdot P_{\text{total}} \cdot T_{\text{ah}} + A_6 \cdot T_{\text{ah}} \cdot T_{\text{amb}}$$

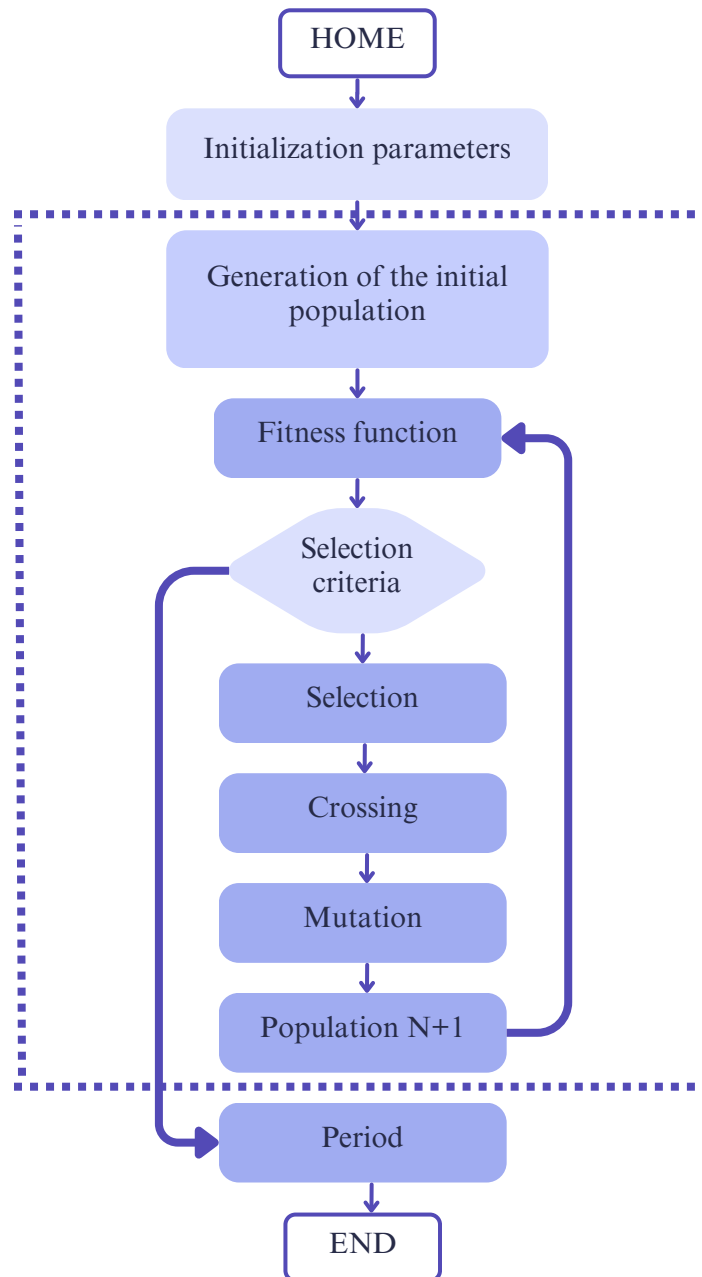


Figure 5. Flowchart of the genetic algorithm for optimization.

3. Calculate total condensation heat (Q_{cond}) for each compressor:

$$Q_{\text{cond}} = P_{\text{total}} \cdot Q_{ch}$$

4. Define chiller operating parameters and calculate recovered heat in the cycle:

$$Q_{\text{rec}} = m_r \cdot C_p \cdot (T_2 - T_{\text{cond}})$$

5. Set parameters for the genetic algorithm:

These parameters were selected to strike a balance between robustness and convergence speed [28]:

- Number of variables = 2
- Population size = 200
- Mutation function = @mutationadaptfeasible

- Number of elite individuals = 2
- Crossover fraction = 0.8
- Number of generations = 100
- Stopping criterion for fitness = 1×10^{-15}
- Lower bounds = [0.5, (maximum sanitary water consumption flow)]
- Upper bounds = [5.83, 3.59]
- Initial values = [1, 1]
- Objective function = @fitnessFun
- Other parameters = Default values

6. Plot the results

Objective Function: fitnessFun

The objective function `fitnessFun` takes as input the variables to optimize [flow₁, flow₂] and returns the evaluation of the objective function $\text{Obj} = \sum Q_{ca}$. The auxiliary heating required (Q_{ca}) is determined through the following steps:

1. Initialize calculation variables.
2. For each time step k (every 10 min):
 - Calculate mixing temperature:

$$T_{mc}(k) = \frac{T_{kc}(k) \cdot m_{Ret}(k) + m_{Consumo}(k) \cdot T_{rep}}{m_{Ret}(k) + m_{Consumo}(k)}$$

- Calculate inlet and outlet temperatures of the hot fluid in the exchanger [$T_{ca}(k)$, $T_{6c}(k)$] based on the cold fluid inlet/outlet temperatures [$T_{mc}(k)$, $T_{sumc}(k)$] and flows [m_{cp} , m_{cs}].
- Compute the outlet temperatures from the heat recovery system $T_7(k, :)$ for each chiller.
- Determine the outlet temperature of the recovery unit $T_{9c}(k)$ as the average of the c -point temperatures.
- Perform an iterative process to adjust parameters such that $T_{9c}(k) \approx T_{ca}(k)$.
- Assume return sanitary water temperature is 5 °C less than the supply temperature.
- Calculate $T_{kc}(k+1)$ for the next time step.
- Determine auxiliary heating:

$$Q_{ca}(k) = m_{cp} \cdot C_p \cdot (T_{ca}(k) - T_{9c}(k))$$

3. Sum all Q_{ca} values over time to compute the final objective function.

4. Results and Discussion

A procedure based on the energy analysis of the system is developed, which allows determining the cooling load profiles, the hot water demand, and the heat recovery potential under the operating conditions of the installation. This procedure is supported by an energy model implemented in MATLAB software, which integrates the energy characteristics of this type of installation and the operational regularities of domestic hot water (DHW) systems in tropical climates. The model considers the particularities of the thermal demands of both the building and the DHW circuits. In this context, the optimal mass flow in the primary hot water circuit is defined to maximize heat recovery. From this parameter, the values of the mass flow in the secondary circuit, the necessary amount of auxiliary heat, and the water outlet temperature that complies with the technical requirements established for hotel installations are determined.

Based on the model developed, an operational strategy is proposed that seeks to maximize heat recovery in the primary circuit and minimize the energy consumption associated with the auxiliary heater. This strategy optimizes the energy consumption of the domestic hot water production system by establishing specific set points for different operating conditions. In addition, it adjusts the mass flows in the primary and secondary circuits and regulates the operation time of the auxiliary heater, thus ensuring efficient and sustainable operation.

To bring this study as close as possible to real operating conditions and the behavior of the hotel dynamics, flowmeters were installed at specific points in the DHW circuits. The DHW consumption profile for a typical day was obtained from hot water flow measurements in the supply and return pipes of the system using digital flowmeters. Figure 6a shows the daily DHW consumption profile, where two significant peaks in demand are highlighted in the morning (6:30–8:30 am) and (afternoon 5:00–8:00 pm). The measurements were taken during the high tourist season, according to the hotel's occupancy behavior for a typical year (Figure 6b), which ranges between 80 and 100% occupancy in the months with the lowest ambient temperature.

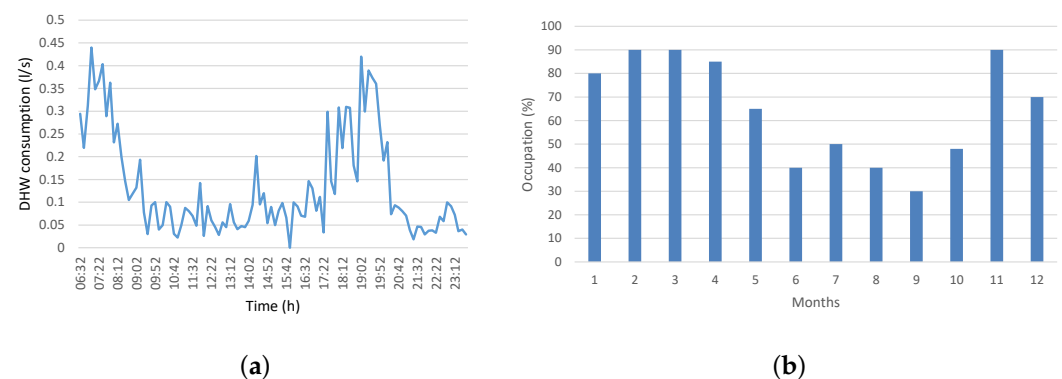


Figure 6. Hotel consumption data: (a) daily profile of domestic hot water consumption typical of a winter day; (b) hotel occupancy during the year.

4.1. Results of the Thermodynamic Evaluation

It is assumed that the operating conditions are steady-state, which implies that the mass flow rate of water in the primary hot water circuit (PHWC) remains constant under all circumstances. Based on the operating regimes established for the chillers and the input variables to the thermodynamic model, as detailed in Figure 7, several key operating parameters of the system are obtained and presented in Table 1.

To evaluate the system's operating conditions, two working regimes are analyzed:

- Nominal regime: pressure of 1.7 bar ($-10\text{ }^{\circ}\text{C}$) and 12.2 bar ($46\text{ }^{\circ}\text{C}$), with corresponding evaporation and condensation temperatures; for the chilled water circuit, supply and return temperatures of $8\text{ }^{\circ}\text{C}$ and $11\text{ }^{\circ}\text{C}$, respectively;
- Part-load regime: pressure of 1.5 bar ($-7\text{ }^{\circ}\text{C}$) and 11 bar ($43\text{ }^{\circ}\text{C}$), with corresponding evaporation and condensation temperatures; for the chilled water circuit, supply and return temperatures of $8.5\text{ }^{\circ}\text{C}$ and $12\text{ }^{\circ}\text{C}$, respectively.

From the above table, it can be concluded that, when the chillers operate at partial load, the refrigerant temperature at the compressor outlet reaches values of $59.18\text{ }^{\circ}\text{C}$ and $60.67\text{ }^{\circ}\text{C}$, respectively. In turn, the water temperature at the recuperator outlet is $55.11\text{ }^{\circ}\text{C}$ and $56.11\text{ }^{\circ}\text{C}$. These values are insufficient to guarantee an adequate water temperature in the primary DHW circuit, which must be between 60 and $65\text{ }^{\circ}\text{C}$ to comply with the technical requirements established by the standards.

Table 1. Operating parameters of the chillers under nominal and part-load conditions.

Parameters	Unit	Chiller 1		Chiller 2	
		Part-Load	Nominal	Part-Load	Nominal
Suction pressure	bar	1.5	1.7	1.5	2.00
Discharge pressure	bar	10	12.2	11	12.2
Superheating	°C	8	8	3	8
Subcooling	°C	3	3	3	3
Compression work	kJ/kg	40.96	42.65	39.12	43.07
Compressor outlet temperature	°C	59.18	68.01	60.67	69.26
Condensation temperature	°C	40	46.32	43	46.97
Refrigerant flow rate	kg/s	1.6	1.69	1.33	1.81
Compressor power	kW	65.54	72.08	52.03	77.96
Cooling capacity	kW	125.67	234.89	216.84	416.72
Primary circuit water flow	kg/s	2.91	2.91	2.91	2.91
Recovery heat	kW	27.61	95	39.83	158.3
Recovery temperature	°C	55.11	60	56.11	64.99
Heat recovery percentage	%	8.09	21	17.86	25
COP	-	2.21	4.58	3.62	4.87

Under these conditions, heat recovery ranges between 8.09% and 17.86% for each chiller, respectively. These results indicate that, in reduced load situations, the current operating parameters do not ensure efficient operation, as the heat recovery is below its nominal value. The same is true for the coefficient of performance (COP), which is also negatively affected.

It is observed that, when the operating conditions of the system do not coincide with those of maximum demand for which it was designed, the water temperature in the heat recovery system moves away from the desired values. This is because, regardless of the load regime, the design and operating parameters, such as the flows in the hot water circuits and the temperature of the inlet water to the recuperator, remain constant. Although the design parameters cannot be changed without replacing the heat exchanger, it is possible to adjust the working flows in the recovery circuit.

Therefore, the option of varying the water flow in the primary DHW circuit to reach temperatures above 60 °C is considered. By reducing the flow rate in the heat recovery unit, an increase in temperature is achieved (see Figure 7). A balance can be established between the flow rate that maximizes the temperature in the DHW circuit and the heat exchange required to ensure that the domestic hot water supply temperature reaches 55 °C.

In the optimization process using genetic algorithms (GA), a heuristic method designed to identify the optimal values of the key decision variables considered in the analysis was implemented. Through multiple iterations, the GA progressively refine the solutions, converging towards the values closest to the global optimum of the objective function. An illustrative example of GA convergence is presented in Figure 8.

As a result of the optimization procedure, new mass flow values in the primary and secondary hot water circuits are obtained: $\dot{m}_{cp} = 1.19$ kg/s and $\dot{m}_{cs} = 1.77$ kg/s, respectively. For these new flow rates, temperature behavior in the hot water circuits is stabilized, and the domestic hot water (DHW) demand of the hotel is met.

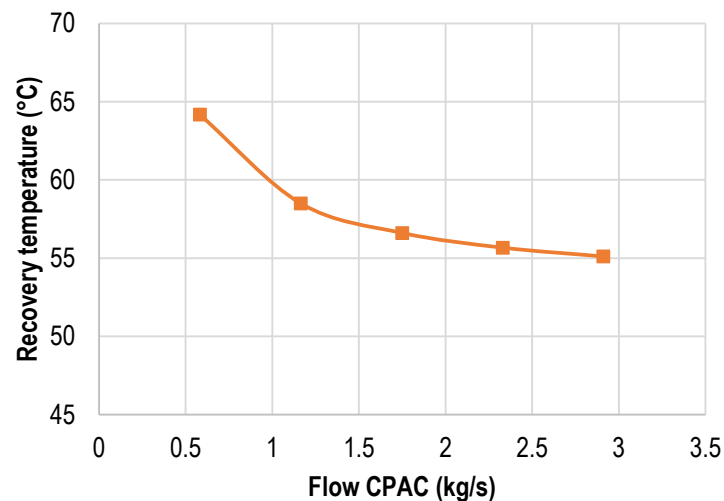


Figure 7. Recovery temperature with flow variation in the DHW circuit at partial load.

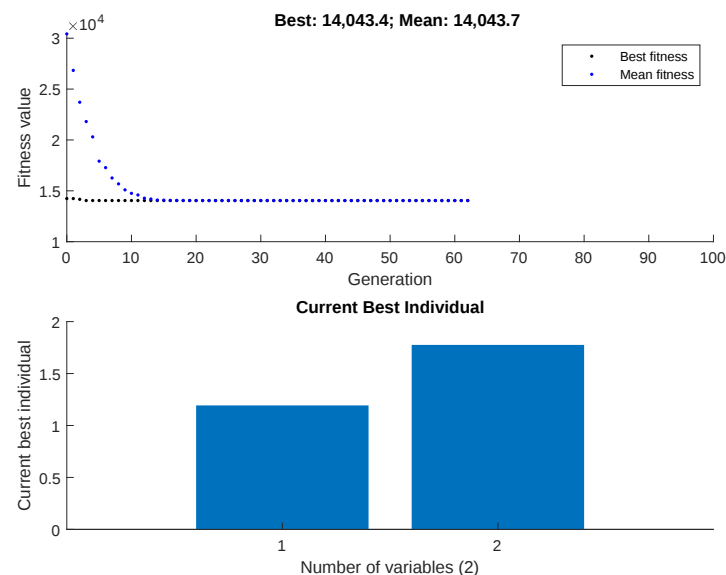


Figure 8. GA convergence.

In this new scenario, a balance is achieved between the heat recovery from the chillers and the temperature of the hot water in the primary circuit, aiming to maintain stability around 60 °C in the primary and 55 °C in the supply circuit (Figure 9a).

With the optimized system, the new mass flow values allow the maximum possible heat to be recovered from the chillers in a stable manner, minimizing the use of the backup device. This results in significant fuel savings for the hot water system, with minimal auxiliary heating consumption, reducing fuel usage by up to 50%, as shown in Figure 9b.

The above clearly demonstrates that, under conditions of maximum DHW demand, the use of backup systems is essential to meet the technical requirements established for these types of comfort service systems, whose parameters are regulated by international standards. However, in a context where reducing energy consumption is a priority, the implementation of effective and rational alternatives becomes necessary.

For this reason, decisions are made to establish rule-based operation strategies, which are common in systems exposed to fluctuating demand throughout the day. This is the case of DHW systems due to their operational dynamics, which exhibit marked variability both daily and seasonally.

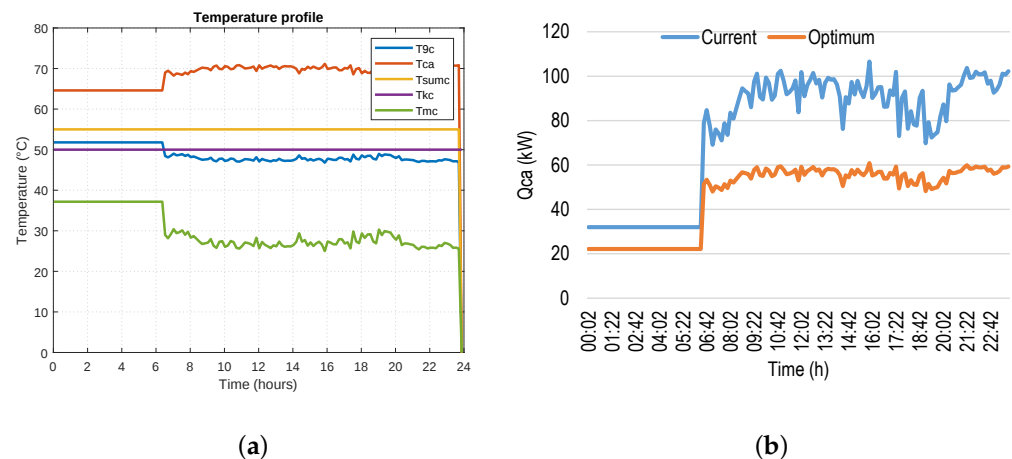


Figure 9. Optimization analysis results: (a) temperature profile for the optimized system; (b) power required in auxiliary heating.

The first strategy evaluated in this study considers the variation of flow rates in the primary and secondary DHW circuits with 100% use of auxiliary heating. The second strategy is to implement a rule-based operation, activating the backup device during the periods from 6:30 am to 8:30 am and from 4:00 pm to 8:00 pm. This second approach corresponds to only 25% use of auxiliary heating over 24 h of continuous ACS system operation.

The advantage of having a model that can predict the operational behavior profile of the system throughout the day is that it enables the definition of an effective and applicable strategy for any typical facility in tropical regions, with similar climatic conditions and guest consumption profiles.

The proposed methodology allows complete modeling of the facility, which includes the centralized air conditioning system with heat recovery. It enables an evaluation of its operational behavior over a 24-h period, assessing the system's response to variations in operating conditions and the extent to which it meets the hot water demand required by the hotel installation.

The system's operational behavior is evaluated in the case study hotel. Thermal demand profiles are determined, including cooling load, recovered heat potential, and hot water demand. Additionally, the water temperature values in the recovery system, thermal storage tanks, and supply to the hotel are analyzed. These profiles provide insight into the variability of these parameters throughout the day and confirm whether the system complies with the required values according to technical specifications to achieve comfort standards in such installations.

4.2. Economic Analysis and Associated Environmental Impact

The economic analysis is based on the period of continuous operation of the auxiliary heater, corresponding to the high tourism season considering maximum occupancy. The economic analysis allows one to know the energy costs of the current hot water production system and to establish a comparison with the optimized system; the results are shown in Table 2. The economic analysis is expressed in international units (USD), using the official exchange rate of the Central Bank of Cuba in effect at the time the study was conducted [29].

With the optimized system, an annual energy saving of 8244 kWh is achieved, which corresponds to 2.3 tons of fuel equivalent. Additionally, 6940 kg of CO₂ emissions are avoided due to reduced energy consumption, along with a savings of 29,717 L of LPG not consumed throughout the year. These results are obtained considering that the auxiliary system operates only 25% of the day as a saving strategy.

Table 2. Economic analysis and associated environmental impact.

Equipment	Total Power (kW)	Current System			Optimized System		
		Operating Time (h)	Energy Cost (\$/Year)	Emissions (kgCO ₂)	Operating Time (h)	Energy Cost (\$/Year)	Emissions (kgCO ₂)
B_{CPAC}	2.20	24	13.55	1292	24	5.53	527.59
B_{CSAC}	1.50	24	55.45	5287	24	27.48	2620
C_{AUX}	99.00	18	4644	282.6	6	1172.39	192.19
Total	102.7	24	4713	6862	24	1205.41	3219
Savings						3507.6	3643

4.3. Life Cycle Cost

The life cycle cost (LCC) of the system is determined for the two evaluated operating strategies, considering the permanent use of auxiliary heating for the optimized system, and the second operating strategy (25% utilization of auxiliary heating). The latter represents a savings of 62,635.66 USD compared to the current system, assuming a service life of 20 years for the installation. The LCC results are shown in Table 3.

Table 3. Life cycle cost and environmental impact of the operating strategies.

Cost Items	Unit	Current System	Optimized (100% Use)	Optimized (25% Use)
Initial cost	USD	1591.97	1591.97	1591.97
Operation (energy)	USD	4713.01	3153.26	1172.39
Maintenance	USD	37.06	37.06	37.06
LCC (Life Cycle Cost)	USD	113,251.00	86,068.46	50,615.34

4.4. Comparison of Results with Literature

The reviewed studies provide a broad overview of the evolution and diversification of heat recovery technologies in air conditioning and hot water systems. Most of the contributions emphasize improvements in COP and energy efficiency, highlighting strategies such as optimizing mass flow rates, temperature control, and integrating storage systems. However, many of these studies are conducted under ideal or controlled conditions, which may limit their applicability in real-world hotel environments, where the demand fluctuates significantly throughout the day and seasons.

The present study builds upon these prior contributions but distinguishes itself by integrating a rule-based operational strategy and evaluating its impact over a complete 24-h period. Unlike earlier approaches, this model captures the operational dynamics of DHW systems typical of tropical climates, accounting for realistic occupancy patterns and consumption behaviors. Additionally, by simulating different levels of auxiliary heating usage, the methodology allows for a more granular analysis of cost-effectiveness and environmental performance. This makes the current research a valuable step forward in bridging the gap between theoretical efficiency and practical implementation in hotel infrastructures.

Table 4 presents a comparative summary of recent studies focused on heat recovery technologies in air conditioning and domestic hot water systems. The table highlights the technological approaches, key operational variables, and main outcomes reported in the literature. This comparison provides a foundation for understanding the performance potential of different configurations, as well as the limitations and opportunities that exist when applying these systems in real-world scenarios. Particular attention is given to studies that propose optimization strategies, either through improved component design or operational rules, which are relevant to the methodology adopted in the present research.

The flexibility of the model and the computational tools employed facilitate its adaptation to various facilities in tropical regions, as well as the exploration of dynamic adaptation scenarios, including periods of low occupancy and smaller hotels, providing a solid foundation for evaluating and improving energy strategies in these contexts.

Table 4. Summary of previous studies on heat recovery systems.

Author	Technology	Variables	Results/Scope
[30]	Air conditioning/heat pump with heat recovery	Sanitary water flow rate, chilling water flow rate, inlet and outlet temperatures of evaporator and condenser, cooling capacity, COP	High COP (about 6.0); a supplementary electric heating device is suggested
[31]	Vapor compressor chillers with heat recovery	Cooling capacity, power consumption, enthalpies and flow rates of cold and hot water, COP, energy efficiency	Potential for energy savings and improved system performance with significantly higher energy efficiency under optimal conditions
[32]	Heat pump with heat recovery	Water temperature at the outlet of heat recovery, temperature difference between discharge and recovery points, water mass flow rate, refrigerant and water side capacity flow rates, COP	Proposes different configuration strategies for the heat recovery; up to 5% savings in electricity with reduced auxiliary energy use in DHW production
[33]	Centralized air conditioning systems with heat recovery	Cooling/heating demand, thermal storage tank capacity/design, condensation and hot water temperatures	Optimizes thermal storage to minimize temperature fluctuations in hot water supply
[34]	Combined cooling, heating, and power system with heat recovery	COP, hot water temperature, condensation temperature, heat exchange efficiency, heat recovery efficiency	5% increase in energy savings, 6.36% increase in economic savings, 2.74% reduction in CO ₂ emissions
[35]	Two-stage multigeneration system (heating, cooling, DHW)	Evaporation temperature, sanitary hot water temperature, COP	Significant COP improvements (7.3 in summer, 3.1 in winter); improved heat recovery, reduced energy use
This study	Centralized air conditioning system with heat recovery	Cooling/heating demand, hot water mass flow in primary and secondary circuits, cold/hot water temperature, heat recovery temperature, auxiliary heating temp, outlet temp, COP	Optimizes temperature in heat recovery and proposes flow values and temperature targets for auxiliary heating and overall energy efficiency

5. Conclusions

The integration of heat recovery into centralized HVAC systems proves to be an effective strategy to enhance energy performance in hotel facilities. While such systems typically operate under partial load conditions and require a backup energy source, their optimization is essential to reduce energy consumption and mitigate environmental impacts. This study demonstrates that heat recovery, when properly managed, can significantly reduce the reliance on auxiliary heating systems based on fossil fuels.

The developed thermoenergetic model successfully integrates the steady-state behavior of a simultaneous air conditioning and domestic hot water (DHW) production system, relying on real operational data. This modeling approach enabled the identification of key performance indicators and decision variables, such as water mass flows in the DHW circuits and the outlet temperature of the backup system. The use of genetic algorithms (GA) for optimization allowed the definition of operating conditions that adapt to dynamic demand profiles while minimizing energy use.

The case study confirmed the effectiveness of the proposed methodology. By adjusting the water mass flow rates to 1.19 kg/s in the primary circuit and 1.77 kg/s in the secondary circuit, the optimized system achieved annual energy savings of 8244 kWh, equivalent to 2.3 tons of fuel, and prevented the emission of 10.5 tons of CO₂ into the environment. These results were obtained with only 25% utilization of auxiliary heating, compared to the continuous operation in the original configuration.

Overall, the findings of this study contribute to the design and implementation of sustainable energy strategies in the hospitality sector. The methodology developed is not only applicable to the specific hotel installation studied but can also be replicated in similar tropical environments where energy efficiency and comfort are critical priorities.

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Abbreviations

The following abbreviations are used in this manuscript:

Abbreviation	Meaning
ASHRAE	American Society of Heating Refrigeration and Air-conditioning Engineers
COP	Coefficient of performance
DHW	Domestic hot water
GA	Genetic algorithm
HVAC	Heating ventilation and air conditioning
IEA	International Energy Agency
LPG	Liquefied petroleum gas
LCC	Life cycle cost
RTO	Real time optimization

Nomenclature

Symbol	Description
C_p	Specific heat, kJ/kgK
m_{cp}	Primary circuit mass flow, kg/s
m_{ret}	Return water mass flow, kg/s
m_{rep}	Replenishment water mass flow, kg/s
P_{total}	Total power, kW
Q_{ch}	Cooling capacity, kW
Q_{cond}	Total condensation heat, kW
Q_{rec}	Heat recovery capacity, kW
Q_{ca}	Auxiliary heating capacity, kW
T_{ah}	Chilled water temperature, °C
T_{amb}	Ambient temperature
T_{ca}	Auxiliary heater water temperature, °C
T_{cond}	Condensation temperature, °C
T_k	Thermal storage tanks water temperature, °C
T_m	Mix water temperature, °C
T_{rec}	Recovery temperature, °C
T_{rep}	Replenishment water temperature, °C
T_{sum}	Hot water supply temperature, °C
T_2	Compression temperature, °C
T_6	Inlet water temperature at heat recovery, °C
T_9	Outlet water temperature at heat recovery, °C

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