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COST-BENEFIT ANALYSIS OF ENERGY EFFICIENCY STRATEGIES FOR HOUSING, APPLYING THE CURRENT REGULATIONS IN NORTHWEST MEXICO

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ANÁLISIS COSTO-BENEFICIO DE ESTRATEGIAS PARA EFICIENCIA ENERGÉTICA EN VIVIENDA, APLICANDO LA NORMATIVIDAD VIGENTE EN EL NOROESTE DE MÉXICO

ANÁLISE DE CUSTO-BENEFÍCIO DE ESTRATÉGIAS PARA EFICIÊNCIA ENERGÉTICA EM RESIDÊNCIAS, APLICANDO AS REGULAMENTAÇÕES ATUAIS NO NOROESTE DO MÉXICO

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RESUMEN

El cambio climático ha afectado de manera desproporcionada a los sectores más vulnerables, y la eficiencia energética en edificaciones emerge como clave para mitigar y adaptarse a estos efectos. En México, los climas cálidos secos predominan en el 53% del territorio, especialmente en el norte, y aunque existe normativa para la eficiencia energética en la edificación, ésta tiene un impacto limitado. El estudio evalúa los costos y beneficios de dicha normativa que considera viviendas comunes en distintos climas de un estado del norte de México donde se analizaron 180 modelos y se concluyó que cumplir con la normativa aumentaría el costo de la vivienda en 1.93%, reduciría el consumo eléctrico en 26% y disminuiría las emisiones de CO2e en 16.95%. Estos beneficios se obtuvieron sin cambiar los sistemas constructivos más utilizados y se priorizó sistemas de sombreado. Los resultados podrían orientar a políticas públicas más adecuadas a los contextos locales.

Palabras clave
cambio climático, vivienda, energía eléctrica, normalización, consumo de energía.

ABSTRACT

Climate change has disproportionately affected the most vulnerable sectors, and energy efficiency in buildings is essential for mitigating and adapting to these effects. In Mexico, hot, dry climates predominate in 53% of the country, especially in the north, and although there are energy efficiency regulations for buildings, they have a limited impact. This study evaluates the costs and benefits of these regulations considering ordinary dwellings in different climates in a state in northern Mexico, analyzing 180 models and concluding that complying with the regulations would increase the cost of housing by 1.93%, reduce electricity consumption by 26%, and decrease CO2e emissions by 16.95%. These benefits were obtained without changing the most commonly used construction systems, although shading systems were prioritized. The results can guide public policies that are more appropriate to local contexts.

Keywords
climate change, housing, electric power, standardization, energy consumption.

RESUMO

As mudanças climáticas afetam desproporcionalmente os setores mais vulneráveis, e a eficiência energética em edifícios surge como uma das chaves para mitigar e adaptar-se a esses efeitos. No México, os climas quentes e secos predominam em 53% do território, especialmente no norte, e, embora existam regulamentações para a eficiência energética em edifícios, elas têm impacto limitado. O estudo avalia os custos e benefícios de tais regulamentações considerando residências comuns em diferentes climas em um estado do norte do México. Ele analisou 180 modelos e concluiu que a conformidade com a norma aumentaria o custo da moradia em 1,93%, reduziria o consumo de eletricidade em 26% e reduziria as emissões de CO2e em 16,95%. Estes benefícios foram obtidos sem alterar os sistemas de construção mais comumente usados e os sistemas de sombreamento foram priorizados. Os resultados podem orientar políticas públicas mais adequadas aos contextos locais.

Palavras-chave:
mudança climática, habitação, energia elétrica, padronização, consumo de energia

INTRODUCTION

The sixth report of the IPCC (2023) says that the effects of climate change have been more severe than anticipated, affecting natural systems and socio-economic sectors, especially the most vulnerable ones. These impacts include physical and mental health problems, the result of phenomena such as extreme heat waves, which increase mortality and morbidity. The report highlights the need for governments to address these challenges through adaptation and resilience policies, where the importance of energy diversification, decentralization of generation and demand management, with a particular focus on the energy efficiency of buildings to mitigate and adapt to climate change, stand out.

According to the latest report by the International Energy Agency, IEA (2023), the building sector accounts for 30% of the world's total final energy consumption. This is mainly due to the energy demand for thermal comfort in spaces, where heating is one of the first energy end-use demands, and cooling is the fastest-growing end-use in recent decades. Predictions for a rise in built-up areas worldwide are also around 20% from 2021 to 2030, of which 80% would be in emerging market economies, aggravating the growing effects of climate change (IEA, 2022).

In Mexico, the construction sector, considering residential, commercial, and public buildings, represents 18% of the total end energy consumption, and the primary energy source used is electricity (Ministry of Energy [SENER], 2023). However, energy consumption is mainly determined by climate characteristics that condition habitability to using cooling systems (A/C), and, therefore, the distribution of consumption in the national territory is not uniform. In general, humid and dry hot climates predominate in 89% of the Mexican territory, particularly arid hot climates (very dry, dry desert, dry and semi-dry) that represent 53% of the total area and are located in the northern region of the country (Ministry of Environment and Natural Resources [SEMARNAT], 2024b).

Household energy expenditure comprises fuel, gas, and electricity, and through this expenditure, the energy demand that identifies the energy source can be described, as well as its consumption level (Rodriguez et al., 2022). Notably, the northern states invest most in energy expenditure (Figure 1), and electricity can exceed 60% or up to 70% of that expenditure (Rodriguez et al., 2022).

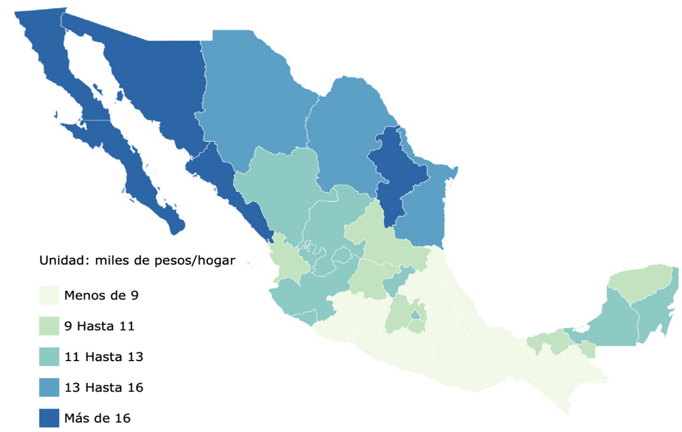

Figure 1. Energy expenditure per household in Mexico. Source: Image taken from the Ministry of Energy [SENER] and National Commission for the Efficient Use of Energy [CONUEE] (2024), MEX$19.80/Dollar for August 2024.

Nationally, the end-uses of electricity in the residential sector are as follows: cooling comprises 30% of the total, food refrigeration 20%, the use of household and other appliances 15%, entertainment, specifically television, has a demand of 13%, lighting 8%, laundry 6%, water heating 5%, heating 2%, and pumping 1% (Contreras et al., 2022). It is necessary to emphasize that these data are national averages and that the end-use percentage from cooling would be higher in areas with higher temperatures. There is no exact information, but in tropical climate zones, 14% more electricity is consumed than in temperate climate zones, while in northern states with dry climates, this consumption is 29% higher than in those with temperate climates (Rodriguez, 2018; INEGI, 2022). This difference is assumed to be mainly related to the increased energy used for cooling due to the temperatures.

It should also be considered that it is highly likely that energy needs for thermal comfort will increase. To evaluate the uncertainty, according to the National Atlas of Vulnerability to Climate Change (INECC, 2022), for the northern states of Mexico, in a medium-term and an RCP4.5 scenario of average stabilization, the anomaly in the average temperature would be 1.9°C, and for a high emission RCP8.5 scenario, it would be 2.4°C (López-Díaz et al., 2022).

This problem is aggravated further when it is acknowledged that achieving thermal comfort requires sufficient economic and energy resources, especially when a population sector is vulnerable due to limited access. In the last decade, interest in this topic has grown, with research on the phenomenon of energy poverty (Siksnelyte-Butkiene et al., 2021). It has been argued that this depends not only on access to energy but is also

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determined by the territory's characteristics, the temporal context, and the specific socio-technical and socio-cultural conditions.

In this regard, income levels (García Ochoa, 2022; Méndez et al., 2021; Panca & Calatayud, 2021), energy prices, and subsidies (Durán & Condori, 2021; Méndez et al., 2021) are important factors, but other elements also have an impact, such as weather conditions (García Ochoa, 2022; Santillán et al., 2020), regulations on the quality of housing and its installations (García Ochoa, 2022; Hernández, Aguayo & Duque, 2018; Méndez et al., 2021; Garcia Ochoa, Ávila-Ortega & Cravioto, 2022; Panca & Calatayud, 2021), as well as the affordability of energy technologies (Hernández, Aguayo & Duque, 2018; García Ochoa, 2022; Garcia Ochoa, Ávila-Ortega & Cravioto, 2022).

In this context, the uncertainty about the capacity of buildings and conditioning systems to guarantee thermal comfort, together with the economic limitations of governments and individuals, poses a public policy challenge with an impact on health (IEA, 2022). This is where the importance of this research lies, as energy efficiency is identified as the strategy to provide these living conditions, at least to some extent.

In Mexico, there is a specific regulatory structure for energy efficiency in buildings, with a series of Official Mexican Standards (NOM) that regulate several technical aspects, such as the labeling of air conditioners, household appliances, glazing systems, and the thermal envelope of buildings. However, the regulations for the thermal envelope, specifically NOM-008-ENER-2001, Energy Efficiency in Buildings, Non-Residential Building Envelope and NOM-020-JAN-2011. Energy Efficiency in Buildings, Residential Building Envelope, established to rationalize energy use in air conditioning systems, considering a reference building as a base, have not had the expected impact despite being mandatory. Diverse factors, including logistical and technical aspects, explain why these regulations have not had the expected impact.

Among the logistical details, it is highlighted that neither standard is integrated into local construction regulations. There is also a lack of coordination by the three levels of government; there is no technical capacity of professionals for their implementation, it is not mandatory in programs run by credit and housing entities, or in any case, only optional criteria are sought and, there is an objection from the construction sector, precisely because it entails an additional cost (Rodriguez, 2018; Martin-Domínguez et al., 2018)

Among the technical details for the calculation methodology, an overestimation of the solar absorption of the building envelope is identified (Martin-Dominguez et al., 2018). The heat capacity of the materials is also omitted, as the calculation model does not consider variations in ambient temperature over time (Huelsz et al., 2014), which leads, in essence, to an over-dimensioning of the insulation. In addition, the meteorological data needs to be updated to respond to the phenomenon of climate change, and the standard does not provide a comfort model (Guízar Dena et al., 2021).

The application of energy efficiency regulations in buildings in Mexico is unavoidable and urgent, especially in homes in the country's northern regions, given the critical conditions of climate change, the increase in energy demand, and the high economic and social costs. Given this urgency, it would be important to maximize the potential of the current regulations, as their application could generate significant results, especially when considering this region's climate.

This study focuses on the application of NOM-020-JAN-2011 - Energy Efficiency in Buildings, Residential Building Envelope methodology, and the aim is to identify combinations of strategies that maximize the impact on the assessment of regulatory compliance with the least economic investment. This would allow defining benefits in terms of energy savings and emissions reduction, as well as the cost of achieving the level of compliance, at least at its minimum level. In addition, the region's most common designs and construction systems and, finally, the results that could contribute to guiding public policies that best adapt to local contexts are considered.

METHODOLOGY

In this exercise, localities in a northern state of Mexico, specifically Sonora, were analyzed, where 95% of the region has a hot and dry climate (INEGI, 2024) and as of 2017, 71% of households had A/C (National Commission for the Efficient Use of Energy [CONUEE], 2024).

This study considered the analysis of 9 housing models in the four orientations and five types of climates in the State for a total of 180 analyzed models. An initial evaluation was carried out without considering efficiency conditions, and based on the results, strategies were implemented to achieve the desired efficiency level, quantifying the costs and possible savings.

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Table 1: Localities included in NOM-020 for Sonora, the corresponding electricity tariff, and climate. Source: Prepared by the authors, with information from CFE (2024), NOM-020 (2011), INEGI (2024).

Locality	Latitude	Tariff	Description of the Tariff	Climate	Consumption level
Hermosillo	29.10N	1F	Domestic service for localities with an average minimum summer temperature of 33°C	Very dry, very warm	The first level is from 1 to 1,200kWh, the second is from 1,201 to 2500kwh, and the rest is surplus.
Obregón	27.49N	1F		Dry very warm	
Guaymas	27.92N	1E	Domestic service for localities with an average minimum summer temperature of 32°C	Very dry, very warm	
Navojoa	27.07N	1E		Dry very warm	
Nogales	31.31N	1A	Domestic service for localities with an average minimum summer temperature of 25°C	Semi-dry temperate	The first level is from 1 to 300kWh, the second from 301 to 1200kWh, and the third from 1201 to 2500kWh; the rest is surplus.

For the analysis, NOM-020-JAN-2011 - Energy Efficiency in Buildings, Residential Building Envelope (2011) was used, which, from now on, will be referred to as NOM-020. This is applied in homes located in cities whose electricity supply has the following electric tariffs: 1C, 1D, 1E, and 1F (NOM-020-JAN-2011 Resolution, 2016).

The Federal Electricity Commission sets these rates (CFE, 2024) and they are defined according to a minimum average summer temperature classification. The tariffs range from 1A to 1F, and a high consumption domestic tariff (DAC). The 1F tariff is for the highest minimum average temperature and applies to the highest subsidy for the summer season. Consumption levels structure the subsidies, and each has an increase in cost per kWh. Given the high temperatures recorded in 2023, electricity users in the State of Sonora recorded consumption far higher than those in other regions of the country, leading to an extraordinary level of social clamor for support. In this context, the Collaboration agreement for tariff support for the State of Sonora (2024) was prepared, which outlines a larger subsidy that benefits the entire State, covers the months of April to October, considers adjustments in consumption levels, standardizes the 1E and 1F tariffs, and improves the conditions for the rest of the tariffs. See Table 1.

NOM-020 includes values in its tables to calculate the heat flow through the envelope for specific cities. Sonora considers only five localities: Hermosillo and Ciudad Obregón for the 1F tariff, Guaymas and Navojoa with 1E, and Nogales with 1A (see Table 1). Although NOM-020's resolution indicates that Nogales is not subject to the verification of the standard, the analysis will be made to expand upon the possible observations.

Some of the representative characteristics of social housing design in the hot, dry climate are usually unique for the area and are deployed on one of the property's boundaries. This means the dwelling does not share walls or have insulation systems. Although they may vary in their distribution, they comprise a common area (living room, dining room, and kitchen), one or several bedrooms, and a bathroom. The facades also lack solar protection (Romero Moreno et al., 2020), and the largest proportion of windows are located on the main and rear facades. In terms of construction area, 58% of the housing in the state of Sonora is between 46 m^2 and 150 m^2 (INEGI, 2020), and regarding the most commonly used construction systems, 92% of the homes in the state have brick, block, cement or concrete walls (INEGI, 2022), particularly 0.12m thick concrete block walls (Romero Moreno et al., 2020). Finally, concrete ceiling slabs or joists are found in 72% (INEGI, 2022), where particularly 0.15m thick joist slabs predominate (Romero Moreno et al., 2020).

Nine housing model projects were chosen for this analysis, considering the characteristics described in the previous paragraph. The information on the projects was provided by different property developers, who will remain anonymous. These one—and two-floor models range from 43m^2 to 126 m^2. In Table 2, each model's information is detailed, including, among other data, the wall-to-window (%) of the houses. The table also includes a nomenclature to identify each model in the following figures.

The calculation method of NOM-020 estimates the heat gain by conduction and radiation of the projected building and compares it with a reference building. To comply with the regulations,

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the projected building's heat gains must be equal to or less than those of the reference building. The results are presented as a percentage of savings from the difference in thermal load (W) between the projected and reference buildings. For compliance, at least 0% savings or more must be achieved. A negative number represents spending and non-compliance with the standard.

Table 3 outlines the construction systems used in the initial evaluation. Regarding the floor slab, according to NOM-020, the portion of the envelope directly above the ground is considered a zero-heat gain; therefore, it was not included.

The conductivity values of each material were taken from the tables available in NOM-020 (2011) and NMX-C-460 (2009). The values not available in these lists were taken from the commercial product's technical data sheet, see Table 3.

The U reference values established by the Mexican regulations may imply a high level of thermal insulation. This entails using materials with very low thermal conductivity, such as insulators, to meet the requirements. However, according to the standard's methodology, it is possible to optimize the envelope's thermal behavior by adopting different construction strategies, such as using lightweight materials, new geometries, and innovative solutions. In addition, combining these approaches with efficient glazing technologies and shading systems makes it possible to reduce the demand for insulation. Similarly, having more accurate information on the thermal conductivity values of locally produced materials is essential, as it would facilitate adapting construction solutions to the region's specific conditions.

In the first analysis, the results describe the level of compliance with the current state of housing, namely, without additional strategies for compliance with NOM-020. The results are described by relating some design characteristics, such as the WWR and orientation, as well as the impact of the climate, with the results of NOM-020.

A second analysis applies energy efficiency strategies that impact the NOM's calculation. The strategies were applied to those dwellings that did not comply in the first analysis. The intention was to achieve compliance with NOM-020, at least at its minimum level. The criteria for selecting the strategies consider not modifying the original design; they must use common materials available in the market and should represent the lowest possible cost. A unit price analysis was made to determine these costs, considering material,

Table 2: Characteristics of the analyzed models: 9 models in 4 orientations in the 5 climates available in NOM-020, totaling 180 models. Source: Preparation by the Authors.

Number of floors	Built area (m2)	WWR ratio (%) and without shading	Nomenclature
1	43.00	12.08	1N_43
1	54.00	9.43	1N_54
1	61.00	9.21	1N_61
1	66.00	8.60	1N_66
1	78.00	5.65	1N_78
2	97.00	6.62	2N_97
2	104.00	8.45	2N_104
2	113.00	8.19	2N_113
2	126.00	7.40	2N_126

Table 3: Description of the construction systems and values used to calculate the initial evaluation. Source: Preparation by the Authors.

System	Description	Conductivity (λ) W/mK	Source of λ values	Thickness (m) as per the project
Hollow concrete block walls	Cement sand mortar	0.17	NMX-460	0.015
	Concrete block with 2 or 3 holes	1.11	NMX-460	0.120
Joist slabs	Reinforced concrete	1.74	NOM-020	0.040
	Expanded nominal density polystyrene 12 kg/m3 (Polystyrene joist)	0.04	Commercial product technical data sheet	0.090
	Reinforced concrete joist	1.74	NOM-020	0.090
	Flattened plaster	0.372	NOM-020	0.01
Windows without shading	Single glazing, shade coefficient (SC) 1.00	0.93	NOM-020	0.006

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Table 4: Description of the constructive systems and values used to calculate the evaluation with improvement strategies. Source: Preparation by the Authors.

Improved System	Description	Conductivity (λ) W/mK	Source of λ values	Thickness (m) as per the project
Hollow concrete block walls	Cement sand mortar (outside)	0.17	NMX-460	0.015
	Expanded nominal density polystyrene - 12 kg/m3 (Outer plate)	0.04	Commercial product technical data sheet	0.025
	Concrete block with 2 or 3 holes	1.11	NMX-460	0.120
	Cement sand mortar (inside)	0.17	NMX-460	0.015
Joist slab	Reinforced concrete (compression layer)	1.74	NOM-020	0.040
	Expanded nominal density polystyrene - 12 kg/m3 (Polystyrene slab)	0.04	Commercial product technical data sheet	0.090
	Reinforced concrete (Joist)	1.74	NOM-020	0.090
	Flattened plaster (inside)	0.372	NOM-020	0.01
Single-glazing with film	Single glazing with solar control film and a shading coefficient (SC) of 0.40	0.93	NOM-020	0.006

labor, and equipment with current costs to 2024. In addition, the total direct cost of housing was determined using a parametric analysis of the project items and the estimated cost per m^2 of affordable housing in 2024. With this information, the economic cost overrun of complying with the standard was estimated.

The strategies used are detailed below:

- Horizontal window shading: In all cases where the project did not comply with the regulations, horizontal window shading was implemented as a first strategy. The criterion for defining the element's longitude was to consider the city's latitude, as indicated in Table 1. An overheating period spanning from May to October was also considered using the available climatological databases and the window's vertical dimension. This results in an ideal shading system that protects from radiation in critical periods and allows heating during colder periods.

If the shading systems do not comply with the standard, wall insulation is added, or the quality of the windows is improved.

- Insulation in one or two walls with 0.025m expanded polystyrene on the outside. The criteria for defining the wall to be insulated were as follows: if the main facade is north- or south-facing, the west wall is insulated. The south wall is insulated if the main facade is east or west-facing. In some cases, it was necessary to insulate a second wall, adding the south or west wall, as appropriate. The configuration of the improved construction systems is shown in Table 4.
- Improvement of windows. The strategy consists of improving the windows with one of the following two options: If the house measures less than 100 m^2, a solar control film with at least a shading coefficient value of 0.4 (CS) is used, or if the house measures more than 100 m^2, a double-glazing system with Double Low-E film and a shading coefficient (CS) of 0.64 is included. The criterion for one option or the other depends on the cost of the strategy vs the housing cost, with the intention of not having an excessive impact on the final cost. The configuration of the improved construction systems is shown in Table 4.

In critical cases, wall insulation was used, and the quality of the windows was improved. A critical case is those models that require all the strategies together to reach the minimum level of the standard.

To calculate the energy consumption in kWh, the thermal load results were taken along with A/C use from April to October, corresponding to the subsidy period defined in the Collaboration Agreement for tariff support for Sonora (2024) and an 11-hour daily usage that corresponds to the daily A/C average use in housing in the state (INEGI, 2018).

To define the energy cost, the consumption calculated for A/C plus the proportion of electricity consumption by other devices described in the introduction was considered, in addition to the current subsidy tariff scheme of the collaboration agreement for tariff support for the State of Sonora (2024).

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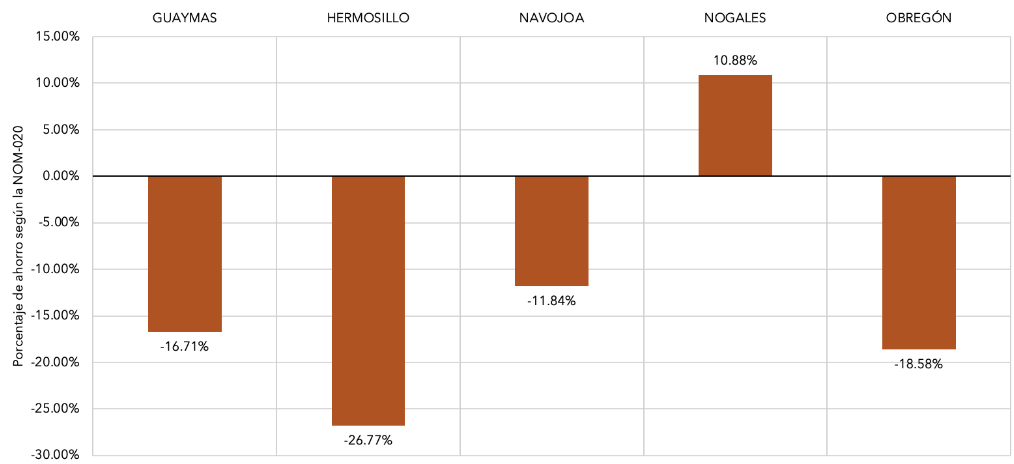

Figure 2. Average savings of all the models per city in all orientations according to NOM-020, without energy efficiency strategies. Source: Preparation by the Authors.

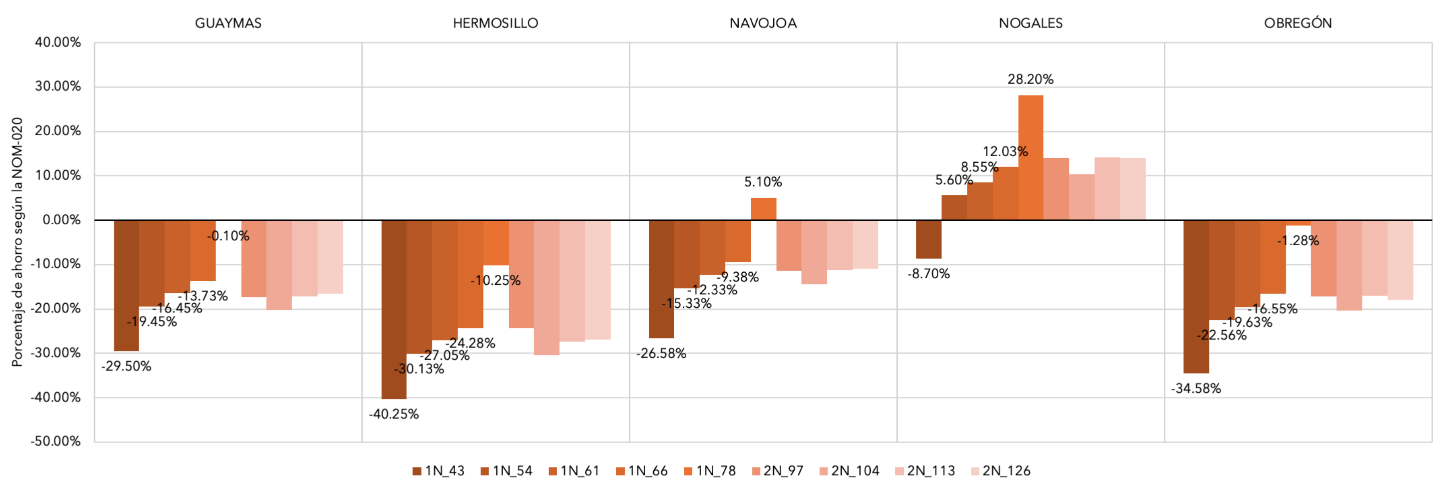

Figure 3. Average savings for each model in all its orientations by city according to NOM-020, without energy efficiency strategies. Source: Preparation by the Authors.

Finally, an estimate of the potential savings in CO_2 emissions is made, considering the emission factor of the National Electricity System, which represents the calculation of indirect greenhouse gas (GHG) emissions from electricity consumption for 2023 (SEMARNAT, 2024a).

RESULTS

FIRST ANALYSIS

Figure 2 shows the average savings of all the models analyzed in 4 orientations for each city without considering any energy efficiency strategy. The models with the highest expenditure or that are further from complying with NOM-020 are those located in Hermosillo, with -26.77%, followed by Obregón, Guaymas, and Navojoa, with -18.58%, -16.71%, and -11.84%, respectively. In the case of Nogales, the models' average savings level complies with NOM-020, with an average savings level of 10.88%.

Figure 3 shows the average savings per model in its four orientations per city. This shows the impact of the specific design variations of each model. In Guaymas, Hermosillo, and Obregón, all the percentages are negative, and the model with the lowest savings is 1N_46, which is the one with the lowest m^2 and highest percentage of glazing, reaching up to -40.25% savings in Hermosillo. In Nogales, all models, on average, have a positive percentage, but the 1N_46 model is still negative with -8.70%. In Navojoa, all the models have negative savings on average except for 1N_78 with 5.10%. In fact, this model is the best evaluated in all localities, either with a negative percentage closer to zero or with a savings percentage of up to 28.20% in Nogales.

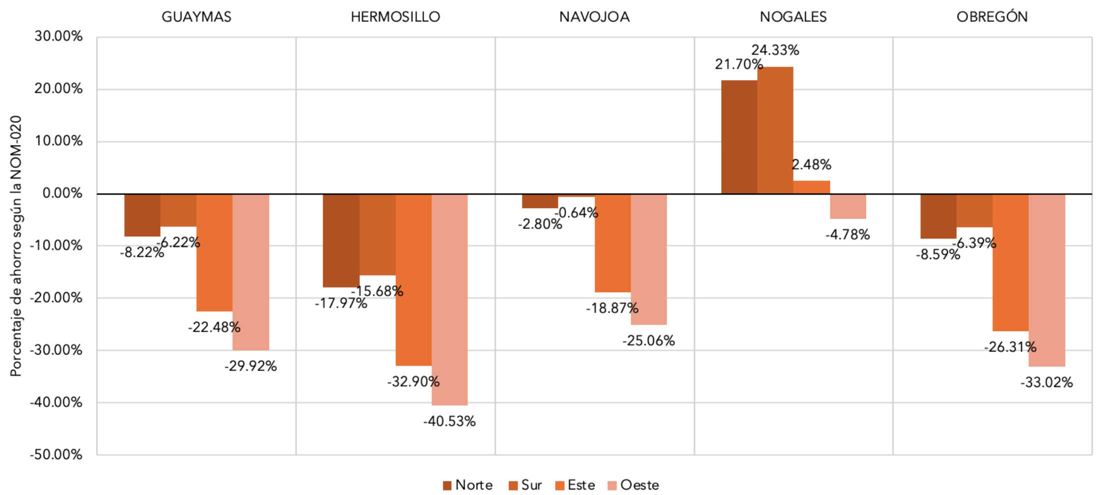

Figure 4. Average savings of all models by orientation per city according to NOM-020, without energy efficiency strategies. Source: Preparation by the Authors.

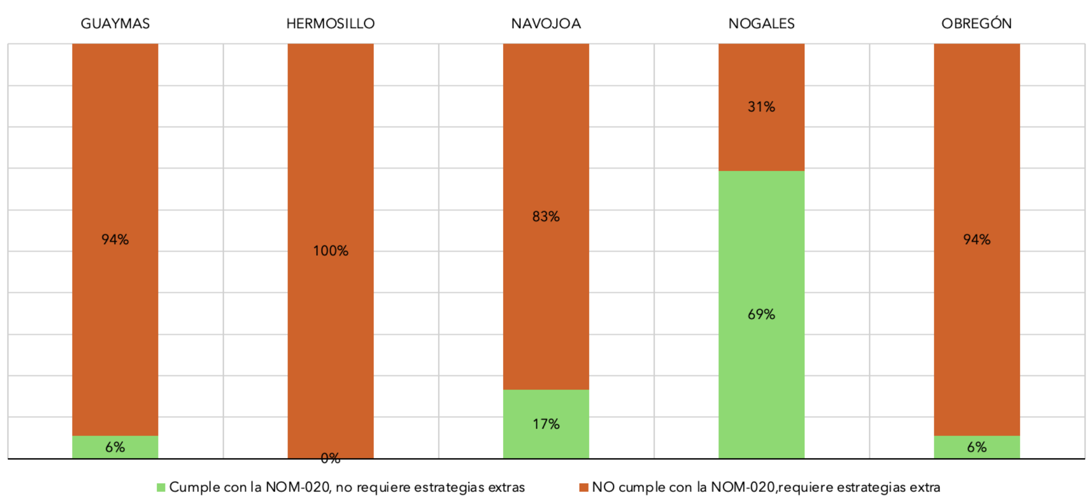

Figure 5. Percentage of cases by city that require additional strategies to comply with NOM-020. Source: Preparation by the Authors.

Figure 4 shows the savings averages of all the models analyzed by orientation and city. This allows us to visualize the impact that orientation has on any model. The most unfavorable orientations are east and west, with negative values in almost all cities, reaching up to -40.53% in the west orientation in Hermosillo. North and south facing are also negative in almost all cities, but closer to savings than the previous ones. The exception is Nogales, with positive values in the north, south, and east, although the west orientation remains negative at -4.78%.

Finally, Figure 5 shows the percentage of cases that would require energy efficiency strategies by city. That is to say, of all the models analyzed in Guaymas, Navojoa, and Obregón, 94%, 83%, and 94%, respectively, need energy efficiency strategies to comply with NOM-020. In Hermosillo, 100% of homes require it, and in Nogales, only 31%.

SECOND ANALYSIS

Figure 6 shows the average savings of all the models in 4 orientations per city, with and without strategies. The most significant impact was in Hermosillo, where the average savings percentage went from -26.77% to 6.39%, representing 33.16 percentage points. This was followed by Obregón, with a difference of 25.29; Guaymas, with 21.5; Navojoa, with 18.78 percentage points; and finally, Nogales, where although the average savings was positive, with 10.88%, it increased savings to 17.39%, representing 6.51 percentage points.

To achieve compliance with NOM-020 with the

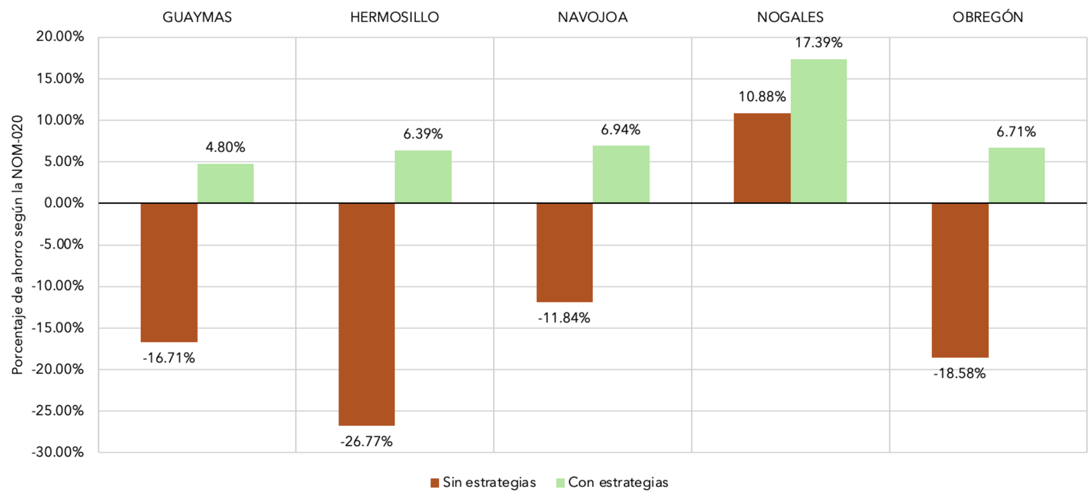

Figure 6. Comparison of the average savings of the models by city according to NOM-020, with and without energy efficiency strategies. Source: Preparation by the Authors.

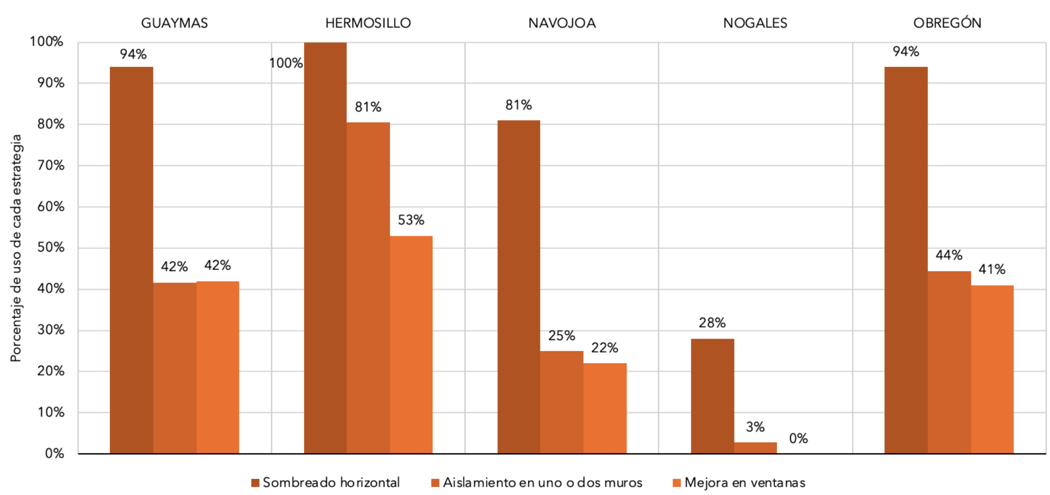

Figure 7: Percentage of use strategies implemented by city to comply with NOM-020. Source: Preparation by the Authors.

savings levels plotted in Figure 6, Figure 7 shows the percentage of each strategy used by city. That is, the percentage of each strategy represents the proportion of times the particular strategy was used relative to the number of models analyzed. To comply with NOM-020, 100% of the houses in Hermosillo were horizontally shaded, 81% required insulation on at least one wall, and 53% of the models had the window quality improved either with film or a double-glazed window. Obregón and Guaymas are very similar, where about 94% of the models included shading, and about 40% required insulation and/or improvement in windows. In the case of Navojoa, 81% required shading, while only about 20% of the models required wall insulation and or window improvement. Finally, in Nogales, the shading strategy was applied to 28%, only 3% required insulation, and the strategy of improving windows was not used.

COST OF IMPLEMENTING THE STRATEGIES TO COMPLY WITH NOM-020

Implementing the above strategies increased direct housing costs, as shown in Figure 8. Hermosillo has the highest cost overruns to achieve compliance with NOM-020, with an average of 2.95%. Obregón and Guaymas follow, with similar average cost overruns of 2.23% and 2.17%, respectively. In Navojoa, the average cost overrun is 1.61%; finally, Nogales has a 0.68% average cost overrun.

ESTIMATION OF SAVINGS

The difference between the first and second analyses generates estimates of possible savings in electricity consumption and costs and GHG reductions in CO_2e.

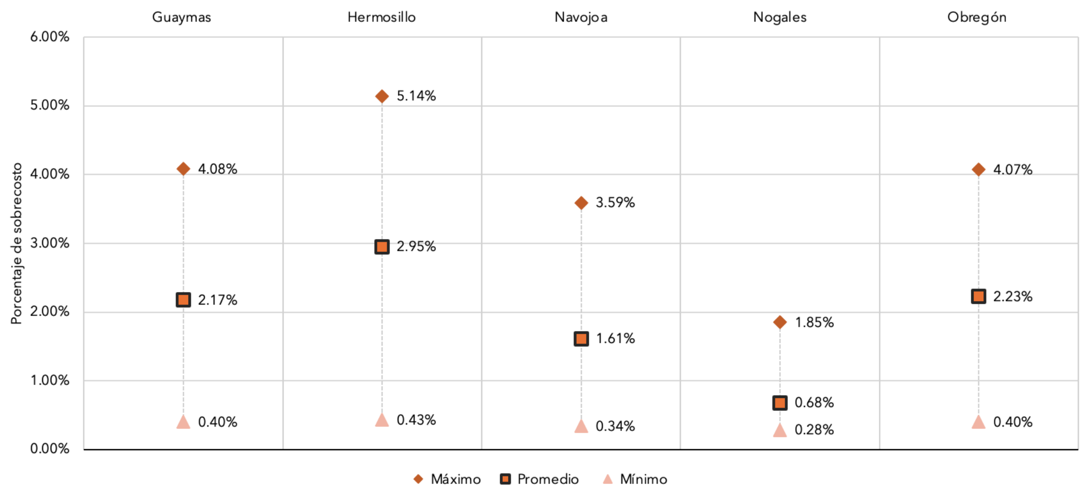

Figure 8: Cost overruns by implementing strategies for compliance with NOM-020 by city. Source: Preparation by the Authors.

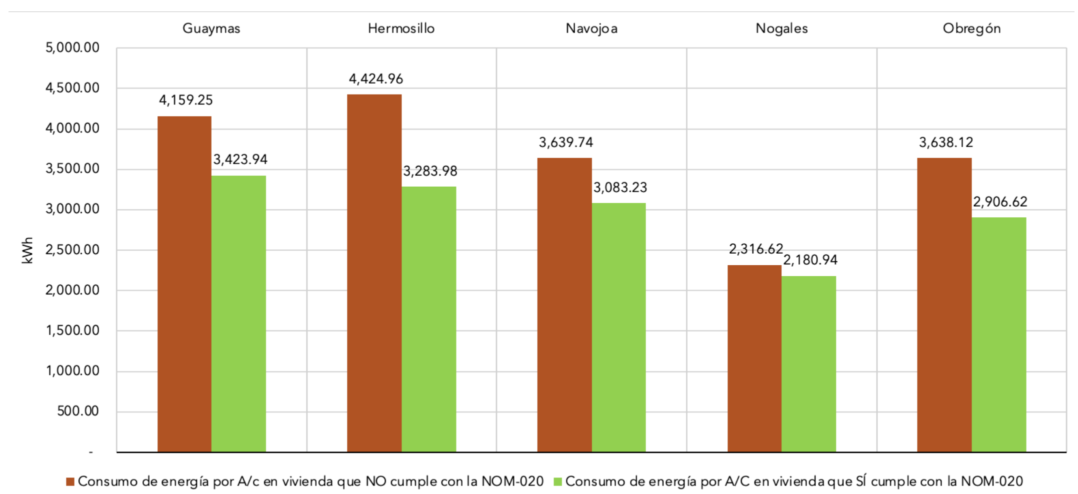

Figure 9: Estimated average A/C energy consumption in kWh of all models by city that do not comply with NOM-020 against the estimated energy consumption of those that do comply with NOM-020. Source: Preparation by the Authors.

Figure 9 shows the estimated average energy consumption in kWh of all homes by city that do not comply with NOM-020 against the estimated energy consumption of the homes that do. These consumption values are from April to October, with an average A/C use of 11 hours a day (INEGI, 2018). The calculation is limited only to A/C consumption, i.e., it does not consider the energy consumption by other devices. The most significant impact is in Hermosillo, with a 25.43% decrease in energy consumption, followed by Obregón and Guaymas, with 20.22% and 17.53%, respectively. The case with the least impact is Nogales, with 6.04%.

In Figure 10, the estimate of the total expenditure for energy consumption of the dwelling that does not comply with NOM-020 is presented against the total expenditure of the dwelling that does. For the calculation, it was estimated that air conditioning, as described in the introduction, represents 60% of the total energy consumption. The calculations contemplate the subsidy of the current CTE tariff scheme (Collaboration Agreement For Tariff Support For The State of Sonora, 2024) and are the accumulated expenditure during the season from April to October. According to the results, in Hermosillo, on average, $20,168.95 Mexican pesos would be allocated for the subsidized season in housing that does not comply, against $13,149.07 Mexican pesos in housing that does comply with NOM-020, a 35.32% savings. In Obregón, the average savings was 30.95%, Guaymas 25.10%, Navojoa 24.27%, and Nogales 15.80%. It is worth emphasizing that the subsidy percentage could reach up to 75% if compared with the regular tariff and that this percentage varies because it depends on the level of consumption.

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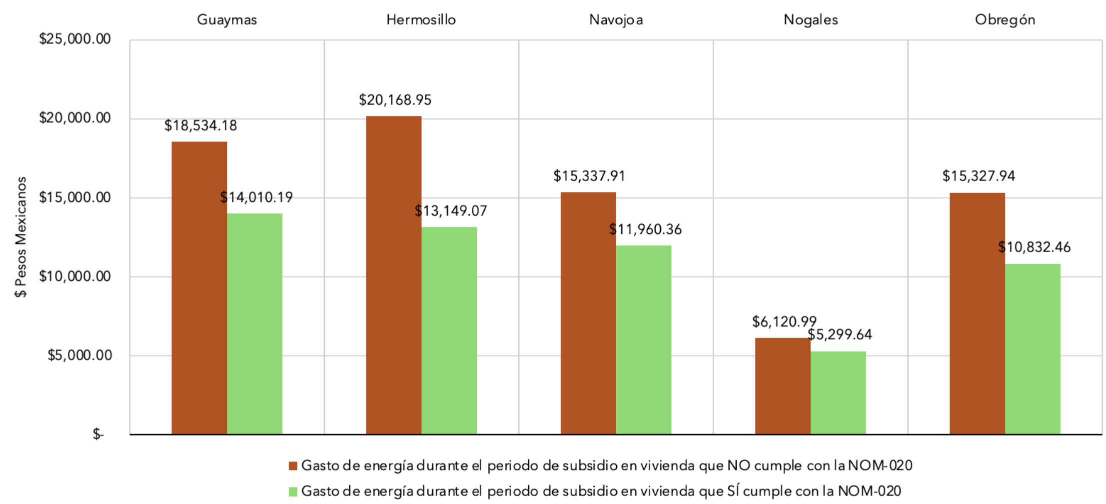

Figure 10: Estimated average energy expenditure from April to October, in Mexican pesos, of all dwellings by city that do not comply with NOM-020 against the energy expenditure of dwellings that do. 19.80 $MEX/dollar for August 2024. Source: Preparation by the Authors.

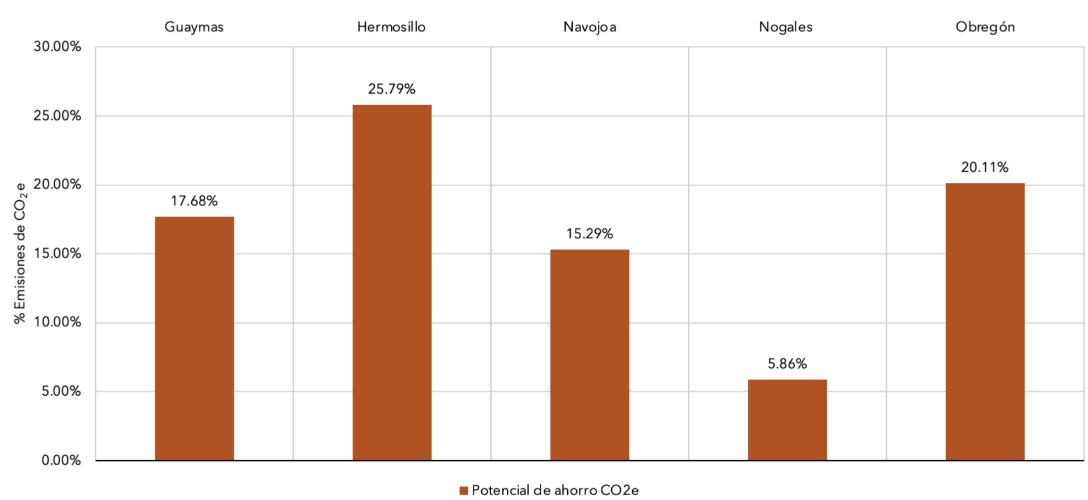

Figure 11. Potential CO2e savings per A/C season of the housing that complies with NOM-020 by city. Source: Preparation by the Authors.

Finally, the estimated CO_2 e saving potential of the dwelling that complies with NOM-2020 for the A/C use season is presented with the following values: Hermosillo 25.79%, Guaymas 17.68%, Navojoa 15.29%, Nogales 5.86% and Obregón 20.11%.

ANALYSIS AND DISCUSSION OF THE RESULTS

This study analyzes housing models located in a specific context, which considers particular climatic conditions, constructive characteristics typical of the region, and a specific energy tariff scheme. These factors vary considerably between regions, and consequently, energy poverty depends not only on the availability and cost of energy but also on the structural and cultural constraints that condition its efficient and safe use in each context.

This study considered housing of 43, 54, 61, 66, 78, 97, 104, 113, and 126 m2 to cover various areas according to the data of INEGI, (2020). Given its predominance in the region, the joist slab is used as a baseline (Romero Moreno et al., 2020). In addition, the study prioritizes shading strategies, limits insulation to 1 or 2 walls to a maximum of 1 inch, and uses up-to-date construction prices. These characteristics, together with the special tariff scheme for the State, represent the main differences compared to the analysis conducted by CONUEE (2017); no comparable study was found.

This study argues that although the current regulations require significant improvements in the calculation methodology, if applied today, at least at its minimum level, benefits would be obtained, and it is possible to achieve the energy efficiency range specified in the standard by combining various strategies.

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Since the same models were used for all the cities analyzed, Figure 2 shows the impact of climate on the efficiency level according to the calculation method, where Hermosillo is the most critical case. The case of Nogales suggests that, on average, homes in their initial state meet the efficiency level. This compliance would only apply to the efficiency of air conditioning, but there is no way to evaluate the efficiency conditions in the period with low temperatures. In Figure 3, the 1N_43 model has the smallest area and the highest WWR percentage, being the worst evaluated in all cities, even having negative percentages in Nogales. However, NOM-020 would not apply in Nogales according to the resolution of NOM-020 (2016). The 1N_43 model exemplifies a housing segment requiring summer efficiency strategies, especially for the more vulnerable.

On the other hand, in Figure 3, the 1N_97 model is the best evaluated as it complies in Navojoa, Nogales, and the rest of the cities. Although it has a negative value, the values are closer to zero. What can be seen from this is that this model has the lowest WWR (see Table 2).

When it comes to orientation, as expected, the east or west-facing houses are the most critical, but a significant change is observed when the same models face north or south. For example, in Hermosillo, the west-facing models have an average of -40.53%, but the same models facing south achieve an average of -15.68, obtaining a difference of 24.85 percentage points; see Figure 4. It should be clarified that some of the analyzed models had a higher WWR on the rear façade. Therefore, houses with a south-facing main façade get a better evaluation than the north-facing one. Thus, a fundamental strategy to comply with the regulations would be to modify designs to minimize transparent surfaces in unfavorable orientations, regardless of where the main façade is.

As already mentioned, NOM-020 would not be mandatory for Nogales. However, 31% of the homes analyzed required improvements (Figure 5), most solved with shading systems. In very few cases, walls used insulation (Figure 7), representing an average cost overrun of 0.68% (Figure 8).

In the case of Navojoa, 83% of the analyzed models required strategies (Figure 5), where most cases were solved with shading systems, and about 20% would require insulation and window improvement (Figure 7), with an average cost overrun of 1.61% (Figure 8).

Guaymas and Obregón required improvements in 94% of the evaluated cases (Figure 5). The strategies to achieve this include shading in all the improved models. About 40% of the cases required insulation in one or two walls and improving the window characteristics (Figure 7), representing an average overrun of about 2% per dwelling (Figure 8).

Finally, the most critical case is Hermosillo, where all the models evaluated required strategies; 100% were shaded, 81% required insulation on one or two walls, and 53% required window improvements. This city represents the largest average overrun with 2.95%, but also represents the greatest savings in energy consumption and expenditure (Figures 10 and 11). It should also be considered that Hermosillo is the most populous city in the state of Sonora, so energy savings by applying the standard would potentially have more impact than in other cities.

It is important to highlight the impact of the tariff scheme on energy expenditure, as the subsidy can cover up to 75% of the total bill depending on the level of consumption, where the cost of the surplus kWh can be up to five times higher than that of the first level. Although this measure is not sustainable in the long term for the treasury or the environment, it is effective and benefits a large part of the population. Without this government support, most households would find the estimated energy costs unaffordable. In the absence of energy efficiency in housing, energy subsidies have worked as a temporary solution to alleviate this economic burden.

CONCLUSIONS

Complying with the minimum level of NOM-020 in the State of Sonora would represent, on average, an overrun of 1.93% in construction, benefiting from a potential economic savings of 26% for electricity from April to October and a decrease of 16.95% in CO_2e emissions. This was achieved without needing to change the construction systems commonly used in the region's housing or using excessive insulation. Also, priority was given to shading systems, and insulation was limited to 1 inch on a wall for a maximum of 2 walls.

The most critical cases are homes with a smaller surface area because the WWR is higher and considerably impacts the calculation, especially if the windows are placed in critical orientations, especially in extreme climates like Hermosillo. On the other hand, models were identified that required additional improvements in cooler climates, such as the case of Nogales. However, these could have been avoided if an orientation and adequate window protection for the hot season had been considered from the design stage. In no case is the efficiency of the envelope during the cold season known. Implementing efficiency strategies to "correct" these models considerably impacts the housing cost due to the ratio of the investment cost versus the housing cost.

In addition, with the analyzed data, the following appropriate configurations are proposed for each analyzed locality:

- For Nogales, shading windows during the hottest season can be effective in complying with regulations, as can avoiding west-facing windows or, where appropriate, placing the smallest windows on this side.
- For Navojoa, besides the shading strategy in the hottest season, it is important to avoid east—and west-facing windows or place the smallest windows on these sides. In some cases, the wall insulation strategy is required.
- For Guaymas and Obregón, apart from the shading strategy in the hottest season, insulation on one or two walls and/or an improvement in the window quality is relevant, depending on the dwelling's specific design. It is important to avoid, as far as possible, east—and west-facing windows. If needed, smaller ones must be used on these sides.
- Finally, for Hermosillo, the shading strategy is essential in the hottest season. The vast majority of cases require insulation on one or two walls, and an improvement in the window quality has a considerable impact depending on the specific design of the house. Avoiding east- and west-facing windows as far as possible, particularly in the west, is imperative.

Habitability of spaces is guaranteed through a regulatory framework that integrates building regulations and energy efficiency standards, aligned with their objectives, and adapted to the specific context, requiring developers and builders to comply with minimum standards of quality, accessibility, and sustainability in the context of climate change. However, in reality, this is not the case. In this sense, it would be advisable for municipalities to include a series of best local design practices in the building regulations that consider specific temperature conditions and minimum and maximum window-to-wall ratios by orientation without neglecting the issue of ventilation and daylighting. In addition, it could also be established in the regulations that the base construction systems analyzed here, or similar, are considered as minimum constructive characteristics for urban housing.

Although improving the current calculation method of NOM-020 and considering the municipality's and architecture and construction professionals' implementation capabilities are necessary, its application must begin immediately. Applying the current regulations represents an opportunity to improve living conditions; in the meantime, the work on improving the current regulations must continue.

In future research, it would be essential to conduct more accurate projects on the thermal conductivity values of locally produced materials to facilitate the adaptation of constructive solutions to the region's specific conditions. Also, since the tariff scheme is based on consumption levels, it would be relevant to develop innovative strategies that allow users to monitor and manage their consumption to maximize the benefits of this tariff structure.

CONTRIBUTION OF AUTHORS CRediT

Conceptualization, C.M.G.B., A.C.B.A., J.M.O.de la T., I.M.L.; Data curation, C.M.G.B.; Formal analysis, C.M.G.B., A.C.B.A., J.M.O.de la T., I.M.L; Acquisition of financing, J.M.O.de la T.; Research, C.M.G.B.; Methodology, C.M.G.B., A.C.B.A., J.M.O.de la T., I.M.L.; Project management, J.M.O.de la T.; Software, C.M.G.B.; Supervision, A.C.B.A., J.M.O.de la T., I.M.L.; Validation, C.M.G.B.; Visualization, C.M.G.B.; Writing - original draft, C.M.G.B.; Writing - revision and editing, C.M.G.B., A.C.B.A., J.M.O.de the T., I.M.L.

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