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RESEARCH ARTICLE

Integration of Energy Management and Efficiency System for Buildings With Zero Carbon Emissions: A Case of Study

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ABSTRACT Hospitality institutions are significant consumers of water, electricity and gas resources. These resources may be scarce or critical in several locations. Authors have investigated strategies for efficient building operation, considering various energy carriers. Despite reported methods to enhance efficiency, nowadays they commonly have to be integrated into hotels from the design process through regular operation. This study aims to provide a detailed analysis of sustainable architecture in hotel design to decrease resource usage without compromising the quality of services provided. The considered design process is based on using a structured methodology focused on a energy management system that guarantees an efficient use of resources. The present study also considers incorporating renewable energy sources for the nominal operation of the hotel to achieve a net-zero energy building classification. The design of the building resulted in the proposed architecture that can maintain a comfortable temperature range of $17°C$ to $24°C$ in the guest rooms throughout the year. The energy generated from the proposed photovoltaic, thermal solar systems and rainwater harvesting can guarantee a nearly negligible net consumption of these resources for the hotel.

INDEX TERMS Photovoltaic energy systems, zero emission carbon building, passive heating, energy management and efficiency, water management strategies.

I. INTRODUCTION

During the last 60 years, the tourism sector has seen expansion and variety, driven by increased energy use and an increase in environmentally conscious consumption patterns [1], [2]. Sustainably constructing hotels enhances the quality of service, increases energy efficiency, and encourages recycling. Green building design caters to the values of visitors, improves the attractiveness of eco-friendly hotels, and promotes environmental responsibility [3], [4].

The research study by Trivsic et al. [3] explores the implications of eco-certificates and green procurement in the hotel industry for the development of sustainable tourism. Previous research, such as the study conducted by Abdou et al. [5], examines the perceptions of hoteliers regarding the contribution of green hotel practices to achieving sustainable development goals. These studies emphasize the importance of sustainable hotel construction in protecting the environment, reducing energy consumption, and attracting future tourists. However, research on the construction process and the challenges associated with building green hotels is still needed.

Implementing sustainable construction in the hospitality business is a crucial concern, but it presents a delicate balance between costs and advantages. Therefore, a thorough examination, exploring both the environmental consequences and the economic feasibility of environmentally friendly actions, becomes essential. This careful assessment is crucial

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for proving sustainability, reliability, and feasibility in this process design. This research explores the delicate balance between environmental imperatives and economic realities, providing an understanding of the intricate relationship between sustainability objectives and practical implementation strategies.

The present research work is focused on a specific case study, which provides the opportunity to thoroughly examine the use of solar energy by a hotel and the implementation of water management strategies. These techniques lead to a notable reduction in operational expenses. The main objective of this research is to examine some techniques employed by hotel builders and explore their applicability to other construction projects for improving environmental sustainability. It is also important to remark that these techniques can be applied to any residential building. The main contributions of the present research work are the following:

- A set of sustainable practices is evaluated and implemented in a hospitality institution, emphasizing efficient use of gas, water, and electricity resources.
- Eco-friendly architecture is considered when designing hospitality buildings, and solar orientation and passive heat systems are considered.
- A comprehensive analysis of resource utilization, guided by the *ISO-50001* standard, is used to identify improving the oto improveency of the hotel and establish some measures to obtain more opto-efficacy.
- Water management policies, such as rainwater harvesting and grey-water treatment, are considered to reduce reliance on the external water network.
- The design of a *PV* solar system is undertaken to reduce electrical consumption, with the design process aligned with the specific requirements and characteristics of the institution.
- The design of a thermal solar system was also carried out considering the requirements of hot water management associated with hotel services. This measure has proven to be a commendable approach to reducing gas and electricity consumption in this institution.

A. ORGANIZATION

This work is structured as follows: Section II shows a background related to the management of hospitality institutions resources, which motivates the development of the present research work. In Section III, the Materials and Methods used in this research are detailed, encompassing the steps inherent in the methodology, along with the necessary data and equations essential to determine the energy demand of the building. Section IV presents the results derived from the proposed methodology, which include newly assessed resource demands such as water and electricity and the analysis of the behavior at room temperature. Within Section V, a detailed discussion is conducted to compare the results obtained with those of other study cases reviewed in the bibliography. Finally, Section VI encapsulates the Conclusions drawn from the study.

II. RELATED WORK

Sustainable construction in the hotel industry encompasses various practices and strategies to minimize the environmental impact of hotel buildings throughout their life cycle. These practices include energy-efficient designs [6], renewable energy sources [1], water conservation measures [7], waste management [8] and the use of eco-friendly materials [9]. Ahn and Pearce [10] conducted a case study on two green hotels, namely the Proximity and Bardessono hotels. They presented a table outlining sustainable building practices and their potential benefits. Some of these practices include solar orientation of the building, water-saving fixtures and technologies, rainwater harvesting systems, and onsite renewable energy sources, among others.

Sustainable architecture is based on the design with a focus on sustainability and energy conservation [11]. By implementing sustainable construction techniques, hotels can significantly reduce their carbon footprint, conserve resources, and foster a healthier, more sustainable environment for guests and staff. Huiying et al. [4] emphasize the integration of green attributes throughout the entire life cycle of buildings, including planning, site selection, building design, and the operational phase. Green building design is crucial for achieving high operational efficiency through a significant reduction in life-cycle energy consumption [12].

Using passive energy-saving measures is a crucial aspect of sustainable architecture. Xu et al. in [13] describe passive energy-saving design as efficiently using natural conditions and addressing unfavorable factors in the layout of the building or architectural design. These measures aim to create a comfortable indoor environment, conserve energy, and facilitate active energy-saving strategies. This energy savings is mainly justified due to the reduction of the energy required by the Heating, Ventilation and Air-Conditioning (*HVAC*) system, which generally requires about half of the total energy consumed in hotels [14].

The research by Abdelhady et al. [1] examined a grid-connected *HRES* in an Egyptian hotel. The analysis included technical, economic, and environmental factors. The optimal system had 143 *kW* solar panels and a 20 *kW* 18-*m*-hub wind turbine. The hotel received 70% of generated electricity and the remaining 30% was fed into the grid. Research by Lopez et al. [15] and Torres et al. [16] highlights the importance of energy-efficient *HVAC* systems in decreasing carbon emissions and resource consumption in hotels. *HVAC* systems generally account for 30-50% of the energy usage in buildings. According to Torres et al. [16], incorporating renewable energy sources can cut *HVAC* energy use by 30% for electricity and 60% for gas. A study [17] found that using thermo-chromic windows, phase change materials, and photovoltaic panels reduced hotel energy consumption by 34% during a parametric analysis.

Tirado et al. [18] concluded that incorporating water-saving measures in hotels can effectively reduce water consumption, significantly improving water resources. A review of the literature suggests that hotels can achieve water savings ranging from 20% to 50%. In [19], Alhudaithi et al. observed that there is currently no straightforward or reliable method to establish a minimum water use standard or starting point for hotels based on their features. In [20], the authors delineated that savings in water consumption can be achieved through actions categorized into four groups: water consumption, water management, impacts of water use, and good practices. These actions typically involve identifying significant water consumption variables and measuring their impact.

Several research studies have analyzed the energy efficiency of hotels in Latin America and the Caribbean regions. For instance, in the work presented in [21], the authors proposed several opportunities for improving energy efficiency in a Cuban hotel based on *ISO-50001* standard. The suggested interventions include upgrading lighting technology and implementing a photovoltaic solar system on the roofs of hotel buildings. Higuerey et al., in their research documented in [22], aimed to assess the efficiency and productivity of the Ecuadorian hotel industry. They selected a substantial sample comprising 147 businesses that offer such services to achieve this objective. In the research work developed in [23], a proposal is made for a photovoltaic (*PV*) solar system to fulfill approximately 50% of the electrical demand for a high-consumption hotel.

However, a significant gap exists in the current literature on the energy-efficient hotel design process and the validation of the associated results, particularly within the Latin American context. Furthermore, no studies address the comprehensive integration of all the measures mentioned above to optimize hotel services in terms of resource usage efficiency.

III. METHODS AND MATERIALS

Hospitality establishments require significant energy to deliver services to guests. They can implement energy management procedures to reduce energy consumption, focusing on energy efficiency and integrating renewable energy resources. These measures improve service quality while reducing resource demands such as electricity, water, and fuels, influencing the economic performance of these establishments.

The study examines Casa Antares Hotel, located 3 *km* from the Intercontinental Airport of Queretaro, Qro, Mexico. Figure 1a shows a panoramic photograph of the hotel. It has a large green area with several fruit trees, a pond with Koi fish, and a terrace. In addition, it has a parking lot with a capacity of 10 cars. Figures 1b, 1c, and 1d show the different types of rooms provided by this hotel to its guests.

The methodology used for the design, construction and operation is shown in Figure 2. This methodology comprises a series of steps, each meticulously applied to ensure the optimal performance of the hotel from various perspectives. Sustainable architectural design involves optimizing the orientation of the building for solar efficiency and selecting materials with specific passive heating and cooling criteria in hotel interiors. Energy characterization assesses the energy consumption of the building by collecting data on gas, electricity and water. Location is analyzed based on climate and geography, and three-dimensional modeling defines space for renewable energy sources. Solar systems are designed to meet hotel service needs, and an investment and environmental impact analysis proves the feasibility of building services.


(a)

(b) (c) (d)

FIGURE 1. Photograph of the hotel exterior (a), and an internal view of the rooms: King (b), Twin (c), Single (d).

As a first step in the present research work, a preliminary design is proposed based on the location, terrain geometry, and size of the hotel building. This step includes arranging the number of rooms, recreation areas, service areas, and other areas. Furthermore, bioclimatic aspects are used in the design phase.

Once the above-mentioned stage is executed but subject to changes, an energy consumption estimate is suggested, considering complete occupation. In this estimate, which includes resource consumption such as water and electricity, all hotel equipment is characterized according to its nominal operation. In addition, billing data analysis is conducted to complement this study on resource consumption.

The methodology extends to the following objective considering the data collected at this step: Identify opportunities for enhancing energy efficiency and minimizing costs related to the services provided to the guests. Analysis of hotel energy usage adheres to the criteria outlined in the *ISO 50001:2018* standard, aligning with a similar approach detailed in [21].

1) **Historical data collection:** Retrieve historical records of the energy consumption of the hotel, encompassing electricity, gas, and water bills. These records will serve as a foundation for assessing the current efficiency of building energy use.
2) **Consumption analysis:** Examine historical data in detail to identify consumption patterns and seasonal trends. This detailed examination aims to uncover

TABLE 1. Characteristics of rooms in the hotel.

Room type	Appliances	Consumption
King	Private bathroom	3 L
	Private shower	4 L/min
	Hairdryer	1650 W
	Bar fridge	200 W
Twin	Private bathroom	3 L
	Private shower	4 L/min
	Bar fridge	200 W
Single	Private bathroom	3 L
	Private shower	4 L/min
	Bar fridge	200 W

high-consumption areas and identify periods of the year characterized by particularly elevated resource demand.

3) **Energy audit:** Undertake a comprehensive energy audit of the hotel. This audit thoroughly examines all systems and equipment, from lighting and air conditioning to hot water systems and room appliances.
4) **Measurement and monitoring:** Install energy meters and sensors at key hotel points to measure real-time consumption. This measure may include electricity, water, gas meters, and temperature and humidity sensors.
5) **Energy management:** Implement an energy management system that allows real-time monitoring and control, automatically adjusting temperature, lighting, and other parameters as necessary.
6) **Building envelope evaluation:** Inspect the building envelope, such as walls, windows, and roofs, to identify possible energy losses, air leaks, and a lack of insulation. Improving the envelope can have a significant impact on energy efficiency.
7) **Renewable energy:** Consider installing *PV* panels or solar thermal energy systems to generate renewable energy on-site and reduce dependency on conventional energy sources (photovoltaic solar system (*SSFV*) and solar thermal system (*SST*)).
8) **Education and training:** Train hotel staff on energy efficiency practices and promote awareness of the responsibility of energy consumption among guests.

The hotel was built in 3 modules. The first module has 10 rooms, of which 7 are single bed and twin beds and a staff office. The second one has 1 King room, 1 Queen room and suits. Table 1 shows the characteristics of each type of room. All rooms have the same size of 4 m wide, 6 m long and 2.5 m height. Rooms on the first floor have a higher ceiling due to the terrain inclination. Finally, the third module has a restaurant on the first floor, and its second floor has a gymnasium and a conference room.

A corridor or balcony connects all three modules, and they all have the same roof. This characteristic gives the hotel building enough area for *PV* modules installation. Given the location near the airport, the hotel receives 1 kW/m^2 of solar radiation during summer and 0.75 kW/m^2 during winter. Figure 3 shows the radiation throughout the year and the precipitation.

As previously mentioned, one highly effective method for reducing the electrical consumption of any building involves integrating renewable energy resources [24]. Among these energy sources, *PV* solar systems (*PVSS*) stand out as one of the most widely employed sources in applications to mitigate the electrical demand of high-consumption institutions, such as hotels [25], [26]. Another applied method involves utilizing thermal solar systems (*TSS*), which rely on installing thermal collectors to harness solar energy for heating water through the application of heat transfer principles [27]. By employing these systems, the need for electricity and gas to heat water is drastically reduced.

Based on data provided by *INEGI* (*Instituto Nacional de Estadística y Geografía*), it is reported that approximately 51% of the land area in Queretaro exhibits a dry and semi-dry climate [28]. This climatology is expected in the central region of the country. Also, there are reported problems with water in the region. The geographical position of Queretaro is at $20.64°N$ and $100.204°W$, with an altitude of 1935 m. The relative humidity (RH) averages 57.1%. Also, the average temperature is $19°C$, and the wind speed is 4.1 m/s. Based on the Köppen-Geiger climate zone classification, the location falls into the *BSh* climate zone.

Figure 4 shows the solar orientation of the building. In summer, at solstice and noon, the sun is at 1.95° azimuth and 87.16° altitude. On the other hand, in winter, at solstice and noon, the sun is at 179.99° azimuth and 45.90° altitude. The orientation selection for the building was based on recognizing that traditional urban design patterns are inefficient in energy utilization. In light of this, researchers have proposed ten methodologies, also referred to as solar control techniques, to lessen the effects of excessive solar radiation on building facades and lower cooling requirements [29].

In [30], the authors said North-South facades receive twice the sunlight during winter, while those facing East-West get at least four times the insolation value during summer. In the research conducted by Chan et al. [31], it was observed that orienting the more extensive facades towards the north-south direction resulted in a 19.76% reduction in the total annual sensible cooling load of the building.

The orientation of the hotel building was determined based on the previously mentioned results, leading to the alignment of the rooms with the north direction due to the following conditions:

- In the winter season, the sun trajectory passes behind the building, causing the walls to be exposed to direct sunlight during the day. Consequently, the walls absorb and retain heat, releasing it during the night.
- The sun path is above the building in the summer, preserving a comfortable room temperature.

Day length also plays a significant role in heat absorption and retention. In winter, the shorter days mean less time for the walls to absorb heat from the sun. However, in summer,

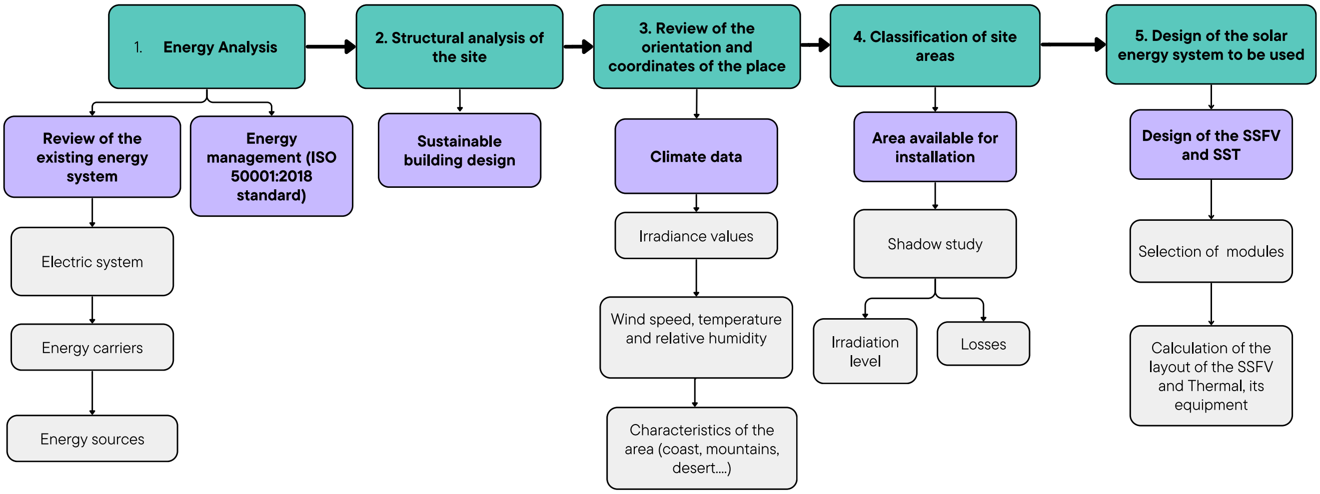
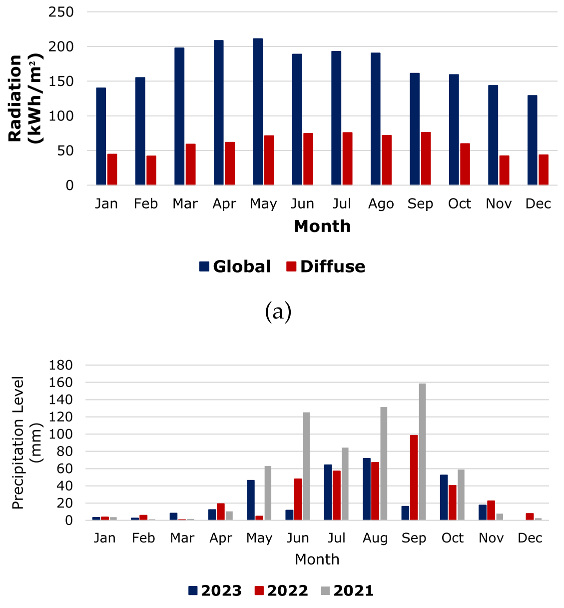


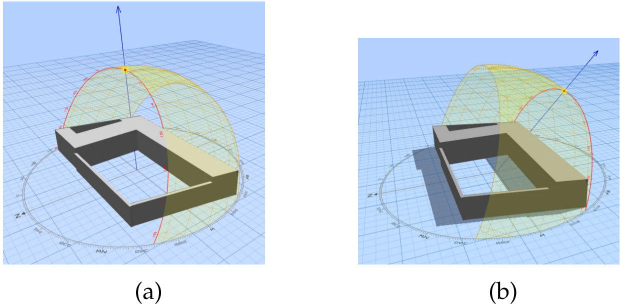
FIGURE 2. **Methodology for the design of the sustainable hotel.**



(a)

(b)

FIGURE 3. **Monthly weather characteristics of the place where the building is located: (a) Behavior of monthly direct and diffuse radiation in a year, and (b) Behavior of the monthly precipitation level (Data obtained from *CONAGUA*).**


(a)

(b)

FIGURE 4. **Solar orientation of the building. The summer solstice with an azimuth of 1.95°, and altitude of 87.16° (a), and the winter solstice with an azimuth of 179.99°, and altitude of 45.98° (b), both at solar noon.**

the longer days allow for more heat absorption, resulting in a warmer environment. The angle of the sun rays during different seasons also affects the heat absorption and retention capabilities of walls. All the above factors shape a dynamic thermal environment within the structure throughout the year.

Figure 5 shows the day-length of Queretaro throughout the year. As shown previously in Figure 4, in summer, the sun path is more prolonged, meaning more time for the surface to absorb more heat, such as walls and ceiling. In winter, the path is shorter with an inclination, so there is less time and heat for the wall to absorb energy. In summer, sunrise is at 6:01 *am*, and sunset at 7:24 *pm*, giving daylight 13:23 hours. On the other hand, in winter, the sunrise is at 7:13 *am* and sunset is at 6:06 *pm*, giving a total daylight of 10:53 hours. These characteristics are essential aspects to consider for solar energy harvesting.

A. PASSIVE HEATING AND COOLING ARCHITECTURE

Some methods explored for enhancing energy efficiency involve active and passive energy-saving measures. Passive solutions refer to strategies that minimize energy demand by mitigating heat losses in a building. These measures encompass thermal insulation of the building envelope, substituting or utilizing window and door frames with lower heat transfer coefficients, and eliminating cold bridges [32]. Charles et al. [33] studied a two-story office building in Vancouver to underscore the impact of the building envelope on energy demand reduction. Optimization of the building envelope results in a 45% reduction in annual energy consumption, e.g., air-tightness and insulation. Kumar et al. highlight that an energy-efficient envelope design considers several design variables, including geometric factors,

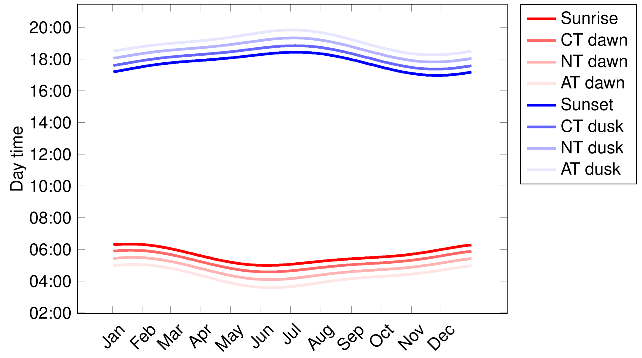
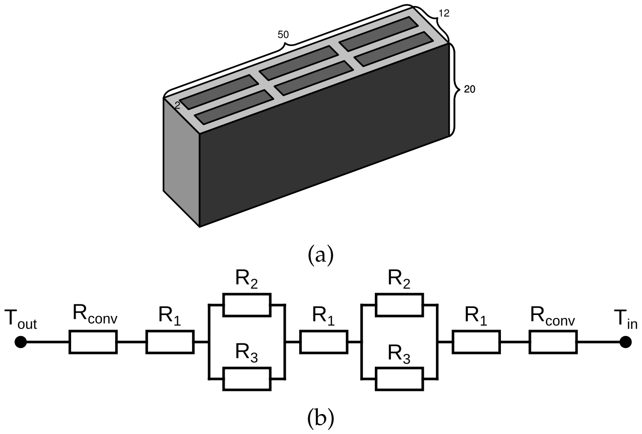


FIGURE 5. **Day-length of Queretaro, Mexico.**



(a)

(b)

FIGURE 6. **Representation of the hollow block used in the construction of the building (a), for inner walls and facade. The thermal resistance diagram of the block (b), where *R* is the thermal resistance, *conv* subscript is the convective part far away of the wall, 1 is the conductive part before the hollow section 2 and connections 3.**

envelope material properties, dimensions, air conditioning system and internal loads [34].

Figure 6 represents the hollow block used for the facade and division walls between rooms. The blocks are made of concrete. The wall behind the building is made out of solid blocks of concrete. This last one acts as the heat storage during winter. Figure 6 shows a thermal resistance diagram of the hollow block. It is crucial to comprehend the specific heat capacity and thermal conductivity coefficient of the construction materials for getting insight into the thermal properties, [35].

The heat flow per unit area of a given surface can be obtained by applying the Fourier Law. This law is established in Equation 1 [36].

$$q = -k\nabla T \tag{1}$$

where q is the heat flux and is expressed in W/m^2, the thermal conductivity coefficient k $(W/(mK))$ and the term ∇T is the temperature gradient. Along the thickness e of the bricks, the previous expression can be simplified as follows:

$$q = -k\frac{dT}{de} \tag{2}$$

from here, the thermal resistance R can be derived as:

$$R = \frac{dT}{Q} \tag{3}$$

with R being $R = e/Sk$. Similarly, from the Convection Newton Law $q = h(T_s - T_\infty)$, R_{conv} becomes $\frac{1}{Sh}$ where h is the convective heat exchange coefficient, T_s is the temperature at the surface, and T_∞ is the temperature far away of that surface.

B. WATER MANAGEMENT

The tourism sector acknowledges that the efficient utilization of water resources is a crucial sustainability issue. However, implementing efficient, clean water and wastewater management is a complicated undertaking [37]. Various elements, including the availability of financial resources, firm size, and knowledge levels, are critical in influencing a company's capacity to embrace and begin using water and wastewater management techniques [38]. Hotels are identified as large consumers of water. Hence, it is imperative to strike an equilibrium between tourist development and the green utilization of water resources [39].

The hotel has three separate water management systems:

1) **Tap water**: This system is used for water sinks and showers. It is stored in a 30 m^3 cistern.
2) **Rainwater**: It is used for the irrigation system with a storage capacity of 18 m^3. It is divided into a cistern of 9 m^3 and 3 tanks of 3 m^3 each.
3) **Graywater**: This is also stored in a 9 m^3 cistern and the water comes from the shower and washing service. The recycling of greywater is possible due to the use of biodegradable soap.

1) HOT WATER MANAGEMENT

Concentrated solar power technologies have achieved more attention in the last two decades due to their capacity to absorb incoming solar energy from sunlight, transforming it into heat, and being more efficient than conventional ones [40], [41]. The hotel has implemented glass evacuated tube collectors [42], totaling 1 330 L capacity.

The energy required to heat that amount of water is computed by Equation 4.

$$E = mc_p(T_f - T_i) \tag{4}$$

where the mass m is the volume of water required times its density (1000 kg/m^3), c_p is the heat capacity of water (4.18 $kJ/(kgK)$). T_f is the final temperature reached by the heater ($50°C$) and T_i is the initial temperature of water introduced into the system.

The mass of water is given by the equation 5:

$$M = n_p \rho_{H_2O} V_p \tag{5}$$

where n_p is the number of people. V_p is the required volume of water per capita in $\frac{liters}{person-days}$. The water density is 1000 kg/m^3, denoted as ρ_{H_2O}.

Determining the number of collectors in the heating system by the equation 7.

$$N_C = \frac{A_{C_{ap}} F_s}{A_C} \tag{6}$$

N_C is the amount of required thermal collectors. $A_{C_{ap}}$ is the absorption area in m^2. The safety or projection factor is denoted as F_S. The last defined term represents a security percent in the computing done by relation 7. This security factor is set to 1.4. A_C is the collector area, which depends on the size of the thermal collector area. The collector considered in the present work has an area equal to 2.34 m^2. The value of $A_{C_{ap}}$ is computed by equation 7.

$$A_{C_{ap}} = \frac{E}{H_p \eta_g} \tag{7}$$

where H_p is the average daily solar radiation at 30° inclination and it is expressed in $kWh/m^2 day$. η_g is the overall system efficiency set to 70%

C. PHOTOVOLTAIC SOLAR SYSTEM DESIGN

1) PV MODULE

The chosen *PV* module corresponds to serial number *SRP-450-BMB-HV*, and it is manufactured by Seraphim company, which is classified as a *TIER 1*. *TIER 1* classification means that the company has an established reputation and financial stability, making it a reliable choice when selecting components for a solar installation.

This module is based on *PERC* technology, which incorporates a reflective layer on the rear side of *PV* panel. This layer boosts efficiency by redirecting photons back into the cell. In 2019, *PERC* technology contributed significantly to the global *PV* industry, accounting for about 50% [43]. This manufacturing technology increased efficiency to 20%–22% with minimal additional fabrication costs. *PERC* technology is rapidly becoming a benchmark and is projected to be a leading technology in the future [44].

This *PV* module is also chosen for its noteworthy feature of employing half-cut cells. These cells effectively double the cell count within the module while halving the current on each busbar compared to standard solar cells. This characteristic is advantageous, as module power losses are mainly affected by the generated current, as emphasized in a study by Joshi [45]. This *PV* module comprises 156 monocrystalline silicon solar cut-cells of the *PERC* type.

The size of the *PV* module is 2180 × 1002× 35 *mm* (length, width, and thickness), with a weight of 24 *kg*. This module can generate a peak power output of 450 *W*, featuring an open-circuit voltage of 52.9 *V* and a short-circuit current of 10.7 *A*. At the maximum power point, the module can deliver a voltage of 44.6 *V* and a current of 10.09 *A* under standard test conditions (*STC*). The variation of thermal coefficients for the module electrical parameters is 0.05% per degree Celsius (current), −0.34% per degree Celsius (voltage), and −0.26% per degree Celsius (module power). The overall efficiency of the module is 20.60%.

2) PV SUPPORT

The proposed rooftop *PV* support is east-oriented, allowing for two modules on each support. This strategic arrangement optimizes space utilization, accommodating a maximum number of modules within a specified area [25]. The focus on efficient space use is crucial in the current context, addressing the increasing energy demands while prioritizing environmental responsibility. Figure 7 illustrates an example of the support structure from the [46] proposal.

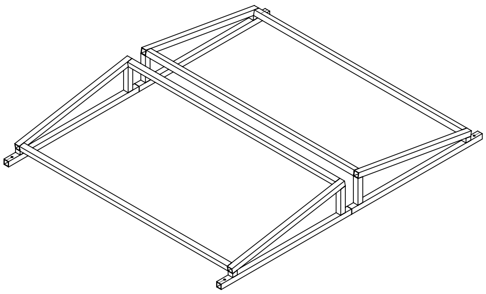


FIGURE 7. **East-west oriented mounting structure.**

Aligning the mounting supports in an east-west configuration provides substantial advantages, ensuring consistent sunlight exposure for *PV* modules throughout the day. This alignment minimizes shadows on adjacent modules and has the potential to moderate enclosure temperatures, leading to reduced air conditioning costs for buildings. Additionally, the aerodynamic design of this mounting support enhances security against wind gusts [23].

3) PV SIZING COMPUTING

Designing a viable *PV* installation requires a systematic approach to sizing, encompassing a series of carefully planned steps. The first step depends on the electrical demand of the building. This parameter will define the number of required *PV* modules. This step is essential to avoid an excessive over-sizing of the *PV* installation. One practical way to obtain the number of *PV* modules is based on the peak sun-hour (*PSH*) [47]. This term assists in evaluating the energy that a panel can produce daily at a given location. The *PSH* number is obtained with the following formula [48]:

$$PSH = \frac{Rd_t}{1000\ W/m^2} \tag{8}$$

where Rd_t is the daily total radiation in the region of interest and is expressed in $\frac{Wh}{m^2}$ at a day, the number of *PV* modules to be installed will be given by the hotel consumption (E_p) and the energy that is capable of producing each module throughout the day or the season of the year as:

$$N_m = \frac{E_p}{\mu P_m PSH} \tag{9}$$

where N_m is the required number of the required *PV* modules, P_m is the nominal power that the module can supply to the electrical network and correction factor (μ) includes the effects of additional losses, as possible dirt on the module surface, reflection in the moments of oblique incidence. In [48], μ was set in 0.9 considering the Mexican context.

Once the number of *PV* modules is computed, the inverter will be chosen based on their nominal power. The nominal power of each chosen inverter must be lower than the total power that the *PV* modules connected to it can supply. This measure is considered to avoid the operation of the inverter inside an inefficient operational region. The inverter may operate in this region because the operational conditions where the *PV* modules typically operate are non-ideal [49]. The following equation must be used during this step:

$$Pi_k = \lambda_k P_m N_{m_k} \tag{10}$$

where k is the number of inverters considered for the projected *PV* installation, P_i is the nominal power of the k-th inverter, and λ is the oversizing parameter, which must be lower than the unity. The minimum value of λ chosen for sizing the inverter nominal power is 0.85.

The configuration of *PV* arrays depends on the nominal voltage and current values of both *PV* modules and *PV* inverters. A crucial consideration is the voltage supplied by each series-connected module to each input of the inverter, denoted as Vm_p. This voltage should not exceed the maximum voltage (Vi_{max}) the inverter can handle. Additionally, it should align with the *MPPT* voltage of the chosen inverter (Vi_{mppt}) for efficient operation. Thus, the following relations must be satisfied:

$$Vm_p \approx Vi_{mppt} \tag{11}$$

$$Vm_p < Vi_{max} \tag{12}$$

The arrays, previously organized in a structured manner, are input into *PVsyst* 7.3 software to estimate the electricity generation they can supply to the hotel electrical network. This process aims to validate the pre-sizing conducted using the equation introduced earlier.

IV. RESULTS

Once the methodology has been designed in the previous section and the necessary database has been defined, we begin to carry out and present in this section the results and findings of this research, detailing and responding to the methodology and objectives.

A. ROOM TEMPERATURE BEHAVIOR

Figure 8 shows the average temperature of the room over 2 years. It also shows maximum and minimum average high and low temperatures for each month. We can see that the temperature of them keeps 4°C above the average of those four values. The building structure acts as a thermal mass that keeps the room fresh during the summer and comfortable in the winter. According to the World Organization of Health, room temperature should lie between 18°C and 26°C for a comfortable temperature.

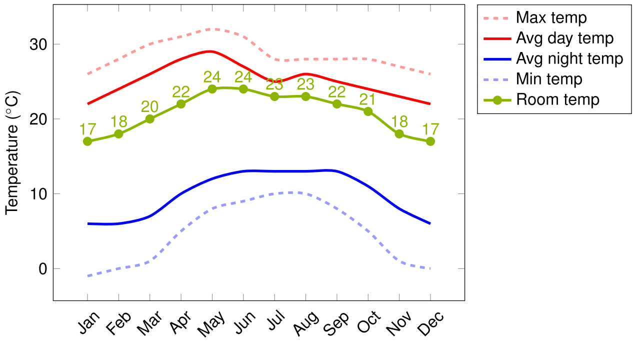


FIGURE 8. Temperature inside the room throughout the year.

Considering summer and winter, which are the extreme cases, the measured temperature of the room corresponds with the calculations. Equation 13 shows the total thermal resistance of the hollow block following the logic of Figure 6b. The results are for a single wall.

$$R_{tot} = 3R_1 + 2(R_2 \parallel R_3) + 2R_{conv} \tag{13}$$

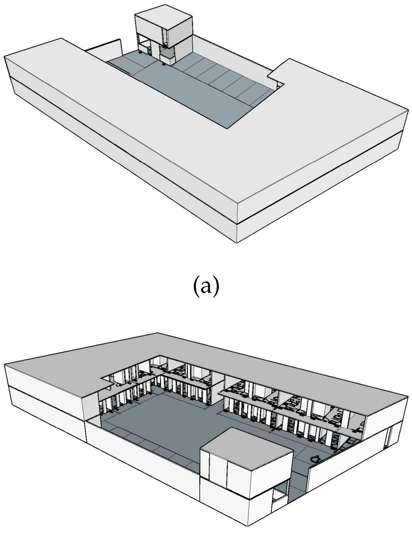
where R_1 is the thermal resistance of the continuous part of the brick, R_2 is the solid part between the hollow part R_3. R_{conv} is the thermal resistance of convection near the wall on both sides. Finally, R_{tot} is the total resistance of the block, being 11.82 K/Wm^2, so for the 10 m^2 wall, the resistance is 1.182 K/Wm^2. In winter, there is a heat flow of 10.15 W when the outside temperature is 6°C and the inside temperature is 18°C. On the contrary, in summer, there is a heat flow of 8.46 W with temperatures of 24°C and 34°C inside and outside, respectively.

In Asadi et al. [36], the authors claim that the low thermal conductivity of concrete blocks lowers the heat loss in buildings and energy consumption. Hollow concrete blocks exhibit particular properties attributed to their thermal characteristics due to the associated geometry. A value of 0.5 $W/(mK)$ is considered for the thermal conductivity of concrete.

The solar radiation that strikes the solid blocks on the wall is crucial during the winter, as it is a significant heat source for the room. By measuring the temperature of the wall during solar heating, we recorded a maximum of 45°C, although the interior temperature remained at 30°C. The heat is retained and subsequently released during the night. Additionally, during the night, the human itself also generates heat. With a low wind speed of 0.1 m/s, the convective heat transfer of the human body is 0.2 W/m^{2}K [50], and with a room temperature of 17°C, there is a heat flow of 3.8 W/m^2.

B. GENERATED 3D MODEL

Accurate field measurements are imperative for determining the appropriate sizes of the *TSS* and *PVSS*. These measures are crucial to ensure the efficient utilization of hotel space. The spatial configuration must be meticulously planned to prevent shadows on the collecting surfaces of thermal collectors and *PV* modules, as these surfaces are integral to



(a)

(b)

FIGURE 9. *3D* **model developed in Sketchup of the hotel building.**

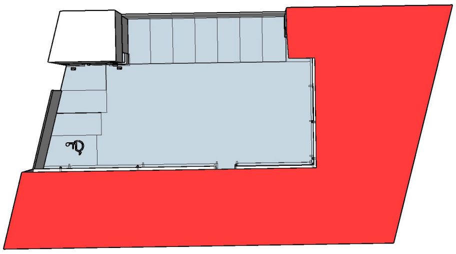


FIGURE 10. **Selected area for mounting** ***TSS*** **and** ***PVSS*****.**

the energy generation process. In such scenarios, the creation of a detailed *3-D* model becomes indispensable, serving as a valuable tool as it was shown in the research work conducted in [23] and [51]. Figure 9 presents two perspectives of the hotel building model constructed using Sketchup software.

Figure 10 illustrates the selected roof area of the hotel building designated for installing both solar system components. The area is highlighted in a distinct light red color. This area was chosen due to its optimal sun exposure, more significant than all other options. This expansive surface provides a significant area that comfortably meets the hotel resource demands the solar systems have to cover, spanning 416 m^2. Additionally, the absence of structural components on or near this surface is noteworthy, as it eliminates any potential sources of shadows that could affect solar energy absorption.

C. THERMAL SOLAR SYSTEM SIZING

Referring to the methodology outlined in the materials and methods section for calculating the solar thermal system, the design of this system aims to fulfill the entire thermal energy demand of the installation using solar collectors. The average daily hot water requirement per person is 25 liters, as cited in references [52], [53], and [54]. The hotel consists of 15 rooms, a meeting room, a kitchen, an employee area, and an owner space, each accommodating an average of 3 people, and considering a peak occupancy of 55 people, the maximum daily hot water consumption is estimated at 1375 liters.

In terms of energy demand, it amounts to 201162.5 kJ/day based on the previously estimated water consumption. The specific conditions, including initial and final water temperatures and heat capacity, were defined in the preceding section.

To calculate the number of collectors in the heating system, information on the collection area and the overall efficiency of the collector is essential. The average daily solar radiation in the computation process is 5$kWh/(m^2day)$, assuming a 30° inclination. The collection efficiency of the solar thermal system, as per its technical sheet [55], [56], [57], is 70%. So, the catchment area is 14.51 m^2, and the number of collectors is 8.68, approximated to 9 for meeting the previously estimated requirement.

TABLE 2. **Electrical consumption components connected to the hotel network.**

Units	Electrical Power (kW)	Power	Useful Time (h)	Estimated Consumption (kWh)
Refrigerator	0.0582	2	24	2.7936
	0.0099	1	24	0.2376
Washing Machine	1	2	2	2.7944
Drier	0.72	2	2	2.88
Light Bulbs	0.0085	100	2	1.7
Iron	0.0625	2	2	0.25
Electrical oven	0.0625	1	0	0
Water pump	1.2	4	1	4.8

D. PVSS SIZING

In Table 2, details of the electrical consumer components of the hotel are presented. The parameters used to characterize these components include mean electrical power, quantity of each component, duration of their usefulness and estimated consumption. This data is valuable for generating a first approach to size the *PV* installation.

The daily electricity consumption, obtained from the data in the previous data table, is approximately 15.6052 kWh, resulting in a monthly consumption of 468.156 kWh if a 30-day month is considered. This monthly value has been selected as a validation parameter for sizing the proposed photovoltaic *PV* installation. The daily term has been chosen for estimating the number of *PV* modules required.

It is crucial to obtain the peak sun hours specific to the location of interest to compute the required number of *PV* modules based on the previously mentioned consumption data, using Equation 8. As illustrated in Figure 3a, the annual global radiation in Queretaro is equivalent to 2077.4 kWh/m^2. Hence, the estimated daily global radiation is approximately 5.69 kWh/m^2, corresponding to a peak sun-hours value 5.69. Applying Equation 9 with the given parameters $\mu = 0.9$, $P_m = 450$ W, and $E_p = 15.6052$ kWh, along with the previously computed peak sun-hours value, it is necessary to install a minimum of 7 *PV* modules to meet the estimated electrical demand. For the configuration of the *PV* arrays, a total of 8 *PV* modules are selected. This quantity corresponds to a total electrical power output of 3.6 *kW* for the electrical network of the hotel.

These 8 *PV* modules require an estimated area of approximately 20.6 m^2, factoring in the individual area of each *PV* module (17.5 m^2) and allowing for additional space to accommodate mounting supports. This extra space also considers the necessary clearance between rows and columns to facilitate maintenance operations. The above-computed area is considerably smaller than the available rooftop surface area of the hotel building. This calculation was derived from a comprehensive 3*D* model analysis.

The estimated electrical power generated by the computed number of *PV* modules requires using just one small-size inverter. Using equation 11, considering $\lambda = 0.95$ and $N_{m_1} = 14$, the inverter power is equivalent to 3.42 *kW*. The chosen inverter belongs to the Sunny Tripower (*STP*) family, produced by the German company *SMA*. Specifically, the selected inverter is the *SMA* Sunny Boy 1.5, designed for smaller power applications and utilized when a limited number of *PV* modules is needed. The manufacturer highlights its high efficiency and reduced weight. The nominal power of the *PV* inverter is 1.5 *kWh*. It operates within a voltage range, with a minimum input voltage of 80 *VDC* and a maximum allowable voltage of 600 *VDC*.

The proposed configuration for the photovoltaic *PV* array involves using two of the inverters mentioned above, and each one manages the electrical power delivered by four *PV* modules connected in series. *PV* modules connected in series must have the same orientation to prevent a mismatch in generation by this cause. The optimal operational condition in this scenario mandates a mean voltage of 178.4 *V* for each inverter input. This value falls within the range where the inverter functions efficiently. Notably, the maximum open-circuit voltage is 211.6 *V*, lower than the maximum permissible for each inverter input.

From *PVsyst*, various outcomes about the projected energy generation of the *PV* installation are derived, encompassing metrics like produced energy and performance ratio. The anticipated annual generation is 5.636 *MWh*, averaging 15.44 *kWh* daily. This daily average is slightly lower than the estimated for the consumption data recollected and shown in Table 2. Figure 11 shows the monthly energy generated by the installation, where the red line indicates the previously estimated energy demanded by the electrical devices there is in the hotel (468.156 *kWh*).

The energy output from the proposed installation is notably higher from March to August, surpassing the levels observed in the remaining months. This pattern is attributable to the maximum solar height during this time frame, resulting in elevated solar irradiation on the *PV* module surface. During the months when the projected energy estimation is higher, the actual generation consistently exceeds the monthly estimate above. Conversely, in the remaining months, mainly January and December, the estimated generation falls below the previously determined parameters from the collected data.

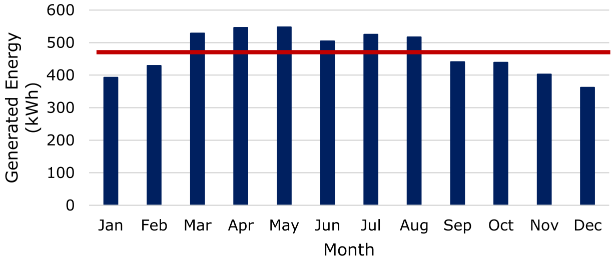


FIGURE 11. Estimated monthly generated energy.

The performance ratio, a standard metric for evaluating the effectiveness of any *PV* installation, typically ranges from 0 to 1. A value of 1 means optimal design and performance. The mean performance ratio over a year is 75.89%, which is an acceptable value for this installation. The monthly behavior of this performance index is shown in Figure 12. The sub-optimal performance ratio is based on the number of *PV* modules series-connected, resulting in a low voltage supplied to each inverter. Additionally, under certain operational conditions, the efficiency of the inverters is adversely affected.

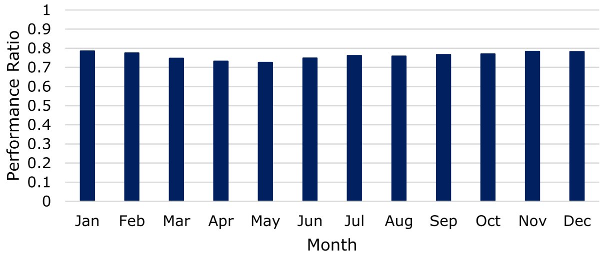


FIGURE 12. Estimated monthly performance ratio.

E. WATER MANAGEMENT

The collected rainwater depends on the rain season to capture the most water. From the precipitation shown in Figure 3b and the roof area of 416 m^2, the hotel harvests 128 m^3 of rainwater annually, or 10.6 m^3 per month on average. From the historical records of water consumption of the hotel from *CEA* (*Comisión Estatal de Aguas*) [58], there is an average demand of 42 m^3 of water per month. This data correlates with the calculations of 40 *L* of water per guest, and considering 22 guests, there is a demand of 880 *L* of water plus 500 *L* per day of irrigation, giving a total of 41.4 m^3 of water per month. Table 3 shows the source of consumption. The rainwater harvested is enough to irrigate the green areas because it is mainly used in the dry season.

Table 4 shows the installed *TSS* with a total capacity of 1330 *L*. The energy required to heat that amount of water is 416.955 *kJ*.

TABLE 3. Sources of water consumption.

Source	Units	CPD* [L]
Shower	13	40-50
Toilet	15	3
Washing machine	5	40
Irrigation system	1	500
Kitchen	1	50

*CPD: Consumption per day

TABLE 4. Thermal solar tanks systems installed in the hotel (Temperature of operation (90 °C) and Max. Pressure (50 Pa).

Quantity	Capacity (L)	No. Tubes
1	150	15
2	240	24
1	300	30
1	400	40

F. ENERGY INDICATOR

A correlation matrix of the variables that affect electricity consumption is displayed in Fig 13. As shown, two linear relationships correlate electrical consumption with external variables. These external variables are Temperature and Room-Day-Occupied (*RDO*).

The Temperature variable corresponds to the ambient temperature in a certain period. Temperature negatively correlates with hotel electrical demand, $R = -0.3$. This value correlation means that as temperature increases, electrical consumption moderately decreases.

A relationship of $R = 0.26$ can also be observed concerning the average daily occupancy of the rooms, which indicates that consumption increases slightly when this indicator increases. As in [21], a correlation lower than 0.7 means a poor correlation between both variables considered in this statistical analysis. Furthermore, this research underscores the complexity of deriving an energy indicator. Factors such as the construction characteristics of the hotel, geographic location, service quality, and size are among the variables considered in formulating an energy performance indicator.

The results derived from these linear indices align with the typical characteristics of sustainable buildings. In this context, neither the ambient conditions nor the daily occupancy of rooms significantly influence the electrical consumption of such buildings. This observation underscores the resilience and efficiency of sustainable design in minimizing dependencies on external factors that may traditionally impact energy consumption patterns. Finally, it is important to highlight that the hotel uses renewable energy and resources, derived from conservation practices and intelligent use of energy to demonstrate a low environmental impact.

V. DISCUSSION

Table 5 presents the outcomes from various global studies aiming to enhance hotel resource usage efficiency. These studies encompass diverse climatic characteristics from different regions worldwide. In this case, [1] provided a study that designed the energy performance indicator for energy characterization. The works of [17], [21], [23], and [27] provided a design and calculation of *SSFV*.

As demonstrated in the preceding table, the exploration of efficient resource utilization in hospitality institutions constitutes a field with a diverse array of proposals that can be applied based on the specific characteristics of these buildings. Many authors only consider a few considerations for achieving an improvement in the operational efficiency of hotels. In the current research work, several options were explored with the potential to transition the building towards a net-zero status. This classification is achievable as the hotel demonstrates the capability to self-provide the resources required to deliver services to its guests.

This research emphasizes the critical importance of conducting a thorough analysis of each case to optimize resource utilization in hospitality institutions. The initial phase of achieving this enhancement is integral to the building design process, wherein vital data such as meteorological conditions and the geographical location of the institution come into play. Notably, certain research studies, like [4] and [6], incorporate this approach during the analysis of the design process of hotels.

It is essential to acknowledge that implementing this initial step is not feasible for all institutions that have already been constructed, as observed in previous studies [1], [21], and [23]. Consequently, this approach is highly conditioned and may only sometimes be employed. However, in the specific case addressed in this study, the approach was satisfactorily applied, leading to outstanding results. This success is attributed to the savings in managing interior temperatures through strategic building orientation.

Meteorological data and geographical location emerge as pivotal factors, significantly influencing the optimal orientation of any building. This decision-making process holds the potential for substantial improvements in resource utilization. In conjunction with this, the meticulous selection and utilization of construction materials with specific thermal properties become paramount in achieving these savings. These considerations are instrumental in ensuring the design of a net-zero building, as corroborated by findings in studies such as [17], [34], and [6]. The results of this research align with those reported by other authors, indicating improved guest room comfort with a decrease in mean temperature achieved without using energy-intensive air conditioning devices.

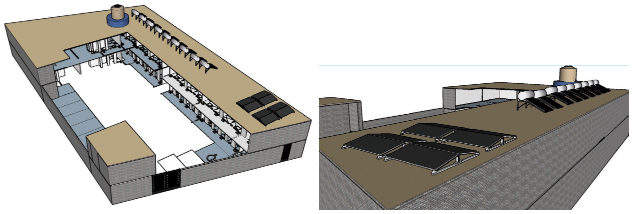
Precipitation levels are also noteworthy, particularly in areas dealing with water distribution challenges. Taking

FIGURE 13. Correlation analysis of the variables.

TABLE 5. Comparison of case studies applied in the reviewed literature.

Ref	SAD	EC	SSFV	SST	EUW	ZEPC (%)
[1]	✗	✗	✓	✓	✗	70.00
[18]	✓	✓	✓	✗	✗	34.00
[22]	✗	✓	✓	✗	✗	84.64
[24]	✓	✓	✓	✗	✗	30.00
[60]	✓	✗	✗	✗	✓	-
[28]	✗	✗	✗	✓	✗	10.00
[6]	✓	✗	✓	✓	✗	20.5
Our Work	✓	✓	✓	✓	✓	>90.00

✗= No Apply; ✓= Apply; - = Information not found; SAD = Sustainable- based architectural design; EC = Energy characterization; EUW = Efficient use and utilization of water; ZEPC = Zero external power consumption.



(a) (b)

FIGURE 14. View of the proposed ***PV*** solar system and thermal solar system.

these characteristics into account enables the implementation of measures to enhance rainwater collection processes, thereby reducing the reliance of the hotel on external water distribution networks. Several of these measures significantly influence the structural design of buildings. Moreover, water management is crucial for optimizing resource consumption, incorporating procedures such as graywater treatment and rainwater collection. The results showcase complete coverage of the hotel irrigation needs, signifying a substantial saving in water resource utilization. These findings align with those obtained in a related study [9], [59].

In the ongoing analysis conducted in this research, an energy audit based on *ISO-50001* standard was implemented. This procedure proved invaluable in identifying key areas of opportunity for enhancing resource utilization, specifically gas and electricity consumption. The areas identified as high consumers align with the findings from studies conducted in similar institutions, primarily focusing on guest rooms [23]. An interesting aspect related to the hotel energy demand is the guest room consumption ratio compared to other areas, which is lower than reported in the literature. This trend is attributed to the architectural design of the building, optimizing energy usage from solar radiation through passive methods to achieve comfortable temperatures without the need for air conditioning devices. Additionally, owing to the structural design of the building, the day grades, a commonly used index for predicting consumption trends, exhibit a weak correlation with electrical consumption. These findings serve as an indicator to assess the practical application of passive cooling methods in institutions of this nature.

The solar irradiation on the roof area should also be analyzed to propose measures for harnessing this energy throughout the year. These studies can be instrumental in assessing the feasibility of installing both *PV* solar systems and thermal solar systems. Several authors have suggested designing *PV* installations to cover all available areas with *PV* modules. However, in this research work, this approach is not considered. In this region, covering only the building electrical demand is more feasible. The cost of energy sold to the distribution network does not justify such an investment for the hotel administration. In the proposed design in this work, the *PV* generation does not aim to cover the maximum electrical demand for the entire year. It is recognized that institutions of this kind experience their highest consumption during summer. Therefore, the installation of the *PV* is strategically planned to supply its generation peaks during these months, as indicated by the highlighted results based on estimations.

Also, the available area after sizing the *PV* system is used to install thermal collectors to supply hot water to hotel services that require it. As many researchers highlighted, this technology is appropriate in this kind of building when the guests require this resource, and it is crucial to supply comfortable services to them. As the results show, this measure is essential to saving for decreasing gas consumption. In Figure 14, the depicted solar systems illustrate the incorporation of 8 *PV* modules and 9 thermal collectors. This design aims to reduce dependence on gas and electricity distribution networks.

VI. CONCLUSION

The resource usage by hotels, which is required by the services provided to guests, is critical to evaluating their feasibility from an economic and environmental viewpoint. Examining the specific characteristics of each institution becomes crucial, even during the design process led by architects. The design phase emerges as a pivotal step for achieving significant savings in the regular operation of this kind of institution. Selecting appropriate construction materials and ensuring an optimal building orientation contribute to maintaining comfortable interior temperatures, potentially eliminating the need for specialized devices to achieve such conditions.

Furthermore, despite the considerations mentioned above regarding the design process, a comprehensive analysis of energy carrier consumption is crucial to establish an ongoing efficiency improvement process for service provision. This analysis should be conducted cyclically to identify potential areas where enhanced efficiency can be achieved. A valuable approach to conducting this analysis is to follow the methodology outlined in the *ISO-50001* standard, which provides a set of steps serving as a reliable reference framework for improving the operational efficiency of several kinds of institutions. In the present research, some energy indexes are computed. However, no correlation was found because the architectural design of the hotel can decrease the dependence on ambient temperature and other environmental factors on energy consumption.

For two reasons, implementing measures such as designing a water management policy, utilizing gray water treatment, and incorporating thermal and photovoltaic systems are well-suited for hospitality institutions. Firstly, these initiatives contribute to reducing resource consumption from distribution networks, resulting in cost savings reflected in utility bills without affecting the services provided to the guests. Secondly, adopting such eco-friendly practices enhances the prestige of the hospitality building, appealing to environmentally conscious tourists and earning it an attractive classification as an eco-friendly establishment.

Integrating renewable source generators in hotels to supply their services to guests emerges as a strategy that decreases the overall demand for resources and increases the comfort of their guests. The following three keys stand as the basis of the present research work:

- **Optimal Energy Balance**: Integrating renewable energy sources ensures an equilibrium between energy consumption and generation. Increasing operational efficiency and decreasing costs can be achieved in this way.
- **Water Sustainability**: Implementing rainwater harvesting and grey-water recycling systems contributes to sustainable water management, significantly reducing water consumption.
- **Optimal Architectural Design**: An efficiency-oriented design optimizes energy carrier use in this building. This approach reflects a commitment to both environmental responsibility and guest satisfaction.

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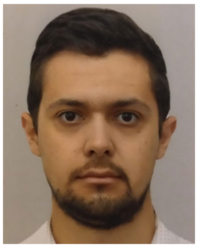

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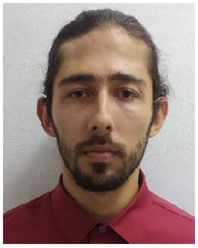

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