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Bermed Earth-Sheltered Wall for Low-Income House: Thermal and Energy Measure to Face Climate Change in Tropical Region

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Abstract: Climate change impact is one of the most important global concerns at present. In the building environment, climate-responsive design may help to enhance the adaptation capacity through a better building energy performance. In this sense, this study addresses an adaptation strategy to reduce the effects of global warming on low-income houses, for which bioclimatic passive strategies should be prioritized, aiming to improve environmental sustainability. The technique chosen to be analyzed is thermal mass for cooling. Thus, the goal is to evaluate the energy consumption and thermal performance impact of implementing bermed earth-sheltered walls on bedrooms in low-income housing (LIH), considered deployed in tropical climate regions. 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) computational simulation to estimate the annual energy consumption demand and (ii) quantification of the cooling degree-hours (CDH), with the subsequent comparative analysis based on Brazilian regulation for energy efficiency in buildings (RTQ-R). The predictions show that there will be an increase in the energy consumption for cooling and in the CDH in both 2020 and 2050 scenarios, regardless of using a bermed earth-sheltered wall. Nonetheless, this adaptive measure enables the building to be resilient in terms of cooling energy demand in the 2020s, since it is 12.3% lower than in the building without the strategy use, compared with the base scenario. In the 2050s, resilience was almost reached with energy consumption only 10.7% higher, for the same conditions described previously. Therefore, bermed earth-sheltered walls work as a climate-responsive design strategy to face the potential global warming effects, promoting building sustainability in tropical climate regions.

Keywords: thermal performance; building simulation; climate-responsive; energy consumption; cooling degree-hours; bioclimatic measure; passive measure

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1. Introduction

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 [1,2]. 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 the building environment is a 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 [3]. Thus, the strategic framework conceived to mitigate and adapt buildings environments to climate change increases the importance of the thermal mass effect as a strategy to counterattack its impacts, especially within warm regions located in South America with tropical Savannah climate (Aw), which is the second most common climate in the world, covering 11.5% of the world's land area, 60.1% of South America [4], and 81.4% of the Brazilian territory [5].

Mitigation and adaptation are two strategies to address climate change. The first focuses on the causes (accumulation of greenhouse gases in the atmosphere) whereas the second on adaptation to the impacts [6]. Adaptation may respond mainly by reducing or eliminating the risks of climate change impacts, and on the building environment, it can be done by enabling the capacity of adaptation through a better building energy performance. In the last decade, some studies have evaluated the potential of buildings' energy efficiency adaptation measures to face climate changes effects. In Australia, a study investigated, in five regional climates (from cold to hot humid), the potential impact of climate change on the heating and cooling energy requirements of residential houses. It was observed that energy-efficient or high star rating houses may experience fewer absolute changes in energy requirement due to their better thermal insulation [7]. In the Netherlands, three traditional residential house projects were used to investigate the effectiveness of passive climate change adaptation measures. The following strategies were tested in the building components using thermal simulation analysis: (i) increased thermal resistance, (ii) changed thermal capacity, (iii) increased short-wave reflectivity (albedo), (iv) vegetation roofs, (v) solar shading, and (vi) additional natural ventilation. The increase in thermal resistance/ thermal capacity and short-wave reflectivity resulted in a higher and lower number of overheating hours, respectively. The application of a vegetated roof, the use the natural ventilation, and the addition of operable exterior solar shading produced a decrease in the number of overheating hours [8].

A study conducted in three different bioclimatic zones in Brazil (at Curitiba, Florianópolis, and Belém cities) accessed individual passive strategies, such as solar shading, low absorptance, and thermal insulation, to reduce energy consumption in a low-income house under the global warming effects. The aforementioned measures were able to reduce up to 50% of the future annual cooling and heating energy demand in houses, contributing to their sustainability [9]. In Guangdong Province, South China, the global warming impacts on multi-family residences were predicted in two edification typologies: one with lower thermal insulation (3.5 stars-building envelope) and the other with higher performance (5.5 stars-building envelope). The total heating and cooling energy demand of 3.5 and 5.5 star-buildings due to global warming are projected to increase 20% and 25% in the 2080s, respectively, despite their better insulation compared to the existing housing stock [10].

A medium-sized office building located in five US cities (Miami—FL, Phoenix—AZ, Los Angeles—CA, Washington—DC, and Akron—CO) was accessed under the climate change impacts. The adaptation measures focused on the operation heating, ventilation, and air conditioning system (HVAC), which included the adjustment of thermostat set-points, the reduction of HVAC operation hours, the reduction of the variable air volume box minimum flow setting, and mixed-mode ventilation, strategies considered to neutralize the increased energy consumption in the research building. The mixed ventilation strategy proved to be an effective measure to reduce energy consumption, and thus mitigate the impacts of climate change in most research cities in the 2020s and 2050s scenarios [11]. Low-income housing located in the cities of São Paulo and Salvador, Brazil had its envelope improved with isolated and combined measures to face the impact of climate change. The most effective isolated adaptation measures to improve thermal performance and energy consumption were those related to lower solar absorptance of the walls, insulated roofs with lower solar absorptance, and shading to windows in all main rooms. For both cities, it was demonstrated that it is possible to obtain a good performance in the 2050 period, compared to the current climate, with the combination of isolated measures [12].

Practical measures were proposed to counterattack the impact of climate change on energy consumption in a house located at Cuiabá, a region of Tropical Savannah climate (Aw), Brazil. The house envelope was enhanced, elevating the building system's thermal resistance and reducing the solar absorptance. Despite the improvements, energy consumption is predicted to increase by 19.6% in the 2020s and 30.1% in the 2050s, compared to the base scenario [13]. A study quantified the application of an adaptive comfort control measure in mixed-mode office buildings in Cadiz, southern Spain. A daily setpoint temperature, based on the adaptive thermal comfort approach, was applied in a building to simulate the present and future conditions under climate change. Taking the current scenario as a reference, a 74.6% reduction in energy demand and a 59.7% drop in energy consumption was quantified when the adaptive comfort control was implemented in the model [14].

Thus, the specified previous predictions indicated that, despite the enhancement in the building energy performance, no individual passive strategies might completely neutralize the increasing of cooling and heating energy usage, suggesting the combination of passive strategies to counteract the effects of climate change. Some typical measures prescribed in bioclimatic codes and energy-efficient regulations have been considered in these studies, however, to reduce energy use for cooling/ heating demands, additional measures must be considered, especially those that act as a climate-responsive design strategy.

When designing new buildings to face climate change, the traditional strategies, such as construction elements of the envelope, building geometry, and orientation, may not be sufficient to achieve adequate levels of energy consumption and thermal performance. Thus, alternative bioclimatic passive techniques are also important measures to be considered during the design phase. For hot regions, *thermal mass for cooling* is an alternative measure to accumulate and retain heat during the day and return it to the exterior environment at night, acting as a climate-responsive design strategy. This behavior reduces the indoor air temperature fluctuations and maximizes the thermal lag of heat transfer of the walls, which oscillate in a damped manner [15–17]. 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 [8].

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 a south-facing wall in cold regions and with a north-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 [18]. 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 [19].

For this reason, the bermed type of construction may contribute to resilience to the urban heat island phenomenon, and constitutes an alternative measure to adapt buildings to the impacts of climate change, one of the most important global concerns at present. Thus, this research strategy is aligned to the principles of sustainable development goals (SDGs) to promote the 2030 agenda, especially the SDG 7 (affordable and clean energy) and SDG 11 (sustainable cities and communities), which should guide the production of sustainable and efficient buildings [20]. Besides, this passive measure, understood as a measure that does not use the energy once implemented in the building, may help designers and builders to attend the premises of bioclimatic architecture and thus achieve the fulfillment of sustainable performance requirements established by the building's certifications systems, especially concerning energy efficiency and application of climate-responsive design [21].

Thus, this study aims to evaluate the potential thermal and energy impact of implementing bermed earth-sheltered walls as a passive cooling strategy for a residential building's bedrooms, located in a region with a tropical climate to face climate change effects. The study helps to deepen the knowledge of this potential climate-responsive strategy as an adaptation measure for building to be deployed in the regions with hot climate conditions, where future scenario projections of climate change have indicated the increase of hot days frequency, which will induce changes in building energy demand due to the increase of air conditioning systems used for cooling [22,23]. The analyses are made considering a base scenario (without the influence of climate change) and two future scenarios (2020 and 2050) contemplating potential 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) selected for this study is considered to be 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 [24]. Similar climate classification can be found in several locations around the world, such as Australia, 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 (15°36′56″ S; 56°06′01″W) is used as a base of this research.

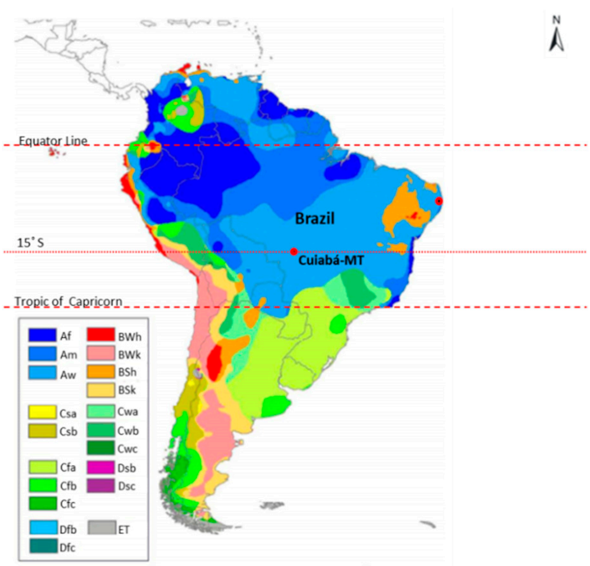


Figure 1. Location of the city of Cuiabá in South America. Source: adapted from Peel et al. [4].

The Brazilian Association of Technical Standards (ABNT) for 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 [16]. The recommendations and constructive guidelines for adequate LIH for the Savannah climate region are detailed in Table 1, in accordance with the Brazilian Bioclimatic and as prescribed by the Brazilian Technical Quality Regulation for Energy Efficiency Level of Residential Buildings (RTQ-R) [25]. As indicated in Table 1, thermal mass for cooling is a strategy recommended to adapt the building to the climate where it is located. Thus, this research focuses on verifying if this potential passive strategy may be adequate to adapt a building to the projected climate change scenarios.

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

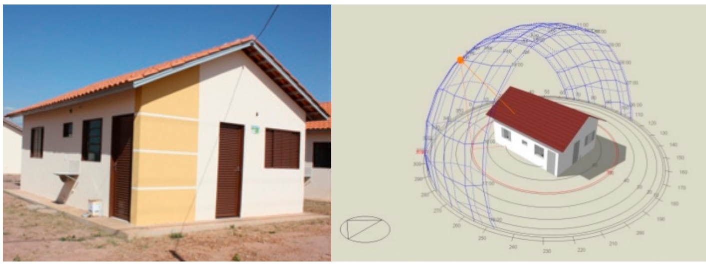
Code	Opening's Recommendations	Guidelines for Building Envelope				Strategies for Passive Thermal Conditioning
		Wall System		Roof System		
NBR 15220 [1]	Small openings: 10% < A < 15% Shade openings	A: NR Type: Heavy U ≤ 2.2; CT:NR φ ≥ 6.5 h SF ≤ 3.5%		A:NR Type: Heavy U ≤ 2.0; CT: NR φ ≥ 6.5 h SF ≤ 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/m^2K); CT: thermal capacity (kJ/(m^2K); φ: thermal lag; SF: sun factor; NR: no requirement established; T_{int}: internal temperature; T_{ext}: external temperature.

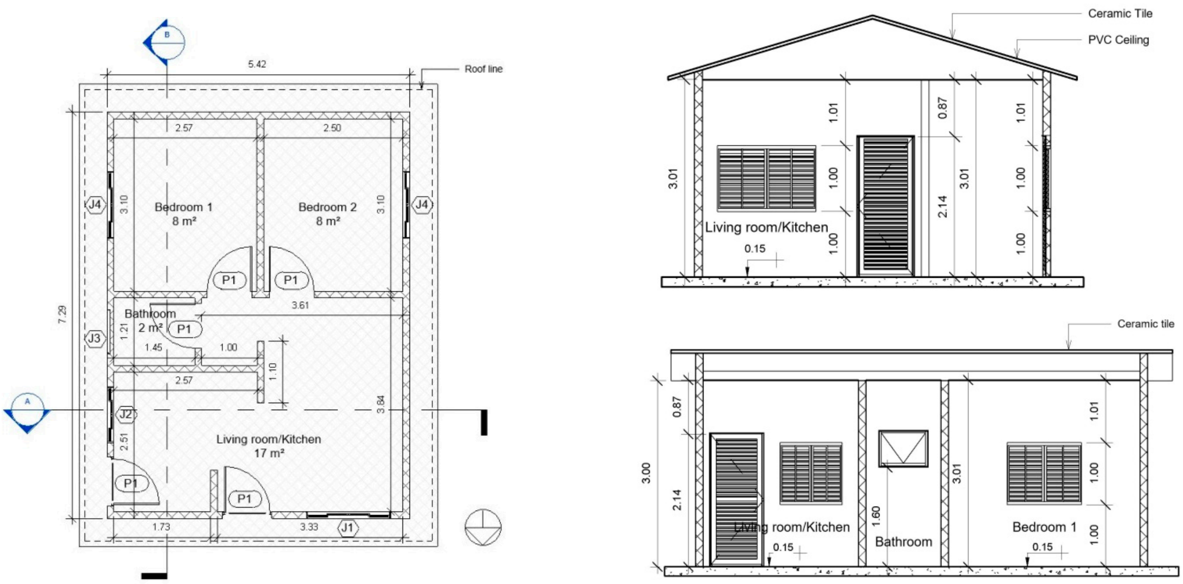
2.2. Characterization of the Study Case

A typical low-income house, 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 [26] (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. This typology is handed out to the users without any concern about climatic adaptation to the implantation region, with a poor thermal performance [9,12,13], compromising its indoor thermal comfort conditions as well as increasing energy consumption for cooling [13,27]. Due to these facts and how this research focuses on the thermal mass strategy as a climate-responsive measure, the original standard building project was redesign to attend Brazilian RTQ-R level 'A' of efficiency [25], thereafter named as "LIHe". It is characterized by a one-story detached house in contact with the ground. LIHe presents 39.18 m^2 of total area and 34.54 m^2 of internal floor area, distributed in four designated areas, namely: living room/kitchen (17.44 m^2), bedroom 1 (7.78 m^2), bedroom 2 (7.57 m^2), and bathroom (1.75 m^2) (Figure 2a–c). The roof construction is dual pitched with an overhang of 0.30 m depth. The rooms' ceiling height 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 of four panels, two of them being single glass fixed panels and the other two sliding metallic Venetian panels. The kitchen's window is a metallic tilting type of 1.00 × 1.00 m. The external doors are made of metallic sheets, while interior doors are wood-made. The thermal resistance of the external walls and roof were improved to provide building efficient level "A". The external walls consist of ceramic bricks (six-hole type) coated on the outside with expanded polystyrene sheets (EPS) (0.04 m) and plaster (0.025 m) in the outermost and innermost layers. The internal partitions consist of ceramic brick (six-hole type) coated on both sides with plaster (0.015 m). The external walls absorptance was reduced from 0.3 to 0.15 by changing the painting to white color. The roof system is composed of ceramic tile, aluminum foil for thermal insulation, an air gap layer, and ceiling panels of polyvinyl chloride (PVC) (0.01 m). The outermost layer of the tiles was painted with white color (ranging the absorptance of the roof from 0.8 to 0.15). Regarding the roof air gap, this layer presents 0.61 m^2K/W thermal resistance (R-value), with a thickness greater than 0.05 m and low thermal emissivity due to the installation of aluminum foil. The Brazilian Association of Technical Standards NBR 15.220 [16] was used to redesign the building envelope and to determine the thermal properties of the building system envelope of the efficient low-income house (LIHe), which are presented in Table 2.



(**a**) External image and 3D DesignBuilder model of the low-income house (LIH).



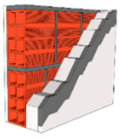
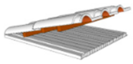
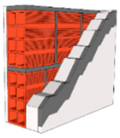
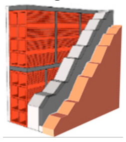
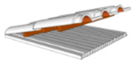
(**b**) Floor plan (dimensions in meters)

(**c**) Sections AA′ and BB′

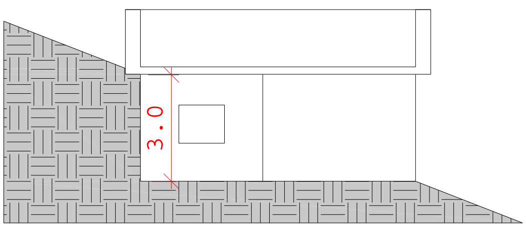
Figure 2. (**a**) Standard low-income housing picture, (**b**) floor plan, and (**c**) section plans.

To evaluate the thermal inertia strategy, bermed earth-sheltered walls were implemented in the original housing design (hereafter named as LIHb), so that bedrooms walls came into direct contact with the soil (Figure 2), resulting in the "LIHb" design strategy (see properties in Table 2). For that, the external walls of bedrooms 1 and 2, which do not present openings, were selected to be 3.00 m (ceiling height) grounded 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.

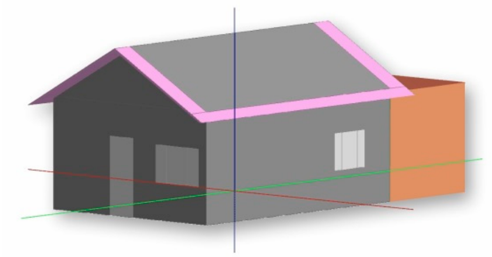
Table 2. Thermophysical properties adopted for building systems envelope of the efficient low-income house (LIHe) and bermed earth-sheltered low-income house (LIHb).

Building Characteristics	Envelope	Materials Layers	Thickness (m)	R-Value [1] (m^2K/W)	U [2] (W/m^2K)	CT (J/m^2K)	α
Efficient low-income house systems (LIHe)	Wall System 	White painting		1.128	0.886	169.38	0.15
		Mortar	0.025				
		EPS sheet	0.040				
		Ceramic brick	0.09				
		Mortar	0.025				
		White painting					
	Roof System 	White painting		0.847	1.18	41.92	0.15
		Ceramic tiles	0.01				
		Aluminum foil	-				
		Attic space	>0.05 m				
		PVC ceiling	0.01				
Bermed earth-sheltered low-income house systems (LIHb)	Wall System 	Similar Layer and Thickness of the Efficient LIH		Similar properties of the LIHe			
	Wall System in contact with ground 	Similar Layer and Thickness of the LIHe + ground contact		Evaluated by the Energyplus program according to the Basement (GDomain) input data.			
	Roof System 	Similar Layer and Thickness of the LIHe		Similar properties of the LIHe			

[1] Thermal Resistance and [2] Transmittance include the internal e external superficial air resistance. Properties estimated by NBR 15.220 [16].



(**a**)



(**b**)

Figure 3. (**a**) Schematic section and (**b**) modeled bermed earth-sheltered wall located in the bedrooms.

2.3. Simulation Method

The impact of the bermed earth-sheltered wall in the building performance was evaluated through computer simulation, using the DesignBuilder Software (Gloucestershire, United Kingdom, England) [28], to compare the performance of the LIHe and LIHb models. The simulation results were evaluated following the RTQ-R [25] methodology, which considers the quantification of the energy consumption and the cooling degree-hours for a full year of operation. The simulation was carried out considering 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.

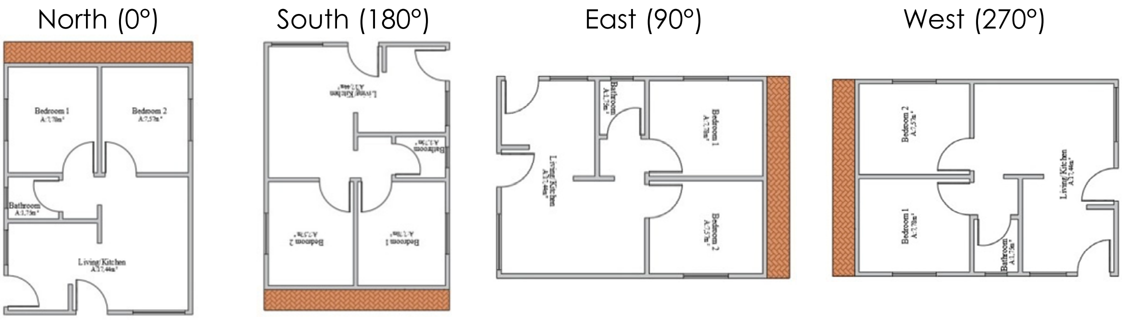


Figure 4. Variation of the embedded earth-sheltered wall orientation.

The earth-sheltered wall strategy was configured within the simulation model through the GroundDomain: Basement (GDomain) input (Table 3), 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 [29]. The simulation was carried out considering the "Finite Difference" model as the ground temperature type, which considers the weather data to define boundary conditions [30]. The manual developed by [31] was used as a reference to the GroundDomain input data.

Table 3. Input data considered in GDomain simulation.

Input Data	Adopted Input Values
Ground Domain Depth (m)	15
Soil Thermal Conductivity (W/m K)	0.52 [32]
Soil Density (kg/m^3)	1700 [32]
Soil Specific Heat (J/kg K)	840 [32]
Mesh Density Parameter	6

The GroundDomain requires the monthly soil temperature data under the dwelling, since it influences, significantly, the thermo-energy simulation. Thus, the Slab input tool was used to obtain the soil temperature under the LIH for the base and future scenarios (Table 4).

The occupancy and equipment power density data were adopted following RTQ-R [25], considering two people in each bedroom and four people in the living room. Regarding the occupancy metabolic activity rate, 45 W/m^2 was considered in bedrooms and 60 W/m^2 was set in 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. during the weekdays and from 9 p.m. to 10 a.m. on the weekend days, while the living room is used from 2 p.m. to 9 p.m. during the weekdays and from 11 a.m. to 9 p.m. on the weekend days.

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

Month	1961–1990	2020s	2050s
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

2.4. Generating Future Climate Scenarios Weather Data

The "morphing" methodology, developed and described in [33], was adopted in this research, aiming to analyze the implications of climate change on the building's thermal/energy performance. The morphing method has been used to generate future EnergyPlus Weatherfiles (EPW) for any location in the world using the *Climate Change World Weather File Generator for World-Wide Weather Data (CCWorldWeatherGen) tool* (Southampton, United Kingdom) [33–35]. 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-year period, which is the building life expected for low-income houses [36].

2.5. Indicators for Energy Consumption and Thermal Performance Evaluation

2.5.1. Estimation of the Cooling and Heating Energy Consumption

Through the use of computer simulation, it is possible to obtain the thermal performance and the energy demand for heating and cooling when heating, ventilation, and air conditioning (HVAC) system is utilized in the indoors environment. In energy consumption analysis, two different conditions were utilized that express the habits of local habitants: (i) from 8 a.m to 9 p.m building operating naturally ventilated, considering 20 °C as the indoor temperature control of the windows; and (ii) from 9 p.m. to 8 a.m with use of artificial conditioning system operating in the bedrooms, considering the split system with heating and cooling setpoint adjusted to 18 °C and 24 °C, respectively. In this case, the thermal load due to occupation, equipment, lighting, and energy performance of the air conditioning system followed the prescription of the Brazilian regulation for energy efficiency in buildings (RTQ-R) [25].

The energy consumption was assessed only for cooling, excluding heating demand, because the local population does not use heating systems due to the hot weather conditions in the region, while attending the RTQ-R methodology for the region under evaluation [25].

The air conditioning system was considered only in the bedrooms, which is a common behavior observed in the residences of this region [37]. The coefficient of performance (COP) for cooling was assumed to be 3.00 W/W (level "A" in the Brazilian Energy Labelling), and continuous fan operation mode (fan efficiency 0.7 and motor efficiency 0.9), following the simulation parameters for air conditioning system modeling used in the Brazilian Energy Label for residential buildings [25]. The estimated final cooling consumption of the (LIHe and LIHb) typologies were analyzed in terms of kWh/ (m^2/year) in both the base (1961–1990) and future climate change scenarios (2020 and 2050). Since the sum of energy spent by equipment and lighting remained almost constant between the present and future time-slices, not affecting building performance, it was not presented in final energy results. In this study, energy demand was only quantified for the bedroom zones where the bermed earth-sheltered walls were deployed, focusing on capturing the influence of the thermal mass as a passive strategy for cooling.

2.5.2. Indicator of the Envelope Performance by RTQ-R

The cooling degree-hours (CDH) parameter was used as an indicator of building thermal performance under natural ventilation conditions, based on the RTQ-R recommendations [25]. The heating degree-hours parameter (HDH) was ignored due to their low occurrence in the study region. The base temperature used to calculate the CDH was set at 26 °C, which was obtained by means of Equation (1):

$$CDH = \sum \begin{matrix} 8760 \\ i = 0 \end{matrix} \begin{cases} \text{for } T_{op} > 26°; & (T_{op} - 26°) \\ \text{for } T_{op} \leq 26°; & (0) \end{cases}, \quad (1)$$

This indicator was estimated annually based on the hourly indoors operative temperatures (T_{op}), with the two bedrooms and living room/kitchen considered as long permanence rooms. 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, the naturally ventilated condition was considered for 24 h a day [23]. The efficiency level of the envelope varies from level A (CDH $\leq$ 12.566 °Ch) to level E (CDH > 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/ year [25].

Table 5. Building envelope efficiency for the researched bioclimatic zone according to the Brazilian Technical Quality Regulation for Energy Efficiency Level of Residential Buildings (RTQ-R).

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

2.5.3. Adaptive Thermal Comfort Conditions in the Indoors Long Permanence Rooms

The effectiveness of the bermed earth-sheltered walls measure adopted for improving indoor building thermal comfort was evaluated, since it is common for the low-income population not to have an air conditioning system installed at home due to the costs of its operation. In this way, it was considered the index based on the study of adaptive thermal comfort proposed by De Dear and Brager [38]. The methodology may be applied to represent the user's thermal comfort conditions inside of buildings naturally ventilated, considering only the user's occupancy and internal heat sources. The thermal comfort levels are defined by the ideal indoor operative temperature or the monthly neutral temperature

(T_n, in °C) related to the monthly averages of outdoor air temperature (T_{Emed}, in °C), following Equation (2). This equation is only valid for T_{Emed} between 10.0 °C and 33.5 °C.

$$T_n = 17.8 + 0.31 \times T_{Emed} \quad (2)$$

Thermal comfort ranges were determined by the definition of the month neutral temperature (T_n) following procedures established in Standard 55 [39]. The monthly upper and lower limits for 90% of satisfied users were obtained by the use of Equation (3), where T_{op} represents the hourly indoor operative temperature. Indoor thermal comfort is reached when the operative temperature is between the intervals prescribed in Equation (3).

$$(T_n - 2.5) \leq T_{op} \leq (T_n + 2.5), \quad (3)$$

To quantify hot or cold discomfort hours and thermal comfort conditions of the long permanence rooms for the base scenario and future climate projections, the building was considered to operate in exclusive use of natural ventilation 24 h per day. Only one indoor operative temperature pondered by the area of the long permanence rooms was considered to assess the effectiveness of the measure to improve building performance. In turn, it was also considered the indoor operative temperature pondered by the area of bedrooms where the strategy was deployed.

3. Results and Discussion

3.1. Energy Consumption in Accordance with RTQ-R

The energy consumption of both models was quantified by summing only the energy consumption of the bedrooms, which was not considered in living room/kitchen spaces since the strategy had a low impact on their performance. Since the region does not present a well-defined winter season, there are few hours of heating demand, with lower temperatures only occurring during cold weather fronts. With the climate change impact projections, it is reduced to almost nil values in 2020 and 2050 scenarios. Thus, heating loads were disregarded in this study, as the main consumption in typologies comes from cooling demand in the long permanence rooms.

The energy consumption of both the reference typology (LIHe) and the thermal mass strategy with the bermed earth-sheltered walls (LIHb) can be seen in Figure 5. In the LIHe typology, the highest and lowest average energy demand in the bedrooms occurs when walls are oriented to the north (66 kWh/m^2) and to the west (63 kWh/m^2), respectively. Similar results to the latter are obtained when they are oriented east and north (~64 kWh/m^2). Thus, when the thermal mass strategy is not set in the building, the bedroom's wall orientations have a low impact on energy demand (reduction of 2% from north to west). This behavior may be attributed to the building envelope, which has been improved by increasing its thermal insulation in order to obtain level A of energy efficiency [40]. In fact, the energy consumption for cooling demand observed in this study is slightly lower to that quantified for LIHs with combined passive measures located in the Salvador and Belém city (both Am Köppen–Geiger climate type), in the northern region of Brazil, which displayed annual energy consumption of 75 kWh/m^2 and 85 kWh/m^2, respectively [9,12]. Thus, the combined adaptation measures implemented in the standard LIH are more effective in improving the building energy performance in the base scenario than in the previous studies.

The incorporation of the thermal mass strategy in the LIH provides a reduction in the bedroom's energy demand for cooling for all the orientations considered (Figure 5). In the LHIb, differently from the LIHe demand pattern, the highest year energy demand of the bedrooms can be seen when the strategy is oriented to the south (42.7 kWh/m^2), while the lowest is obtained when the strategy is oriented west (39.6 kWh/m^2), providing a reduction of 7.8% in the annual energy demand. Thus, the design consideration for thermal mass strategy orientation aiming to improve energy performance follows a different recommendation, regarding that observed for buildings without its use. In this sense, the adoption of the strategy in bedrooms with the bermed earth-sheltered in the orientations tested present a 34% to 38% reduction in energy demand for cooling, with a greater reduction in the west, almost reaching the relative cooling consumption indicator established for the region of 34.48 kWh/m^2 to achieve level A efficiency. Thus, from a technical perspective, even for building envelopes already displaying an adequate thermal performance, the bermed earth-sheltered wall is recommended for the tropical climate region as an alternative passive measure to improve building cooling energy performance.

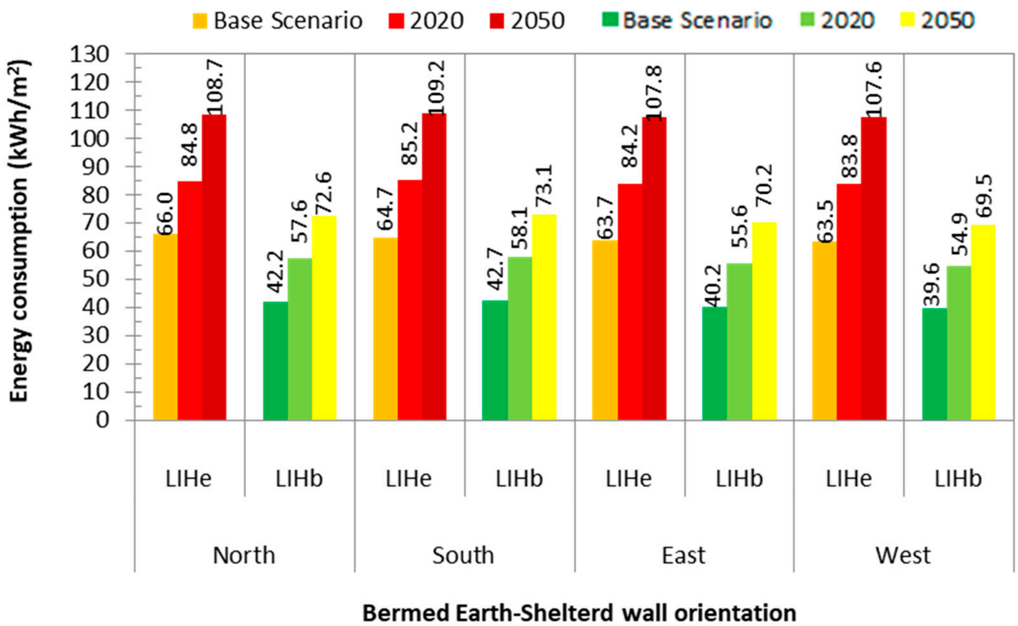


Figure 5. Annual energy consumption of the bedrooms.

The strategy impacts are similar to those observed in previous building simulation studies. Thermal performance analysis of earth-sheltered residential buildings was conducted for the city of Yazd, in Iran (hot and dry region) [41]. Building Case 900 ASHRAE was employed in a prospective study, with progressively changing depth of the soil surrounding the housing prototype [42]. In this case, the highest energy consumption was found when the main façade (not in contact with the earth) was oriented to the north, i.e., when the bermed earth-sheltered wall was displayed in the south, confirming the best disposition obtained in this research. However, southern orientation had the lowest energy consumption, while west obtained the best performance in this research, due to the fact that current LIHb has only one wall sheltered by earth, and different opening locations for ventilation in the facades. The total energy consumption of a residential 1.0 m deep earth-sheltered (which corresponds to an entire wall sheltered by the earth, as in this study) was reduced by about 67% (south orientation), bringing annual energy consumption to 80 kWh/m^2. Despite the reduction being more expressive than in this work, final energy consumption for cooling was close to that found here. In another study in the Mediterranean climate (temperate), the annual air conditioning energy demand of a prototype building with southern elevation located in Poznan (Poland) was evaluated. The building wall was installed above and completely under the ground, with 0.1 m of thermal insulation thickness on the walls. This configuration provided reductions varying from 12% to 30%, depending on the type of soil on which the building was founded, which demonstrates the soil type influence on the building performance of bermed houses [43]. The highest reduction was obtained for the soil with similar physical and thermal characteristics to those considered in the current study.

Despite of the implementation of combined adaptation measures and bermed earth-sheltered strategy in the standard typology envelope, it is observed that the global warming projections influence the annual cooling energy demand within the spaces under study. In the 2020 future scenario, the impacts are high in the LIHe typology, varying from 28% to 32%, when compared to the base scenario, depending on the orientation. The same trend is observed for the LIHb typology, but with higher percentages, between 36% and 39%. In the 2050 scenario, the increase in energy demand exceeds 50% for all orientations when compared to the base scenario: from 64% to 70% in LIHe, and from 71% to 75% in LIHb.

The projected increase in terms of percentage corroborates with previous studies conducted in cities located in other countries with the same climate type (Aw). In Darwin, Australia, the projected increase in air temperature for some emissions scenarios varied between 1.8 °C to 2.5 °C in the 2050 scenario, inducing an increment in energy consumption for cooling which varied between 40% and 80%, depending on the type of thermal insulation considered for the building envelope [7]. In Miami, The Unites States, the projected increase in air temperature in the 2050 scenario (2.52 °C) is similar to those predicted for Australia and lower than in the current research (3.2 °C). Despite having similar projections for air temperature to Australia, the possible induced increase in energy consumption for cooling is lower (between 27% and 37% in 2050 emissions scenarios), including in relation to this research [44].

In Brazil, similar projections have been observed for low-income houses deployed in regions with hot weather conditions. At Salvador (Af), the cooling energy demand is expected to increase by 30% and 46.6% in 2020 and 2050 scenarios, while at Belém (Af), 43.5% and 70.5% and, at Cuiabá (Aw), 20% and 30%, respectively [9,12,13]. The projection variations are attributed to the different types of passive strategies used in building envelopes. However, they are lower than those observed for the standard LIH studied in the same region, where the energy demand reaches more than double in the 2050 scenario due to its lack of adequate thermal insulation [45].

Despite the thermal load reduction, the LIHb serves as an effective passive strategy to counteract the effects of climate change, since its performance always remains superior to that of LIHe typology. For the 2020 scenario, the reduction provided by the strategy, when compared to the annual cooling energy demand of the building without its implementation, is significant, varying from 32% to 35% depending on the orientation. The same occurs for the 2050 scenario, with a variation between 33% and 36%. The highest reduction in thermal load was observed when the thermal mass strategy was positioned facing west, with a 36% average reduction. Notice that a partially-bermed earth-sheltered wall has the potential increased building resilience to face the global warming impacts, since cooling energy consumption in the 2020s is on average 12.3% lower than the base scenario, while in 2050, it is surpassed only by 10.7%. For the last time-slice, resilience is almost achieved, providing a considerable reduction in energy consumption (on average 37 kWh/m^2/year, based on energy consumption for LIHe in the 2050s) and promoting sustainability in tropical climate regions.

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 [12]. The three best performing solutions were found when the wall absorptance in buildings was reduced to 0.3 (base scenario reduction: 21.86% | 2050 Scenario reduction: 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 the bermed earth-sheltered walls, when compared to the previous strategies, is more effective at counterbalancing the climate change effects, in turn, reducing the energy consumption of the building. Thus, as an isolated passive adaptation measure, as well as the other strategies tested in the previous study, it is not capable of completely counterbalancing the impact of climate change on cooling energy consumption. However, when combined with other adaptation measures, as proposed in this research, it may be an alternative to improve the building envelope and counterattack the effect of global warming, as observed in this study and previous ones [9,12,13]. For cities under hot weather conditions, the idealization of climate-responsive design on residential buildings in the design phase is an alternative to reducing energy consumption demand due to the increase of air conditioning systems used for cooling.

3.2. Envelope Performance According to RTQ-R

The CDH performance behavior differs from that observed in energy demand. When operating with an HVAC conditioning system, the thermal exchanges caused by the winds, that may affect the indoor' spaces, are minimized since the windows remain closed and the winds basically remove heat from external facades, entering indoors spaces by fenestrations that exist on the window's panel (Figure 6). For the LIHe typology, the worst average performance is observed when walls are oriented to the north (10,269 °Ch). In contrast, the best average performance is obtained when the walls are oriented west (9339 °Ch). In this case, a 9% reduction in the CDH is achieved, being the best orientation for the building without the bermed earth-sheltered wall. Similar to the cooling energy demand, the incorporation of the thermal mass strategy with bermed earth-sheltered walls provides a CDH 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 (7585 °Ch), and the best performance when the walls are oriented to the west (5810 °Ch, 23.4% reduction).

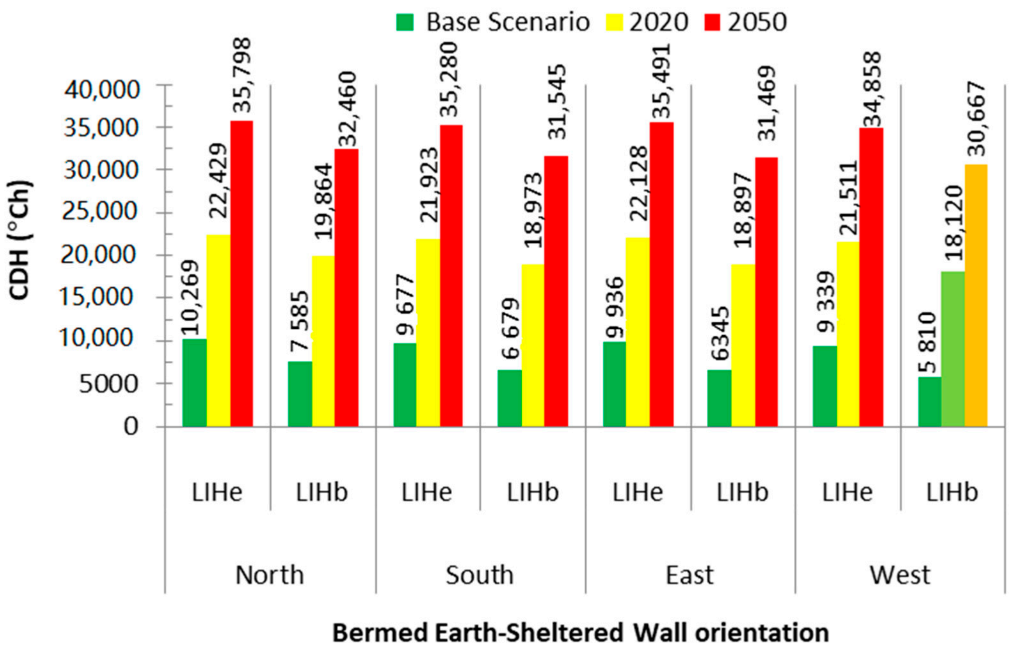


Figure 6. Weighted annual average cooling-degree hours (CDH) indicator in baseline and future scenarios (colors in west orientation for LIHb in the 2050s was changed to match with the colors established in the RTQ-R).

Regarding the performance of the CDH, the same design recommendation for the orientation of the thermal mass strategy for buildings without the tested strategy should be followed for the building with the bermed earth-sheltered wall. CDH reduction is expressive, varying from 26% to 38%, as much as those observed in the previous cooling demand analysis. For the LIH implanted in Salvador city, the combined adaptation measures in the current climate resulted in decreasing in cooling degree-hours ranging between 33% to 68%, compared to the standard LIH, reaching CDH varying between higher than 5000 °Ch and lower than 12,000 °Ch [12]. Notice that LIHe typology presented level "A" energy efficiency rating (CDH ≤ 12,566 °Ch) in all orientations evaluated in the base scenario, as well as LIHb which had its envelope improved with the implementation of the partially-bermed earth-sheltered walls.

The raising of the air temperature, due to climatic conditions that may prevail in future periods due to climate change, will progressively impact the possibility of transferring heat from the indoors to the outdoors environments, reducing the potential use of naturally ventilated strategy in the residential buildings. In the 2020 scenario, an increase in the CDH inside LIHe rooms (18% to 30%) was observed, with the best performance strategy orientation (west) in the base scenario being the most impacted due to global warming effects. In the LIHb, the scenario was even more drastic, with CDH doubling (reduction from 61% to 111%). In the 2050 scenario, the CDH exceeded double in some orientations, when compared to the base scenario, for both LIHe (148% to 173%) and LIHb (227% to 327%) (Figure 6). The impact in the CDH may be assigned to the predicted increasing of the outdoor air environment (projected rising of 1.5 °C and 3.3 °C for 2020 and 2050, respectively) and reduction in the humidity, but also due to the elevation of global horizontal radiation. In turn, the rising in ground temperature (see Table 4) also corroborates degeneration of the building's thermal performance [9,13].

Despite the observed impacts, LIHb typology is proposed as a climate-responsive design strategy to counterbalance the effects caused by climate change in a situation where natural ventilation occurs 24 h per day, However, its impact is lower than that observed in cooling energy demand, in which the HVAC system is switched on at night when the indoor temperature is above the thermostat temperature, defined as a baseline thermal comfort temperature in the RTQ-R [23]. In the 2020 scenario, the reduction provided by the implementation of the strategy varies from 11% to 16%, 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 9% and 12%. The highest reduction in the thermal performance was shown when the thermal mass strategy was oriented to the west, with a 13.9% average reduction, even so, less expressive than that shown for energy consumption. These projections corroborate the previous study conducted with the same low-income house, but with different types of passive strategies used in building envelopes and without the bermed earth-sheltered wall. Projections in the CDH indicator are expected to increase 31.3% and 28.6% in 2020 and 2050 scenarios [13]. However, in the standard LIH without any adaptation measures and with the use of bermed earth walls, the reduction in CDH is similar to that observed in this research [45].

The bermed earth-sheltered wall strategy, when compared with other isolated measures, displays a lower reduction in terms of percentage [12]: the wall with solar absorptance 0.3 (base scenario reduction: 34.28% | 2050 Scenario reduction: 25.97%), concrete wall with insulation (55.55% | 37.14%), and clay roof replaced by a metal roof with 0.07 m of insulation and solar absorptance 0.3 (57.87% | 39.88%). Thus, in terms of CDH, the bermed earth-sheltered strategy in this study is less expressive when compared to the isolated measures tested in the previous study. One may note CDH is weighted by the areas of the long permanence rooms, including the living room/kitchen, which has the same area as the sum of the bedrooms area and is not in contact with the bermed earth-sheltered walls. Thus, this room reduced the potential strategy impact (by at least half) due to its lower performance than the ones in contact with the ground. Yet, this behavior may be attributed to the fact that before simulations, LIH was redesigned to improve original buildings' thermal and energy performance, which makes it difficult to improve its envelope due to its already high thermal insulation.

Due to the future trend of air temperature raising, foreseen in the future climate change scenarios, the building efficiency level, which is "A" for LIHe and LIHb 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 "C", with an exception in LIHb for west orientation, where level "B" is reached. In the 2050 scenario, all orientation became level "E", again with an exception in LIHb for west orientation, with level "D". Thus, this orientation must be preferred to achieve the best energy and thermal performance. Similar decreasing in building energy efficiency is also reported for five-star buildings analyzed in Darwin, Australia, and in Guangdong Province, South China, due to the raising of the energy requirement in the 2050 scenario [7,10]. This fact indicates the need to establish specific design guidelines in the building environmental certification codes to deal with this potential issue.

3.3. Indoor Operative Temperatures and Thermal Comfort Conditions

The raising in energy consumption and the reduction in the thermal performance previously discussed is related to the tendency of the outdoor air temperature observed in the future scenarios generated by the tool CCWorldWeatherGen (Figure 7). In the base scenario, the annual average air temperature is 26.7 °C and in the futures, a gradual increase is caused due to global warming projections, reaching 28.5 °C and 29.9 °C in the 2020s and the 2050s, respectively. In this sense, an increase of 3.2 °C is predicted until the 2050s, as mentioned previously. The highest increase is observed in the dry season in September (1.9 °C and 4 °C in the 2020s and 2050s, respectively) and the lowest in the wet season in January (1.2 °C and 2.3 °C in the 2020s and 2050s, respectively). The potential global warming is more pronounced in the research region than those observed in other Brazilian cities characterized by different climates [9,12]. This is an important issue, as dwellings in the region usually operate predominantly with natural ventilation, compromising the possibility to maintain adequate indoors thermal comfort in the warming predicted context, as is described below.

The indoors operative temperatures in the house's rooms accompany the observed rise in the outdoor air temperature, progressively moving upwards in each time-slice. In the LIHe, the integrated living room/kitchen operative temperatures related to the building orientations are higher than in the bedrooms, but the differences are small, causing the curves to overlap each other (Figure 7a). This is not happening in the LIHb, where the introduction of bermed earth-sheltering walls caused thermal damping inside the bedrooms (Figure 7b). The observed modulation is an effective measure to reduce temperature fluctuations during the day; however, it can also lead to a slower reduction of the operative temperature during the night, which makes important the use of natural ventilation through the window openings during this period [8]. It is possible to notice that thermal damp is progressively reduced, due to the outdoors air temperature warming and also the raising on the ground temperature, compromising the tested measure effectiveness. Thus, for this reason, thermal comfort conditions inside the building are accessed in the sequence.

The adaptation measure implemented in the LIHb is effective in improving the building thermal performance in the base scenario, increasing the comfort, and reducing hot discomfort hours inside the building (Figure 8). The west orientation is the most effective in providing the highest thermal comfort hours (82%), 12% higher than the LIHe for the same orientation. Therefore, a properly designed bioclimatic passive measure may become an alternative to improve the building's habitability for the researched location, also, in the current weather conditions.

In future scenarios, thermal comfort levels have progressively deteriorated inside the houses, and the raise in the hot discomfort hours is observed in both typologies with the projections established by the IPCC. The small number of cold discomfort hours almost vanishes, due to the forecast outdoor air temperature elevation. Despite that, in the 2020 scenario, the typologies are still capable of providing more hours of thermal comfort than discomfort. Note that LIHb, on average, provides better thermal habitability for the users (59%), when compared to LIHe (51%), which is near the borderline to have a warm environment inside its rooms. The LIHe oriented to the north has higher hot discomfort hours than comfort (49%). In this sense, the impact of climate change is more pronounced in LIHe than in LIHb. Therefore, bermed earth-sheltering walls are a climate-responsive alternative design to help to improve the building's habitability. In turn, in the 2050 scenario, thermal comfort hours are below 50% in both typologies and orientations, with a hot environment predominating within the buildings. In the LIHb, this behavior is attributed to the fact that thermal comfort has been assessed considering all the long permanence rooms, including the living room/kitchen that does not have the researched strategy deployed. This room has a hotter environment than the bedrooms, as described above. This way, it requires a more detailed analysis of the bedrooms without a living room/kitchen thermal influence.

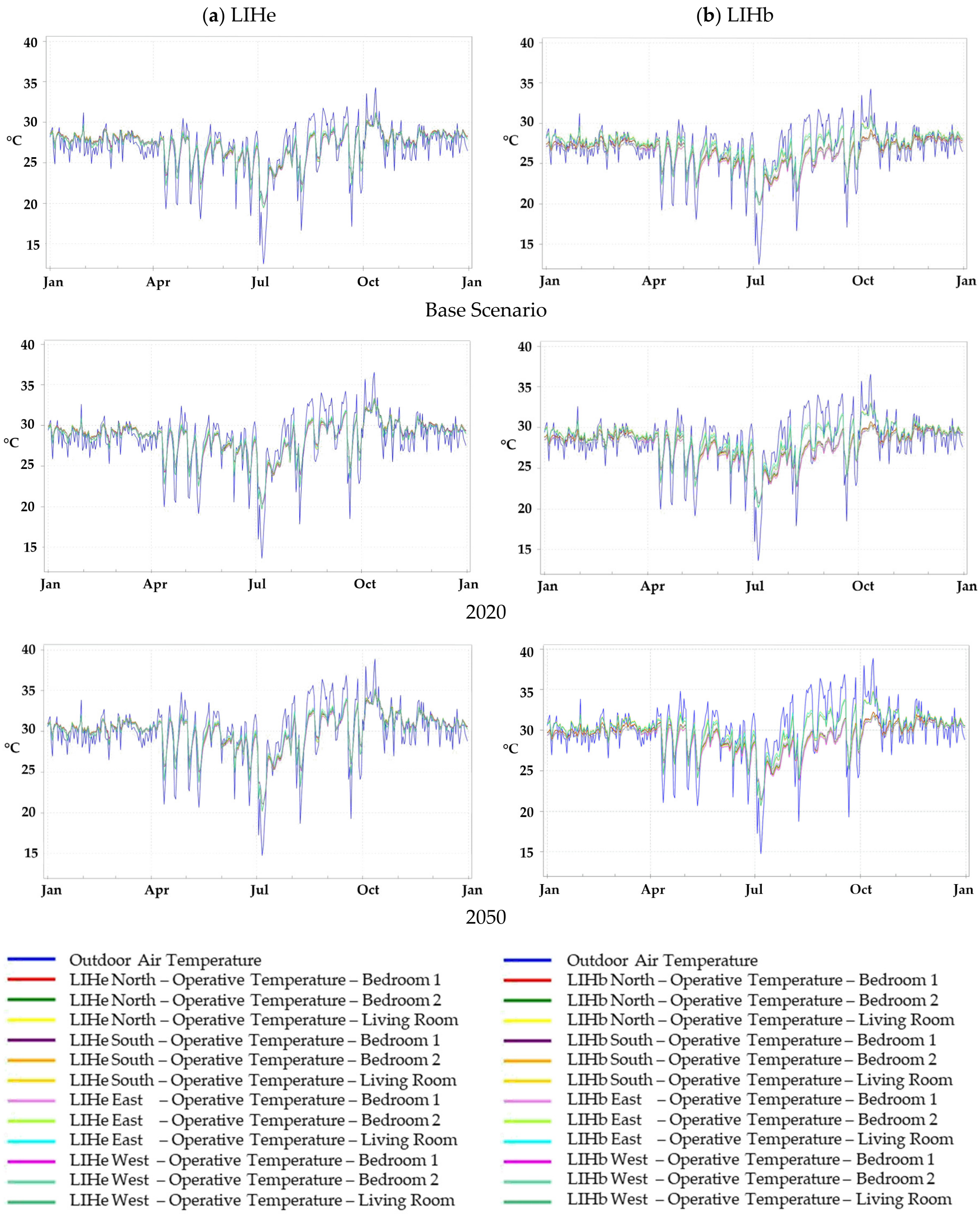


Figure 7. Annual diary course of outdoor air temperature and indoor long permanence rooms operative temperatures for the base and future scenarios in (**a**) LIHe and (**b**) LIHb.

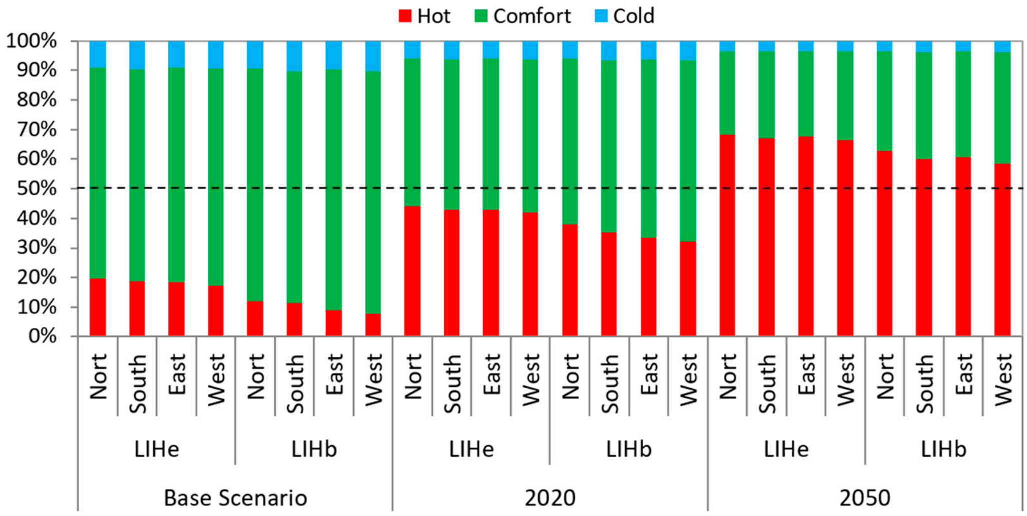


Figure 8. Weighted percentage of comfort and discomfort hours inside the LIHe and LIHb in the base and future scenarios.

Figure 9 depicts thermal comfort conditions inside the bedrooms where the strategy was implemented. Notice that behavior is similar to that displayed in Figure 8; however, thermal comfort conditions preponderates in most orientations and time-slices. All building orientations present the highest percentage of comfort hours than discomfort in the base and 2020 scenario. However, the west orientation is the only one that provides more hours of thermal comfort conditions (51%) in the 2050s.

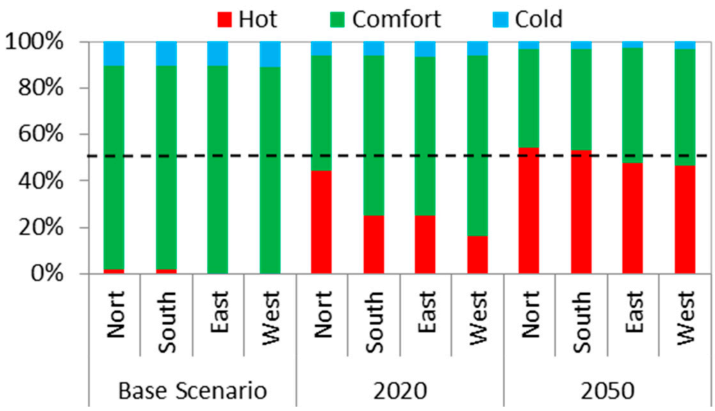


Figure 9. Weighted percentage of comfort and discomfort hours for the bedrooms inside the LIHb in the base and future scenarios.

4. Conclusions

The energy consumption and thermal analysis indicated that the use of bermed earth-sheltered walls as a thermal mass for the bedrooms is a successful measure to improve building performance and habitability, acting as a potential climate-responsive strategy to adapt buildings to face and counterbalance global warming effects that might prevail in tropical climate regions. Higher impacts are observed in cooling energy demand than in the thermal performance, once the spaces in the former are not exposed to the thermal exchanges resulting from natural ventilation, since the windows remain closed when the HVAC system is operating. Due to the expected increase in air temperature in the region (1.5 °C and 3.3 °C for 2020 and 2050, respectively), the potential use of naturally ventilated strategy in the residential buildings is affected, restricting the possibility to transfer heat from the indoors to the outdoors environments, compromising building thermal performance.

The reduction in cooling energy consumption varied from 34% to 38% between the base and future scenarios, being more relevant when the bermed earth-sheltered walls are oriented to the west, that is, the main façade of the building is oriented to the east. Similar reductions for cooling degree-hours, evaluated when the building is in a naturally ventilated mode, are observed, ranging from 26% to 38%, with better performance also following the previous results, i.e., the main façade of the building oriented to the east.

The effects of climate change impact on both operating modes idealized for the building long permanence rooms, i.e., when the building environments are operating naturally ventilated and with the use of HVAC. In the 2020 scenario, the increase in cooling energy consumption is over 28% for LIH, with and without the implementation of the bioclimatic strategy of bermed earth-sheltered walls, while in the 2050 scenario, it exceeds 64%. In the thermal performance, the projected increase in cooling degree-hours is more drastic, reaching 111% and 327% in the 2020 and 2050 scenarios, respectively. In these future scenarios, the reduction provided by the implemented measure depends on its orientation and varied between 32% to 36%, compared to the energy consumption of the building without this passive strategy. Again, the highest reduction in cooling energy consumption was shown when the thermal mass strategy was oriented to the west, with a 36% reduction, on average. Thus, because of future potential impacts of climate change, building efficiency level, which is "A" in the base scenario, decreases to level "E" in the 2050 scenario, an exception in LIHb for west orientation, in which level remains "D". However, it should be pointed out that, for a fair judgment, the energy efficiency benchmarks should also be corrected for the climate change effects. Based on these potential impacts, specific design guidelines should be established by the international sustainable building organizations to enable designers, builders, and stakeholders to anticipate the behavior of the built environment under the potential future global warming scenarios.

The increase in cooling energy consumption, as well as in the cooling degree-hours, can be easily seen when the effects of climate change are incorporated into the weather data and thermos-energetic simulation is performed. However, the building with bermed earth-sheltered walls (LIHb) always presents better performance than the building without it (LIHe) in all orientations, demonstrating the positive impact of this measure. It can be considered as a climate-responsive design strategy because of the improvement in the housing resilience when facing the global warming impacts, since the cooling energy consumption in the 2020s on LIHb is on average 12.3% lower than in the base scenario, compared to LIHe, almost being able to provide full demand in the 2050s (consumption of LIHb surpassed the LIHe in base scenario only by 10.7%). The same behavior is not observed for CDH, due to the way this indicator is calculated, weighing the areas of the long permanence building rooms, including living room/kitchen, which is not in contact with the bermed earth-sheltered walls. This room, considered in the CDH calculation, presents lower thermal performance than the bedrooms, which influenced the final performance, reducing the positive impact of the implementation of the earth-sheltered wall.

LIHb provides better thermal habitability for the users, when compared to LIHe, in all time-slices researched. Despite the progressive deterioration of thermal comfort conditions within the building rooms, the bermed earth-sheltered walls are an alternative to partially neutralize the global warming effects. When its impact, together with environments that do not have the measure deployed (which reduce the positive impact as described above), is analyzed, more hours of thermal comfort conditions may be achieved only until the 2020 scenario. However, considering only the rooms where the strategy is deployed, this condition may be guaranteed until the 2050 scenario by the building's west orientation.

Thus, given the impacts presented, it is possible to verify that bermed earth-sheltered walls correspond to an alternative strategy for the adaptation effects of climate change and should be thought of as an adaptive measure to promote building sustainability, in terms of cooling energy consumption. Therefore, the use of the thermal mass, combined with other passive adaptation strategies, may help to counterattack the climatic conditions that may prevail in future periods due to global warming on tropical climates. A cost–benefit analysis between the studied climate change adaptation measure investment and the energy-saving should be assessed in future work, aiming to evaluate the payback period.

The thermal and energy analysis conducted in this study deals with uncertainties regarding the internal climate variability related to the climate model and premises adopted for future scenario definitions. The latter are based on economic growth, social trends, adaptation/ mitigation policies, technological development, and demographic factors. Therefore, the evaluation conducted in this study for the future scenarios should be treated as a possible trend, rather than as absolute values. However, the potential uncertainties in the future climate data do not invalidate the predictions made by the CCWorldWeatherGen tool, which can confidently be used to anticipate the behavior of the built environment in the potential future global warming scenarios.

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Abbreviations

α	Absorptance (dimensionless)	LIH	Single-family low-income house
φ	Thermal lag	LIHe	Efficient Single-family low-income house
A	Floor area	LIHb	Efficient Single-family low-income house with Bermed Earth-Sheltered in the bedrooms walls
ABNT	Brazilian Association of Technical Standards	HadCM3	Hadley Centre Coupled Model version 3
AR4	Fourth Report of the Intergovernmental Panel on Climate Change	HVAC	Heating, ventilation, and air conditioning
Aw	Tropical Savannah climate	PVC	Polyvinyl chloride chloride
CDH	Cooling Degree-Hours	R-value	Thermal resistance
COP	Coefficient of performance	RTQ-R	Energy Efficiency Level of Residential Buildings
CT	Thermal capacity (kJ/(m^{2}K)	SF	Sun factor
EPS	Expanded polystyrene	T_{int}	Internal temperature
EPW	EnergyPlus Weather file	T_{ext}	External temperature
GCM	General Circulation Model	T_n	Monthly average neutral temperature
GHG	Greenhouse gas	T_{op}	Operative temperature
HDH	Heating Degree-Hours	T_{Emed}	Monthly average outdoor air temperature
IPCC	Intergovernmental Panel on Climate Change	U	Total thermal transmittance

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