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Energy and Thermal Performance of Partially Bermed Earth-Sheltered House: Measure for Adapting to Climate Change in a Tropical Climate Region †

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Abstract: This study addresses passive adaptation strategies to reduce the effects of global warming on housing, focusing on low-income houses, for which passive adaptation strategies should be prioritized, aiming for environmental sustainability. The passive strategy chosen is thermal mass for cooling, through the adoption of earth-sheltered walls in contact with the ground. Thus, the goal of this study is to evaluate the thermal load and thermal impact of implementing a thermal mass strategy for cooling, using bermed earth-sheltered walls in bedrooms, for a building located in a tropical climate region. For that, a base scenario (1961–1990) is considered alongside two future scenarios: 2020 (2011 to 2040) and 2050 (2041 to 2070), both considering the effects of climate change, according to the Fourth Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC). The methodologies adopted are (i) the computational simulation of the annual thermal load demand and (ii) the quantification of the Cooling Degrees-Hours (CDH) with the subsequent comparative analysis. The results show that in both the 2020 and 2050 scenarios there will be an increase in the thermal loads for cooling and the CDH, regardless of using a bermed earth-sheltered wall. Nonetheless, it is shown that this passive strategy works as a global warming adaptation measure, promoting building sustainability in tropical climate regions.

Keywords: thermal performance; building simulation; global warming; energy consumption; cooling degree-hours; bioclimatic measure

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1. Introduction

Building geometry and orientation, construction materials, and climate conditions are important factors to consider when designing new buildings, especially to achieve adequate energy and thermal performance. Thus, bioclimatic passive strategies are important measures to be considered during the design phase. For hot regions, *thermal mass for cooling* is an alternative passive measure. Used to adequate a building to its implantation climate, thermal inertia of the walls can be used to accumulate and retain heat during the day and return it to the exterior environment at night. This behavior reduces the indoor air temperature fluctuations, which oscillate in a damped manner

[1,2]. Thus, this bioclimatic measure may reduce the use of active air conditioning systems during hot days, potentially saving energy and improving thermal comfort in an indoor environment.

In a hilly site, building walls may be designed to be in contact with the earth, increasing its thermal mass properties. In the "elevational" bermed design, the house's main elevation or face, usually with south-facing wall in cold regions and with a northern facing wall in hot climatic zones, remains unexposed while the rest may be bermed by the earth. This type of construction, named Earth sheltered building, are defined as structures built with the use of earth mass against building walls working as external thermal mass to the wall, which reduces heat loss and maintains a steady indoor air temperature throughout the seasons [3]. When the earth is in contact with building walls, it acts as a reservoir, storing the heat in vast spaces inside the soil and modulating indoor air temperatures at different meteorological conditions [4]. For this reason, the bermed type construction is considered as an alternative measure to adapt buildings to the impacts of climate change, one of the most important global concerns at present.

Vast knowledge about climate change, motivated by anthropogenic actions and based on greenhouse gas (GHG) emissions, has been released by the Intergovernmental Panel on Climate Change (IPCC). The IPCC has published various scientific reports on which the behavior of terrestrial ecosystems is studied by scientists from a wide range of fields [5,6]. An increase in the number of hot days in most land regions is expected, with the highest increases in the tropics, therefore, the potential effect of climate change in building environment is an critical issue, especially concerning its design and operation. Furthermore, global warming will directly affect the thermal behavior of buildings, increasing hot season cooling and decreasing cold heating demand, raising its energy consumption during the operational phase [7]. Thus, the strategic framework conceived to mitigate and adapt buildings environment to climate change increases the importance of the thermal mass effect as a strategy to counterattack its impacts, especially in warm regions such as those located in South America.

Thus, this study aims to evaluate the thermal loads demand and thermal impact of implementing a thermal mass strategy for cooling, using bermed earth-sheltered walls in bedrooms within a residential building located in a region with tropical climate. The analyses are made considering a base Scenario (without the influence of climate change) and two future scenarios (2020 and 2050) contemplating climate change effects, according to the Fourth Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC).

2. Materials and Methods

2.1. Local Climate Identification and Bioclimatic Zone Characterization

A single-family low-income house (LIH) is located in a region of Tropical Savannah climate (Aw), characterized by high air temperature throughout the year, wide hygrothermal variations, and undefined or absent winter season [8]. Similar climate classification can be found in several locations around the world, such as Africa and South America, especially in regions located between the Equator and Tropics of Capricorn (Figure 1). The climate database of the Cuiabá city, which is located in the Mid-East, Brazil, in the geometric center of Latin America (Latitude 15°36′56″ S and Longitude 56°06′01″ W) is used as base of this research.

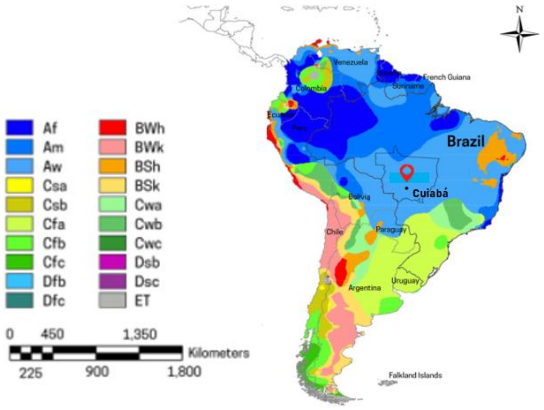


Figure 1. Location of the city of Cuiabá in South America. Source: adapted from Peel et al. [9].

The Brazilian Bioclimatic Zoning establishes a set of technical and constructive recommendations for the region, to optimize the thermal performance of buildings through a better climatic adaptation [1]. The recommendations and constructive guidelines to adequate a LIH for the Savannah climate region are detailed in Table 1, in accordance to the Brazilian Bioclimatic and as prescribed by the Brazilian Technical Quality Regulation for Energy Efficiency Level of Residential Buildings (RTQ-R) [10]. This research focuses on whether the thermal mass strategy is an adequate passive measure to adapt a building to climate change.

Table 1. Recommendations and constructive guidelines for bioclimatic zoning of the building implantation.

Code	Opening's Recommendations	Guidelines for Building Envelope				Strategies for Passive Thermal Conditioning
		Wall System		Roof System		
NBR 15220 [1]	Small openings: $10\% < A < 15\%$ Shade openings	A: NR Type: Heavy U ≤ 2.2; CT:NR φ ≥ 6.5 h SF ≤ 3.5%		A:NR Type: Heavy U ≤ 2.0; CT: NR φ ≥ 6.5 h SF ≤ 6.5%		Evaporative Cooling; Thermal mass for cooling; Selective ventilation ($T_{int} > T_{ext}$)
RTQ-R [1]	A ≥ 5%	α ≤ 0.6	α > 0.6	α ≤ 0.4	α > 0.4	No requirement established
		U ≤ 3.70	U ≤ 2.50	U ≤ 2.30	U ≤ 1.50	
		CT ≥ 130	CT ≥ 130	NR	NR	

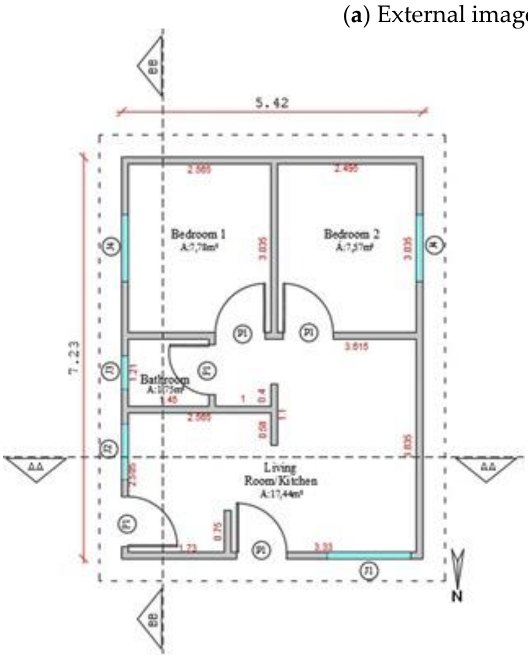
[1] A: floor area (%); α: absorptance (dimensionless); U: total thermal transmittance (W/m²K); CT: thermal capacity (kJ/(m²K); φ: thermal delay; SF: sun factor; NR: no requirement established; T_{int}: internal temperature; T_{ext}: external temperature.

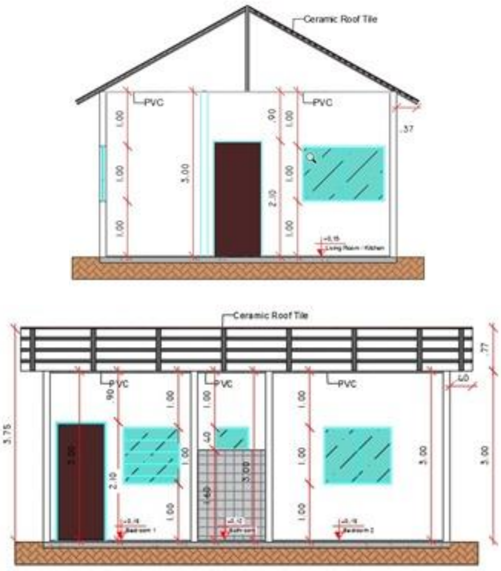
2.2. Characterization of the Study Case

A typical low-income housing, widely replicated in all regions of Brazil by the Brazilian government under the social housing program named "My House My Life", was chosen for this study [11] (Figure 2a). This choice is based on the fact that this population is the most vulnerable to the impact of climate change, especially in developing countries. The standard building project, thereafter named as "LIHs", is characterized by one-story detached house in contact with the ground. LIHs present 39.18 m² of total area and 34.54 m² of internal floor area, distributed in four designated areas, namely: living room/kitchen (17.44 m²), bedroom 1 (7.78 m²), bedroom 2 (7.57 m²) and bathroom (1.75 m²) (Figure 2a–c). The roof construction is dual pitched with overhang of 0.30 m depth. The ceiling height of the spaces is 3.00 m.

Regarding openings, living room and bedroom spaces present metallic sliding windows with dimensions of 1.50 × 1.00 m and 1.20 × 1.00 m, respectively, composed by four panels, two of them being single glass fixed panels and the other two sliding metallic Venetian panels. The kitchen window is a metallic tilting type, 1.00 × 1.00 m in size. The external doors are made of metallic sheet, while interior doors are made of wood. The external walls and internal partitions consist of ceramic bricks (six-hole type) coated on both sides with plaster. The roof is composed of ceramic tile, air gap layer, and Polyvinyl chloride (PVC) ceiling panels. The NBR 15.220 [1] standard was used to select the design strategies and to determine the thermal properties of the building materials, which are presented in Table 2. Regarding the air gap, this layer presents 0.21 m²K/W thermal resistance (R-value), with a thickness greater than 0.05 m and high emissivity.

(**a**) External image of the LIH



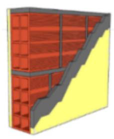
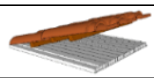


(**b**) Floor plan (dimensions in meters)

(**c**) Sections AA′ and BB′

Figure 2. (**a**) Low-Income Housing, (**b**) Floor Plan and (**c**) Sections plans.

Table 2. Thermal and physical properties of the building materials. Source: NBR 15.220 [1].

Building Envelope	Construction Layers	Thickness (cm)	α [1]	c [1] (J/KgK)	λ [1] (W/m²K)	ρ [1] (Kg/m³)	
External walls and internal partitions	External plaster	2,50	0,30	1000	1,15	1800	
	Ceramic brick	9,00	0,85	920	1,05	1600	
	Internal plaster	2,50	0,30	1000	1,15	1800	
Roof	Ceramic tile	1,00	0,85	920	1,05	1600	
	PVC ceiling	1,00	0,30	960	1,20	1300	

[1] α: absorptance (dimensionless); c: thermal capacity; λ: thermal conductivity; ϱ: density.

To verify the thermal inertia strategy, bermed earth-sheltered walls were placed in the original housing design (hereafter named as LIHs), so certain walls have direct contact with the ground, resulting in the "LIHb" design strategy. For that, the external walls of the bedrooms 1 and 2, which do not present openings, were selected to be 3.00 m (ceiling height) underground earth-sheltered (Figure 3). The bermed earth-sheltered walls were evaluated in all four cardinal orientations (Figure 4). This strategy allows taking advantage of natural sloping ground while providing a passive design measure to improve indoor thermal comfort conditions.

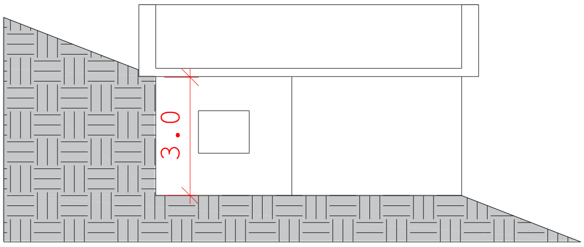


Figure 3. Schematic section of the bermed earth-sheltered wall located in the bedrooms.

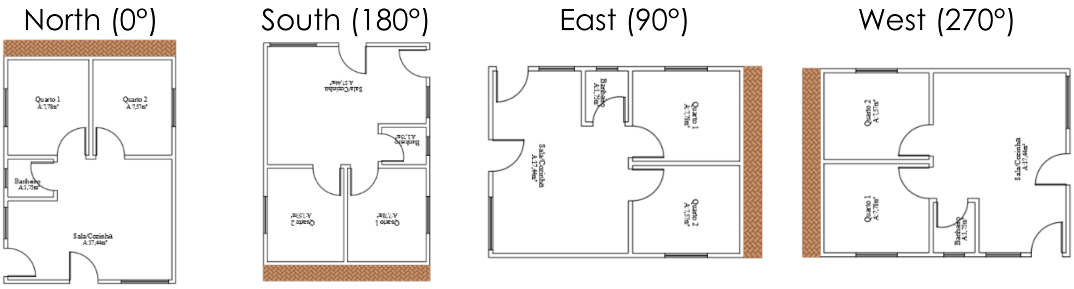


Figure 4. Variation of the embedded earth-sheltered wall orientation.

2.3. Simulation Method

The impact of the bermed earth-sheltered wall in the house performance was analyzed by comparing the results generated by the LIHs and LIHb typologies. The results were evaluated considering the energy efficiency level in line with RTQ-R [10] and through the quantification of the cooling degrees-hours required for three distinct climatic scenarios: base scenario (1961 to 1990 period), 2020 future scenario (2011 to 2040), and 2050 future scenario (2041 to 2070), the last two presenting the climate change influence.

To evaluate the thermo-energetic performance of the strategy, the EnergyPlus [12] software was used through the GroundDomain: Basement (GDomain) input, which calculates the temperature of the interface between the soil, the external walls, and the slab of the bermed earth-sheltered spaces, obtained three-dimensionally by the simulations [13]. Thus, the simulation was carried out considering temperature models named "Finite Difference", which use a model with finite differences to obtain the soil heat transfer. The manual developed by [14] was used as a reference to the Ground Domain input data. The soil data were adjusted for the region of this study, considering the research presented in [15] (Table 3). The chosen soil is lateritic gravel, formed in vast regions of tropical climate.

Table 3. Input data considered in GDomain simulation.

Input Data	Adopted Input Values
Ground Domain Depth (m)	15
Soil Thermal Conductivity (W/mK)	0,52 [15]
Soil Density (kg/m³)	1.700 [15]
Soil Specific Heat (J/kgK)	840 [15]
Mesh Density Parameter	6

The Ground Domain requires the monthly soil temperature data, which were calculated using the Slab input tool (Table 4).

Table 4. Monthly soil temperature for the base Scenario (1961–1990) and future estimates (2020/2050).

Month	1961–1990	2020	2050
January	27.94	28.73	29.87
February	27.76	28.32	29.71
March	27.73	28.63	30.11
April	26.78	27.65	29.59
May	26.10	27.05	29.04
June	25.67	26.90	28.32
July	24.35	24.87	26.51
August	26.38	28.95	30.82
September	27.36	29.08	31.13
October	28.36	30.78	32.62
November	27.83	29.09	30.91
December	28.21	28.87	30.26

The occupancy and equipment power density data were adopted in accordance with RTQ-R [10], considering 2 people in each bedroom and 4 people in the living room. Regarding the occupancy metabolic activity rate, 45 W/m^2 was considered in bedrooms while 60 W/m^2 was set for the living room. The lighting power densities adopted were 5.0 W/m^2 in the living room and 6.0 W/m^2 in the bedrooms. The occupancy schedule estimates that the bedrooms are used from 9 p.m. to 8 a.m. for weekdays and from 9 p.m. to 10 a.m. for weekend days while the living room is used from 2 p.m. to 21 p.m. for weekdays and from 11 a.m. to 9 p.m. for weekend days.

2.4. Generating Future Climate Scenarios Weather Data

The "morphing" methodology, developed and described in [16], was adopted in this research, aiming to analyze the implications of climate change on building's thermal/ energy performance. The morphing method has been used to generate future EPW (EnergyPlus Weatherfiles) for any location in the world by means of the *Climate Change World Weather File Generator for World-Wide Weather Data* (CCWorldWeatherGen) tool [17–22]. This methodology considers the climatic anomaly by modifying a set of historical climatic variables (1961–1990) of 8760 h per year, disregarding the influence of urbanization while incorporating the effects of global warming on the climate archives, making obtaining projections of future climate data possible.

The CCWorldWeatherGen tool consists of an excel template that couples the EPW weather files to the "Hadley Centre Coupled Model version 3" (HadCM3) General Circulation Model (GCM). The HadCM3 is a coupled atmosphere-ocean general circulation model and has a resolution of 417 km × 278 km in the Equator region and 295 km × 278 km at 45° Latitude, coupling the A2 Scenario of the IPCC 4th Assessment Report (AR4) for the 2020s time-slice (which covers the 2011–2040 period) and also the 2050s time-slice (2041–2070 period). The selected time-slices were based on a 50 years period, which is the building life expected for low-income houses.

2.5. Indicators for Evaluation for Thermal Load Demand and Thermal Performance

2.5.1. Estimation of the Thermal Load Demand According to the Thermal Balance Method

According to [23], the thermal load of a building is defined as the amount of heat from the air that must be removed, in the case of cooling, or added, in the case of heating, to maintain adequate indoors thermal comfort conditions. These loads result from heat gains from internal sources, such as lighting, people, equipment, artificial conditioning (HVAC), ventilation and infiltrations and, external sources, such as heat transfer through the building envelope. In this sense, thermal energy demand can be estimated using thermal balance based on the magnitude of the internal load and the heat exchanges by building vertical and horizontal sealing systems. This methodology was proposed by [24] as a strategy measuring thermal loads for cooling and for heating in kWh.

For this purpose, the "Input Output Reference and Engineering Reference" of the EnergyPlus software was used to quantify the thermal balance, considering the cooling and heating load demand through an ideal load air conditioning system (HVACTemplate: Zone: IdealLoadAirSystem) that estimates the ideal thermal load required to maintain the indoor thermal balance. In this work, only the bedrooms were built with bermed earth-sheltered walls once the influence of the thermal mass in other occupied spaces performance was not relevant.

The total thermal load for cooling and heating (kWh) of the bedrooms was calculated through the Output: Zone Ideal Loads Zone Total Cooling Energy output, which includes lighting, equipment air infiltration, and HVAC thermal loads in the calculation. For that, the temperature range had to be defined in HVACTemplate: Thermostat input, defined as 29.26 °C for cooling and 22.54 °C for heating in accordance with the comfort range presented by De Dear e Brager [25], applied in the region of Cuiabá-MT [26]. The operating schedule from 9 p.m. to 8 a.m. was considered for the calculation of the HVAC thermal loads. To the other period (9 a.m. to 8 p.m.), Naturally Ventilated housing was adopted, following RTQ-R [10]. The estimated thermal loads for the base (1961–1990) and future climate change scenarios (2020 and 2050) are expressed in kWh/year for each typology under study (LIHs and LIHb).

2.5.2. Indicator of the Envelope Performance by RTQ-R

The Cooling Degree-Hours (CDH) parameter was used as indicators of building thermal performance under natural ventilation conditions under the RTQ-R recommendations [10]. The Heating Degree-Hours parameter (HDH) was ignored due to their low occurrence in the study region. The base temperature used to calculate the Cooling Degree-Hours was set at 26 °C, which was obtained by means of Equation (1):

$$\text{CDH} = \sum_{i=0}^{8760} \begin{cases} for \;\; Top > 26°; & (Top - 26°) \\ for \;\; Top \leq 26°; & (0)' \end{cases} \tag{1}$$

This indicator was estimated annually based on the internal operating temperature (Top) at long permanence rooms (bedrooms and integrated kitchen/living room). Only one indicator was considered in the thermal performance evaluation, obtained by the ponderation of the room areas. To classify the building's energy efficiency, the indicator proposed for the Brazilian bioclimatic zone in the RTQ-R was used. In this evaluation, Naturally Ventilated housing was considered for 24 h a day [10]. The efficiency level of the envelope varies from level A (CHD ≤ 12.566 °Ch) to level E (CHD > 30.735 °Ch), as presented in Table 5. Occupancy and internal thermal loads were considered in the simulation, which was carried out for the 8.760 h of the year [10].

Table 5. Building envelope efficiency according to the RTQ-R.

Level of Efficiency	Cooling Degree-Hours Condition
A	CDH ≤ 12,566 °Ch
B	12,566 < CDH ≤ 18,622 °Ch
C	18,622 < CDH ≤ 24,679 °Ch
D	24,679 < CDH ≤ 30,735 °Ch
E	CDH > 30,735 °Ch

3. Results and Discussion

3.1. Thermal Loads in Accordance with the Thermal Balance Method

The thermal loads of both models were quantified by summing the cooling thermal loads of the bedrooms, which was not considered in other house spaces since the strategy had a low impact on their performance. Since the region does not present a well-defined winter season, there are no heating loads in this case, with lower temperatures only occurring during cold weather fronts. It should be noticed that thermal loads values refer to the thermal energy required for cooling, therefore, they are not the real consumption of a HVAC system in operation.

The thermal load demand of both the reference typology (LIHs) and the thermal mass strategy with the bermed earth-sheltered walls (LIHb) can be seen in Figure 5. In LIHs typology, the highest average annual thermal demand in the bedrooms occurs when the bermed earth-sheltered walls are oriented to North (87 KWh/year) and the lowest demand occurs when the walls are oriented South (70.5 KWh/year). Similar results to the latter are obtained when the walls oriented West (71 KWh/year). Therefore, the best position to locate the house, when the thermal mass strategy is not set in the building, is orienting the bedroom walls South, while the main façade of the house is oriented North, resulting in a 19% reduction in the annual thermal load demand.

The incorporation of the thermal mass strategy in the house provides a reduction in the thermal loads demand of the bedrooms for all the orientations considered (Figure 5). In LHIb, differently from the LIHs demand pattern, the highest average thermal load demand of the bedrooms can be seen when the main façade is oriented to the South (68 KWh/year), while the lowest is obtained when the main façade is oriented West (49 KWh/year), providing a reduction of 19KWh/year.

Based on the previous findings, the design consideration for thermal mass strategy orientation follows a different recommendation regarding to that observed for buildings without its use. In this sense, the adoption of the strategy in bedrooms with the bermed earth-sheltered walls oriented South is not recommended, since the difference in the annual thermal load demand between LIHs e LIHb typologies is inexpressive. On the other hand, the others orientations tested present a 31 to 45% reduction in thermal load demand, with greater reduction in the West. Thus, from a technical perspective, this measure is recommended for the tropical climate region as an alternative to improve building thermal load performance, and consequently, energy consumption. The strategy impacts are similar to those observed in previous studies. A thermal performance analysis of earth-sheltered residential building was conducted in the city of Yazd, in Iran (hot and dry region). In that case, the total energy consumption of a residential 0.5 m deep earth-sheltered was reduced by about 45% [27]. The reduction was more expressive than in this work because all sides of the earth-sheltered building were covered by soil. In turn, in the Mediterranean climate, the annual air-conditioning energy demand of a building with southern elevation located in Poznań (Poland), installed above and under the ground with 0.1 cm of thermal insulation thickness, was reduced from 13% to 42%, depending on the type of soil on which building was founded [28].

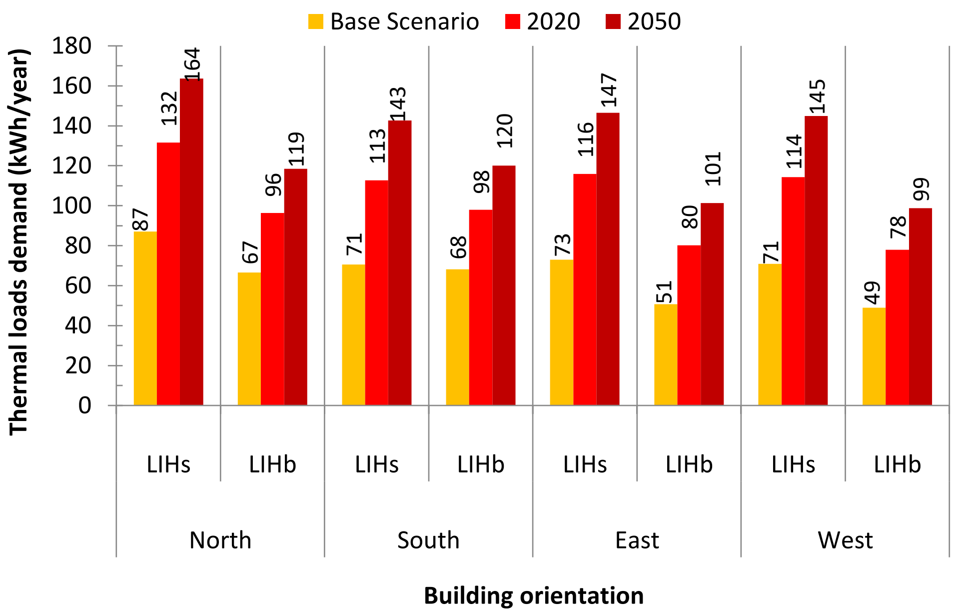


Figure 5. Weighted average annual thermal loads demand of the bedrooms.

Regarding the impact of climate change, it is observed that the global warming projections influence the thermal load demand for cooling within the spaces under study, considering that the location of the house presents a tropical climate. In the 2020 future scenario, the impacts are high in the LIHs typology, varying from 51 to 62% when compared to the base scenario, depending on the orientation. The same trend is observed for the LIHb typology, but with lower values, between 44 and 59%. In the 2050 scenario, the thermal load demand doubles for almost all orientations when compared to the base scenario: from 188 to 204% in LIHs and from 178 to 202% in LIHb. These projections are in accordance with previous studies conducted in South America for similar low-income houses [20,22,29].

Despite the thermal loads reduction, the LIHb serves as an effective alternative to counteract the effects of climate change since its performance always remains superior to that of LIHs typology. For the 2020 scenario, the reduction provided by the implementation of the strategy when compared to the thermal load demand of the building without its implementation is significant, varying from 15 to 47% depending on the orientation. The same occurs for the 2050 scenario, with a variation between 18 and 46%. The highest reduction in thermal load was observed when the thermal mass strategy is positioned facing West, with a 46.5% average reduction.

Previously isolated measures tested in similar low-income houses located in the southeastern and northeast regions of Brazil were also effective in reducing the building energy consumption of HVAC [22]. The three best performing solutions were found when the wall absorptance in buildings was reduced to 0.3 (reduction in the base scenario: 21.86% | 2050: 20.98%), when the brick wall was substituted by insulated concrete (40.82% | 21.74%) and when the clay roof was replaced by a metal roof with 0.07 m of insulation and solar absorptance 0.3 (34.07% | 23.64%). Note that the thermal mass strategy provided by bermed earth-sheltered walls, when compared to the previous strategies, is more effective in reducing thermal loads, in turn, improving the energy consumption of the building. Thus, bermed earth-sheltered walls, as an isolated passive adaptation measure, is not capable of completely counterbalance the impact of climate change on the thermal load demand, and consequently, in energy consumption as well as the other strategies tested in the previous study, however, when combined with other adaptation measures it may be an alternative to improve the building envelope and counterattack the effect of global warming [20,22,29].

3.2. Envelope Performance According to RTQ-R

The performance of the Cooling Degree-Hours (CHD) is different from that observed in thermal load demand. When operating with HVAC conditioning, the thermal changes caused by the winds that affect the spaces are minimized since the windows remain closed and the winds only impact on the external face of the window's panel, not entering the spaces (Figure 6). For LIHs typology, the worst average performance is observed when walls are oriented to the South (12,071 °Ch). In contrast, the best average performance is obtained when the walls are oriented West (10,696 °Ch). In this case, a 13% reduction in the Cooling Degree-Hours is achieved, being the best orientation for the building without the bermed earth-sheltered wall.

Similarly to the thermal load's case, the incorporation of the thermal mass strategy with bermed earth-sheltered walls provides a Cooling Degree-Hours reduction in bedrooms for all orientations (Figure 6). For LIHb, the worst performance is seen when the bermed earth-sheltered walls are oriented to the North (10,912 °Ch) and the best performance occurs when the walls are oriented to the West (9244 °Ch, 30.5% reduction). Therefore, the worst performance scenario at LIHb differs from LIHs.

Regarding the performance of the cooling indicator, the same design recommendation for the orientation of the thermal mass strategy for buildings without bermed earth-sheltered wall should be followed for the building with bermed earth-sheltered wall. Except for the case of the façade oriented to the North, where the reduction is inexpressive and therefore the incorporation of the thermal mass strategy is not recommended, in the other orientations, a reduction in the Cooling Degree-Hours is observe, varying from 14 to 17%, despite less expressive than that observed in the previous thermal load analysis.

Notice that both typologies analyzed—LIHs and LIHb—presented level A energy efficiency rating, with Cooling Degree-Hours ≤ 12,566 °Ch, in all orientations evaluated in the base scenario. In fact, LIHs were redesigned before simulations to improve original buildings' thermal and energy performance to attend Brazilian regulations [20].

The raising in the air temperature due to climatic conditions which may prevail in future periods due to climate change will progressively impact the heat transfer process from the indoor to outdoor spaces through natural ventilation. In the 2020 scenario, the impact of global warming increases the Cooling Degree-Hours in bedrooms of both LIHs and LIHb typologies in almost a 60%. In the 2050 scenario (2041–2060 period), the Cooling Degree-Hours has duplicated in almost all orientations compared to the base scenario, for both LIHs (205 to 217%) and LIHb (210 to 228%) (Figure 6).

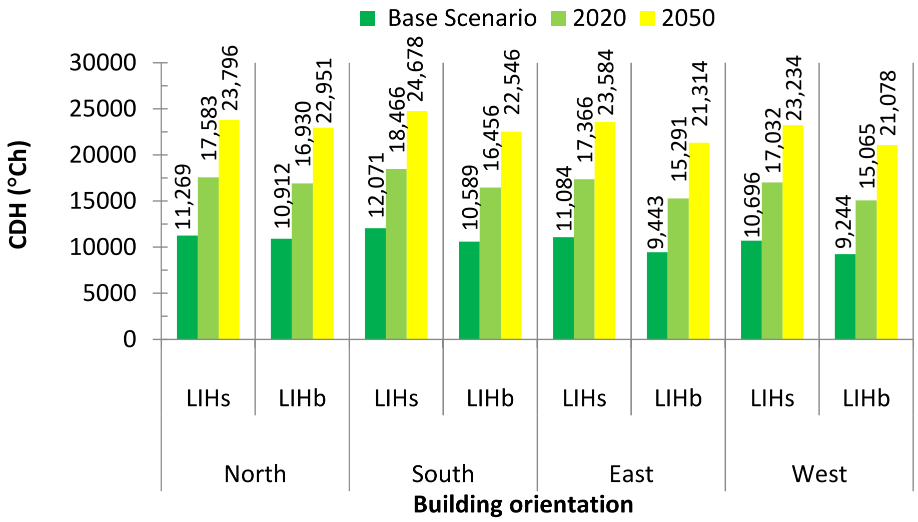


Figure 6. Cooling Degree-Hours indicator in baseline and future scenarios.

Despite the observed impacts, LIHb typology is proposed as a suitable measure to counterbalance the effects caused by climate change in a situation where the natural ventilation occurs 24 hours per day but with less impact than that observed in thermal balance analysis, in which the HVAC system is switched on at night when the indoor temperature is above the thermal comfort temperature, as defined by the adaptive model. In the 2020 scenario, the reduction provided by the implementation of the strategy varies from 5 to 14%, depending on the orientation, when compared to the thermal performance of the building without the strategy. The same occurs in the 2050 scenario, with a variation between 3 and 10%. The highest reduction in consumption was shown when the thermal mass strategy was oriented to the West, with 13% average reduction. The climate change impact was also observed in previous studies conducted in South America for similar low-income houses [20,22,28]. The aforementioned studies also tested the effectiveness of isolated measures to reduce the LIH Cooling Degree-Hours [22]. Results are similar to those observed for energy consumption but differ in terms of percentage: the wall with solar absorptance 0.3 (base scenario: 34.28% ǀ 2050: 25.97%), concrete wall with insulation (55.55% ǀ 37.14%), and clay roof replaced by a metal roof with 0.07m of insulation and solar absorptance 0.3 (57.87% ǀ 39.88%). One may note that, in terms of Cooling Degree-Hours, the bermed earth-sheltered strategy is less expressive when compared to the measures tested in the previous study [22].

Finally, because of the future trend of air temperature raising foreseen in the future climate change scenarios, the building efficiency level, which is "A" in the base scenario, decreases when the future potential impacts of climate change are incorporated into the weather data. In the 2020 scenario, the building energy efficiency is reduced to level "B", while in the 2050 scenario, to level "C". However, for a fair judgment, the energy efficiency benchmarks should be corrected for the climate changes effects.

4. Conclusions

This research studies the impact of incorporating bermed earth-sheltered walls to improve the thermoenergetic performance of a low-income building to counterattack climate change in regions of tropical climate. This passive measure may be implemented in hilly sites to take advantage of natural sloping grounds to improve indoor thermal comfort conditions.

The thermoenergetic analysis indicated that the use of bermed earth-sheltered as thermal mass for the bedrooms is a successful measure to improve building performance. Higher impacts are observed in thermal loads demand than in the thermal performance, once the spaces in the former are not exposed to the thermal changes resulting from natural ventilation, since the windows remain closed when the HVAC system is operating.

The reduction in thermal loads for cooling varied from 31 to 45%, being more relevant when the bermed earth-sheltered walls are oriented to the West, this is, the main façade of the building is oriented to the East (causing a 39% reduction when compared to the baseline case). The Cooling Degree-Hours, evaluated when the building is in a naturally ventilated mode, suffer reductions ranging from 14 to 17%, with better performance also following the main façade oriented to West (reduction of 15.7% compared to the baseline case).

The effects of climate change cause significant impacts on both operating modes, idealized for the building long permanence rooms. In the 2020 scenario, the increase in thermal load demand for cooling is over 40% for LIH, with and without the implementation of the bioclimatic strategy of bermed earth-sheltered walls, while in the 2050 scenario, in some cases, it exceeds a 200%. Similar performance was observed in Cooling Degree-Hours, with an increase of 60 and 200%, in the 2020 and 2050 scenarios, respectively. In these future scenarios, the reduction provided by the implementation of the strategy varies from 3 to 14%, depending on the orientation, when compared to the consumption of the building without the strategy. Again, the highest reduction in thermal load was shown when the thermal mass strategy was oriented to the West, with a 13% reduction in average. Thus, because of future potential impacts of climate change, building efficiency level, which is "A" in the base scenario, decreases to level "C" in the 2050 scenario. However, it should be pointed out that, for a fair judgment, the energy efficiency benchmarks should also be corrected for the climate change effects.

The increase in thermal loads for cooling, as well as in the Cooling Degree-Hours, is clear when the effects of climate change are incorporated into the weather data and thermoenergetic simulation. In that regard, the adoption of the strategy in bedrooms with the bermed earth-sheltered walls oriented South is not recommended, since the difference in the annual thermal energy demand for cooling between LIHs and LIHb typologies is inexpressive (both in the base and future scenarios). The same occurs for the Cooling Degree-Hours indicator when the thermal mass is oriented to the North. However, in the others orientations, the building with bermed earth-sheltered walls (LIHb) always displays a better performance than the building without it (LIHs), demonstrating the positive impact of this measure. Thus, bermed earth-sheltered walls constitute an alternative strategy to adapt to climate change effects. Therefore, the use of the thermal mass combined with others passives adaptation strategies may help to counterattack the climatic conditions which may prevail in future periods due to global warming on tropical climates.

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