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ASSESSMENT OF THE REGULATORY AND CONSTRUCTION FRAMEWORK FOR ROOFS IN HOUSES IN SAN FRANCISCO DE CAMPECHE: IMPLICATIONS FOR THERMAL, ENERGY, AND ENVIRONMENTAL PERFORMANCE

ANÁLISIS DEL MARCO NORMATIVO Y CONSTRUCTIVO DE TECHOS EN VIVIENDAS DE SAN FRANCISCO DE CAMPECHE: IMPLICACIONES EN EL DESEMPEÑO TÉRMICO, ENERGÉTICO Y AMBIENTAL

ANÁLISE DO QUADRO NORMATIVO E CONSTRUTIVO DOS TELHADOS EM HABITAÇÕES DE SAN FRANCISCO DE CAMPECHE: IMPLICAÇÕES NO DESEMPENHO TÉRMICO, ENERGÉTICO E AMBIENTAL

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ABSTRACT

The thermal, energy, and environmental impacts of roof construction in social housing in San Francisco de Campeche, located on the Yucatan Peninsula, Mexico, were analyzed. A housing model was calibrated using temperature and relative humidity measurements collected over one year, which was then used to evaluate scenarios not covered by national regulations, varying ceiling height, and considering four roofing configurations based on passive technologies, including the widely used terracotta cladding. Results show that exceeding the heights established in the regulations improves thermal performance and energy savings. While the terracotta cladding increases energy consumption and emissions, reflective waterproofing optimizes comfort and reduces environmental impact. It is noted that the use of thermal insulation does not outperform the cladding, contrary to expectations set by national regulations, emphasizing the urgency of updating regulations to incorporate strategies adapted to the regional climatic context.

Keywords
mexican regulations, hot-humid climate, energy efficiency, urban heat island

RESUMEN

Se analizó el impacto térmico, energético y ambiental de la estructura constructiva en techos de viviendas sociales en San Francisco de Campeche, ubicado en la Península de Yucatán, México. Se calibró un modelo de vivienda con mediciones de temperatura y humedad relativa durante un año, que se usó para evaluar escenarios no contemplados en las normativas nacionales. Este modelo varió la altura del techo y consideró cuatro configuraciones de cubierta basadas en tecnologías pasivas, e incluyó el recubrimiento terracota, muy arraigado en la población. Los resultados muestran que superar las alturas establecidas en los reglamentos mejora el desempeño térmico y ahorro energético. Mientras que el recubrimiento en terracota incrementa el consumo y las emisiones, los impermeabilizantes reflectivos optimizan el confort y disminuyen el impacto ambiental. Se destaca que el uso de aislantes térmicos no supera en desempeño a los recubrimientos, contrariamente a lo esperado por la normativa nacional. Se subraya la urgencia de actualizar los reglamentos para incorporar estrategias que se adapten al contexto climático regional.

Palabras clave
normativa mexicana, clima cálido-húmedo, eficiencia energética, isla de calor urbano

RESUMO

Foi analisado o impacto térmico, energético e ambiental da estrutura construtiva em telhados de habitações sociais em San Francisco de Campeche, localizado na Península de Yucatán, México. Foi calibrado um modelo de habitação com medições de temperatura e de umidade relativa ao longo de um ano, que foi utilizado para avaliar cenários não contemplados nas normas nacionais. Este modelo variou a altura do telhado e considerou quatro configurações de cobertura baseadas em tecnologias passivas, incluindo o revestimento de terracota, muito arraigado entre a população. Os resultados mostram que superar as alturas estabelecidas nos regulamentos melhora o desempenho térmico e a economia de energia. Enquanto o revestimento em terracota aumenta o consumo e as emissões, os impermeabilizantes refletivos otimizam o conforto e reduzem o impacto ambiental. Destaca-se que o uso de isolantes térmicos não supera o desempenho dos revestimentos, o que contraria o esperado pela regulamentação nacional. Ressalta-se a urgência de atualizar os regulamentos para incorporar estratégias adaptadas ao contexto climático regional.

Palavras-chave
regulamentação mexicana, clima quente-úmido, eficiência energética, ilha de calor urbana

INTRODUCTION

Currently, more than 50% of energy consumption in homes worldwide is used to meet occupants' thermal comfort needs, which are directly influenced by regional environmental conditions. In this context, it is expected that climate change and its effects on the environment will increase the energy demand of buildings, leading to energy efficiency and adaptation strategies in the face of these changes (Manzano-Agugliaro et al., 2015). This situation intensifies in countries with hot or tropical climates, such as Mexico, where the high temperatures, which prevail throughout the year, significantly increase the demand for electricity to achieve conditions of thermal well-being (Gamero-Salinas et al., 2021).

In Mexico, the regulation for thermal envelopes pays particular attention to roofs, since flat masonry roofs predominate in the country and, in hot-humid climates, they can contribute more than 60% of the daily thermal gains in homes. The NMX-C-460-ONNCCE-2007 (Organismo Nacional de Normalización y Certificación de la Construcción y Edificación, 2009), which establishes the requirements for thermal resistance in building roofs according to the type of climate; the NOM-020-JAN-2011 (Secretaría de Energía, 2011), which presents constructive criteria for the envelope's design and air conditioning systems; and the Building Code (Secretaría de Desarrollo Agrario, Territorial y Urbano [SEDATU], & Comisión Nacional de Vivienda [CONAVI], 2017), which determines the minimum height of dwellings, stand out. However, in practice, their implementation is complex because local building codes take precedence over national regulations. Even so, several authors have evaluated their impact from different approaches in different climatic regions of the country. Castro-Bello et al. (2024) reviewed the national strategies and incentives for the residential sector, which identify that, since they came into force, energy consumption in housing has gradually reduced. Galindo-Borbón et al. (2024) analyzed the impact of NOM-020-JAN-2011 for the north of the country (hot-dry climate). It was found that, by applying the orientation and envelope strategy, energy consumption is reduced by up to 26% and CO_2 emissions by more than 15%. Vázquez-Torres et al. (2022) identified that compliance with the NMX-C-460-ONNCCE-2007 in the temperate climate conditions of the center of the country significantly contributes to energy savings and thermal comfort. In the same way, these standards have been used to evaluate the viability of new proposals and materials for social housing (Guillén Guillén & Muciño Vélez, 2020; Ruiz Torres, 2019). However, studies such as that of Martin-Dominguez (2018) emphasize that the regulations focus only on the thermo-physical properties, leaving aside the optical phenomena that develop in the envelope due to the cladding effect, which could contribute even more than simply using thermal insulators. These are vital for regions with a prevailing hot-humid climate in the south of the country, as has been demonstrated by Vargas (2021).

San Francisco de Campeche is a relevant case in this context due to its population growth and distribution. Dwellings are characterized by being either self-built or from national agency housing programs, and they use thermally inefficient materials. More than 45% of homes have shortcomings associated with both material quality and overcrowding (Comisión Nacional de Vivienda [CONVI], 2022). The population of San Francisco de Campeche has also grown by more than 25%, due to an unplanned urbanization that has transformed green areas into housing complexes (Canul-Turriza et al., 2024). This has caused the region's temperature to increase by more than 6 °C, increasing the energy demand in homes. Hence, it is imperative to analyze strategies that promote thermal comfort and energy efficiency in homes, thus improving the quality of life for the population.

In this context, this study proposes to analyze the roofs of dwellings when implementing passive strategies, with two main objectives: (i) determining the technical relevance of the NMX-X-460-ONNCCE-2009 standard (Organismo Nacional de Normalización y Certificación de la Construcción y Edificación, 2009) against the local construction and climatic conditions, in particular regarding building height; (ii) evaluating, from a thermal and energy perspective, the insulation materials established by NOM-020-JAN-2011 (Secretaría de Energía, 2011), considering that this standard does not contemplate the use of reflective cladding on roofs. In the first phase, information was collected on the construction and materials of a standard social housing unit in the region, as well as on the installation of sensors to record indoor humidity and temperature for a year, along with the city's meteorological data. This information was used to calibrate an energy model for the dwelling and to compare three slab modifications against the base case by varying the roof height. This is to contrast passive cooling strategies with the habits in materials commonly used by people or under national regulations. The second phase consisted of preparing a computational model using the EnergyPlus package. This model was calibrated with data from the first phase and used to evaluate and compare the building's thermal and energy performance against modifications to the slab

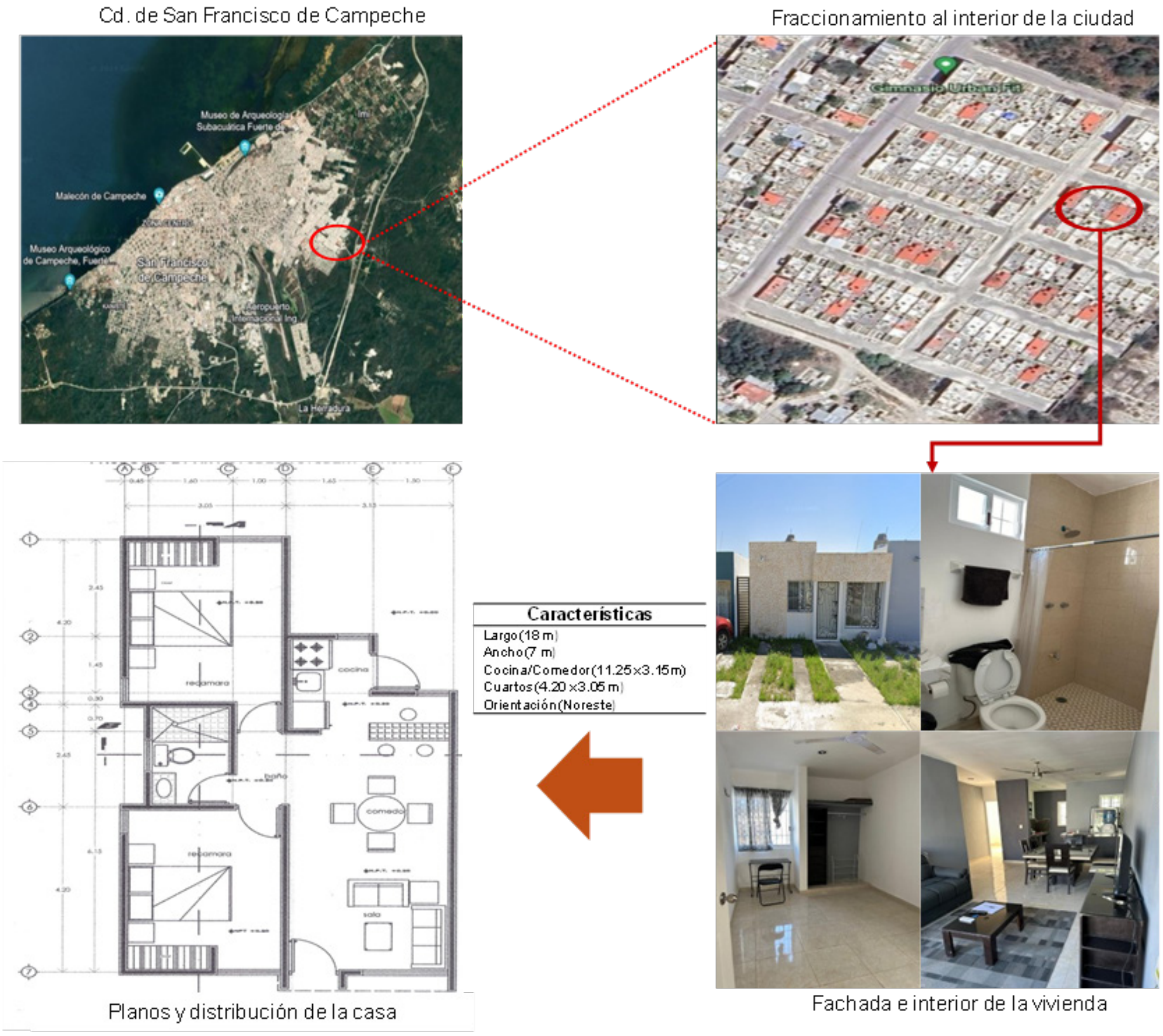

Figure 1. Aerial view, facades, interiors, and floor plans of the case study. Source: Prepared by the authors.

structure, including the use of insulating materials and cladding, as well as variations in the house's height. The results allowed identifying the impact of the modifications to the roof slab on the dwelling's thermal, energy, and environmental performance. In particular, the hours of comfort, cooling demand, and electrical consumption associated with the air conditioning (A/C) equipment were determined. Similarly, the environmental impact was evaluated at the scale of the residential complex in terms of CO_2 equivalent emissions and their influence on the formation of Urban Heat Islands (UHI).

METHODOLOGY

DESCRIPTION OF THE LOCATION AND DWELLINGS UNDER STUDY

The study focuses on the upper envelope of a social housing model located in San Francisco de Campeche (19°50'N, 90°28'E), a coastal city and capital of the Mexican state of Campeche. The city has a hot-humid climate with an average annual temperature of 30°C (with highs exceeding 40°C in summer) and a relative humidity above 75% most of the year. The annual rainfall varies between 1,200 and 2,000mm (Instituto Nacional de Estadística y Geografía [INEGI], 2024). In this context, a house was analyzed in a recently created neighborhood comprising 120 houses, located on the periphery of the city (Figure 1). It was selected because it had no subsequent structural modifications.

The house has a built area of 64 m^2, a height of 2.60 m, and a south-facing facade. It consists of two bedrooms, a living room, a dining room, a kitchen, and a bathroom. It has 17.0 cm-thick walls, made from 15 cm x 20 cm x 40 cm concrete blocks, with a 1.0 cm exterior mortar coating and an interior plaster layer. The roof, from exterior to interior, consists of a 5.0 cm layer of cast calcrete, a 16.0 cm vaulted beam, a 2.5 cm layer of expanded polyurethane (EPU) foam, and a final plaster coating. The physical properties of the materials are listed in Table 1.

Table 1. Thermal properties of envelope materials in social housing. Source: Data obtained from (American Society of Heating, Refrigerating and Air-Conditioning Engineers, 1979).

Envelope		**Specifications**			
Envelope element	Material	Thickness (m)	Conductivity (W/m K)	Specific heat (J/kg K)	Density (kg/m^3)
Walls	Whitewash	0.015	0.720	840.00	185.00
	20 cm block	0.200	0.490	880.00	512.00
	Plaster	0.015	0.380	1090.00	1120.00
Ceiling	Calcrete	0.050	1.740	920.00	2300.00
	Vaulted beam	0.160	1.580	1000.00	600.00
	EPU Insulation	0.068	0.035	1400.00	25.00
	Plaster	0.015	0.380	1090.00	1120.00

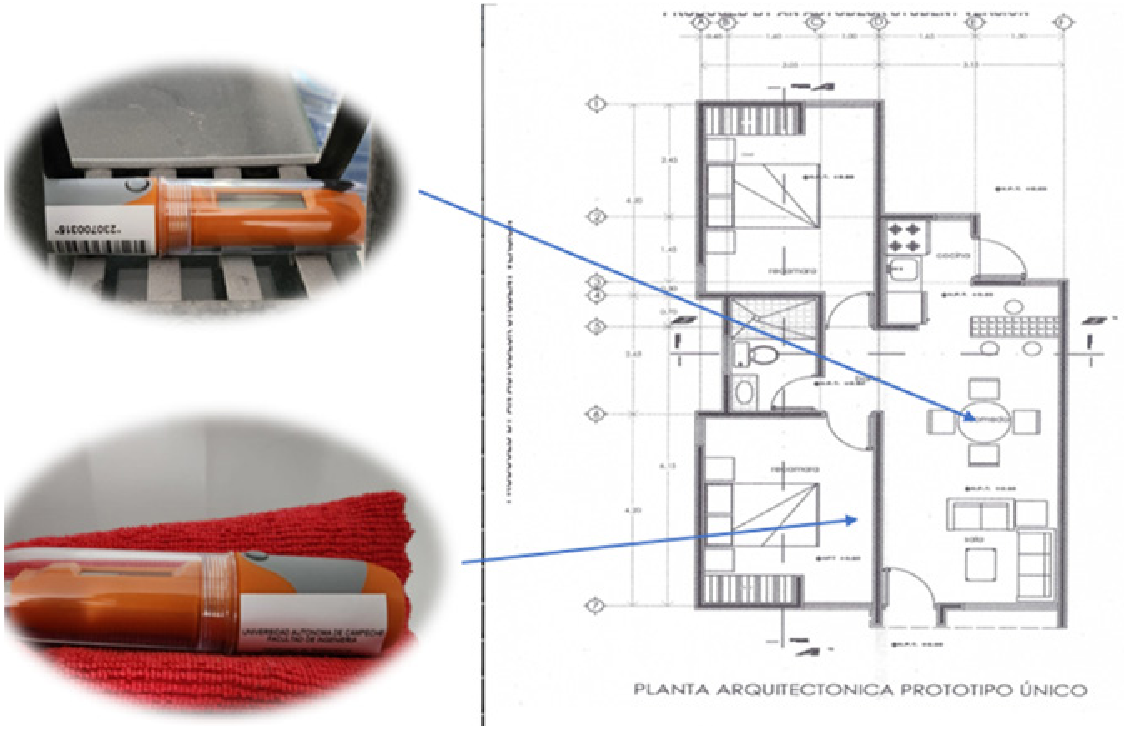

Figure 2. Location of the datalogger inside the dwelling. Source: Prepared by the authors

CALIBRATION OF THE HOUSING MODEL

Experimental temperature and relative humidity data were collected inside the dwelling using RC-51H model Dataloggers, with an accuracy of ±0.5 °C and ±3% RH; operating ranges from -20 °C to 40 °C and 10 % RH to 90 % RH (Haupt et al., 2025). The data loggers were installed in the living-dining room and the main bedroom (Figure 2), since these are the spaces where users spend the most time. The measuring devices were programmed to collect information in 60-minute intervals over 14 months, from July 25th, 2023, to September 30th, 2024. This period was chosen, together with the dwelling's occupants, based on the logistical facilities for the installation, verification, and continuous review of the equipment's operation. As for the environmental variables that influence the dwelling's thermal behavior (relative humidity, temperature, irradiance, atmospheric pressure, and wind speed and direction), climatological data generated by the METEONORM 8 software were used, corresponding to the coordinates of San Francisco de Campeche for 2023 and 2024. The selection of this dataset was made considering the experimental sampling period, which covered both years. A climate file representative of the indoor measurement period was generated with this information and used to calibrate the computational model. Subsequently, the thermal and energy analyses were carried out using the 2024 climate file. Finally, the operational profile of the energy equipment, as well as the use of natural and mechanical ventilation systems, was determined through a survey applied to the owner. All the information was input into the DesignBuilder software to build the dwelling's model.

The computational model was validated using the statistical indicators proposed by the ASHRAE standard in the field of computational models in buildings, considering the Mean Bias Error (MBE) (Equation 1) and Coefficient of Variation of the Root Mean Square Error (CV RMSE) (Equation 2), comparing the experimentally collected data with the simulated data (Corrado & Fabrizio, 2019; Cui et al., 2022):

$$MBE = \frac{\Sigma_{i=1}^{N_P}(m_i - s_i)}{\Sigma_{i=1}^{N_P}(m_i)} \qquad \text{(Equation 1)}$$

$$CV(RMSE) = \frac{\sqrt{\Sigma_{i=1}^{N_P}(m_i - s_i)^2/Np}}{\Sigma_{i=1}^{n_P} m_i/Np} \qquad \text{(Equation 2)}$$

Where m_i and s_i represent the measured and simulated data, respectively, and Np is the number of measurements analyzed. The acceptable range for MBE on hourly data is up to 10%, and for CV (RMSE) is 30%. Table 2 shows the calibration results, with temperature and relative humidity kept within acceptable limits, validating the thermal representation of the dwelling.

Table 2. Validation parameters of the dwelling according to statistical calibration indicators. Source: Prepared by the authors.

Parameter	MBE(%)	CV(RMSE)(%)
Room temperature	0.10	4.31
Relative humidity	7.60	11.92

MODIFICATION PROPOSAL FOR THE UPPER ENVELOPE

The variation in roof height from 2.60 to 3.40 m, in 10 cm increments, was analyzed to evaluate the thermal impact. In parallel, four roof construction scenarios were defined to examine the most widely used reflective cladding technologies in the southeastern region of Mexico. The simulated scenarios were Case A: conventional dwelling roof structure (referred to as the base case) formed from outside to inside by a layer of calcrete, vaulted beam, EPU and plaster; Case B: formed from outside to inside by a layer of terracotta cladding, calcrete, vaulted beam, EPU and plaster (Case A, placing terracotta cladding on the outside); Case B: formed from outside to inside by a layer of white reflective paint (*cool-roof*), calcrete, vaulted beam, and plaster (the EPU thermal insulation is eliminated); and Case D: formed from outside to inside by a cool-roof layer of cladding, calcrete, vaulted beam, EPU and plaster (Case A, a white reflective cladding is placed). Figure 3 shows the construction systems considered, and Table 3 presents the optical properties of the materials used. In particular, the white reflective cladding (cool-roof) analyzed is a widely available commercial product in Mexico, available in all municipalities of the country. This facilitates its access and reproducibility in other studies or construction projects. This cladding has ENERGY STAR certification, which guarantees its reflective performance and durability. According to the supplier's technical datasheet, its estimated useful life is up to 5 years, one of the highest reported for commercially available reflective cladding in the country. Regarding the terracotta cladding, this is also a product from the same supplier and has quality certifications under current Mexican regulations,

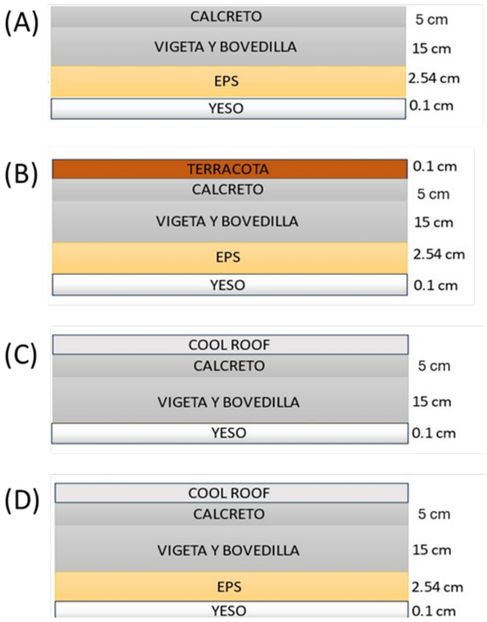

Figure 3. Constructive scenarios of roofs for thermal evaluation: Case A (base), Case B (terracotta), Case C (cool-roof without EPU), and Case D (conventional cool-roof). Source: Prepared by the authors.

Table 3. Optical cladding properties used in the study. Source: Data obtained from Hernández-Pérez et al. (2014).

Envelope	Material	Emissivity (-)	Absorbance (-)	Reflectance (-)
Roof	Calcrete	0.87	0.67	0.33
	Terracota	0.78	0.16	0.84
	Cool-roof	0.90	0.67	0.30

guaranteeing its chromatic stability and performance as a waterproofing material (Hernández-Pérez et al., 2018).

CALCULATION OF INDICATORS

Thermal indicator

Cooling degree hours (CDH) were used as a metric to quantify the amount of cooling required to maintain a target temperature (T_T) in the dwelling over a given period. The CDH was calculated (Equation 3) considering T_T = 25 °C, where T_a is the room temperature, z is the total hours per year, and the apostrophes (+, h) refer to the cumulative positive and hours, respectively (May-Tzuc et al., 2023):

$$CDH = \Sigma_{h=1}^{z} \left(T_a - T_T\right)_j^+$$

(Equation 3)

The percentage of hours of comfort (HC) within the house was calculated in the same way using Equation 4.

$$HC = \frac{100 \sum_i^z h_i}{8760} \times 100$$

(Equation 4)

ENERGY INDICATOR

The energy used by the air conditioning system to cool the indoor space (E_e) was calculated using Equation 5. In this expression, the COP is the equipment's performance coefficient, while represents the sum of all the thermal loads acting on the house during the analysis period. These loads include heat transfer effects by transmission, ventilation, infiltration, internal gains, solar radiation, and energy losses (Szokolay, 2014). For the case study, an intermediate-performance air conditioning system was considered, with a COP of 2.8 and a capacity of 12,000 BTU/h, because it is the standard equipment installed in homes in the southeast of Mexico (Jiménez Torres et al., 2024).

$$E_e = \sum_{t=1}^{z} Q_{fria}(t)\Delta t / COP$$

(Equation 5)

ENVIRONMENTAL INDICATOR

Equation 6 presents the mitigation of CO_2-equivalent emissions derived from the electricity consumed per A/C unit to reach the target temperature, where E_B represents the electricity consumption of the standard dwelling, E_S is the simulated consumption, and FE is the emission factor. For Mexico, this is reported by the Secretary of the Environment, using the value for 2024 (0.444 tCO_2e/MWh) (Secretaría de Medio Ambiente y Recursos Naturales [SEMARNAT], 2025).

$$CO_2 = FE(E_B - E_S)$$

(Equation 6)

Finally, the effect of A/C on outdoor temperature was rated (ΔT), when estimating the average increase in streets and neighborhood yards due to the heat released by the capacitors, based on an advection-energy balance, in the formation of UHI using the following Equation 7 (Yamamoto et al., 2021):

$$\Delta T = \frac{N \cdot P_{elec}(1 - COP) \cdot 1000}{\rho c_p v A_{ab}}$$

(Equation 7)

Where P_{elec} and N represent the electricity consumed and the number of pieces of equipment when operating in the neighborhood, respectively. For its part ρ, c_ρ and v are the density, specific heat, and velocity of the surrounding air, while A_{ab} is the effective area of air renewal. For the case study, N was considered equal to all the houses of the neighborhood (120 dwellings). Regarding the urban control volume, it had a height of 10m and a neighborhood floor area of 2,300 m^2.

RESULTS AND DISCUSSION

Figure 4 presents the average temperature profile inside the house for a typical day in each month of the year and for the four scenarios analyzed. It is observed that the interval between 18:00 and 06:00 hours (period of greatest activity and permanence of the occupants) concentrates the highest indoor temperatures, regardless of the month considered. A consistent behavior is observed within this time range: Case B, associated with the terracotta cladding, increases the indoor temperature by 1.1-1.5 °C compared to the conventional construction system (Case A). On the contrary, the application of cool-roof cladding that maintains the base configuration (Case D) yields a maximum reduction of approximately 0.5 °C. In contrast, its incorporation, which eliminates the thermal insulation (Case C), reduces the temperature by up to 1.1 °C. These results show that reflective cladding can significantly affect thermal comfort. In particular, replacing a terracotta finish with a cool-roof cladding can result in temperature reductions of up to 2.6 °C, representing considerable potential to improve the passive thermal performance of homes, especially during periods of higher occupancy.

To complement this, the CDHs that determine the need for air conditioning inside the building were analyzed. The higher the CDH, the greater the cooling demand. Figure 5 shows the monthly behavior over a year for the cases studied in the social housing, along with a visual summary of the trends for each month. Accordingly, the months of January and December have the lowest cooling demand, which gradually increases until reaching its maximum in May. In addition, homes with

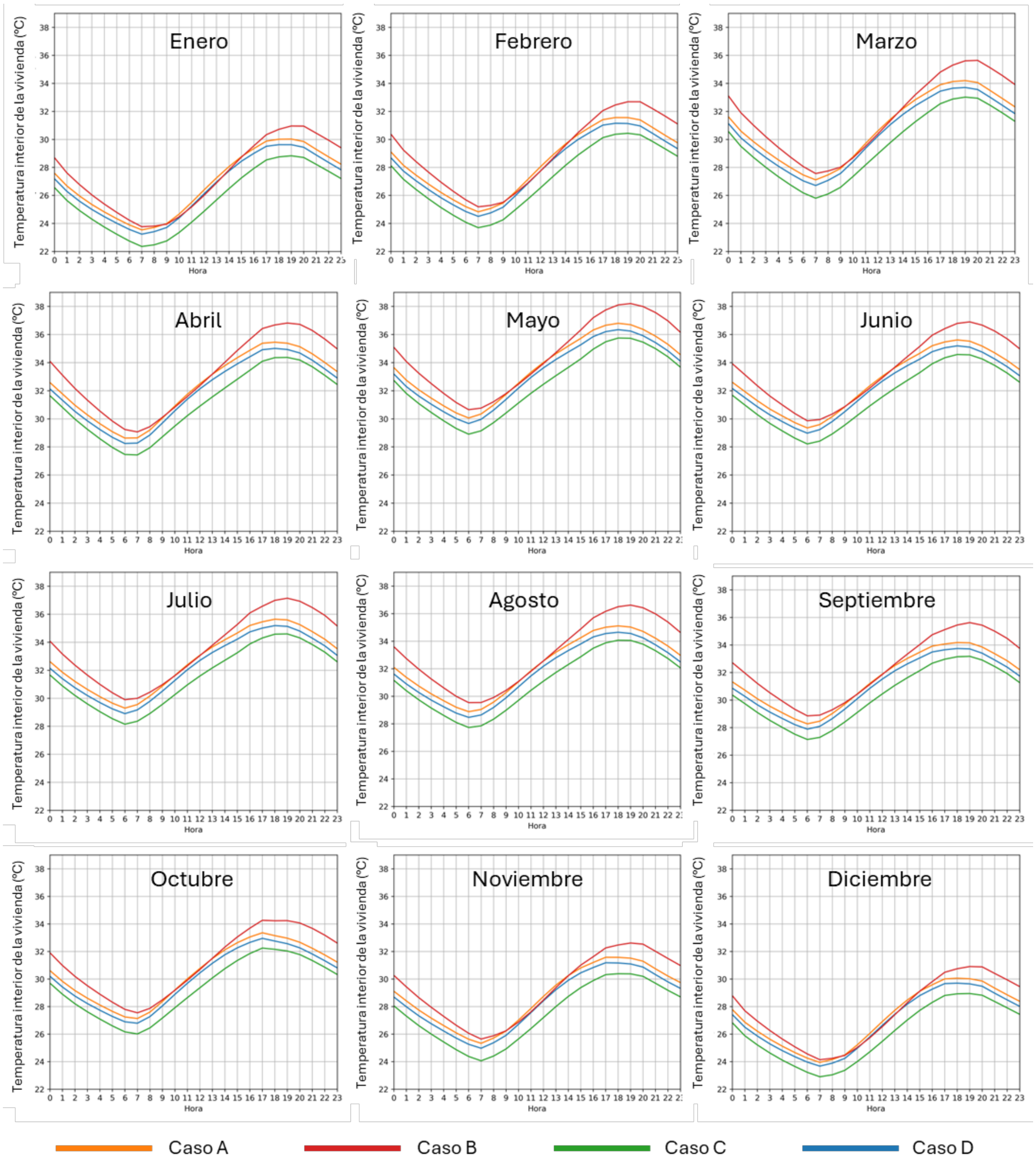

Figure 4. Hourly profile of indoor temperature by month for the four constructive scenarios. Source: Prepared by the authors.

a height of 2.60m exhibit a higher CDH demand than those with a height of 3.40m, which contrasts with the building standard (SEDATU & CONAVI, 2017), which establishes 2.54m as the minimum height to ensure thermal comfort conditions in this type of climate. This is because a higher elevation favors the stratification of the air's thermal gradient, which is not taken into account in the construction of working-class housing in the city. Among the simulations, the terracotta-cladded roof registered the highest cooling demands (hovering between 53,000°C/h and 55,000°C/h annually), due to its optical properties: high absorbance and low transmittance in the infrared spectrum. In contrast, the cool-roof type of waterproofing showed the lowest demand, at close to 40,000°C/h per year, due to its white hue and the composition of materials that favor high solar reflectance and reduce heat absorption.

When analyzing the different technologies implemented on the roof at a height of 3.40m (Table 4), it is observed that conventional housing has a CDH of 52.049 °C/h. In comparison, the use of terracotta

Figure 5. Annual behavior of the CDH for the roof height scenarios and materials used: (a) Case A; (b) Case B; (c) Case C; (d) Case D. Source: Prepared by the authors.

Table 4. Annual percentage of hours of comfort and accumulated CDHs in the four roof cases analyzed in Campeche homes. Source: Prepared by the authors.

Height (m)	Annual percentage of hours of Comfort (%)					Annual CDH (°C/hour)			
	Case A	Case B	Case C	Case D		Case A	Case B	Case C	Case D
2.60	6.68	5.96	11.39	6.68		54,188	40,279	56,461	47,923
2.70	6.88	6.20	11.39	6.89		53,866	40,389	56,068	47,801
2.80	6.96	6.35	11.45	7.08		53,562	40,492	55,698	47,685
2.90	7.11	6.56	11.46	7.26		53,276	40,588	55,348	47,575
3.00	7.28	6.77	11.47	7.41		53,005	40,68	55,018	47,472
3.10	7.48	6.87	11.52	7.52		52,747	40,765	54,705	47,375
3.20	7.57	7.00	11.59	7.65		52,502	40,847	54,408	47,281
3.20	7.68	7.13	11.62	7.77		52,27	40,923	54,125	47,191
3.40	7.82	7.26	11.71	7.89		52,049	40,995	53,856	47,106
Average	**7.27**	**6.68**	**11.51**	**7.35**		**53,052**	**40,662**	**55,076**	**47,49**

waterproofing increases demand by approximately 2,000 °C/h, while Case C reduces it by more than 11,000 °C/h annually. For its part, applying a cool roof to the conventional structure reduces the temperature difference by nearly 5,000°C/h compared to the base case. These results show the remarkable impact of selective cladding on homes in the region, significantly reducing cooling demand, even from the 2.60 m-high stage. This behavior occurs in both cases C and D. However, although EPS insulation helps reduce indoor temperature, its effectiveness is limited under high-temperature, high-humidity conditions. This is because the reflective paint limits heat gain by the roof envelope, while the insulation acts as a barrier that prevents heat transfer from the outside to the inside and vice versa. Therefore, the EPU retains the accumulated heat, maintaining a greater thermal gradient within the space. Thus, strategies that counteract solar radiation are more effective than relying solely on insulating materials.

Table 4 also summarizes the annual behavior of both the comfort hours and the CDHs. The conventional housing model achieves an average of 7% hours of comfort per year. In contrast, the roof with a terracotta cladding has a slightly lower value (6%), representing a 1% reduction in the occupant's thermal well-being attributable to this material. In the case of the cool-roof, the annual comfort exceeds 11%, equivalent to more than 1,000 hours of comfort in the dwelling. On the other hand, the system with thermal insulation has practically the same results as Case A, indicating that its implementation does not significantly improve the thermal sensation of the occupants in the region. This is consistent with the behaviors observed in the test and simulation cells described in the warm-climate areas in both northern and southern Mexico (Villar-Ramos et al., 2022). This shows the effects of implementing centralized regulations that do not consider the climatic context of a country like Mexico.

ENERGY CONSUMPTION ANALYSIS

Figure 6 shows the electricity consumption by the A/C of the proposed cases. January, February, and December were omitted for comparison because the temperatures were below the target value (T_T= 25°C) and coincided with the occupants' operating habits. As in the CDHs, higher roofs are associated with lower energy demand per dwelling. In line with this, and considering that May is the month of the highest electricity demand, the base case (2.6 m high) registers a consumption of 864,247 kWh, while the terracotta-cladding scenario reaches 891,834 kWh, with a difference of nearly 30 kWh. At an annual level and in the best energy performance conditions (height of 3.40m), the base case has a consumption of 5,643kWh, while the terracotta-cladding model registers 5,822 kWh. This shows that increasing the dwelling's height does not yield a significant energy benefit when the roof is waterproofed with terracotta, as the thermal and energy advantages associated with the increase in height are offset. In contrast, the best performance is achieved by the cool-roof cladding (Case C), whose annual consumption ranges from 4,628.00 to 4,534 kWh for the analyzed heights (2.60–3.40 m).

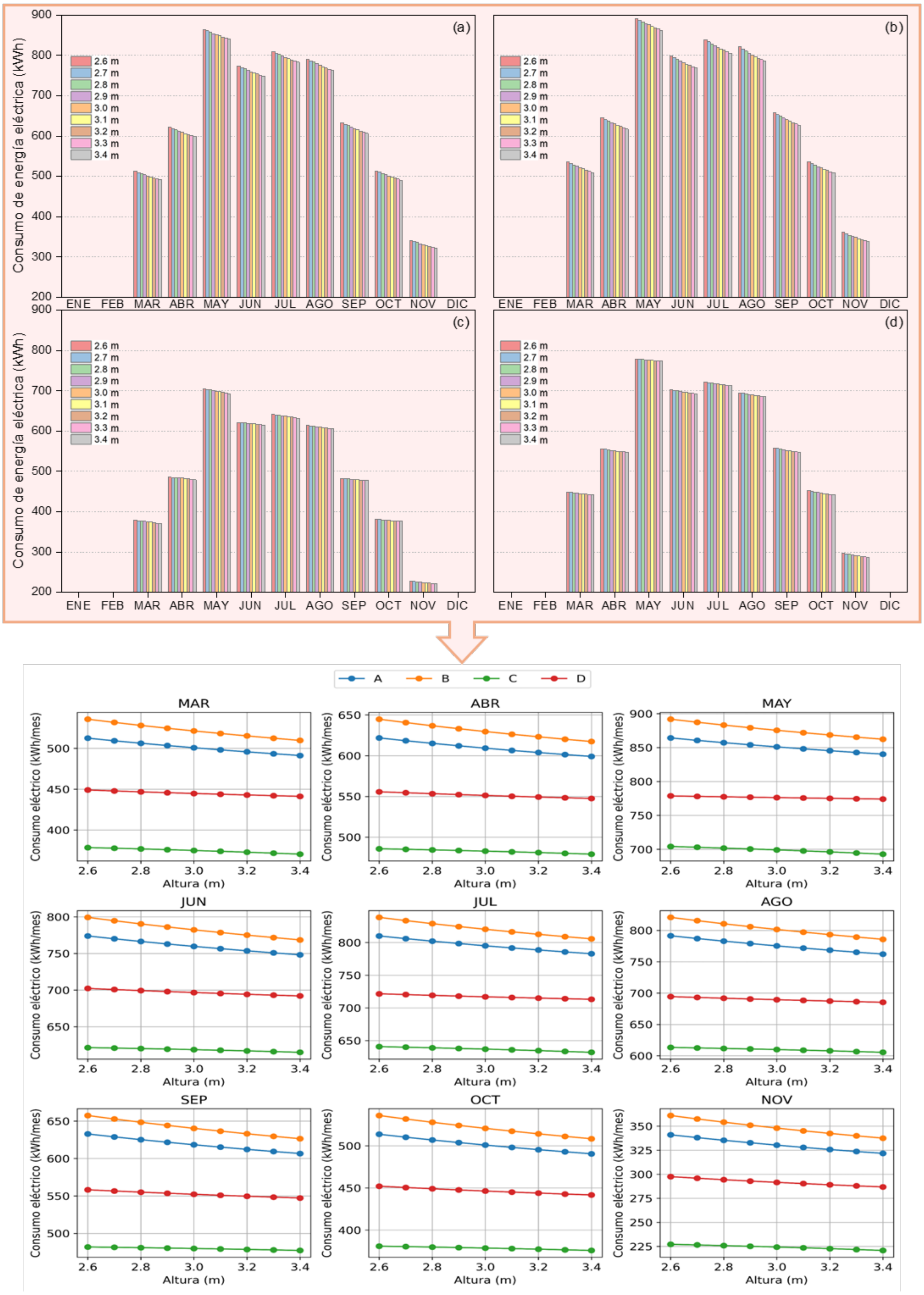

Figure 6. Annual electricity consumption by air conditioning in different scenarios of ceiling height and roofing materials: (a) Case A; (b) Case B; (c) Case C; (d) Case D. Source: Prepared by the Authors.

Table 5. CO2 equivalent mitigation capacity per dwelling based on the integration of bioclimatic strategies. Source: Prepared by the authors.

Height (m)	Mitigation of CO2 by dwelling (kgCO2)				Mitigation of CO2 by neighborhood (TonCO2)				Mitigation of CO2 at 20 years by neighborhood (TonCO2)			
	Case A	Case B	Case C	Case D	Case A	Case B	Case C	Case D	Case A	Case B	Case C	Case D
2.60	-	-97.4	577.5	283.6	-	-12	69	34	-	-234	1386	681
2.70	14.3	-80.2	580.3	288.7	2	-10	70	35	34	-192	1393	693
2.80	27.7	-64.0	583.3	293.7	3	-8	70	35	67	-153	1400	705
2.90	40.5	-48.6	586.5	298.3	5	-6	70	36	97	-117	1408	716
3.00	52.5	-34.0	589.9	302.7	6	-4	71	36	126	-82	1416	727
3.10	64.0	-20.2	593.5	307.0	8	-2	71	37	154	-49	1424	737
3.20	74.9	-7.1	597.3	311.0	9	-1	72	37	180	-17	1434	746
3.20	85.3	5.4	601.4	314.8	10	1	72	38	205	13	1443	756
3.40	95.2	17.3	605.8	318.6	11	2	73	38	228	41	1454	765

ENVIRONMENTAL ANALYSIS

Table 5 shows the impact on annual CO_2-equivalent emissions associated with the four roof construction scenarios at different heights. In all cases, it is clear that the increase in height helps reduce emissions from A/C use. In the conventional roof configuration (Case A), the 80 cm elevation allows for the mitigation of about 95 $kgCO_2$ annually, which, extrapolated to the 120 homes of a typical subdivision, is equivalent to 11 tons avoided per year. The construction scheme under the current regulations shows better results when combined with a reflective coating, achieving a mitigation of 3.5 times that of the conventional structure. However, the best performance is achieved with the reflective cladding (Case C); its simple implementation reduces CO_2 emissions by up to 6 times compared to Case A. In contrast, the En enhances this advantage: the terracotta cladding is the only one with negative values, as it increases emissions due to the greater electrical demand for air conditioning. Only at a height of 3.40 m does terracotta achieve a mitigation capacity comparable to Case A at 2.70 m. Overall, the findings indicate that compliance with current regulations does not necessarily ensure the best environmental solution, since there are alternatives with much more favorable performance. On the other hand, the case of the terracotta cladding shows that a seemingly minor design decision can generate a considerable adverse effect on emissions. This contrast emphasizes the importance of establishing regulatory criteria based on the local climate context, which guarantees not only minimal compliance but a really significant environmental impact.

Figure 7 shows the possible urban impact on the temperature increase generated by A/C operation in a residential complex of 120 houses, considering one representative day for each month, with an average dwelling height of 3.0 m. The results show that, during the warmer months, the simultaneous use of A/C in the confined space of a subdivision can increase the outdoor temperature by more than 1.0 °C throughout the day; while on an annual average, this increase remains above 0.3 °C (Case A). In this scenario, the application of terracotta-colored waterproofing (Case B) causes an additional increase of approximately 3.6% per year in outdoor temperature, which directly contributes to the formation of the urban heat island solely due to inadequate material selection. On the contrary, Cases C and D show a reduction in the increase in temperature with respect to the conventional building. Case C reduces the outdoor temperature by more than 24% in March, October, and November, with an average annual reduction of nearly 22%. Case D, although supported by current national regulations, shows a more minor reduction, ranging from 8.3% to 11.7% per year in the warmest and coolest months, respectively. This indicates that, despite its normative foundation, the energy-environmental impact of Case D is lower than that of Case C, which underscores the need to review and strengthen the legislation to incorporate more efficient criteria for mitigating the urban heat island.

DISCUSSION

The results show that white coating or cladding, especially cool-roof systems, provide energy savings of more than 30% compared to the configuration

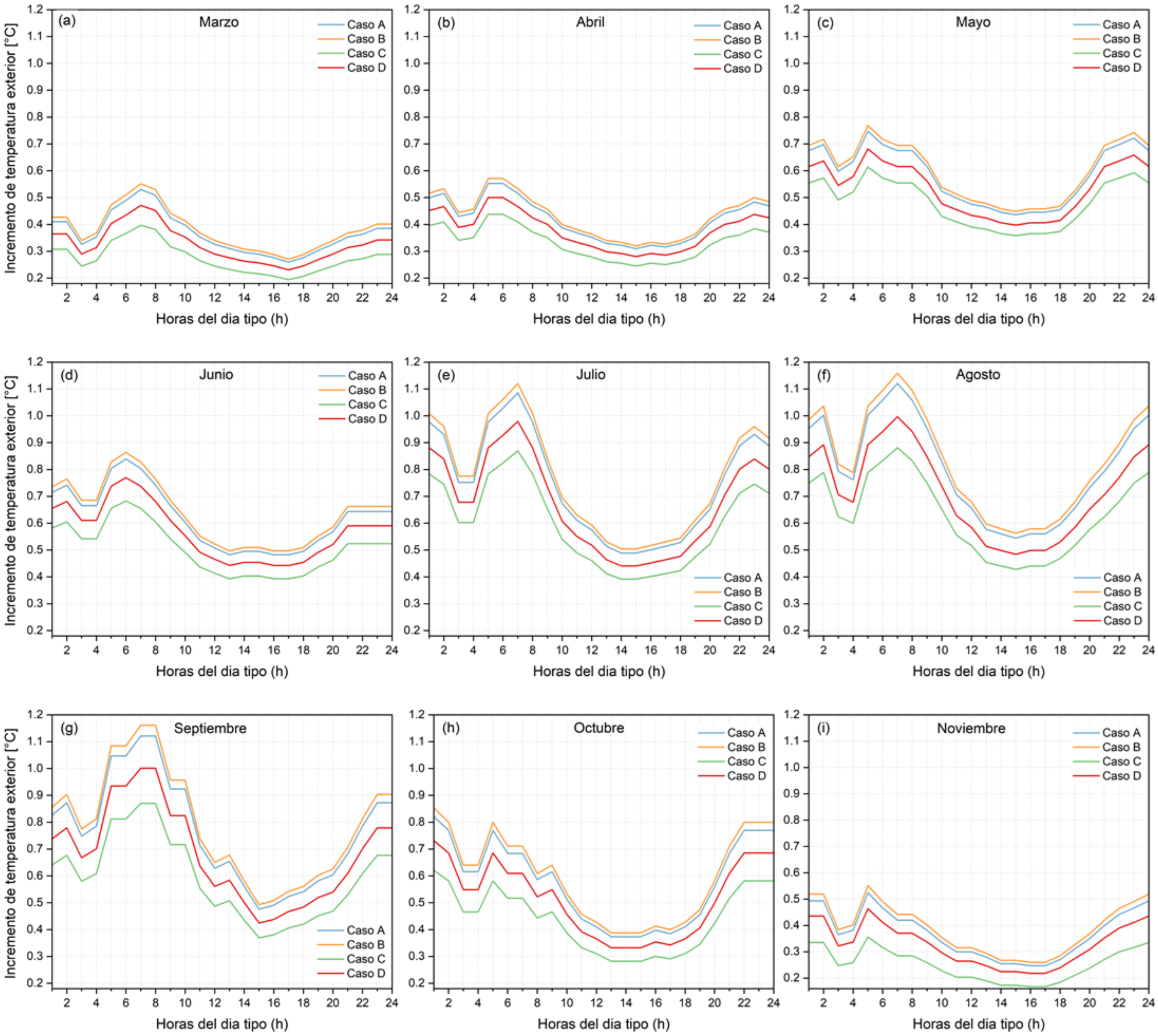

Figure 7. Effect of outdoor temperature on urban heat island formation in a Campeche neighborhood, considering a complex of 120 houses. Source: Prepared by the authors.

established by NOM-020-ENER-2011. In addition, this strategy prolongs the thermal comfort conditions in hot and humid climates, confirming its effectiveness. In contrast, the use of terracotta-toned cladding resulted in a higher energy demand than projected for conventional buildings. This is especially relevant in contexts such as the city of Campeche, where this material is massively applied in residential and public buildings (Figure 8). This phenomenology is due to two main factors: the cultural roots of Mediterranean strategies, which incorporate decorative elements such as latticework, and the obligation to use waterproofing to prevent moisture and infiltration. Consequently, families and public organizations opt for red-toned cladding to reduce initial investment costs. However, this decision increases the building's internal temperature, leading to higher cooling demands, higher electricity costs, greater discomfort, and environmental impacts that undermine the building's sustainability.

The phenomena found are of great interest from a multidimensional perspective. On the one hand, they reflect that national regulations have begun to take an appropriate course by promoting the use of insulating materials in the building envelope, thereby reducing energy consumption and lowering UHIs. However, they also show that, in hot and humid regions, insulators can cause thermal accumulation inside the house. This phenomenon occurs because the insulation acts as a barrier that restricts heat transfer to the outside,

Figure 8. Current state of materials used in the upper envelope of housing in San Francisco de Campeche. Source: Prepared by the authors.

prolonging the persistence of high indoor temperatures. Therefore, it is essential to diversify passive regulatory strategies and adapt them to the climatic and socio-cultural conditions of each region. The reflective paints in light shades reflect more than 80% of the solar radiation, reducing the roof's surface temperature and cooling needs, and facilitating the dissipation of interior heat, naturally cooling the house. However, energy regulation should not only focus on the performance or return on investment, but also on its economic and social viability. The passive strategies promoted by government programs entail high initial investment due to envelope modifications and material acquisition, as well as high maintenance costs that vary by climate, making them less accessible to the population. On the contrary, strategies such as reflective cladding represent an up to 60% cheaper option that accounts for material acquisition, implementation, and maintenance, making them a high-potential option for adoption by the population. Although regulations such as the NMX-C-460-ONNCCE-2009 that address thermal aspects of the roof have shown effectiveness in central regions of Mexico (Vázquez-Torres et al., 2022), studies make it clear that both this and the NOM-020-JAN-2011 do not approach true energy saving and environmental impact mitigation scenarios by not contemplating aspects such as the cladding of materials, mainly in the dwelling's slab (Martin-Dominguez et al., 2018). These phenomena are validated in the results of this study.

This shows that legislation and regulations should not only promote the incorporation of efficient passive technologies but also raise awareness among the population about optimal materials and construction strategies, since many prioritize aesthetics over energy efficiency and thermal comfort. Likewise, the results show the need to rethink the regulations, transitioning from a centralized model to regional or municipal regulations that allow adaptation of solutions to local climatic, social, and cultural conditions, thereby favoring rooting and adoption. This would also promote the use of local materials and construction techniques, thereby improving energy performance and generating economic and environmental benefits.

CONCLUSIONS

The work focused on analyzing the applicability of the NMX-C-460-ONNCCE-2009 and NOM-020-JAN-2011 standards to social housing in the hot-humid climate of southeastern Mexico. Also, passive comfort alternatives were compared with a material commonly used in the region: a terracotta-colored cladding. To do this, an energy model of a typical house was built and calibrated using experimental measurements of indoor temperature and humidity recorded over one year. Four scenarios were evaluated: (i) standard roof, (ii) roof with terracotta cladding, (iii) roof without thermal insulation with cool-roof cladding, and (iv) conventional roof with cool-roof. Finally, the cases were analyzed in three dimensions: thermal, energy, and environmental.

Among the results, it was demonstrated that the application of a material deeply rooted in rural communities, such as terracotta waterproofing, adversely affects occupant comfort, increases energy consumption, increases CO_2 emissions, and contributes more to urban heat islands in residential areas. In contrast, integrating national regulations with reflective cladding significantly mitigates these effects. However, the most favorable scenario identified is the omission of insulating materials established in the regulations and the exclusive application of reflective cladding, which increases annual comfort hours by more than 11%, reduces cooling demand by 21% and electric energy consumption by 20%, in addition to increasing CO_2-equivalent emissions mitigation by more than six times per dwelling and reducing the increase in outdoor temperature associated with the operation of air conditioning equipment by 24%. These results show that, although the current regulations represent an advance, being designed in a centralized manner and without considering climatic particularities, they miss substantial opportunities for improvement. In this sense, there is a need to generate regional, local, and even municipal regulations that promote sustainability, social welfare, and greater relevance in the application of constructive strategies. Finally, this work gives rise to the development of lines of opportunity for future research, particularly in the context of materials and finishes typical of local architecture, such as the incorporation of a static or ventilated air chamber to improve the thermal performance of the roof without significantly modifying the height or volumetry of the building, among others.

The study highlights the importance of rethinking the regulatory framework for energy efficiency in buildings so that it is not limited to homogeneous national guidelines, but incorporates differentiated approaches that respond to the country's climatic, social, and cultural diversity. The inclusion of low-cost, easy-to-implement passive strategies, such as reflective coatings, is a viable alternative for improving thermal comfort and reducing energy consumption. From this perspective, it becomes evident that there is a need to move towards regulations with greater regional relevance that promote both the use of local materials and techniques and public awareness of the benefits of efficient construction design, thereby contributing to energy and environmental sustainability in the housing sector.

CONTRIBUTION OF AUTHORS CRediT

Conceptualization, O.M.T.; Data curation, J.J.A.P.; Formal analysis, F.N.D.L., J.I.H.; Acquisition of O.M.T. funding; Research, O.M.T., J.I.H.; Methodology, F.N.D.L.; Software. J.J.A.P., F.N.P., M.A.J.T.; Supervision, O.M.T., F.N.P., M.A.J.T.; Validation, F.N.P., M.A.J.T.; Visualization, J.I.H., M.A.J.T.; Writing - original draft, O.M.T., F.N.D.L., M.A.J.T.; Writing - revision and editing, O.M.T.

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BIBLIOGRAPHIC REFERENCES

American Society of Heating, Refrigerating and Air-Conditioning Engineers. (1979). International Journal of Refrigeration, 2(1), 56-57. https://doi.org/10.1016/0140-7007(79)90114-2

Canul-Turriza, R. A., Aké-Turriza, K., May-Tzuc, O., & Jiménez-Torres, M. (2024). Análisis espaciotemporal de islas de calor aplicado en la ciudad costera de San Francisco de Campeche, México. *Urbano, 27*(49), 08–23. https://doi.org/10.22320/07183607.2024.27.49.01

Castro-Bello, M., Gómez-Muñoz, L., Marmolejo-Vega, C. V., Morales-Morales, C., Valencia-Díaz, E. F., Maldonado-Catalán, J. F., & Marmolejo-Duarte, C. (2024). Public Policies for the Energy Efficiency of Buildings in Mexico. *Buildings, 14*(11), 3437. https://doi.org/10.3390/buildings14113437

Comisión Nacional de Vivienda [CONVI]. (2022). *Rezago Habitacional 2022. Desarrollo Territorial*, Secretaría de Desarrollo Agrario, Territorial y Urbano [SEDATU]. https://siesco.conavi.gob.mx/doc/analisis/2023/Rezago_Habitacional_2022.pdf

Corrado, V., & Fabrizio, E. (2019). Chapter 5- Steady-state and dynamic codes, critical review, advantages and disadvantages, accuracy, and reliability in F. Asdrubali & H. Desideri (Eds.), *Handbook of Energy Efficiency in Buildings* (pp. 263–294). Elsevier. https://doi.org/10.1016/B978-0-12-812817-6.00011-5

Cui, Y., Zhu, Z., Zhao, X., Li, Z., & Qin, P. (2022). Bayesian Calibration for Office-Building Heating and Cooling Energy Prediction Model. *Buildings, 12*(7), 1052. https://doi.org/10.3390/buildings12071052

Galindo-Borbón, C., Borbón-Almada, A., Ochoa-de-la-Torre, J. M., & Marincic-Lovriha, I. (2024). Análisis costo-beneficio de estrategias para eficiencia energética en vivienda, aplicando la normatividad vigente en el Noroeste de México. *Hábitat Sustentable, 14*(2), 32–47. https://doi.org/10.22320/07190700.2024.14.02.03

Gamero-Salinas, J., Monge-Barrio, A., Kishnani, N., López-Fidalgo, J., & Sánchez-Ostiz, A. (2021). Passive cooling design strategies as adaptation measures for lowering the indoor overheating risk in tropical climates. *Energy and Buildings, 252*, 111417. https://doi.org/10.1016/j.enbuild.2021.111417

Guillén Guillén, C. A., & Muciño Vélez, A. (2020). Ahorro energético en vivienda social mediante la implementación de materiales regionales. *Vivienda y Comunidades Sustentables*, (8), 59-80. https://doi.org/https://doi.org/10.32870/rvcs.v0i8.142

Haupt, J., Hack, J., & Backhaus, A. (2025). Targeted irrigation to improve the cooling potential of urban trees as a nature-based solution: Insights from a field trial in Hanover. *Nature-Based Solutions, 8*, 100247. https://doi.org/10.1016/j.nbsj.2025.100247

Hernández-Pérez, I., Álvarez, G., Xamán, J., Zavala-Guillén, I., Arce, J., & Simá, E. (2014). Thermal performance of reflective materials applied to exterior building components - A review. *Energy and Buildings, 80*, 81–105. https://doi.org/10.1016/j.enbuild.2014.05.008

Hernández-Pérez, I., Xamán, J., Macías-Melo, E. V., Aguilar-Castro, K. M., Zavala Guillén, I., Hernández-López, I., & Simá, E. (2018). Experimental thermal evaluation of building roofs with conventional and reflective coatings. *Energy and Buildings, 158,* 569–579. https://doi.org/10.1016/j.enbuild.2017.09.085

Instituto Nacional de Estadística y Geografía [INEGI]. (2024). *Aspectos Geográficos de Campeche. Compendio 2023*. Instituto Nacional de Estadística y Geografía – México. https://www.inegi.org.mx/contenidos/productos/prod_serv/contenidos/espanol/bvinegi/productos/nueva_estruc/889463915973.pdf

Jiménez Torres, M., Pérez-Fargallo, A., May Tzuc, O., Ricalde Castellanos, L., Bassam, A., Flota-Bañuelos, M., & Rubio-Bellido, C. (2024). Energy poverty under 2M indicator: Feasibility of decrease by using passive techniques in residential buildings of Southeast Mexico. *Energy and Buildings, 323,* 114761. https://doi.org/10.1016/j.enbuild.2024.114761

Manzano-Agugliaro, F., Montoya, F. G., Sabio-Ortega, A., & García-Cruz, A. (2015). Review of bioclimatic architecture strategies for achieving thermal comfort. *Renewable and Sustainable Energy Reviews, 49*, 736–755. https://doi.org/10.1016/j.rser.2015.04.095

Martin-Dominguez, I. R., Rodriguez-Muñoz, N. A., Romero-Perez, C. K., Najera-Trejo, M., & Ortega-Avila, N. (2018). Analysis of the Methodologic Assumptions of the NOM-020-ENER-2011—Mexican Residential Building Standard. *Environments, 5*(11), 118. https://doi.org/10.3390/environments5110118

May-Tzuc, O., Jiménez-Torres, M. A., Cruz y Cruz, A. del R., Canul-Turriza, R., Andrade-Durán, J. E., & Noh-Pat, F. (2023). Feasibility of the adaptive thermal comfort model under warm sub- humid climate conditions: cooling energy savings in Campeche, Mexico. *Hábitat Sustentable, 13*(1), 120–131. https://doi.org/10.22320/07190700.2023.13.01.10

Organismo Nacional de Normalización y Certificación de la Construcción y Edificación. (2009). NMX-C-460-ONNCCE-2009: Determinación de la transmitancia térmica en elementos que conforman la envolvente en edificaciones. https://platiica.economia.gob.mx/normalizacion/nmx-c-460-onncce-2009/

Ruiz Torres, R. P. (2019). Evaluación del sistema termolosa entre la medición experimental y el calculado con la Norma NMX-C-460-ONNCCE-2009. *Vivienda y Comunidades Sustentables,* (6), 119–136. https://doi.org/10.32870/rvcs.v0i6.126

Secretaría de Energía, (SENER). (2011). Diario Oficial. Norma Oficial Mexicana NOM-020-ENER-2011. 47. https://www.gob.mx/cms/uploads/attachment/file/181660/NOM_020_ENER_2011.pdf

Secretaría de Desarrollo Agrario, Territorial y Urbano [SEDATU], & Comisión Nacional de Vivienda [CONAVI]. (2017). *Código de Edificación de Vivienda* (Conavi, 3ra, pp.1–586). https://onncce.org.mx/images/Publicaciones/publicado-CEV_2017__FINAL_.pdf

Secretaría de Medio Ambiente y Recursos Naturales [SEMARNAT]. (2025). Aviso. Factor de emisión del sistema eléctrico nacional 2024. https://www.gob.mx/cms/uploads/attachment/file/981194/aviso_fesen_2024.pdf

Szokolay, S. V. (2014). *Introduction to Architectural Science*. Routledge. https://doi.org/10.4324/9781315852409

Vargas, A. P., & Hamui, L. (2021). Thermal Energy Performance Simulation of a Residential Building Retrofitted with Passive Design Strategies: A Case Study in Mexico. *Sustainability, 13*(14), 8064. https://doi.org/https://doi.org/10.3390/su13148064

Vázquez-Torres, C. E., Sotelo-Salas, C., & Grajeda-Rosado, R. M. (2022). Efecto de la NMX-C-460-ONNCCE-2009 sobre el Comportamiento Térmico en Viviendas de Interés Social en Clima Templado Sub-Húmedo. *Estudios de Arquitectura Bioclimática, 17*, 109-124. https://zaloamati.azc.uam.mx/server/api/core/bitstreams/619d980f-850d-45a6-b462-ae0a947b99be/content#page=109

Villar-Ramos, M. M., Hernández-Pérez, I., Aguilar-Castro, K. M., Zavala-Guillén, I., Macias-Melo, E. V., Hernández-López, I., & Serrano-Arellano, J. (2022). A Review of Thermally Activated Building Systems (TABS) as an Alternative for Improving the Indoor Environment of Buildings. *Energies, 15*(17), 6179. https://doi.org/10.3390/en15176179

Yamamoto, T., Ozaki, A., & Lee, M. (2021). Optimal Air Conditioner Placement Using a Simple Thermal Environment Analysis Method for Continuous Large Spaces with Predominant Advection. *Energies, 14*(15), 4663. https://doi.org/10.3390/en14154663