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Optimización del Consumo Eléctrico por Refrigeración en Edificios Escolares CAPFCE ubicados en Clima Cálido Seco

Optimization of Electrical Energy Consumption for Cooling in CAPFCE School Buildings Located in Hot-Dry Climates

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Resumen-- **Este estudio evalúa el consumo eléctrico destinado a la refrigeración en un conjunto de edificios del Campus Hermosillo de la Universidad de Sonora, específicamente aquellos construidos en la década de 1940 bajo los lineamientos del Comité Administrador del Programa Federal de Construcciones Escolares (CAPFCE), los cuales no fueron concebidos para responder al clima cálido seco de la región. Actualmente, estas edificaciones constituyen una parte significativa del campus, lo que subraya la relevancia del estudio.**

Para ello, se realizaron simulaciones energéticas en diversos escenarios, incorporando las propiedades térmicas de los materiales, la configuración volumétrica de los edificios, la ocupación de las aulas y los patrones de uso, considerando variables como la temperatura del termostato, la apertura de puertas y el encendido de luminarias. Adicionalmente, se llevaron a cabo mediciones in situ con cámara termográfica y sensores de temperatura para validar las simulaciones. Los hallazgos de esta investigación proporcionan información clave para mejorar la eficiencia en el uso de la refrigeración, así como para establecer criterios operativos más sostenibles, aplicables también a otras instituciones educativas con condiciones climáticas y edificios similares.

Palabras clave— Consumo eléctrico; Clima cálido-seco, Edificaciones escolares CAPFCE, Simulación energética, Envolvente térmica,.

Abstract— **This study evaluates the electricity consumption for cooling in a set of buildings on the Hermosillo Campus of the University of Sonora, specifically those built in the 1940s under the guidelines of the Administrative Committee of the Federal School Construction Program (CAPFCE), which were not designed to respond to the hot dry climate of the region. Currently, these buildings constitute a significant part of the campus, which underlines the relevance of the study.**

To this end, energy simulations were carried out in various scenarios, incorporating the thermal properties of the materials, the volumetric configuration of the buildings, the occupancy of the classrooms and the patterns of use, considering variables such as the temperature of the thermostat, the opening of doors and the lighting of luminaires. Additionally, on-site measurements were carried out with a thermal imaging camera and temperature sensors to validate the simulations. The findings of this research provide key information to improve efficiency in the use of refrigeration, as well as to establish more sustainable operating criteria, applicable also to other educational institutions with similar climatic conditions and buildings.

Index Terms— Energy consumption; Hot-dry climate, CAPFCE school buildings, Energy simulation, Thermal envelope,

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I. INTRODUCTION

Globally, the demand for the use of cooling systems has been on the rise, especially in hot regions, generating challenges for governments and educational institutions (UN Environment, 2017). In Mexico, electricity consumption in warm areas is significantly higher than in other regions. In Sonora, air conditioning accounts for a considerable fraction of total electricity consumption, especially in the hottest months (CONUEE, 2018).

The electrical consumption of refrigerated air conditioning in educational buildings in Hermosillo, Sonora, Mexico, represents a growing challenge due to the region's hot dry climate, characterized by extreme temperatures and high solar radiation. These conditions affect the thermal performance of buildings and increase the demand for mechanical cooling, making air conditioning an indispensable resource to guarantee thermal comfort. This consumption is influenced by factors such as architectural design, climatic conditions and occupant usage patterns. In this sense, it is essential to analyze how the design of educational buildings impacts electricity consumption, especially in hot regions where cooling is essential.

In Mexico, the design of schools has been marked by the Eleven Year Plan of 1958, promoted by the Ministry of Public Education (SEP) under the direction of Torres Bodet, with the aim of standardizing the construction of schools at the national level. Within this plan, the architect Pedro Ramírez Vázquez designed the rural classroom-classroom, a modular and low-cost model that was replicated in various regions without considering climatic particularities (Rueda & Rentería, 2017).

This model, implemented by CAPFCE, was adopted in many institutions, including the Hermosillo Campus of the University of Sonora. However, with the General Law of Educational Physical Infrastructure (INIFED) in 2008, each state assumed responsibility for its educational infrastructure, which led to the disappearance of this model. Despite this, many of these constructions are still in use and have deficiencies to respond to the climatic conditions of the Hermosillo region.

Marincic (2005) quantitatively evaluated the thermal behavior of these architectural prototypes in the region and concluded that they lack an adequate thermal design for the local climate of Hermosillo, which generates unfavorable comfort conditions and high electricity consumption for cooling. In this context, Fuentes (2016) warns that artificial air conditioning can lead to excessive use of electricity when the materials and construction processes are not adapted to the climate.

The concept of optimal electricity consumption is key in this analysis. López (2011) defines it as the benchmark that distinguishes efficient buildings from non-efficient ones, while Castro, San José, Villafruela, Méndez & Guijarro (2008) describe it as a consumption above the average obtained when comparing buildings with similar characteristics, although this does not necessarily guarantee the efficiency of the building.

Among the factors that influence electricity consumption, the building envelope plays a decisive role. Varini (2015) describes it as the main mechanism of heat transfer between the environment and the interior of the building, so its proper design can reduce the need for artificial cooling. Bravo and Pérez (2016) consider it a thermodynamic system in constant interaction with the environment, while González and Molina (2017) highlight its correct planning as a key factor in minimizing electricity consumption.

Fig. 1. Hermosillo, Sonora, Mexico (polygon shaded in white) and Facilities of the Hermosillo Campus of the University of Sonora. Made with Google Earth imagery (Google Earth Pro, 2024).

The thermal performance of the enclosure is directly related to usage patterns. Christopher Alexander introduced the concept of pattern in 1977, defining it as the recurrence of a problem in the environment and its corresponding solution, which can be applied multiple times (Guerrero, Suárez, & Gutiérrez, 2013). Subsequently, Zapata (2011) expanded on this idea by focusing on patterns of use in educational settings, highlighting that these arise from frequent problems and optimize the student's attention by involving him in their resolution. In addition, he pointed out that each pattern is linked to a specific context, where problems and solutions are interrelated.

Usage patterns can be described as the daily activities of users that define the thermal operation of the building within a specific time, place, and climatic context, which can be generated in response to problems derived from the physical, spatial, and thermal conditions of the envelope, as well as the habits and customs of the occupants. According to Balvedi, Schaefer, Bavaresco, Eccel, and Ghisi (2018), the great diversity of interactions that make up user behavior introduces considerable complexity in thermal and energy performance studies, even when considering a single architectural typology. This study aims to optimize electricity consumption by cooling taking into account the thermal envelope, usage patterns and the thermal load generated by users, using energy simulations. According to Bravo and Pérez (2016), energy simulation is conceived as a simplified representation of a real system that facilitates the assessment and prediction of the energy behavior of a design, offering information both on its performance in a specific period and on its future evolution. For Balvedi et al. (2018), one way to evaluate the thermal load represented by the user's occupancy is through simulations, where representative profiles of user behavior can be inserted statically (using fixed occupancy times), and considering the interactions derived from the use of windows and doors, with distinction only for working days.

Considering the theoretical analysis exposed, it is possible to optimize electricity consumption in CAPFCE buildings (structures designed without adequate climatic criteria) by adjusting usage patterns and implementing thermal insulation.

II. CASE STUDY: SELECTED BUILDINGS AND EVALUATION METHODOLOGY

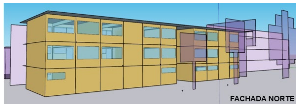
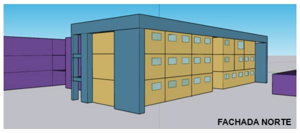
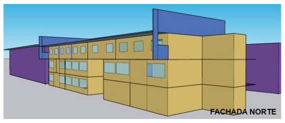
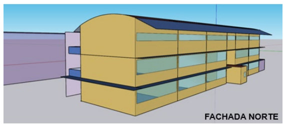
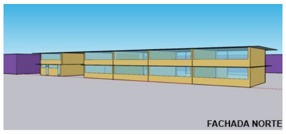
The Hermosillo Campus of the University of Sonora is located on Blvd. Luis Encinas J, in the center of the city of Hermosillo, in the state of Sonora, Mexico, at latitude 29.1026 and longitude -110.97732 (Fig. 1). This region has a warm dry climate with a marked seasonal pattern. From May to September, maximum temperatures regularly exceed 40 °C, reaching peaks close to 45 °C in June and July. During this period, nights are also warm, with lows rarely dropping below 25°C, limiting natural cooling capacity. Relative humidity is lower in the months of extreme heat, intensifying the feeling of dryness and increasing the demand for cooling air conditioning.

Considering the extensive educational infrastructure of the campus, an evaluation methodology focused on a specific selection of buildings was applied. CAPFCE-type classrooms were identified, as they are the spaces most used during academic training. These buildings were designed under a modular scheme, generally with two to three bays, with predominant eaves in a north-south orientation. Originally, they had conventional construction systems, with a concrete structure and walls of solid concrete block or double hollow brick filled with mortar, some with ceramic façade coating. Over time, these walls were modified by incorporating insulating materials, and third levels were added built with steel structures, exterior walls of drywall with extruded polystyrene and interior walls of gypsum panel. From this selection, five buildings were chosen whose variations in geometry and construction systems respond to the conditions previously described. (Fig. 2 and Table I).

Subsequently, an on-site study was carried out to determine the thermal conductivity of the construction systems. With this data, energy simulations were developed to analyse electricity consumption during the month of August based on five different scenarios. The validation of the results was carried out through thermal monitoring with a thermal imaging camera and temperature sensors installed in the selected buildings. Finally, a comparative analysis of electricity consumption by cooling was carried out from which recommendations for its optimization were established.

Fig. 2. Selection of CAPFCE Buildings at the Hermosillo Campus of the University of Sonora. Made with image from Google Earth (Google Earth Pro, 2024).

TABLE I
CONSTRUCTION SYSTEMS OF THE SELECTED BUILDINGS AT THE HERMOSILLO CAMPUS OF THE UNIVERSITY OF SONORA

	Construction system	Real and simulated building image in OpenStudio
1	**Exterior Walls:** Solid concrete block 19 cm thick. **Interior Walls:** Solid concrete block 19 cm thick. **Roof and Mezzanine:** 15 cm thick structural concrete. **Enclosures:** 3 mm thick monolithic glass, 3 mm thick metal door.	 
2	**Exterior Walls:** 19 cm thick solid concrete block with 1" thick extruded polystyrene. **Interior Walls:** Solid concrete block 19 cm thick. **Roof and Mezzanine:** 15 cm thick structural concrete. **Enclosures:** Double glazing 7 mm thick, galvanized metal door 45 mm thick.	 
3	**Exterior Wall:** 1/2" double-sided cement board, reinforced with 6" metal profiles, posts and 20-gauge channel, with 1 cm thick extruded polystyrene. **Interior Walls:** 1/2" two-sided drywall. **Cover:** Sandwich panel. **Mezzanine:** 15 cm thick structural concrete. **Enclosures:** Double glass 7 mm thick, Galvanized metal door 45 mm thick.	 
4	**Exterior Wall:** Double hollow brick block 18 cm thick filled with mortar, covered by a 1 cm thick ceramic façade. **Interior Walls:** 18 cm thick brick. **Roof and Mezzanine:** Structural concrete 40 cm thick. **Enclosures:** 3 mm thick monolithic glass, 3 mm thick metal door.	 
5	**Exterior Wall:** 18 cm thick hollow brick block filled with mortar, covered with 1 cm thick insulation, and by a 1 cm thick ceramic façade. **Interior Walls:** 18 cm thick brick. **Roof and Mezzanine:** Structural concrete 40 cm thick. **Enclosures:** 3 mm thick monolithic glass, 3 mm thick metal door.	 

III. IN-SITU THERMAL CONDUCTIVITY STUDY

A thermal conductivity study was carried out only in buildings whose materials do not have thermal properties documented in technical sheets. The study was done through the thermal needle method, with the KD2 Pro portable device using the KS-1 sensors of 6 cm long, and 1.3 mm in diameter for insulating materials; the SH-1 with a double needle of 3 cm

Fig. 3. Measurement of thermal conductivity in a concrete wall and a hollow brick block wall. Own photographs, 2022.

long, and 1.3 mm in diameter for solid materials; also, a paste called Arctic Silver 5 High-Density Polysynthetic Silver Thermal Compound was used. which works as a highly heat-conductive compound to fill the gap when the sensor is inserted, which helps to minimize the range of error in measurement.

Before starting, the calibration of the thermal properties meter was verified through the measurement standards indicated in the manual; then, a hole was drilled in the wall through two pieces of drilling depending on the thickness and depth of the sensor; in some measurements, one or more sensors were inserted to verify whether it was an insulating or conventional material; the samples were replicated at different points in the building, and a total of eighteen insertions were made to verify the veracity of the results obtained in the measurements (Fig. 3).

The margin of error in most thermal measurements is within the allowable limit according to the measuring equipment manual, with an error range ranging from 0.0548 to 0.0029. The specific values are presented in Table 3. Once the thermal conductivity values of the materials were obtained, they were incorporated into the simulation scenarios described in the following section.

IV. ENERGY SIMULATION SCENARIOS

To evaluate the electricity consumption of refrigerated air conditioning systems, five simulation scenarios were defined. In each one, three thermostat temperature ranges were established: 17°C minimum, 24°C as an intermediate value and 28°C as a maximum. Each scenario analyzes a specific variable to determine its impact on electricity consumption. The scenarios evaluated are described below (Table II).

For the construction of the scenarios, the buildings were modeled in *SketchUp*® using the *OpenStudio*® plugin. The envelopes were oriented according to their angle, orientation and geolocation on the university campus. The surfaces exposed to solar radiation and wind were defined, the heat flow between spaces was modelled, and boundaries and vegetation were represented as prisms.

TABLE II

SCENARIOS PROPOSED FOR OBTAINING THE ELECTRICITY CONSUMPTION OF REFRIGERATED AIR CONDITIONING

Scenario	Variable Analyzed	Objective
1	Thermal properties and enclosure geometry	Assess the impact of the envelope on electricity consumption.
2	Thermal load of users	Determine how the presence of users influences electricity consumption.
3	Lighting of luminaires	Analyze the effect of lighting use on electricity consumption.
4	Opening windows and doors	Studying the impact of uncontrolled ventilation on electricity consumptio
5	Proposals for optimal use and improvements in the envelope	Evaluate energy efficiency strategies to optimize electricity consumption.

In OpenStudio, the EPW file with climate data for Hermosillo and soil temperatures from the Climate.OneBuilding.org repository was incorporated. Construction systems were added using thermal conductivities obtained in situ. To complement the physical properties of the materials, roughness, density, specific heat, and thermal absorption data from OpenStudio software were integrated, which uses a material library with parameters based on *ASHRAE Standard 90.1-2010*.

The properties of insulating materials (expanded polystyrene, fiberglass mat, sandwich panel), thermal mass (polypropylene, structural concrete, metal frame, steel) and enclosures (monolithic windows, double windows and doors) were included. The solar and visible absorption values, corresponding to the surface finishes, were obtained from the *EnerHabitat software* (National Autonomous University of Mexico [UNAM], 2014) (Table III).

In the thermal mass section, the volumetric calculation of the construction elements (concrete columns, steel, beams, beams, metal frames of the cement board and gypsum board walls, as well as the furniture, together with the thermal properties of the materials) was included. An infiltration value of 0.6 renewals per hour was assigned, used in Hermosillo for areas with envelopes that present thermal bridges and materials with air gaps.

The characteristics of the refrigeration equipment present on site were simulated so that the results of electricity consumption were as similar as possible. For this reason, two cooling units were loaded per classroom, configured as "unitary system-single speed DX cooling- Cycling-Elec reheat" (equivalent to non-inverter minisplits), adjusting their characteristics according to the existing air conditioning systems on site. An efficiency of 15% for the fan and 20% for the motor was defined, according to Energy Star. An efficiency of 13 SEER and a COP of 4.9 were established, verified in Energy Plus. In addition, an air flow rate of 800 CFM and a nominal capacity of 2 tons per equipment were set, with operating hours from 7:00 a.m. to 9:00 p.m., Monday through Friday, in August, and three temperature ranges for the thermostat: 17°C, 24°C and 28°C. All the above applies to all scenarios, thus configuring Scenario 1 with these base conditions. From this point, specific parameters were incorporated into the other scenarios to assess their impact on electricity consumption. In Scenario 2, the number of users was included and a metabolic rate of 108 W/person (sit-still) was assigned. In Scenario 3, LED luminaires were added, taking the consumption values in watts from the Philips catalogs, and a lighting schedule was established from 7:00 to 9:00 p.m. in August. In Scenario 4, the stack ventilation measure was used in OpenStudio, as it is the closest variable available to represent the effect of air entering the interior when doors and windows are opened. To simulate this condition, high temperatures were forced that reflect the typical climate of Hermosillo, promoting the entry of air during the hours of 7:00 to 9:00 p.m., Monday through Friday in August.

TABLE III
THERMOPHYSICAL PROPERTIES OF THE MATERIALS ANALYZED

Material	R	(m) [a]	(w/mk) [b]	(Kg/m³) [c]	(j/gk) [d]	(T/S/V) [e]
Ceramic façade	Rough medium	0.010	**0.302**	1500	1480	0.9/0.3/0.3
Brick insulation	Rough medium	0.010	**0.045**	43	1210	0.9/0.3/0.3
Brick with double hollow filled with mortar	Rough medium	0.180	**0.281**	1500	1480	0.9/0.3/0.3
Concrete Block	Rough medium	0.150	**0.338**	2000	840	0.9/0.3/0.3
Tablacemento	Rough medium	0.013	0.099	898	1000	0.9/0.7/0.7
Polystyrene	Rough medium	0.012	0.030	43	1210	0.9/0.3/0.3
Brick	Medium Mild	0.180	**0.925**	1970	800	0.9/0.3/0.3
Gypsum board	Medium Mild	0.013	0.30	800	1090	0.9/0.3/0.3
Fiberglass mat	Rough medium	0.125	0.030	43	1210	0.9/0.5/0.5
Concrete (roof-mezzanine)	Medium Mild	0.15 y 0.40	**0.731**	1280	840	0.9/0.15/0.15
Sheet	Medium Mild	0.002	45.006	7680	418	0.9/0.25/0.25
Sandwich panel	Rough medium	0.025	0.030	43	1210	0.9/0.25/0.25
Polypropylene	Rough medium	0.254	0.190	1400	1200	0.9/0.7/0.7
Concrete (columns-beams)	Rough medium	0.400	1.720	2243	837	0.9/0.7/0.7
Steel (columns-beams)	Medium Mild	0.100	45.310	7833	500	0.9/0.25/0.25
Aluminum structure	Medium Mild	0.001	50.000	7680	418	0.9/0.2/0.2
Metal (Door 3 mm)	—	0.003	45.28	—	—	—
Galvanized metal (Door 45 mm)	—	0.045	1.2	—	—	—
Simple glazing	—	0.003	5.8	—	—	—
Double glazing	—	0.007	2.6	—	—	—

The numbers in bold correspond to the thermal conductivity values obtained in-situ. The remaining data are obtained from EnerHabitat (UNAM, 2014) and the ASHRAE 90.0-2010 materials library.

[a] Thickness in meters (m); [b] Thermal Conductivity (W/m·K); [c] Density (Kg/m³)
[d] Specific heat (j/gk); [e] Absorption (Thermal/Solar/Visible)

In Scenario 5, strategies were implemented to optimize the electricity consumption of air conditioning systems, considering usage patterns, thermal insulation and improvements in the efficiency of refrigeration equipment. During the month of August, a natural ventilation routine was established that consisted of opening doors and windows between classes and keeping them closed during sessions. This procedure was applied daily from 7:00 a.m. to 9:00 p.m. In terms of lighting, the luminaires were turned off when there was no activity and remained on during classes to ensure adequate living conditions, as it was observed that students used them in both morning and afternoon sessions (Yeomans, Alpuche, & Borbón, 2025).

In addition, in non-insulated buildings, a 1-inch layer of extruded polystyrene was added to walls and ceilings, and monolithic windows were replaced with double-glazed units. The efficiency of the air conditioning systems also increased, raising the SEER from 13 (basic) to 16 (intermediate), which contributes to lower electricity consumption and more efficient operation. These proposals are detailed in Table IV.

TABLE IV
PROPOSALS MADE IN BUILDINGS TO OPTIMIZE THE ELECTRICITY CONSUMPTION OF REFRIGERATED AIR CONDITIONING COOLING SYSTEMS

Building	Optimal usage patterns (ventilation and lighting)	Thermal insulation	Double glazed windows	Improved efficiency of air conditioners by Refrigeration
1	✓	✓ Walls and slab	✓	✓
2	✓	—	—	✓
3	✓	—	—	✓
4	✓	✓ Walls	✓	✓
5	✓	—	✓	✓

V. VALIDATION OF ENERGY SIMULATIONS

For the validation of the simulations of electricity consumption by cooling, two types of thermal monitoring were carried out in situ. The first consisted of capturing thermographic images of the exterior surfaces of buildings 1, 2 and 4. These measurements were carried out on August 22 and 24, 2022, in the morning and afternoon, covering the north, south, east and west orientations. A Fluke Ti25 thermal imaging camera was used to obtain thermal images, with an accuracy of ±2°C, a measurement range of -20°C to +350°C and a resolution of 160 × 120 pixels. Subsequently, the average temperatures of the surfaces were analyzed using the SmartView® software (Fig. 4).

In December 2023, temperature sensors were installed inside the classrooms of the buildings pending validation: 3 and 5.

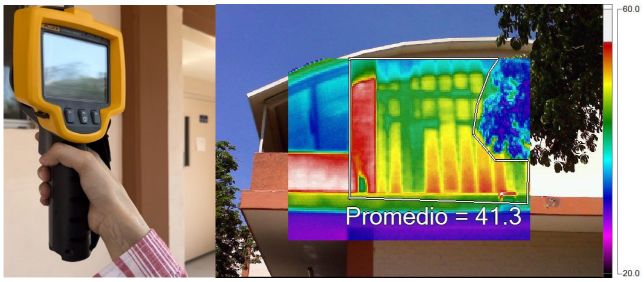


Fig. 4. A handheld device used for thermal imaging on exterior surfaces, and thermal photography of a wall taken with the Fluke thermal imaging camera. Own photo, 2022.

Fig. 5. Installation of HOBO Data Logger sensors in classrooms of buildings. Own photos, 2023.

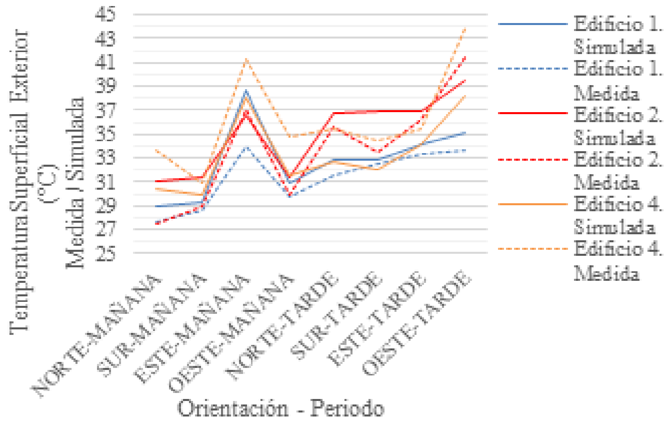


Fig. 6. Temperature Comparison: Simulation vs. On-Site Measurement with Thermal Imaging Camera in Buildings 1, 2 and 4.

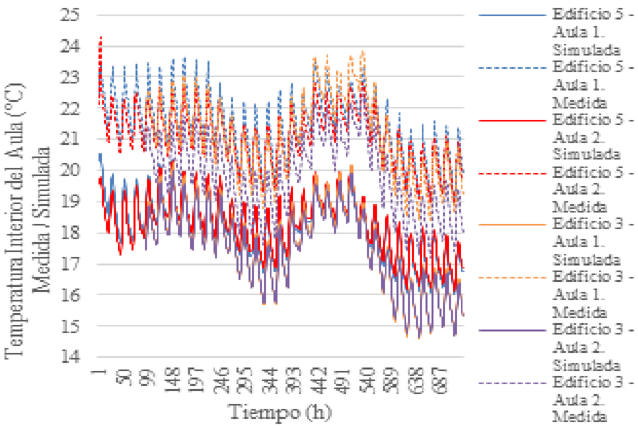


Fig. 7. Temperature Comparison: Simulation vs. On-Site Measurement with Indoor Temperature Sensors in Buildings 3 and 5.

During this period, classrooms remained unoccupied, with no users and no functioning air conditioning systems, allowing data to be collected more accurately and without interference.

The methodology used consisted of the installation of four HOBO Data Logger sensors, with a measurement range of -20°C to 70°C. These sensors were suspended from the existing projectors in the classrooms, located at half the total height of the space. In both buildings, the sensors were installed in a classroom on the west corner and an intermediate one, maintaining the same distribution. The difference lies in the fact that, in Building 5, they were located on the first level, while in Building 3, on the third. The collected data were downloaded and analyzed using the HOBOware® software (Fig. 5).

The results of the in-situ thermal monitoring were compared with simulations in OpenStudio®, using NASA's EPW climate archive for the monitored periods. For validation, two output variables were defined: "Zone Mean Air Temperature (°C)", which represents the indoor mixing temperature of the classroom, and "Surface Outside Face Temperature (°C)", which reflects the outdoor temperature of the surfaces. Subsequently, comparative graphs were generated between the values measured in the field and those obtained in the simulation, allowing the analysis of the dispersion of the data. The coefficients of determination (R^2) obtained reflected a high correlation between both datasets, with values of 0.84 for Building 1, 0.87 for Building 2, 0.85 and 0.84 for Building 3, 0.85 for Building 4, and 0.88 and 0.86 for Building 5. These results confirmed that the simulations were representative of the real conditions of the site, allowing the investigation to continue (Fig. 6 and 7).

VI. ELECTRICAL CONSUMPTION OF REFRIGERATED AIR CONDITIONING

Subsequently, the monthly electricity consumption per unit area (kWh/m²) for the month of August is analyzed, without efficiency strategies, considering different thermostat temperatures (17°C, 24°C and 28°C). The results indicate that the thermal envelope (Scenario 1) is the main consumption factor, representing between 74% and 78% of the total, followed by the thermal load generated by the occupants (Scenario 2), which contributes 20% to 25%. In contrast, the use of luminaires and the opening of doors represent only between 1% and 2% of consumption.

It was observed that an increase in the temperature of the thermostat, from 17°C to 28°C, reduces electricity consumption between 25% and 28%. Regarding the comparison between buildings, Building 5 presented the lowest monthly electricity consumption, followed by Buildings 4, 3, 1 and 2, the latter being the one with the highest consumption. In all cases, a decrease in consumption was recorded when the thermostat temperature was set to 28°C (Fig. 8).

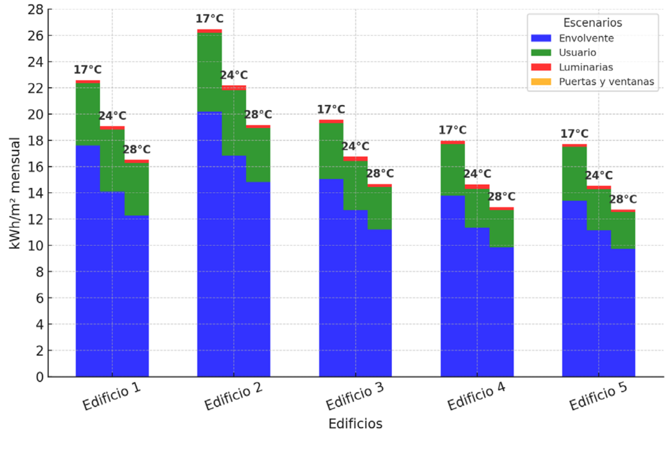


Fig. 8. Monthly Electricity Consumption per unit area (kWh/m²) of cooling "No strategies" according to Scenarios and Thermostat Temperature.

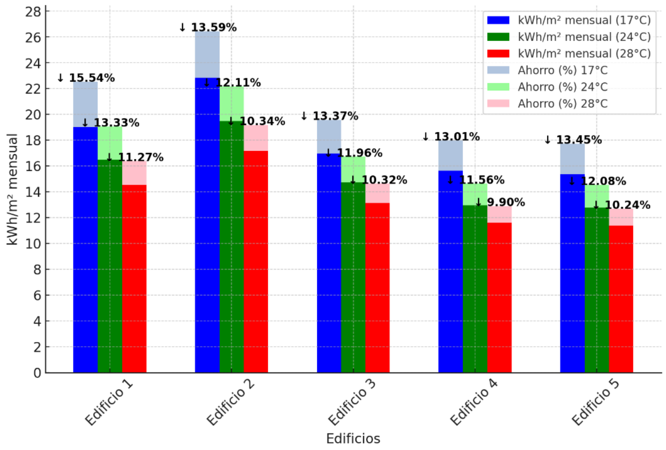


Fig. 9. Monthly Electricity Consumption per unit area (kWh/m²) of cooling "With strategies" according to Scenarios and Thermostat Temperature.

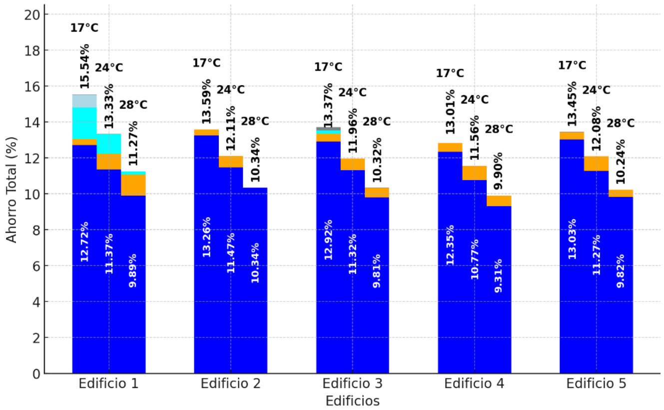


Fig. 10. Monthly Electricity Consumption per unit area (kWh/m²) of cooling "With strategies" according to Scenarios and Thermostat Temperature. Own elaboration.

Below is a graph illustrating Scenario 5, in which the savings in the electrical consumption of air conditioning by refrigeration are quantified, with implemented strategies. The light-colored bars represent the reduction in consumption attributed to these strategies. The analysis considers three thermostat temperatures: 17°C, 24°C and 28°C.

The results show that electricity consumption is less than 28°C, but the reduction is more significant when the thermostat operates at 17°C. The variation in savings between buildings is minimal: at 17°C, it ranges between 15.54% and 13.01%; at 24°C, between 13.33% and 12.08%; and at 28°C, between 11.27% and 9.90% (Fig. 9).

The light-colored bars presented in Graph 4, identifying the impact of each strategy on electricity consumption. The influence of thermal insulation, the reduction of ventilation and lighting schedules during breaks, and the efficiency of the air conditioning system are analyzed. The impact of thermal insulation is limited and ineffective at all operating temperatures and buildings. However, its greatest benefit is recorded at 17°C, reaching a maximum saving of 1.75% in walls, followed by slabs (0.71%) and, to a lesser extent, double-glazed windows (0.03%). In buildings 1, 4 and 5, excess insulation combined with temperatures of 24°C and 28°C led to a slight increase in electricity consumption. Finally, the efficiency of air conditioners represents the greatest impact in reducing electricity consumption, reaching savings values of up to 13.26% at 17°C (Fig. 10).

To compare the electrical consumption of refrigerated air conditioning according to the operating temperature, 28°C was established as a reference (100%), since it was the temperature with the lowest electricity consumption in the buildings analyzed. From this reference, the relative proportions of electricity consumption at 17°C and 24°C were calculated, obtaining increases of 33.0% and 13.3%, respectively. To facilitate the interpretation of this relationship, a bar graph was generated that illustrates the impact of electricity consumption as a function of operating temperature, allowing to visualize the increase in consumption when the thermostat is adjusted below 28°C (Fig. 11).

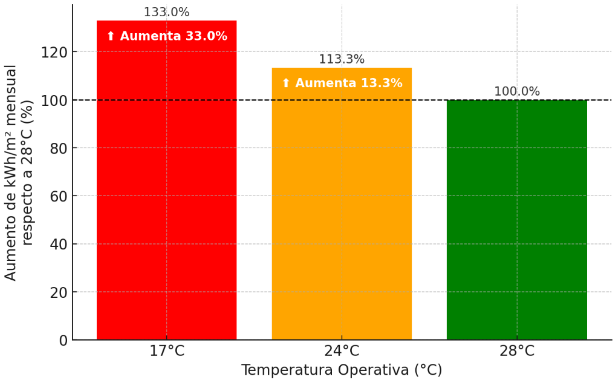


Fig. 11. Comparison of the electrical consumption of refrigerated air conditioning as a function of operating temperature. Own elaboration.

VII. DISCUSSION

A. *Validation of simulations*

The coefficients of determination (R^2 between 0.84 and 0.88) indicate that, in general terms, the simulated model is representative of the real conditions of the site. However, occasional discrepancies have been observed: the buildings that have lower electricity consumption in the simulation do not necessarily coincide with those that register the lowest temperatures in the measurements. These differences are due, in part, to the way in which different thermal phenomena are captured and modelled.

Thermographic monitoring of exterior surfaces measures the temperature of the surface layer of the walls, which is strongly influenced by immediate environmental factors, such as direct solar radiation, convection with the surrounding air and local wind variability. This can cause some facades to show high surface temperatures, without fully reflecting the overall thermal behaviour of the building. On the other hand, the energy simulation carried out in OpenStudio integrates the entire thermal envelope, jointly considering the conduction, convection and radiation processes, as well as the heat dynamics as a function of thermal mass and insulation. This comprehensive approach allows for a more complete model of heat transfer to the interior, which explains the differences in the optimal consumption order with respect to the measured surface temperatures.

In the interior measurements carried out during December, it was evident that, in winter, buildings with higher thermal mass tend to have higher internal temperatures. This is because, under conditions of low external thermal load and limited thermal amplitude, a high thermal mass leads to greater absorption and retention of heat, which is slowly released. In contrast, during the summer, the high thermal amplitude, in combination with the thermal mass, acts as a buffer allowing the building to absorb heat during the hours of maximum solar radiation, delaying its transfer inside. It is essential to highlight that the effectiveness of thermal mass depends on having a high thermal amplitude.

B. Electrical consumption of refrigerated air conditioning

Based on the results obtained on the monthly electricity consumption per unit area of refrigeration air conditioning systems in August, the following discussion arises.

The higher electricity consumption of refrigerated air conditioning is attributed to the building envelope, which shows the influence of construction and architectural design on thermal performance. The original CAPFCE-type buildings were designed for a temperate climate, which has resulted in the loss of passive design strategies in dry hot climate environments. Consequently, its thermal envelope is not optimal for minimizing the thermal load under these conditions.

In addition to the impact of the envelope, electricity consumption is also influenced by the thermal load generated by the occupants, including factors such as occupancy and metabolic activity, which generate an internal thermal gain that increases the demand for cooling. On the other hand, the use of luminaires has a lower impact compared to the envelope and the thermal load of the users, due to the efficiency of the lighting systems and their lower contribution to the thermal gain in the buildings analyzed.

Likewise, it was identified that the methodology used in OpenStudio may have limitations to accurately simulate the electricity consumption associated with the opening of doors and windows in periods of high temperatures. Heat transfer by infiltrations is not always accurately represented, which may underestimate the influence of these variables on the building's electricity consumption.

Fig. 12. Building 4 and 5. Own photos, 2025.

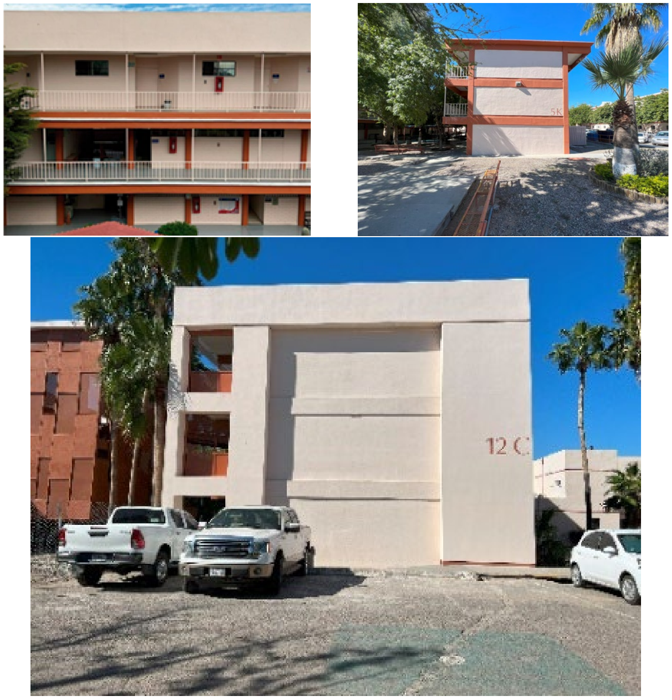


Fig. 13. Building 3, 1 and 2. Own photos, 2025.

A relevant aspect is the relationship between the temperature of the thermostat and the effectiveness of strategies to reduce electricity consumption. It was observed that the greatest savings are obtained when the thermostat is set to 17°C, since at lower temperatures the cooling system has a higher base consumption, which allows strategies such as equipment efficiency to generate a more significant reduction in consumption. In contrast, when the system operates at higher temperatures (24°C and 28°C), the initial consumption is already lower, which limits the relative impact of savings strategies.

When comparing the monthly electricity consumption per unit area of the refrigerated air conditioning systems, it was identified that Building 5 has the lowest consumption, followed by Building 4 and, subsequently, Buildings 3, 1 and 2. This behaviour is due to the fact that Building 5 has an optimised envelope with a combination of thermal insulation and 40 cm thick slabs with high thermal inertia, which contributes to reducing heat transfer.

Building 4, although it does not have insulation in walls, has a lower consumption compared to other buildings due to the same reason mentioned above: its 40 cm thick mezzanine slab, which reduces thermal gain. In addition, the presence of a third level built with light and insulating materials protects the lower classrooms from solar radiation, improving their thermal performance (Fig. 12).

Building 3, with exterior drywall walls and extruded polystyrene insulation, has an intermediate consumption compared to the other buildings. This indicates that the combination of lightweight and insulating materials contributes to reducing the thermal load. However, its consumption is higher than that of Buildings 4 and 5 due to its lower thermal inertia, since its light walls do not store or release heat efficiently, which generates a greater dependence on the cooling system to maintain a stable temperature, increasing electricity consumption.

Building 1, despite not having thermal insulation in walls and having thin slabs of 15 cm, does not have the highest consumption. This is due to the presence of dense vegetation on its south façade, where leafy trees cover a large part of the surface and generate effective shade. In addition, its adjoining other buildings on the west façade reduces direct exposure to solar radiation, contributing to greater thermal stability.

Building 2, despite its remodeling with isolated walls, improved enclosures and shading elements, presents the highest electricity consumption, which suggests that these strategies have not achieved the expected impact. In contrast, buildings with less insulation, but favored by dense vegetation, boundaries and urban context, registered lower consumption, which indicates that these passive strategies may be more effective if the interventions in the envelope do not fully fulfill their function (Fig. 13).

The analysis of strategies to reduce the electricity

TABLE V
ELECTRIC CONSUMPTION

Building	17°C	24°C	28°C
1	22.54 kWh/m²	19.05 kWh/m²	16.37 kWh/m²
2	26.45 kWh/m²	22.17 kWh/m²	19.17 kWh/m²
3	19.57 kWh/m²	16.73 kWh/m²	14.64 kWh/m²
4	17.97 kWh/m²	14.64 kWh/m²	12.89 kWh/m²
5	17.73 kWh/m²	14.53 kWh/m²	12.68 kWh/m²

consumption of refrigerated air conditioning shows that its effectiveness varies according to the architectural and thermal configuration of each building. However, the differences are not highly contrasting or conclusive. In buildings with higher consumption, the application of reduction strategies is more effective, while in those with lower demand, their impact is more limited due to less room for improvement.

The implementation of thermal insulation contributes to the reduction of consumption, although in some cases, an excess of insulation combined with higher thermostat temperatures can generate a slight increase in consumption. This occurs because a highly insulated envelope reduces internal heat dissipation, making it difficult to lower the temperature without an additional cooling system.

It is highlighted that improving the efficiency of air conditioning systems and proper management of the thermostat temperature are among the most effective strategies to reduce electricity consumption.

To contextualize the results, we searched for studies on monthly electricity consumption per unit of cooling area in schools located in hot dry climates. However, the available information is mainly based on annual averages without reflecting seasonal variations, and does not focus on educational buildings in general, nor on those with a specific typology, such as CAPFCEs, nor do they include usage patterns.

The results obtained in this study during August show that electricity consumption varies according to the temperature of the thermostat and the characteristics of the building (Table V).

VIII. CONCLUSIONS

In this research, the monthly electricity consumption per unit of area cooled by air conditioning was calculated in CAPFCE type educational buildings, located in an extremely hot dry climate, such as that of Hermosillo. This consumption was optimized through isolation strategies and adjustments in usage patterns. The results indicate that the thermal envelope is the main factor that increases consumption, followed by the internal load generated by the occupants and the management of temperature through thermostats. This underscores the importance of designing buildings with appropriate architectural criteria and efficiently managing the use of equipment.

The study constitutes a relevant contribution to literature, since no previous research has been found that specifically addresses the electricity consumption in CAPFCE buildings in hot-dry climates or their usage patterns. The findings provide a basis for developing strategies aimed at optimizing air conditioning consumption and highlight the need to adapt building design to local climatic conditions, rather than replicating models for temperate climates.

Likewise, the importance of developing precise methodologies for the simulation of electricity consumption in extreme climates is highlighted, considering determining variables such as air infiltration. Finally, this research opens the possibility of exploring future lines of study that incorporate deep architectural modifications such as the modeling of shading elements, the integration of vegetation and cost-benefit analysis, to achieve greater electrical efficiency in this type of buildings.

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