Predicted Medium Vote Thermal Comfort Analysis Applying Energy Simulations with Phase Change Materials for Very Hot-Humid Climates in Social Housing in Ecuador

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Abstract: This work aims to estimate the expected hours of Predicted Medium Vote (PMV) thermal comfort in Ecuadorian social housing houses applying energy simulations with Phase Change Materials (PCMs) for very hot-humid climates. First, a novel methodology for characterizing three different types of social housing is presented based on a space-time analysis of the electricity consumption in a residential complex. Next, the increase in energy demand under climate influences is analyzed. Moreover, with the goal of enlarging the time of thermal comfort inside the houses, the most suitable PCM for them is determined. This paper includes both simulations and comparisons of thermal behavior by means of the PMV methodology of four types of PCMs selected. From the performed energy simulations, the results show that changing the deck and using RT25-RT30 in walls, it is possible to increase the duration of thermal comfort in at least one of the three analyzed houses. The applied PCM showed 46% of comfortable hours and a reduction of 937 h in which the thermal sensation varies from “very hot” to “hot”. Additionally, the usage time of air conditioning decreases, assuring the thermal comfort for the inhabitants during a higher number of hours per day.

Keywords: predicted medium vote; thermal comfort; energy simulation; phase change materials; social housing

1. Introduction

Worldwide, the construction sector is responsible for over one-third of the overall consumption of electric energy, and it produces nearly 40% of the total direct and indirect CO₂ emissions. Moreover, the energy demand of buildings is increasing and is driven by factors such as a wider access to energy in developing countries as well as a greater usage of high energy-consuming appliances [1]. On the other hand, residential buildings consume about 10% of world delivered energy, which is increasing at the rate of 1.5% per year as reported by the International Energy Agency (IEA) [1]. Likewise, building electricity consumption accounts for 28% of the total energy use in non-OECD countries, which are continuously rising. Under these constraints, the goals of different studies and national laws are to identify the most effective policies, standards, and practical energy efficiency measures as viable alternatives for saving energy. Those measures, in terms of parameters and indicators, can be taken from worldwide experience and incorporated in existing regulations considering local conditions. Particularly, in Latin America, Mexico, Brazil, Uruguay, and, recently, Chile and Colombia have created their own standards of energy efficiency in buildings [3,4] with sustainable certifications such as LEED (Leadership in Energy and Environmental Design), BREEM (Building Research Establishment Environmental Assessment Methodology), or EDGE (Excellence in Design for Greater Efficiencies).
Moreover, the usage of air conditioning systems (A/C) makes one of the highest contributions to the increment of energy consumption in buildings. To illustrate, in South America, the installation of individual equipment (splits) aligned with each window of the home is a common practice, especially in social housing, due to its low price. However, this technique has a high energy consumption, and the normal solution is to install centralized systems at the top of buildings. Several studies have found that the location of the A/C systems can influence the temperature outside of buildings [5]. This effect is the global rise of temperatures inside cities, and it produces adverse environmental conditions for long periods of time, even during the night. This effect is known as Urban Heat Island (UHI).

Several South American cities have grown up very fast during the last years, and these cities are affected by UHI because of their weather conditions and A/C systems usage. The research conducted by Palme et al. [5] shows UHI effects on the climate of Guayaquil in Ecuador, Lima in Peru, and Antofagasta and Valparaiso in Chile. The main results of Palme et al. found that Valparaiso and Guayaquil seem to have higher UHI effect than Lima and Antofagasta because of the difference in the temperature ranges (higher maximum temperatures) of the analyzed cities. In this sense, some hypotheses are considered to explain the UHI effect such as the influence of the Pacific Ocean, urban form, heat generation on the street, building energy consumption (especially cooling), and impervious materials. To point out, it was verified that the UHI intensity can increase by 20–40% in cities like Lima or Guayaquil because of informal urbanization [6]. Accordingly, urban socio-economic segregation suggests that the impact might be tremendous in the poorest neighborhoods, where heat vulnerability is driven by inappropriate housing materials.

Taking into consideration the climate vulnerability in the poorest neighborhoods and data mapping versatility, Gallardo et al. [7] forecast the thermal comfort deficit inside of the social housing built in Ecuador. To this end, building energy simulations for those dwellings were carried out considering the climatic conditions of all parishes in continental Ecuador. Here, thermal comfort was evaluated by means of the adaptive comfort model included in CEN Standard EN15251 [8]. The results show areas in the Andean Highlands where there is a significant thermal comfort deficit, which may cause health problems for inhabitants. Thus, the study recommends that future public investments in building refurbishment use the obtained mapping as a support tool to promote and prioritize the retrofit of the social housing stock at a national scale.

Due to the high complexity of climatology studies for any attempt to summarize their features, software tools are essential to collect and analyze a large amount of this data. Therefore, mapping is a suitable solution for presenting and summarizing this information. Recently, several studies have displayed complicated phenomena using mapping, which enables making decisions easier and enclosing future study cases in smaller samples. For example, delimitation of the final energy use in the urban space of New York is presented by [9], and [10] shows a space-time characterization of the energy consumption for finding patterns in districts and neighborhoods in Switzerland.

Furthermore, climate and weather play an important role in shaping the patterns of energy consumption in buildings. Energy demand is typically more dependent on climate and weather changes in the residential sector than in the commercial sector [11]. Therefore, the influence of temperature in their energy demand in the residential sector makes the relationship between temperature and energy demand a crucial aspect to be considered in the management of energy in urban areas. As an illustration, the study of Ang et al. [12] in Singapore (hot and humid climate) found that a temperature increment of 1 °C will increase the residential electricity consumption by 7.8%, which is much higher than the corresponding increment in commercial and industrial sectors. Likewise, the findings from previous studies suggest that temperature is the most important factor to influence the per-capita residential electricity consumption, explaining about 68% of the variation in electricity consumption. In Singapore during 2008–2016, it was much lower than during 2005–2007, although the temperature did not show much difference in both periods of time. A possible explanation is the various energy-conserving measures taken by Singapore
government since 2008. This finding may shed some light on the effectiveness of the impact of public policies on residents’ energy consumption behavior.

In addition, Xian-Xiang Li et al. [11] present that public households, like social housing, are sensitive to the outdoor climate, and their electricity consumption per household has a higher correlation with climate variables compared with private households in tropical cities. Moreover, because of the increasing ownership rate of electricity-consuming appliances (e.g., air conditioners and refrigerators) in households, their electricity consumption has a growing trend, so its correlation with climate variations is poor. Under the worst climate change scenario, the projected raise in per-capita and household electricity consumption could be 47% and 41%, respectively.

In this sense, it has been shown that regulatory approaches must be applied in order to encourage the decrease of energy consumption in buildings. Specifically, energy conservation measures (ECMs) such as insulation, better-performing glazing, solar shading, incorporation of new materials (phase change materials and others) [12], and integration of renewable or clean energy technologies within the building services can be suitable solutions. Nonetheless, the intermittency of clean energies presents a challenge to downstream applications that require a steady energy supply. In contrast, in recent years, Thermal Energy Storage (TES) has drawn the attention of researchers owing to its capability of resolving it. Among the other types of TES systems, the Latent Heat Thermal Energy Storage (LHTES) system charges and discharges the heat power by utilizing phase transformation of Phase Change Materials (PCMs). Being able to provide a high storage density and a constant temperature output, LHTES is regarded as a very promising energy storage technique [13].

Literature shows that incorporating LHTES into air conditioning systems is crucial to maximize the solar harness as well as to provide a reliable and steady alternative to the air conditioning system subject to the requirements of buildings. In this way, a proper selection of the PCM is the first important step in the design stage, and it is necessary to consider the phase change temperature, specific heat, density, thermal conductivity, and materials with high latent heat of fusion [13]. PCMs with adequate selection of thermal mass properties in building envelopes reduce indoor temperature oscillations and lag thermal conduction. Moreover, PCMs have a better application in climates with outdoor temperatures oscillations with magnitudes of 10 °C [14].

Regarding studies for selection of PCMs applied in buildings, Rastogi et al. [13] supply an accurate approximation of the PCM behavior and simulation methods. Nevertheless, the effects of the climatic conditions of surroundings on the performance of PCMs are not considered. In fact, there is no clear data about both location and constructive/architectural characteristics of the building. Even though the results show a good agreement in thermal properties such as fusion heat, specific heat capacity, thermal conductivity, and density for the applied simulation methods, the study did not consider the effect of the environment to assess the performance of PCMs. Subsequently, the study states that the thermal performance is appropriate for the entire day in cold and semi-humid climates.

In this way, the coastal zone of Ecuador presents environmental conditions of prolonged periods of heat during most of the year. The thermal conditions of this zone, a very hot humid climate, are almost constant with a temperature range of 23 °C to 36 °C. This is a feature characteristic of the coastal zones of the equatorial area [15]. This problem has been solved by using fans and A/C systems. Nonetheless, as explained before, it has a negative effect, which is the raising of the environmental temperature of cities. To avoid this fact, studies have already been carried out in Ecuador on the use of PCM, which, added to construction materials, allows the temperature to be kept constant, therefore creating the appropriate environmental conditions inside the houses and avoiding the excessive use of mechanical-electric systems [16–18]. The study conducted by [16] demonstrates with simulations that it is possible to use PCM in very hot humid climates, like the conditions of Guayaquil city in Ecuador. PCMs in walls and roofs could misbehave during the night due to the accumulation of thermal energy during the day. However, it is possible to determine
proper PCMs for different weather conditions through energy simulations in houses even with air conditioning systems.

Castilho’s et al. [19] carried out simulations to evaluate the performance of PCMs. A PCM was used in a school building with high energy gain provided by computers (i.e., 28 W/m²). The PCM was inserted into the roof and walls of the building. In addition, the authors evaluated the material considering zones with air conditioning systems and without it. Even though an hour-by-hour evaluation of the inner temperature was carried out, the effects of the surface temperature, heat gain, and heat losses through walls were neglected. In this sense, simulation modeling, the widely anticipated energy performance assessment methodology, is distinguished with its capability to replicate the thermal behavior and energy performance of a building [20]. Validation and testing became of utmost importance to accurately assess the realistic energy performance of buildings.

Despite the accurate assessment presented for building energy performance in national/international standards, the discrepancy between design predictions and the as-built energy performance in buildings is still significant. It is highly influenced by factors which affect the energy consumption (such as occupant behavior, simulation model simplifications, poor assumptions, etc.) [20]. In addition, simulation modeling was well-designated as an assessment methodology that requires a certain degree of confidence. Hence, to holistically address a whole-building energy performance assessment by means of a simulation model, it is imperative to implement a calibrated building energy simulation approach [21].

Although building energy simulation (BES) models were intended to be applied in the design phase, these models have become tools that allowed complex calculation of the energy performance in existing buildings, mainly to evaluate the effects of ECMs. This approach emphasizes the importance of acquiring climate data for the case building (1), building design (2), geographical data (3) (location, orientation, obstructions etc.), construction data (4), building installation characteristics (5), building operations (6), occupancy (7), and schedules (9) [22]. However, an inadequacy in the abovementioned data could result in a discrepancy between simulation results and the actual thermal behavior of the building. In this sense, several studies have established that simulation models out of calibration produce discrepancies between the monitored and calculated consumption levels in the range of ±30%, and they suggest that those discrepancies can even rise to a range of ±90% for end uses such as chilled water, hot water, and electricity consumption.

In order to evaluate the effects of ECMs in building energy performance, it is necessary to obtain a base case simulation model which represents the existing thermal behavior of the studied building as closely as possible. In this respect, the findings of the study conducted by Guyceters [21] suggest that long term data monitoring (full year) could facilitate an accurately calibrated building energy simulation model through a manual iterative method. Such an approach could also be influential on reducing the energy performance gap and discrepancy between the simulated and monitored energy performances of buildings.

Bearing in mind the reliability of simulation models and the fact that buildings should be designed to provide comfort for inhabitants, Vautherot et al. [23] carried out energy simulations to evaluate both energy requirements and discomfort hours when different PCMs are used in air conditioning systems of houses. The energy requirements of HVAC (heating, ventilation, and air condition) systems were compared with the discomfort hours associated with each PCM. Nevertheless, the energy calibration of the analyzed model based on monitoring environmental parameters was not considered.

The study of comfort is particularly important for vulnerable populations, such as those who inhabit social housing because they can be more sensitive and prone to illness under the exposition to high or low temperatures, resulting in a constant problem [24]. Studies demonstrate that buildings had a high prevalence of discomfort due to high heat in summer, with some places most of the time above 28 °C. Literature on social building reveals that thermal discomfort is produced by high temperatures instead of low ones. However, the same sources identify that there are few researchers who address this problem using long term measured hygrothermal data and surveys of inhabitants.
In fact, Gaudy Bravo y Gonzales Bravo, 2006 [25], applied measurements and comfort surveys to inhabitants in their research. Moreover, the PMV method was used in three types of social and emergent housing in Maracaibo, Venezuela. The PMV indicator [26] allows evaluating the thermal sensation of the environment and is useful for projecting or modifying a thermal environment by identifying the percentage of comfortable hours and type of discomfort [27]. It is stated that inhabitants felt comfort sensations around $-1 < 0 < 1$ against high values of dry bulb temperatures, relative humidity, and limited airspeeds. As a result, people preferred slightly colder or fresher environments (73% y 75%, respectively). Moreover, the linkage between discomfort manifestation and acceptance range is reflected by the prevailing selection of options of predominant manifestation of heat in the applied surveys. In this way, and in response to environmental conditions (outside and inside), people dress in light clothing, or they spend much time outside their homes.

In Ecuador, it is clear that the residential sector occupies the third place amongst energy demand sectors. This represented 13.2% of the total energy consumed in 2018. Besides, this sector consumed 29.7% of the national electricity generated, and it produced 8.4% of the total greenhouse gasses emitted in 2018 [28]. For this reason, the implementation of thermal comfort strategies represents a priority for cities because of the positive impact in the reduction of energy demand over socio-economic dynamics and natural environment [29]. Therefore, buildings and their materials should assure a performance that is efficient in energy terms by limiting heat losses and fulfilling comfort conditions. Nonetheless, there is no available evidence regarding the evaluation of thermal comfort hours per year in buildings with the use of PCMs following a standardized methodology, and there are no studies with calibrated simulations with monitored information to obtain results closer to reality. In this sense, the aim of this study is to analyze the effect of four different PCMs (Commercial stearic acid esters supported on spent diatomite [14,17,18], paraffin of the type n-Octadecane, Bio PCM-Q29, and RT25-RT30) on the thermal comfort in social housing under very hot-humid climatic conditions by using the Predicted Medium Vote Thermal Comfort Analysis.

In this context, the present research answered a crucial question:

What is the contribution of the use of PCMs as building materials to the thermal comfort in social housing and to the reduction of electricity consumption?

To provide an answer for this question, this work estimated the hours of PMV thermal comfort in three types of social houses (low, medium, and high electricity consumption) with the same architectural features in the social neighborhood, “Socio Vivienda 1”, in Guayaquil-Ecuador [27]. It should be highlighted that the last three PCMs are commercial and they were analyzed by [16] in Guayaquil. Therefore, in order to determine the most suitable PCM and its envelope location for the studied houses, this research included both simulations and comparisons of thermal behavior in 2019 using the methodology of predicted medium vote (PMV). Furthermore, the influence of climate conditions on energy consumption and its impact on social buildings is studied as are strategies for future refurbishments and new constructions. This study can be used as an adjustment mechanism for the mitigation of global warming impact, which is also responsible for the UHI effect in cities.

2. Materials and Methods

This study initially analyzes the electricity consumption, the geographical location, and the influence of the climate on an urbanization that has houses with similar architectural characteristics. Through this analysis, 3 representative case studies were selected. The results of the thermal behavior of the study cases were obtained through energy simulation, and the thermal comfort was evaluated using the PMV method during 2019. In addition, 5 alternatives for improvement were proposed that were compared with the results of the current state. The alternatives evaluated include the use of phase change materials in walls. The methodology used in this research follows the steps shown in Figure 1.
2. Materials and Methods

This study initially analyzes the electricity consumption, the geographical location, and the thermal comfort was evaluated using the PMV method during 2019.

2.1. Selection of Reference Dwellings

In the coastal zone of Ecuador, social housing is one of the most affected sectors due to lack of thermal comfort. In this zone, the environmental conditions present prolonged periods of high temperatures during most of the year. For this reason, the social housing of Guayaquil, a coastal city, has been selected to evaluate the thermal comfort and possible sustainable solutions to allow the temperature to be kept constant, propitiate an appropriate environmental conditions inside the houses, and to avoid the excessive use of mechanical-electric systems [16–18].

2.1.1. Description of the Area under Study and Electricity Billing Fees

In this study, the first stage of the social housing program “Socio Vivienda 1” (SV1), which aims to provide an offer of houses for low-income population in Guayaquil City [30–32], was selected to analyze thermal comfort. The houses are located in northwest Guayaquil, and the first stage, estate SV1 (Figure 2), delivered the first houses in 2010.
On the other hand, in Ecuador, at the residential level, there are three electricity fees: a “commercial” fee for houses that involve a business or trading activity, a “PEC” fee (efficient cooking program) for houses with an induction cooker, and a “residential” fee [33]. Eight hundred and ninety residential fee customers were selected due to their lower energy consumption, as shown in Table 1. The data of monthly energy consumption of every energy-meter of the estate SV1 from 2013 to 2018 were provided by the official Ecuadorian provider of the electric service of Guayaquil (CNEL-EP).

Table 1. Energy fees in Ecuador for residential uses.

| Quantity of Households | Fee                              | Mean Energy Consumption [kWh-Month] (2013–2018) |
|------------------------|----------------------------------|--------------------------------------------------|
| 1266                   | Commercial, PEC, and others      | 319.5                                            |
| 890                    | Only Residential                 | 135.96                                           |

Once the data was sorted, consolidated, and processed, it was complemented with the geographic location of every house by using online information from the “Geoportal” tool developed by CNEL-EP [34]. This spatial analysis allows to identify historical variations in electricity consumption of the 890 homes and to identify the correlation between location and energy consumption.

2.1.2. Spatial Distribution Analysis

The energy consumption was determined by using the stochastic interpolation method of Kriging and Cokriging. However, this method does not assure that all variables can be interpolated. For that reason, it is necessary to fulfill conditions such as normality, homogeneity, enough quantity of available points, the spatial distribution of the points, seasonality type, and correlation to other variables for a valid variable interpolation.

The analysis started from a sample of 890 points that show a homogeneous spatial distribution over a 417,000 m² area, where the houses and service buildings of SV1 are located. For this matter, an experimental semivariogram was configured for each evaluated year from 2013 to 2018. The spatial distribution of the points and the average annual energy consumption of the sample were considered. Then, a linear model was used and adjusted with the iterative estimation of least weighted squares. The weights were determined as a function of the point-pairs number and the distance. Using this method, the value of the variable: consumption of a non-considered/non-existing location, in the sample, was obtained.

Finally, this method is presented yearly to visualize the evolution of consumption and to estimate the variation rate from 2013 to 2018. Besides, the intention is to learn how close the houses’ consumption rate is to the considered moderate values. The results are presented in rasterized images.

2.1.3. Climate Influence in Energy Consumption Analysis

Considering that the energy consumption related to air conditioning systems is highly influenced by ambient temperature [11], it is necessary to know the correlation that exists between these factors (monthly electricity consumption and monthly ambient temperature mean). To define the correlation grade between these factors, a mathematical function was defined by developing a linear regression between the analyzed variables. It was established as a function of the determination coefficient $R^2$ [35].

The environmental protection agency (EPA), establishes a minimum $R^2$ of 0.4 for correlations of simple adjustment and 0.7 for more complex correlations. Complementarily, in [36], it establishes that the adjustment curve is satisfactory for $R^2$ values greater than 0.75. This analysis was performed, and it determines that some buildings are adjusted to the established behavior. This made it possible to analyze some buildings, of the total sample, with the influence of the environment over the energy consumption and to determine
whether the houses have A/C devices or not. Furthermore, the customer’s house selection for means of analysis was performed.

For the selection of the reference houses, the variation of the historical electricity consumption was considered based on the spatial analysis. In addition, the climatic influence and other factors were considered to analyze 3 types of house (low, medium, and high electricity consumption).

2.2. Building Simulation

The present research seeks to evaluate the impact of the use of PCMS in walls on the thermal comfort. For this, once the analysis houses have been identified, an energy simulation of them is carried out to know the internal conditions and the thermal behavior of the envelope. For the energy simulation, DesignBuilder (V.4.7.0.027) is used to calculate and to estimate the thermal and energy behavior of a building considering several factors such as architecture design, meteorological conditions of the location, usage, equipment, and others. These simulations are calibrated according to the gathered data from sensors and measurement equipment installed in situ.

Nodal energy-transfer models for the three dwellings were constructed with DesignBuilder in order to obtain the variables to calculate thermal comfort. Once the energy base models were tuned to a good enough degree of precision, the energy simulation process was then used to predict, for 2019, the comfort scenarios that include the use of PCM in external walls. With the goal of obtaining a result close to reality, the solution algorithm was changed from conduction transfer function (CTF) into a finite differences algorithm. The main conditions contemplated in the construction of those energy models were the following:

- Each dwelling was considered as a unique space, although partitions were introduced between its rooms.
- The operational conditions, further described, were uniformly applied to the dwellings.
- The adjacent dwellings were considered as a unique space and without partitions between rooms and equipped and with the same operational conditions as the modeled house, which is why the transfer through the surfaces in contact with them was considered adiabatic.
- Only the kitchen and living room were considered as conditioned spaces, which is why it was assumed that there was thermal transfer through the surface in contact with the modeled dwelling.
- Shade from the building itself and that thrown by surrounding buildings and trees was considered.

2.2.1. Input Data

In SV1, each lot of one-family house area is 90 m\(^2\), and the total built area is 42 m\(^2\). The house is distributed in two bedrooms, one communal area for dining and kitchen, one complete bathroom, one porch, and one rear patio, as shown in Figure 3. The original houses were delivered first to have the same typology (architectural model and construction materials). They were built in blocks for two houses (paired). These houses were built for meeting the habitational needs of an average family of four members.

On the other hand, over the last year in this estate, it was noticed that some houses were modified from the original design, as evinced in Figure 3. The mentioned modification consisted in using the area intended as a patio for building additional rooms, such as bedrooms, bathrooms, storages, etc. All of this was done without demolishing the original house model delivered. Thermal properties of materials of the envelope elements for original and modified houses are the same, and they are shown in Table 2.
The climatic profile is an EnergyPlus weather file (EPW), developed by the U.S. Department of Energy. The file selected for Guayaquil was created from the data originating from the Meteorological station installed in Socio Vivienda 1. The hourly and daily data in 2019 are shown in Figure 4. The information was compared with the official Ecuadorian meteorological institution INAMHI, which supposes hot and rainy winters (August and September) and very hot and dry summers (January to July and October to December).

**Figure 4.** Guayaquil environmental air temperature at 2019.

- Location: Guayaquil (Ecuador) (S 2°7’ (W 79°57’) (GMT-5.0 Hour)
- Elevation: 4 m.s. Standard atmospheric pressure: 101,277 Pa
Table 2. Thermal properties of envelopment materials.

| Element    | Material                  | Thermal Conductivity [W/m°C] | Density [kg/m³] | Specific Heat [J/kg °C] | Solar Absortance [37,38] | Emisivity | Thickness [mm] [7] | Solar Transmittance [7,39] | Solar Heat Gain Coefficient (SHGC) [7] | U-Value [W/M²k] [7] |
|------------|---------------------------|------------------------------|-----------------|-------------------------|--------------------------|-----------|------------------|-----------------------------|---------------------------------|---------------------|
| Roof       | Surface                   | 0.41                         | 1251            | 1086                    | 0.78                     | 0.5       | 0.1              | 160                         | 0.3                             | 0.6                 |
|            | Metal slab                | 160                          | 2800            | 880                     | 0.3                      | 0.3       | 3                | 91                          | 0.6                             | 0.9                 |
|            | Internal Insulation       | 0.04                         | 91              | 836                     | 0.6                      | 0.9       | 8                |                             | 0.9                             | 8                   |
| Wall       | Plaster external (white color) | 0.7                         | 2778            | 840                     | 0.2                      | 0.9       | 5                |                             | 5                               |                     |
|            | Concrete block            | 0.81                         | 977             | 837                     | 0.6                      | 0.9       | 70               |                             | 70                              |                     |
|            | Plaster internal (white color) | 0.7                         | 2778            | 840                     | 0.2                      | 0.9       | 5                |                             | 5                               |                     |
| Window     | Single clear glazing      | 0.9                          |                 |                         |                          |           | 0.84             | 3                           | 0.837                           | 0.861                           |
| External door | Metal door                |                              |                 |                         |                          |           | 16               |                             |                                 | 3.124                           |
| Floor      | Ceramic/clay tiles        | 0.8                          | 1700            | 850                     | 0.6                      | 0.9       | 4                |                             |                                 |                     |
|            | Cast concrete             | 1.13                         | 2000            | 1000                    | 0.6                      | 0.9       | 70               |                             |                                 |                     |
|            | Earth, gravel             | 0.52                         | 2050            | 180                     | 0.6                      | 0.9       | 90               |                             |                                 |                     |
2.2.2. Calibration

Several studies have demonstrated that the results of a simulation are closer to reality when the analysis of a building includes the monitoring of energy consumption and the environmental variables during a proper period. This technique is called calibration. For this reason, sensors of temperature were installed to determine the temperature of the air inside the selected houses.

According to the described methodology by [21], the first step for energy calibration of a building is to set a preliminary analysis to estimate an initial thermal and energy behavior, by using the data from the monitoring of electric consumption, materials, usage, equipment, and architectonical model. This first analysis aims to evaluate the factors that most affect the thermal and energy behavior of the house. This information is used to make a global energy balance. Then, the values of the factors (global heat transfer coefficient $U$, solar absorptiveness, emissivity, and thermal conductivity) were adjusted and modified on the simulation software. This analysis gathered information from studies from [7,37–39], equipment [40], and 10 kW split system as air conditioning [41]. Finally, the verification variable that will grant acceptance of the calibrated model is the air temperature inside the customer’s house. The thermal properties of the considered and calibrated elements are displayed in Table 2.

The model was successfully calibrated after several energy simulations, according to ASHRAE Guideline 14-2014 [42]. This standard establishes that the calibration is accepted when the Coefficient of Variation of the Root-Mean-Square Error (CV[RMSE]) and the Normalized Mean Bias Error (NMBE) are calculated. These parameters arise from the real horary values, which are obtained from the monitoring devices and compared with the simulation results. According to the standard, a calibration is accepted when the values from an energy simulation, compared to real values, must remain within a range up to 30% and 10%, for CV[RMSE] and NMBE, respectively.

It must be considered that the methodology described by ASHRAE Guideline 14-2014 expresses that the raised information is used for energy consumption analysis. Nevertheless, this research counts additionally with the data of air temperature, inner and outer surface’s temperature of a window, roof, and a wall. Besides, to accept the calibration conditions of the construction materials, the methodology described in Guyceter’s work was used [21].

Once the monitored house achieves the previously normalized values, the data of the thermal properties of the materials were used. It helped the simulation of high and low consumption customer’s houses. For usage and electric consumption of the house’s equipment, the models were calibrated with the monthly rates of energy consumption delivered by CNEL-EP for 2018 and also took into consideration that these houses use A/C systems.

After the housing simulation had been calibrated, it was possible to modify any parameter and know its real effect on its behavior. In this sense, this research studies the influence of the use of phase change materials in the walls of the house on its internal conditions through results obtained from the simulation.

2.2.3. Phase Change Materials (PCM) as Alternative to Improve Thermal Comfort

For effective selection and evaluation of PCMs in the study zone, studies from [16,18] were considered. In the study [18], the thermal comfort of rooms located in Quito, Guayaquil, and Zumbahua (cities of Ecuador) that provided diatomaceous earth (material locally obtained) as phase change material in walls and ceiling was evaluated with energy simulation. This material causes a positive effect on the thermal comfort of the occupants; thus, the long-term evaluation of diatomaceous earth is suggested.

On the other hand, the thermal and energy behavior of several PCMs with energy simulation in social housing located in Guayaquil, Quito and, Francisco de Orellana (cities of Ecuador) are evaluated by [16]. By using statistical methods and energy simulation, the
most suitable PCMs were selected for each climate type noting that, for Guayaquil, the best PCMs are n-octadecane (paraffins), RT25-RT30, and BioPCM-Q29 (all commercial types).

Moreover, both studies were conducted for Guayaquil city, which has a humid—very hot climate. According to climate-habitational zoning, the use of PCMs as constructive elements must be directed to walls so the phase changing effect will take place. For this reason, for energy evaluation, the 4 previously described materials were incorporated in the house’s external walls. Furthermore, it was proposed to totally change the actual roof for one, locally accessible, made of insulating materials. PIR (polyisocyanate) material of 23.1 mm thickness was evaluated. The constructive sets for walls and roof are detailed in Figure 5. According to the materials used in walls and roofs, different study cases were defined. The base case corresponds to the house with its original envelope materials; Case 1 corresponds to the house with a 23.1 mm thick polyisocyanate roof. The remaining cases correspond to the house with a polyisocyanate roof and all the external walls with a specific PCM: Case 2 with Bio PCM Q29, Case 3 with n-octadecane, Case 4 with RT25-RT30, and Case 5 diatomite earth unused.

The necessary thermal properties to carry out energy simulation of PCMs were taken from [16,18] studies and complemented with technical data sheets from suppliers. An important aspect is the mathematical method that the software will use for the evaluation of energy and thermal behavior. In this context, the software allows changing the calculation method to finite differences, which, according to studies from [43], permit one to obtain values that are closer to reality. Besides, one of the important aspects to load in the software are temperature [°C] vs. enthalpy [kJ/kg] graphs. The plots of the analyzed PCMs in this research are displayed in Figure 6.

Each type of PCM is implemented in the calibrated model of the three selected types of dwellings. The simulation is conducted, and the necessary variables are obtained from each case study, which allow evaluating thermal comfort using the PMV method described by ASHRAE 55-2017 [27].
2.3. Comfort Evaluation

According to ASHRAE, thermal comfort is a mental condition related to the thermal satisfaction that the inhabitants feel. For that reason, this parameter is subjectively analyzed. Several techniques allow us to determine whether a thermal environment is acceptable or not for occupied spaces. The “Analytical comfort zone method”, outlined by ASHRAE, is the method applied in this research. Its applicability is defined for spaces where air velocity is lower than 0.2 m/s, the occupants develop activities with average metabolic rates from 1 to 2 met and use clothing that represents an insulation between 0 and 1.5 clo.

This method uses as an evaluation parameter the predicted medium vote (PMV). It is defined as an index of the thermal feeling votes. The variation scale is expressed from \(-3\) to \(3\) with \((-3)\) very cold”, “\(-2)\) cold”, “\(-1)\) slightly cold”, “\((0)\) neutral”, “\((1)\) slightly hot”, “\((2)\) hot” and “\((3)\) very hot”. In this research, the thermal comfort was defined for a 0.5 step.

The PMV is calculated by Equation (1):

\[
PMV = TS \cdot (MW - HL_1 - HL_2 - HL_3 - HL_4 - HL_5 - HL_6),
\]  

where \(TS\) is the thermal sensation transfer coefficient; \(MW\) is the internal heat production in the human body; \(HL_1\) is the heat loss difference through skin; \(HL_2\) is the heat loss difference by sweating; \(HL_3\) is the latent respiration heat loss difference; \(HL_4\) is the dry respiration heat loss difference; \(HL_5\) is the heat loss by radiation; and \(HL_6\) is the heat loss by convection. The calculation of PMV requires different input data. Information about occupants is defined as constant values, and the indoor environment characteristics are defined as hourly input
data. The metabolic rate and clothing insulation of the house’s occupants were obtained by on-site verification. Air temperature, radiant temperature, air velocity, and relative humidity were obtained from the energy simulation. The first evaluation of the thermal comfort of the three types of houses is known as the base case.

Next, for the evaluation of thermal comfort of the customer’s houses with energy efficiency strategies, this research aims to learn the impact of using different Phase Change Materials (PCM) as constructive materials to improve the environmental conditions inside the house. Considering that weather conditions fluctuate over the year, the PMV was calculated as 8760 h in 2019 year by using the equations defined in APPENDIX B of Standard 55 by ASHRAE [27]. In total, 6 cases were evaluated and showed for each selected house. The first was the base case (unmodified house), the second was the house with only the roof changed (case 1), and the next cases are derived from an information recompilation of 4 PCMs that were found suitable for the studied zone.

With the previously mentioned data and the environmental conditions obtained from energy simulation inside the houses, the PMV method was applied and its results are shown below further. These results are compared by frequency histograms: (a) total comfortable hours percentage (−0.5 < PMV < 0.5), total uncomfortable hours by low-temperature percentage (PMV < −0.5), and total uncomfortable hours by high-temperature percentage (PMV > 0.5) and (b) total hours for each division, with 0.5 step from “(−3) very cold” to “(3) very hot”.

3. Results and Discussion

In this section, the results of the selection of reference homes are presented, for which a spatial distribution analysis and study of the influence of climate were carried out. In addition, the calibration of the models used for the simulation and the results obtained for each case study are presented. Finally, based on the results of the simulation, an analysis of thermal comfort is carried out by using the PMV method.

3.1. Selection of Reference Dwellings

Through the applied methodology for the selection of the reference dwellings, the following results were obtained: (i) the representative values of the annual electricity consumption of the dwellings for residential use, (ii) the historical trend of electricity consumption depending on the geographical location, and (iii) the level of influence of the climate on the use of electricity.

3.1.1. Description of the Area under Study and Electricity Billing Fees

From the data collected about the monthly electricity consumption, the representative values were obtained and presented in Figure 7. This corresponds to the average annual consumption of 890 homes, only of residential use, from January 2013 to December 2018. Eighty percent of the houses have an average annual consumption between 634 kWh/y and 2410 kWh/y. In addition, it is observed that an average annual consumption greater than 4100 kWh/y and less than 634 kWh/y is unusual. To identify whether the location of the homes influences their electricity consumption, or if there are constant consumption trends over time according to specific areas a spatial analysis is performed.
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![Figure 7. Histogram of mean electricity consumption of 890 houses from 2013 to 2018.](image)

3.1.2. Spatial Distribution Analysis

The spatial distribution analysis was performed from 2013 to 2018, and the obtained results are shown in Figure 8. The linear models applied to the sample allowed us to determine the consumption for the entire area of study. Figure 8 displays the consumption models obtained for SV1 estate.

The spatial analysis shows the similarity between the near values of the sample points, which are permitted to detect local consumption patterns. Thus, it is possible to note that for 2013, the project’s southern zone presents a higher consumption of energy, with an average of 1524 kWh/y, than the northern zone, with an average of 1116 kWh/y. This indicates that human activities were initiated in the southern zone, and this characteristic repeats every year. Another aspect that justifies the growth of energy consumption in the south zone is the higher development of anthropic activities. In this area, schools, business
places, and better access to the main streets that connect people to public transportation and downtown exist. This characteristic is typical of coastal cities of South America, as shown in the study by [5]. This work mentions that for cities with seaports, commercial activities are fundamental for economic development, and they grow informally, as happens in Lima, Peru, and Antofagasta and Valparaiso, Chile.

Figure 8. Spatial distribution of the yearly energy consumption of each lot.

The growing trend, over time, of different levels of electricity consumption in the areas of SV1 shows the importance of studying homes that are located in low, medium, and high consumption areas. This permits us to know the impact of the use of PCM in homes with different energy behaviors despite presenting the same design and materiality.

In Figure 8, a pattern is also observed in the monthly electric consumption as of 2014: February, May, August, and November are the months of higher consumption. This is probably because vacations and/or holidays take place during these months, when people tend to stay at home for longer periods of time.

On the other hand, electricity consumption in some houses does not follow a pattern of specific consumption and typical behavior. Nevertheless, it was observed that energy consumption increases over the years. Whereas the monthly electric consumption of 2013 was 112 kWh, the value for 2018 was 150 kWh. Over six years, it approximately represents a 15% increase. It can be triggered by the increase of purchasing power of the inhabitants. This includes the acquisition of equipment, such as televisions, electric fans, refrigerators,
etc., which raises the load charge of the house. Besides, in some cases, equipment for air conditioning was possibly acquired. However, to define this scenario with precision, it is necessary to collect information of each one of the houses, a difficult task to carry out. Taking the mentioned factors into account, an analysis of the climate influence over the energy consumption was carried out.

3.1.3. Climate Influence in Energy Consumption Analysis

For this analysis, information was collected from a weather station located in the city of Guayaquil from January 2013 to December 2018. Based on the data, the average monthly ambient temperature and relative humidity were calculated. By means of linear regressions, the correlation between the monthly electricity consumption of the 890 dwellings and the corresponding ambient temperature and relative humidity was identified.

When evaluating the climate influence over electric consumption, a correlation with humidity was not observed. Thus, the analysis was focused on the ambient temperature. It was observed that in 2013, 12 houses showed an electric consumption highly influenced by weather, while in 2018, the number of houses influenced reached 263. It is estimated that nowadays, approximately 30% of the analyzed housing units may be using air conditioning systems. Studies such as those of [5] indicate that there has been a growth in the use of A/C systems for cities like Guayaquil, especially the Split type. In this sense, this problem has a great impact, especially in areas destined for the construction of social housing, and its effects are evident in events such as heatwaves [5].

To evaluate the annual climatic influence on electricity consumption in houses with air conditioning systems, the correlation between the average monthly environmental temperature and the average monthly electric consumption, of the 12 houses, was evaluated. The results in Figure 9 show that the method used is accurate since high values of R2 were reached for all the periods.

![Figure 9](image-url)

**Figure 9.** Linear regression analysis between monthly electricity consumption per dwelling and mean temperature from 2013 to 2018.
Figure 9 shows a considerable change in electricity consumption between 2013 and 2018. The minimum monthly consumption in 2013 was 131 kWh, while in 2018 it was 152 kWh. However, the temperature coefficient (T) in 2013 is 19.36. This value is higher than in 2018 (T = 16.21) despite the fact that the average annual temperature is the same. This indicates that the increase in the monthly minimum consumption is due to the growth in the base load of the dwellings. This may be due to the fact that over time people increased the number or capacity of household appliances whose consumption is not sensitive to climatic variations, such as televisions, washing machines, etc., as explained by [11].

On the other hand, it is observed that 2015 and 2018 presented similar temperature coefficients; however, the total annual consumption was higher. This increase in consumption is due to the increase in temperature due to the positive correlation between the two parameters analyzed. Finally, it is observed that every year the environmental temperature contributes positively to the consumption of electricity. In the same way, according to [5], the UHI effect has an important influence on the energy consumption. Specifically, ref. [47] found that UHI could result in 19% of building energy consumption being required for cooling, as in the case of Guayaquil city.

Xian-Xiang [11], in their study, establishes that those houses in which the occupants have greater purchasing power tend to be able to acquire a greater amount of equipment that uses electricity, so their consumption is little related to the climate. However, in homes whose occupants have low income, electricity consumption is highly sensitive to weather conditions, as in the present investigation. Correspondingly, [48] found that low-income neighborhoods are more vulnerable to environmental temperatures and that it results in an increase of energy consumption due to the acquisition of basic A/C equipment. This means that low-income housing inhabitants are population vulnerable to climate change, so the study of alternatives that reduce its impact on consumption and comfort inside the housing is necessary [11].

3.1.4. Selection of Study Dwellings

The identified temperature coefficients, from Figure 9, show a high influence of climate on the electricity consumption of air-conditioned dwellings. Since some of the customers’ houses exhibited this behavior, a visual verification that proves these houses actually have A/C systems installed was necessary. For this matter, the tool Geoportal by CNEL-EP that uses Street View command by Google as an instrument for visualization was used. The dwellings with the lowest and highest consumption were selected within the group of 12 houses located in the northern zone of SV1. This allows evaluation of the impact of the use of PCM on the air conditioning requirement. The low consumption house presents an average annual consumption of 600 kWh/y, and the high consumption house presents an average annual consumption of 5120 kWh/y.

For the calibration of the simulation, it is required to collect real information about the energy behavior of a house. Considering the availability of the occupants for monitoring and that 56% of the houses have an average annual consumption between 1800 kWh/y and 2400 kWh/y (Figure 8), the medium consumption house, located at the southern SV1 zone, was identified. This house has an average annual consumption of 2065 kWh/y, and it does not have an air conditioning system. This allows evaluating the impact of the use of PCM on the thermal comfort of houses without air conditioning. Table 3 shows the annual energy consumption values of the selected houses. These values were obtained from electric consumption analysis, and according to Figure 7, it is evident that each house represents a segment according to the level of average annual consumption. Its geographic location is observed in Figure 8, represented by points.

Sensors and monitoring devices were installed in a medium consumption house to determine its thermal and energy behavior. In addition, the information about usage, equipment, and consumption of the house was gathered. These data were used to create a model rendering an energy simulation for obtaining results as close to reality as possible. When visiting the house, it was noted that expansion from the original model was built,
3.2. Building Simulation

With the gathered information, it was possible to determine the house’s architectonic, energy, and usage characteristics, which were used for the energy simulation. This is in order to obtain data about the thermal behavior of the enclosure and the internal conditions of each dwelling.

3.2.1. Input Data

This section defines specific input data for each dwelling, in addition to those presented in Section 2.2.1, like the house’s equipment and house’s orientation. Furthermore, the energy simulations were performed for every case in each house. The operational conditions are shown in Table 4, and the orientation of the houses are shown in Figure 10.

![Architectonic models of base case obtained from of the analyzed houses (a) low and high, (b) medium consumption.](image)

**Table 3.** Annual energy consumption of selected houses.

| Year | Low [kWh] | Medium [kWh] | High [kWh] |
|------|-----------|--------------|------------|
|      | Σ M       | Σ M          | Σ M        |
| 2013 | 430 39    | 1283 94      | 3814 312   |
| 2014 | 759 64.5  | 1855 127     | 2984 250.5 |
| 2015 | 670 56.5  | 2078 163     | 4819 401.5 |
| 2016 | 680 57.5  | 2120 169     | 6969 549   |
| 2017 | 564 47.5  | 2367 198     | 6127 474   |
| 2018 | 493 41    | 2687 232.5   | 6008 470   |

Average annual consumption [kWh/y] | 600 | 2065 | 5120

Σ: Summatory; M: Median.

**Table 4.** Operational conditions for energy simulations.

| Activity                  | Schedule                  | Value                  |
|---------------------------|---------------------------|------------------------|
| Occupation                | Weekdays: 00:00–07:00 100% 7:00–11:00 75% 11:00–18:00 0% 18:00–00:00 100% | Low: 0.0196 pers/m² Medium: 0.04 pers/m² High: 0.04 pers/m² |
| Equipment and lighting    |                           | Low: 2.16 W/m² + 1 W/m² Medium: 2.16 W/m² + 3.3 W/m² High: 2.16 W/m² + 5 W/m² |
| Infiltration              |                           | 3 renov/hr 3 renov/hr 3 renov/hr |
| A/C set-point temperature | Weekends and holidays: 00:00–24:00 100% | 27 °C None 25 °C |
| Ventilation               | All day                   | 1 renov/hr 1 renov/hr 1 renov/hr |
The orientation of base case can be observed in Figure 10—(a) low and high and (b) medium—and their location is displayed in Figure 8; the architectonic model is shown in Figure 3.

3.2.2. Calibration

The first analysis made was the energy balance, which was obtained as a product of the preliminary energy simulation of the medium consumption house. It was possible to observe that the materials that gain the highest energy from heat exchange with the environment are walls (25% total gains) and roofs (72% total gains). Hence, the heat exchange through windows is lower due to the expansion of the roof that blocks the solar charge. For this, the simulation was calibrated with the inner and outer temperatures of the roof and the wall. Data of air temperature inside the real house, compared to data obtained from energy simulation, during the four days of analysis, are displayed in Figure 11. The analyzed values for the calibration were those corresponding to the monitoring from 25 December to 28 December 2018.

![Temperature Graph](image)

**Figure 11.** Real temperature vs. simulated temperature obtained by energy simulation.

In Table 5, the values of CV (RMSE) and NMBE are shown. It is demonstrated that these values are below the considered maximums on ASHRAE 14-2014 standard for monthly energy consumption. Table 6 indicates the results of analyzed calibrated hourly temperatures as performed by Gucyeter, B (2018) [21].

| Monthly Energy Consumption                  | CV (RMSE) | NMBE |
|--------------------------------------------|-----------|------|
| High consumption household                 | 8.4       | 3.2  |
| Medium consumption household               | 14.87     | 2.2  |
| Low consumption household                  | 10.77     | 2.4  |

As shown in tables, the air temperature and the energy consumption simulated match the behavior pattern of the real conditions. Thus, it is confirmed that the model is properly calibrated.

Once the mathematical models were calibrated by energy simulation, it must be confirmed that the same thermal properties of the construction materials of roofs, walls, floors, windows, and doors were used for all houses.
Table 6. Obtained calibrates parameters for hourly surface and air temperature.

| Temperature [°C] | CV (RMSE) | NMBE | Absolute Average Error (°C) | R  |
|------------------|-----------|------|-----------------------------|----|
| **Roof**         |           |      |                             |    |
| Interior         | 11.71     | 10.68| 3.12                        | 0.91|
| Exterior         | 16.54     | 12.78| 3.89                        | 0.83|
| **Wall**         |           |      |                             |    |
| Interior         | 2.49      | 2.15 | 0.6                         | 0.95|
| Exterior         | 4.19      | 3.36 | 0.92                        | 0.95|
| **Air temperature** |        |      |                             |    |
| Interior         | 2.28      | 1.77 | 0.5                         | 0.91|

3.2.3. Best Improves in the Study Cases

Once performed the previously mentioned calibrations, data closer to reality was obtained. The calibrated models allowed evaluating several strategies that improve thermal comfort in social housing. For this matter, two houses with air conditioning systems were simulated, which are also influenced by the climate in terms of energy consumption besides the monitored house that was simulated too. As a result, for 2019, the PMV of the three customer house types were compared with the unchanged houses and with the houses with 5 proposed improvements.

As determined by energy simulation, the constructive element that affects the thermal behavior of the house the most is the roof. It produces a higher heat gain inside the building during the day. The work conducted by Guichard et al. demonstrated that the use of PCMs in the roofs of houses under tropical and humid climates allows to improve the thermal comfort and reduce the solar irradiation [49]. Nonetheless, studies from Beltran [16] and Romero [18] suggest that PCMs’ usage for roofs is not convenient in a climate like that of Guayaquil because the temperature reached in this zone will not allow the phase change. Therefore, this element must be replaced for a material that provides thermal insulation. For the change, a polyisocyanate roof of local commercialization was selected.

Furthermore, along with the new roof, four PCMs obtained from bibliographical review and suggested for Guayaquil’s climate were evaluated. These materials were added to the customers’ houses walls to reduce temperature oscillations inside the house to evaluate an improvement of the thermal comfort of the inhabitants.

In summary, the energy simulation made it possible to perform, for each house, 6 results. The base case left the house unchanged, and in case 1, only the roof was changed. In cases 2, 3, 4, and 5, in which PCMs in walls are contemplated, Bio PCM Q29, n-octadecane, RT25-RT30 and spent diatomite earth, respectively, were used. Furthermore, Figure 12 shows a comparison of inner wall surface temperature and operational temperature of the dwelling between best results in each case study. In addition, this behavior is evaluated during a period of cold and hot weather in Guayaquil City, obtained by energy simulation for 2019 as show in Figure 4.

In this sense, the best practices obtained through simulation for each case study were: Case 1 for “low consumption” and “medium consumption” housing and Case 4 for “high consumption” housing. To illustrate the thermal behavior of best practices, the figures below have included the ambient temperature for each period of time analyzed (cold period: 16–17 September 2019; hot period: 27–28 December 2019).

In Figure 12a–d, it can be observed that the change of cover produces greater temperature oscillations during the night and during the day compared with case 4, which uses the PCM RT25-RT-30 from Figure 12e,f. For this reason, it can be considered that for low and medium consumption homes, more comfortable conditions can be obtained with the change of the roof, especially at night. In addition, for low consumption housing, there is a lower need for using A/C (set at 27 °C). Likewise, it was determined that in isolated houses that use PCMs, it is possible to reduce the number of overheated hours from 400 to 200 in a year [50]. Consequently, as this study found, the use of an isolation material in the roof could present a crucial contribution to the reduction of temperature fluctuations inside houses.
Figure 12. Comparison of surface temperatures and operational temperatures of the dwelling between base case 1 and case 4: (a) Low consumption: Cold period, (b) Low consumption: Hot period, (c) Medium consumption: Cold period, (d) Medium consumption: Hot period, (e) High consumption: Cold period and (f) High consumption: Hot period.

In Figure 12e,f, it is possible to observe that the usage of PCM allows for keeping the operational temperature of the dwelling close to the set temperature of A/C (near 25 °C) for a longer time in the two evaluated periods. Moreover, it is noted that the temperature of the wall’s surface, when using PCM RT25-RT30, below 25 °C, is in the liquid-solid phase.
at nights, early mornings, and in the greater part of September 17 (cold period). On the other hand, when the temperature is above 25 °C, the material is in liquid phase according to the manufacturer’s data, as shown in Figure 6. In this case, the use of PCMs on the walls allowed less oscillation or sudden changes in temperature throughout all the evaluated days. Nevertheless, an improvement of the efficiency of the PCM performance could be achieved by increasing the number of PCM envelopes [51].

In addition to the simulation results presented in this section, the hourly values of the indoor air temperature, the relative humidity, the air velocity, and the mean radiant temperature during 2019 are obtained for all the study cases. This information is the input data to the evaluation of thermal comfort from the methodology described in section 3.3. Comfort Analysis

In order to evaluate, compare, and show the impact on the thermal comfort due to the use of PCMs, the PMV is calculated with Equation (1). From the simulation, indoor environment data is obtained for three housing types with six enclosure configurations per housing. Six configurations correspond to the low energy house: (1) with the original housing materials; (2) original material exterior walls and 23.1 mm thick PIR roof; (3) PIR roof and exterior walls with a layer of Bio PCM Q29; (4) PIR roof and exterior walls with a layer of n-octadecane; (5) PIR roof and exterior walls with a layer of RT25-RT30; and (6) PIR roof and exterior walls with a layer of unused diatomite earth. The remaining twelve configurations correspond to high and medium consumption houses with the above-mentioned configurations.

This analysis allowed comparing the results of PMV obtained from energy simulation between base case, roof-changed house, and wall-changed house with the 4 PCMs. Finally, due to climate conditions in Guayaquil city and common activities developed in the house, a clothing insulation of 0.57 clo and a metabolic rate of 1.2 met were considered. The following are the results obtained for low, medium, and high consumption dwellings, and the total percentage and the cumulative frequency of total hours of the analyzed year are shown in the plots.

On the other hand, an analysis of the natural ventilation usage as a passive strategy for each previously described case is also shown. This analysis allows to recommend options for mitigating A/C usage and thus obtain energy savings in dwellings. In the energy simulation, functional windows at 25% (Bhikhoo, N., et al. 2017) [52] were considered, as shown in Table 4.

3.3.1. Low Consumption Dwelling with Air Conditioning System

The PMV values obtained for the low consumption dwelling with air conditioning system are detailed in Figure 13. It is observed that in the base case, 43% of the year’s hours are comfortable inside the house, while 50% are uncomfortable because of high temperature, and 7% are uncomfortable because of low temperature. For the observed Case 1, 55% of comfortable hours in the year, an increase of 326 h of discomfort by low temperature (from 632 to 958 as shown in Figure 13b) and a decrease of 1358 h of discomfort by high temperature (from 4385 to 3027).

On the other hand, regarding the cases where the use of PCMs was considered, case 4 (RT25-RT30 as PCM) shows 46% of comfortable hours, a reduction of 937 h in which the thermal sensation varies from “very hot” to “hot” (PMV > 1). Besides, case 4 has the only configuration in which low temperature discomfort hours do not exist (Figure 13a). This means that an air conditioning system does not overly chill the climatized space and does use the necessary energy until comfort conditions are achieved.

In short, for low consumption houses with air conditioning systems, the contribution of A/C systems is the highest. Nonetheless, the use of PCMs, specifically Case 4, can help to reduce the temperature oscillations by not feeling discomfort produced by low temperatures. Similarly, according to Figueiredo et al., although PCM can perform better with the aid of A/C systems, its use reduces drastic peaks in indoor temperatures [51].
In Figure 14 it is noticeable that the low consumption dwelling with natural ventilation shows less discomfort hours due to low temperature than the dwelling with A/C. However, for all cases where PCMs in walls were considered, the total hours of discomfort due to high temperature increased. Only Case 1 shows the highest number of comfort hours when natural ventilation is allowed. Moreover, it was calculated an energy saving of 33.8% when withdrawing the A/C of the dwelling.

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### Figure 13. PMV evaluation in low consumption dwelling with air conditioning systems

(a) Percentage comfort and discomfort hours and (b) Cumulative frequency hours.

In Figure 14 it is noticeable that the low consumption dwelling with natural ventilation shows less discomfort hours due to low temperature than the dwelling with A/C. However, for all cases where PCMs in walls were considered, the total hours of discomfort due to high temperature increased. Only Case 1 shows the highest number of comfort hours when natural ventilation is allowed. Moreover, it was calculated an energy saving of 33.8% when withdrawing the A/C of the dwelling.

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### Figure 14. PMV evaluation in low consumption dwelling without air conditioning systems

(a) Percentage comfort and discomfort hours and (b) Cumulative frequency hours.

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#### 3.3.2. Medium Consumption Dwelling without Air Conditioning System

Results obtained about PMV for a medium consumption dwelling are displayed in Figure 15. For base case, 16% of the year’s hours are comfortable, while the remaining 84% are uncomfortable because of high temperature (PMV > 0.5). When using PCMs in the
walls, the comfortable hours reduce approximately by 3% in all cases. Nevertheless, the discomfort between “hot” and “very hot” (PMV > 2) decreases approximately from 1647 to 151 h in the year, improving the general conditions inside the house. For the observed case 1, 25% of comfortable hours and a reduction of 60% of hours (from 1647 to 612) with PMV > 2. To sum up, these results confirm the research from [51]. To put it in other words, PCM usage avoids discomfort hours due to cold temperatures that can be produced using A/C systems. By the same token, Costanzo et al., demonstrated that PCMs attenuate peak temperatures by 0.5 °C, and the requirement of cooling by 10% [53].

![Figure 15](image)

**Figure 15.** PMV evaluation in medium consumption dwelling. (a) Percentage comfort and discomfort hours and (b) Cumulative frequency hours.

It is observable in Figure 16 that natural ventilation benefits all analyzed cases, in terms of thermal comfort. Nevertheless, the base case shows the most of discomfort hours due to high temperature when PMV > 2 among all cases. In addition, the highest number of comfort hours were shown by Case 2 and Case 3.

![Figure 16](image)

**Figure 16.** Predicted medium vote (PMV) evaluation in medium consumption dwelling with natural ventilation (a) Percentage comfort and discomfort hours and (b) Cumulative frequency hours.
3.3.3. High Consumption Dwelling with an Air Conditioning System

The obtained results for high consumption dwelling are detailed in Figure 17. The base case shows 69% of comfort during the year, 561 and 2145 uncomfortable hours by low and high temperature respectively. For the observed Case 1, there is an increase of 2% of comfortable hours and 279 uncomfortable hours because of the low temperature. Case 2 (Bio PCM) and Case 3 (n-octadecane) show 73% of comfortable hours and a reduction of 148 and 198 h of discomfort by low temperature versus the base case. In this sense, this work reaches the same conclusion as [53], namely that 2% to 10% of comfort increase can be achieved using PCMs. Moreover, it is reflected in a reduction of 12.1% of energy consumption [53].

Conversely, it is important to mention that all cases that use PCMs are characterized for showing uncomfortable hours mostly from 6:00 to 18:00.

Figure 18 shows that there is no benefit when considering natural ventilation for the high consumption dwelling. It could be due to the existence of occupation and equipment loads, which are higher than those found in the other cases. This is displayed in Table 4.
As observed in Figure 17, the implementation of PCM RT25-RT30 in the internal walls of the dwelling and the roof change (case 4) accomplished the highest percentage of comfortable hours compared to the other cases. Furthermore, only 1% of uncomfortable hours are caused by low temperature. These low temperatures could be attributed to the overuse of the A/C systems and can be avoided by using PCMs.

It was clearly observed in the results for the three analyzed customers’ house types that changing the roof shows a higher thermal comfort of the inhabitants in both percentage and total number of hours ($-0.5 < \text{PMV} < 0.5$). Besides, the roof change is the only aspect under which the medium consumption house experienced an improvement without an air conditioning system.

Another remarkable result was observed in both low and high consumption customers’ houses. In these cases, most of the evaluated PCMs contribute to increasing thermal comfort. It was noted that RT25-RT30 material achieved the best results of the PCMs. This formula increased the number of thermally comfortable hours and decreased the total hours of thermal discomfort due to low temperature. This characteristic is corroborated with the datasheet from the manufacturer and is shown by [14], who suggests the usage of this type of material in buildings where air conditioning systems are considered. In this context, it was possible to calculate the energy saving for the low consumption dwelling only in terms of kWh/year. This value aids to estimate the final saved fee. This means that with an energy reduction of 33.8%, an amount of 126.06 kWh/year is no longer consumed, which is equivalent to 12.6 USD of saving (considering an approximate fee of 0.10 USD per kWh). On the other hand, Marin et al. 2017 [54] indicate that there is a clear positive effect when using PCM in all cities, except in Kuala Lumpur and Singapore, both tropical areas like Guayaquil city. This study states that the use of PCM reduces the amount of yearly hours inside comfort range, as shown in this study.

Based on the explained results, it is observed that the three energy simulations made on selected houses to further evaluation strategies to improve thermal comfort inside the houses is a methodology comparable to Guyceter’s [21] research. That study calibrated a building by using the information generated by monitoring systems. Moreover, Guyceter’s research, obtained through energy simulation, obtains results close to reality by applying protocols of verification.

Moreover, the results showed in this research match those obtained in Rastogi et al. [13]. In this study, a building without an air conditioning system was simulated for 8670 h (one year). The study aimed to maintain the temperature of human comfort (21–26 °C) by evaluating various types of PCMs selected from statistical methods. To estimate the thermal behavior, a traditional system of masonry walls made of brick was used. The PCM was a 15 cm layer inserted into the masonry, while the roof was made of concrete cement. Unlike Rastogi’s work, this research evaluated the performance of conventional block masonry in walls (commonly used in social housing), where the PCM was inserted, and the thermal comfort was assessed by PMV method.

However, simulation results of the present work concurred on some level with Vautherot’s study regarding the importance given to an accurate selection of adjustment points (set up) of HVAC systems (as this factor affects the thermal efficiency of PCMs). The study of Vautherot et al. confirms the importance of correct PCM selection through its operating curves and supplier suggestions for effective operation. As could be seen in this research, the best result with the use of PCM was that of the house that had A/C and was set at 25 °C. Additionally, this research considered simulation parameters as climate, architecture, materials, equipment, use, and other details apart from a calibration of the model to obtain values closer to reality.

Still, it is suggested that, in the future, a simulation considering several cases of air infiltration into the house for hot-humid climate, that in Ecuador corresponds to coastal and Amazon regions, be performed. It is known that air infiltration through building envelopes carries a significant impact in energy used by air conditioning systems [55], thus PCMs’ behavior could be modified. Although there are very detailed complex approaches
to model air infiltration by using air flow nets (AFN) and computational fluid dynamics (CFD), often energy simulation tools for buildings use simplified methods to estimate air change rate based on air sealing in the building, measured by pressurization.

4. Conclusions

This research developed the hours of PMV thermal comfort in social houses in Ecuador by energy simulation with the use of Phase Change Materials (PCMs) for a very hot-humid climate. In this way, the spatial analysis did not show a correlation between the selected location and its energy consumption. However, it was observed that for each analyzed year, there is an increasing trend in energy consumption. Moreover, it was evidenced that, for 2016, the highest value was reached, and it coincides with the hottest year. Nonetheless, it must also be considered that this year an earthquake occurred which could cause an increase in electricity consumption.

Since 2013, an increase in the correlation between energy consumption and the temperature has been observed. This indicates that A/C equipment is still being installed since comfort conditions are unfavorable. Hence, the use of PCMs would represent a suitable and crucial alternative for the reduction of energy consumption associated with the use of air conditioning systems. Furthermore, it can be observed that changing the roof with insulating materials improves the hours of comfort in all the dwellings under analysis. Moreover, in this research, it was observed that in some cases the use of PCM in walls should be combined with natural ventilation. It was an interesting improvement that was observed especially in low and medium consumption social housing. In these cases, the usage of A/C is mitigated, and it could represent economic savings.

Simulations results concluded that the performance of PCMs depends on parameters such as climate conditions, equipment, and usage of the house. Specifically, PCMs’ behavior should be carefully studied when located in a very hot-humid climate due to its strong dependence on climate conditions. Particularly, the evaluated PCM showed an accurate performance in houses with air conditioning systems during most of the afternoon, keeping the inner temperature lower than the outer temperature. In this context, the PCM RT25-RT30 wall location shows the best result among all the analyzed PCMs in this research. Moreover, for cold climates, the results showed that the location of the PCM in walls is preferable. Additionally, it was determined that the change of roof material of the houses can improve the thermal comfort inside the house for all the analyzed cases.

The use of the PCM RT25-RT30 showed a reduction of 937 h in which the thermal sensation varies from “hot” to “very hot” (PMV > 1). Consequently, by using this PCM, air conditioning systems usage decreases by assuring the thermal comfort and reduction of energy consumption of the inhabitants’ house. In addition, it was be observed that in the most consuming dwelling, where the A/C system is kept set at 25 °C, the use of this PCM allowed to maintain a temperature near 25 °C for a longer time during periods of rain and hot weather.

Extreme hot indoor temperatures inside houses result in an increment in electricity consumption, people’s productivity reduction, and also health problems, mainly for low-income people who are the most vulnerable to the abovementioned factors. Hence, from an economic and social stance, this study demonstrated that energy consumption will be reduced by implementing PCMs in social houses. This finding is crucial, especially in the investigated area because a reduction in the electricity fee will be very representative for social house owners, who generally have low incomes. Moreover, the lifestyle of people can be improved because they will not be restricted to develop different activities due to high environmental temperatures inside houses. In addition, from a political viewpoint, the results of this research can be used by local and national governments. Specifically, they can design projects for the implementation of phase change materials in the social houses of the coastal zone of the country. In this sense, people will be benefited by living in more eco-friendly houses, feeling more hours of thermal comfort, and paying less for their electricity fees.
Moreover, it is essential to capitalize on the importance of this research to the environment. In particular, in Ecuador, electricity is still produced by the combustion of fossil fuels, which harms the environment due to GHG emissions. Hence, the use of PCMs in buildings indirectly contributes to a reduction in the emissions of harmful gases by reducing the energy consumption related with the usage of air conditioning systems required to maintain the thermal comfort inside social houses.

This study represents the base for further research in this area. In particular, by applying the procedure followed in this paper for having the most accurate data, it would be interesting to analyze different PCMs with higher enthalpy of fusion. This could allow to increase the effectiveness of the use of PCMs in social housing. On the other hand, political and social analysis was not included in this research since the use of PCMs is a new technology that is still being developed in Ecuador. In this research, a new PCM studied in Ecuador, diatomaceous earth, which is a promising material that can be obtained locally as construction material, was considered.

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