

Article

Effects of Climate Change for Thermal Comfort and Energy Performance of Residential Buildings in a Sub-Saharan African Climate

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Abstract: This study presents an analysis of the impacts of climate change on thermal comfort and energy performance of residential buildings in Ghana, in sub-Saharan Africa, and explores mitigation as well as adaptation strategies to improve buildings' performance under climate change conditions. The performances of the buildings are analyzed for both recent and projected future climates for the Greater Accra and Ashanti regions of Ghana, using the IDA-ICE dynamic simulation software, with climate data from the Meteoronorm global climate database. The results suggest that climate change will significantly influence energy performance and indoor comfort conditions of buildings in Ghana. However, effective building design strategies could significantly improve buildings' energy and indoor climate performances under both current and future climate conditions. The simulations show that the cooling energy demand of the analyzed building in the Greater Accra region is 113.9 kWh/m² for the recent climate, and this increases by 31% and 50% for the projected climates for 2030 and 2050, respectively. For the analyzed building in the Ashanti region, the cooling energy demand is 104.4 kWh/m² for the recent climate, and this increases by 6% and 15% for the 2030 and 2050 climates, respectively. Furthermore, indoor climate and comfort deteriorate under the climate change conditions, in contrast to the recent conditions.

Keywords: thermal comfort; energy performance; residential buildings; design strategies; carbon dioxide emissions; climate change mitigation and adaptation; tropical climate

1. Introduction

Climate change is a complex environmental issue and presents significant risks to ecological, infrastructure, and economic systems [1,2]. The Intergovernmental Panel on Climate Change (IPCC) reiterated in its latest assessment report [1] that increasing emissions and concentrations of anthropogenic greenhouse gases (GHGs) are warming and destabilizing the global climate system. The atmospheric concentration of carbon dioxide (CO₂) was about 400 ppm in 2015, an increase of about 27% compared to 1960 levels [3]. Global average surface temperature increased by 0.65–1.06 °C between 1880 and 2012 [1], and 2016 is noted to be the warmest year on modern record, with a global average temperature that is 0.99 °C warmer than the mid-20th century mean [4]. Current projections suggest a global average surface temperature increase of 2.4–3.4 °C by 2071–2100, compared to the average for 1961–1990 [1]. For tropical regions of the world, projections suggest an average surface temperature rise of 1–2 °C by 2050 and 1–4 °C by 2100, compared to the last century [5]. Besides heat waves and sea level rises, other significant negative impacts that may be associated with climate change include drought, flooding, and failure of food production systems. Climate change is also anticipated to adversely affect the performance of buildings [6] and to reduce water availability in some regions [5], which may affect hydropower generation [7].

Efforts are ongoing at regional, national and global levels to minimize potential impacts of climate change, including the Kyoto protocol [8] and the more recent Paris agreement [9]. Climate change mitigation and adaptation strategies may be implemented to minimize risks that may be associated with climate change. Climate change mitigation strategies seek to minimize emissions of GHGs, while climate change adaptation strategies may aim to ensure tolerable and resilient performance of the built environment. Adaptation measures for buildings may aim at ensuring comfortable indoor climate and could encompass passive and active measures to reduce cooling load and overheating risk, which are expected to be dominant under climate change conditions.

Several countries in sub-Saharan Africa are currently facing an energy crisis in the form of inadequate power generation and supply [10]. In Ghana, power generation has been mainly hydro-based and has dwindled in recent years, partly as a result of infrastructure deterioration and reduced water inflows to hydropower plants [11]. However, electricity demand has progressively increased due somewhat to improving living standards and economic growth [12]. Total electricity consumption in Ghana increased from 6214 to 11418 GWh between 2007 and 2016 [13]. In Ghana, comfort cooling is reported to be required for 50%–100% of the annual occupied hours in buildings [14], and about 60% of the electricity used in conditioned buildings is suggested to be for air-conditioning [15]. Hence, strategies to reduce cooling loads and improve thermal performance of Ghanaian buildings are important.

A number of studies were carried out on thermal performances of buildings in Ghana (e.g. [14–17]). Koranteng [16] simulated the performance of different categories of office buildings in the city of Kumasi in Ghana and explored the effectiveness of different measures to reduce cooling demand in the context of the current climate. He found that cooling demand could be reduced by 25%–45% from cumulative implementations of efficient electrical lighting, natural ventilation, efficient windows, and attic insulation. In a related study, Koranteng and Mahdavi [17] conducted simulation and field studies of energy and indoor thermal performances of office buildings in Kumasi, Ghana. They found that cooling loads could be reduced by 20%–35% and associated CO₂ emissions could be reduced by 27% with implementation of fabric retrofit and building control measures. Uba et al. [15] proposed a simplified approach to estimate the cooling load of air-conditioned buildings in Ghana and suggested that such work will facilitate finding strategies to reduce energy use for cooling through the accurate sizing of cooling machines. Amos-Abanyie et al. [14] investigated passive- and low-energy strategies to improve thermal comfort and thereby reduce cooling loads of buildings in different cities in Ghana. The authors found that such strategies can reduce the use of air conditioners in the buildings to below 7% of annual occupied hours. Simons et al. [18] analyzed different measures to reduce cooling loads of multi-story commercial buildings in Ghana and found efficient window glazing and external solar shading to give significant reductions of the buildings' cooling loads.

Studies to increase understanding of how climate change may affect energy and both indoor and outdoor environmental performance of buildings are essential to inform appropriate climate mitigation and adaptation strategies. Different studies have been conducted to explore strategies to improve thermal and environmental performances of buildings under climate change conditions. However, most studies focus on buildings and projected climate conditions for temperate regions ([19–29]). Very few studies are reported on climate change implications for buildings in tropical climates [30]. Radhi [31] studied how global warming may affect energy use for air-conditioning of residential buildings in the hot climate of the United Arab Emirates and investigated the effects of different thermal improvement strategies for buildings. The study showed that energy use for cooling and associated CO₂ emission may increase by 23.5% and 5.4%, respectively, with an average outdoor air temperature increase of 5.9 °C, due to climate change. Ouedraogo et al. [32] investigated strategies for the design of energy efficient public office buildings in Burkina Faso under the context of climate change. The researchers explored the influence of strategies such as external window shading and improved thermal envelope on buildings' cooling energy demands. Compared to the baseline of 2010–2029, they estimated that annual energy demand will increase by 56% and by 99% for the periods of 2030–2049 and 2060–2079, respectively, due to climate change. Yau and Hasbi [30] conducted a literature review of climate change impacts for commercial buildings in tropical climates

and discussed how peak and overall energy demands of buildings may change as a result of a warming climate. The authors emphasized the need for more research on the impacts of climate change for buildings in tropical climates.

While studies have explored strategies to optimize the cooling performance of buildings in Ghana, to date no rigorous analytical study has been reported on how cooling loads and thermal comfort of buildings in Ghana may be influenced by climate change. In a descriptive and hindsight study, Amos-Abanyie [33] presented historical ambient temperatures, relative humidity, and rainfall data for the city of Kumasi Ghana. Without detailed analysis, the researcher suggested how climate change may affect housing in the city and outlined strategies for climate adaptation and mitigation in general. This paper investigates the potential impacts of climate change on thermal performances of residential buildings in the Greater Accra and Ashanti regions of Ghana, focusing on space cooling demand and thermal comfort. It explores the effectiveness of different building-design adaptations and mitigation strategies for reducing cooling demands. The study is based on detailed energy balance simulations at hourly time step and compares the buildings' performance under recent climate conditions and under projected climate conditions for the years 2030 and 2050.

2. Current and Projected Climates

Ghana is situated between latitude 4° and 12° N and longitude 4° W and 2° E in sub-Saharan Africa, and has a tropical climate [34]. The climate of Ghana is dominated by a tropical savanna climate (Köppen climate classification Aw), with a tropical monsoon climate (Köppen climate classification Am) in the southwestern part of the country. It is characterized by dry and wet seasons, with fairly high daily outdoor temperatures, as well as solar radiation all year, resulting in no space heating being needed for buildings. The southern part of the country has two wet seasons, with the first spanning between April and July and the second between September and November, while the northern part has one wet season, which falls between May and September. At base temperatures of 18.3 and 21.1 $^{\circ}\text{C}$, annual cooling degree days of 2687 and 1707, respectively, are reported for Ghana [35]; thus, comfort cooling is required in Ghanaian buildings, and this is typically achieved with mechanical air-conditioning systems or passive strategies, such as window opening, and solar control measures, such as external window shading. The current mean outdoor air temperature, relative humidity, wind speed, and solar radiation are about 27.2 $^{\circ}\text{C}$, 83%, 3 m/s, and 1833 W/m^2 , respectively, for Accra, the capital city of Ghana [36]. Figure 1a shows the mean outdoor daily temperature profiles for different epochs in Ghana, extracted from the third national communication of the Government of Ghana to the United Nations Framework Convention on Climate Change [37]. It shows a warming of about 1 $^{\circ}\text{C}$ since 1960 compared to the climate of 2010, corresponding to a mean daily outdoor air temperature rise of 0.2 $^{\circ}\text{C}$ per decade.

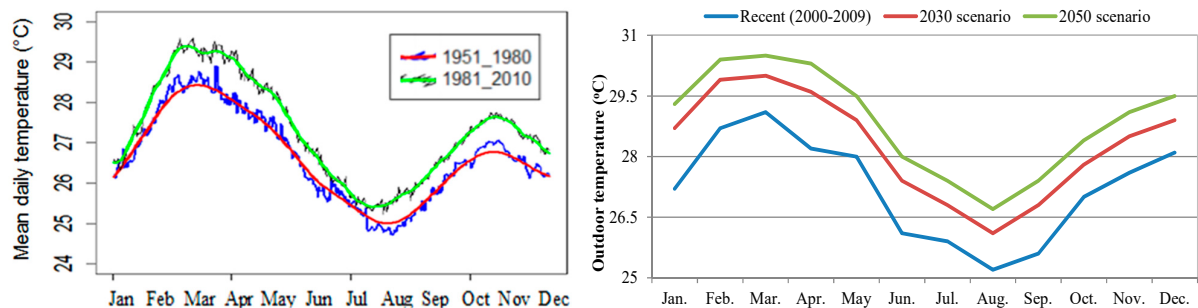


Figure 1. (a) Mean daily temperature profile for Ghana for different periods. Adapted from ref. [37]. The black and blue lines give the precise values, while the corresponding green and red smoothened lines display the trends of the values. (b) Profiles of outdoor air temperatures for Accra for 2000–2009 (recent), and for 2030 and 2050 (projected) climates under the Special Report on Emission Scenarios (SRES) A1B scenario, obtained from Meteonorm global climate database [36].

Figure 1b, based on data obtained from the Meteonorm global climate database [36], shows the profiles of outdoor air temperatures for Accra for the recent climate of 2000–2009, and for the projected climates for the years 2030 and 2050 under the IPCC's balance across all sources (A1B) climate change scenario. The mean outdoor air temperatures for the years 2030 and 2050 are 1.1 and 1.7 °C higher, respectively, compared to the recent climate. The IPCC presented different GHG emissions scenarios with associated future climates change projections in the Special Report on Emission Scenarios (SRES) [38]. The SRES scenarios assume alternative future trajectories of economic, social, technological, political, and environmental developments and have been used in several recent studies (e.g. [39–41]) on climate change implications for buildings' performance. Among the SRES scenarios, the A1B assumes balanced future growth and development in all sectors, technologies, and resources [38].

3. Methodology

3.1. Building Description

The first case-study building is a recently built single-family residence in the Tema metropolitan area in the Greater Accra region of Ghana. The building has a conditioned net floor area of 93.0 m², and it was constructed with concrete blocks. It contained a living room, kitchen, washroom, two bedrooms, and a front porch for a family of about four persons. The roof has a timber structure covered with corrugated aluzinc sheets, and the ceiling was made of a combination of plywood and solid wood panels. The windows are made of glazed louvre blades, while the doors are made of solid wood panels. The building is connected to the national power grid and is mainly naturally ventilated, and its bedrooms and living rooms are equipped with ceiling fans for air movement to create a comfortable cooling effect. The building's biggest windows and entrance door are toward the north, and the remaining windows are oriented to the south. Figure 2 shows illustrations of a model of the building created with the IDA Indoor Climate and Energy (IDA-ICE) software [42]. Tables 1 and 2 summarize key construction and architectural characteristics of the building.

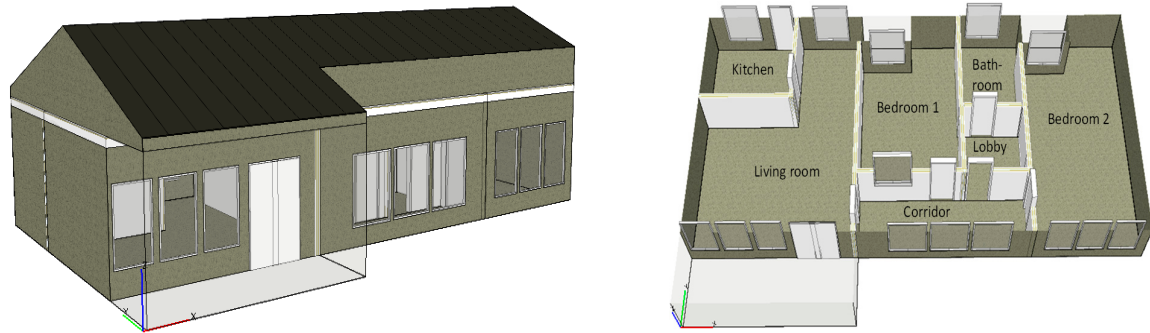


Figure 2. Illustration from northeast direction and layout of the case-study residential building in Ghana.

Table 1. Construction and thermal characteristics of the case-study single-family house.

Building element	Description	Density (Kg/m ³)	Specific heat capacity (J/[KgK])	Conduc-tivity (W/[mK])	U-value (W/m ² K)
Roof	0.45 mm corrugated aluzinc roof covering	2700	900	210	4.39
	Pitch roof with wood framing with tongue	560	390	0.17	
	& groove wood ceiling panels for living-room	560	390	0.17	
	& 6 mm plywood ceilings for other rooms				
External wall	20 mm cement & sand plastering	1300	1000	0.50	2.86
	150 mm concrete block	1800	1050	1.50	
	20 mm cement & sand plastering	1300	1000	0.50	
Internal wall	20 mm cement & sand plastering	1300	1000	0.50	3.16
	100 mm concrete block	1800	1050	1.50	
	20 mm cement & sand plastering	1300	1000	0.50	
Ground floor	10 mm ceramic floor tiles	1922	920	0.84	3.03
	30 mm cement & sand screeding	1300	1000	0.50	
	150 mm mass concrete	2300	880	1.70	
Windows	6 mm glass louvres	2500	700	1.00	5.32
	Wood framing	560	390	0.17	
Doors	45 mm hardwood paneled doors	560	390	0.17	2.33
	Wood framing	560	390	0.17	

Table 2. Key architectural and design characteristics of the case-study single-family house.

Description	Detail
Year of building completion	2015
Net floor area (m ²)	93.0
Total ventilated volume (m ³)	241.8
Overall thermal envelope area (m ²)	353.2
Exterior wall area (m ²)	114.0
Windows area (m ²) [South/ North]	9.0/13.5
Window /floor area (%)	24.1
Window /envelope area (%)	6.4
Envelope area per volume (m ² /m ³)	1.5
Average thermal transmittance (W/m ² K)	2.351
Indoor lighting	Compact florescent lamps

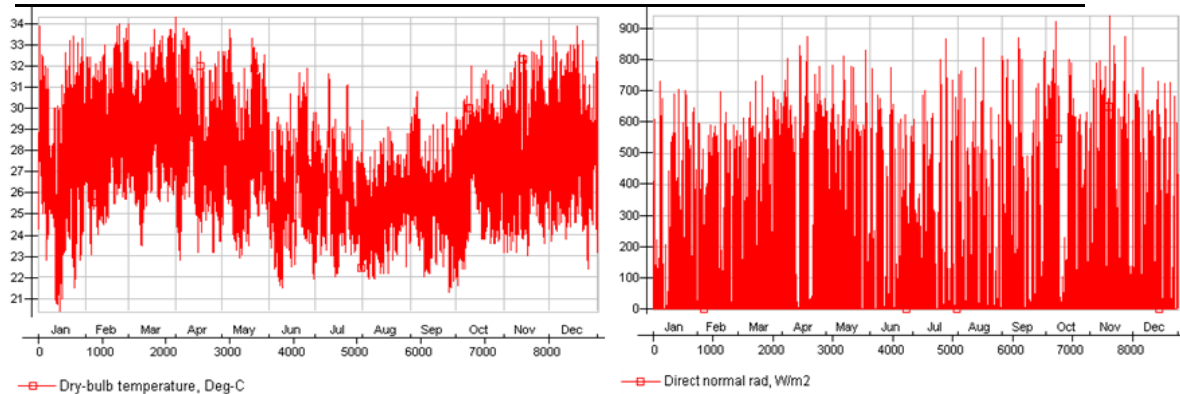
3.2. Thermal Comfort and Energy-Use Simulations

A multi-zone model of the case-study building (Figure 2) created in IDA-ICE [42] was used to explore the energy and indoor thermal performances of the building under the recent climate and future climate change conditions for the Greater Accra region of Ghana. IDA-ICE is a state-of-the-art dynamic simulation program which models the indoor climate and energy balance of buildings in variable time steps, including hourly and minutes time resolutions. It is a whole-building energy simulation program, and it calculates the energy demand for heating, cooling, lighting, and ventilating a building. Major input parameters were taken into account when conducting a simulation in IDA-ICE: building envelope thermal properties (e.g., U-values, infiltration, and g-values of glazing units); orientations; glass areas; HVAC systems; heat gains from lighting, appliances, and human bodies; occupancy and building operation schedule; indoor air temperature; geographical location; and outdoor climate parameters, including ambient temperature, wind velocity and direction, relative humidity, direct normal radiation, and diffuse radiation on a horizontal surface. Validations with ASHRAE 140-2004 and EN 15255-2007 and 15265-2007 [43] showed that IDA-ICE can give accurate predictions of buildings' energy and indoor climate performances in comparison to other state-of-the art simulation programs.

Hour-by-hour simulations of the indoor climate and energy balance of the building were performed with the climate datasets for the city of Accra (latitude 5°33'N; longitude 0°12'W). The datasets were extracted from the Meteonorm database [36] for the period of 2000–2009 and for the years 2030 and 2050, based on the SRES A1B scenario for Accra. To explore the potential impacts of a warming climate on cooling energy demand and indoor thermal comfort, mechanical cooling based on state-of-the-art air-conditioning was assumed to be used in the building when the indoor temperature would exceed 28 °C. The co-efficient of performance (COP) for the air-conditioning system was assumed to be 3.85, based on Harvey [44]. The indoor thermal comfort parameters analyzed for the building included mean indoor air temperatures, operative temperature, predicted mean vote (PMV), predicted percentage dissatisfied (PPD), and the share or percentage of total occupant hours with thermal dissatisfaction, which was calculated according to ISO 7730 [45]. The simulations were conducted with a tolerance of 0.02, and the key input data used are summarized in Table 3. Figure 3 shows the hourly dry-bulb temperature and direct normal solar radiation for the climate of Accra for 2000–2009. Key thermophysical properties of the construction materials comprising the modelled building are given in Table 1, based on data from Groth [46] and the IDA-ICE [42] material database. The internal walls have effects on the thermal mass of the building and were considered in the simulations.

Table 3. Key input data for the energy balance and indoor-environment simulations.

Description	Model input data and assumptions
No. of zones in simulation model	7
Climate data	Hourly climate file for Greater Accra
Cooling set	28 °C
Infiltration	0.5 ACH
Average heat gains from lighting	1.31 W/m ²
Average heat gains from appliances	2.15 W/m ²
Occupancy density (no./m ²)	0.048
Occupancy schedule	Variable
Ventilation/ air-conditioning system	Constant air volume
COP of air-conditioning system	3.85

**Figure 3.** Average hourly dry-bulb temperature (a) and direct normal solar radiation (b) for Accra for the recent climate of 2000–2009.

3.3. Parametric Simulation of Strategies

To explore measures to reduce cooling energy demand and thereby improve indoor environmental conditions of Ghanaian buildings in the context of climate change, different climate adaptation and mitigation strategies related to the design and thermal performance of buildings were modelled. The strategies included implementation of external window-shading devices, improved glazed windows, addition of thermal insulation to the exterior walls and roof, and variations of the orientation and the glazed fraction (window areas) of the building.

3.3.1. Orientation

A building's orientation is a key design decision, and a growing body of literature (e.g. [47–49]) shows that this can have a significant impact on a building's space conditioning loads, as well as on thermal comfort. In this study, the building's original north-facing orientation was varied to south, east, or west to explore the impacts of these on the energy and indoor environmental performances.

3.3.2. External Window Shading

For the studied building, shading from nearby objects (e.g., trees and buildings) was low and the windows had no shading devices. The implication of installing drop-arm awnings as solar control for the building's windows directly exposed to sunlight was modelled.

3.3.3. Glazed Fraction

Large glazed windows are increasingly becoming a common feature of new buildings in Ghana [50], as in other sub-Saharan African countries [32]. The implication of a bigger or smaller glazed fraction was analyzed by varying the window areas of the building by $\pm 20\%$.

3.3.4. Improved Windows

Based on an assessment of Ghanaian buildings presented by Koranteng and Madhavi [17], the implication of changing the studied building's windows to improved glazed type with U-value of $1.8 \text{ W/m}^2 \text{ K}$ was explored in this study. The g-value of windows is affected when thermal transmittance of a window is improved through additional glazing layers, and this was considered in the simulations.

3.3.5. Additional Insulation to Exterior Walls and Roof

Conventionally, buildings in Ghana are constructed with reinforced concrete and masonry materials without thermal envelope insulation. For a hot Chinese climate, Fang et al. [51] found that installation of thermal envelope insulation reduced summer cooling energy use by about 25% for experimental buildings. Nematchoua et al. [52] showed that economic optimum insulation thickness for buildings in the tropical climate of Cameroon, in sub-Saharan Africa, ranged between 90 and 98 mm, depending on the buildings' orientation and construction material used, encompassing either concrete blocks or compressed stabilized earth blocks. This study analyzed the implications of installation of 100 mm light insulation on the exterior walls and roof of the studied building. The U-value of the exterior walls changes to 0.32 from $2.86 \text{ W/m}^2 \text{ K}$, while that for the roof changes to 0.33 from $4.39 \text{ W/m}^2 \text{ K}$ with the installation of 100 mm light insulation.

3.3.6. Improved Building

A combination of the explored individual strategies giving a low final cooling energy demand and improved indoor environmental conditions was analyzed for the buildings. Annual total energy savings and CO₂ emissions reductions achievable from the combination of the strategies were estimated. Electricity carbon intensity of $0.43 \text{ kg CO}_2/\text{kWh}$ was used in the calculations, based on the average emission intensity of electricity generated and supplied in Ghana in 2016 [13].

3.4. Variation of Building Design and Location

Design and location play a key role in the thermal performance of buildings. To quantify the impact of these on the study's findings, a second single-family residential building, designed differently and situated in Kumasi, in the Ashanti region of Ghana, was modelled. The three-bedroom building (illustrated in Figure 4) has a conditioned net floor area of 128.1 m^2 and was constructed between 2004 and 2010, with typical residential-building construction technologies used in Ghana, including concrete blocks for both the exterior and interior walls, glazed louvre blades for windows, and solid wood panels for doors. The roofing system comprises aluminum sheets and hardwood ceilings. The frontage (main entrance) of the building is oriented toward the west. The building's elements U-values, as well as ventilation and lighting systems and occupancy profiles, are similar to those documented in Table 1. Other key architectural characteristics of the building are given in Table 4. A model of the building with eight zones created with the IDA ICE [42] was simulated for the recent and projected climates for the Ashanti region for the years 2030 and 2050. The simulations were performed with similar input data as noted in Table 3 and with climate datasets obtained from the Meteonorm database [36].

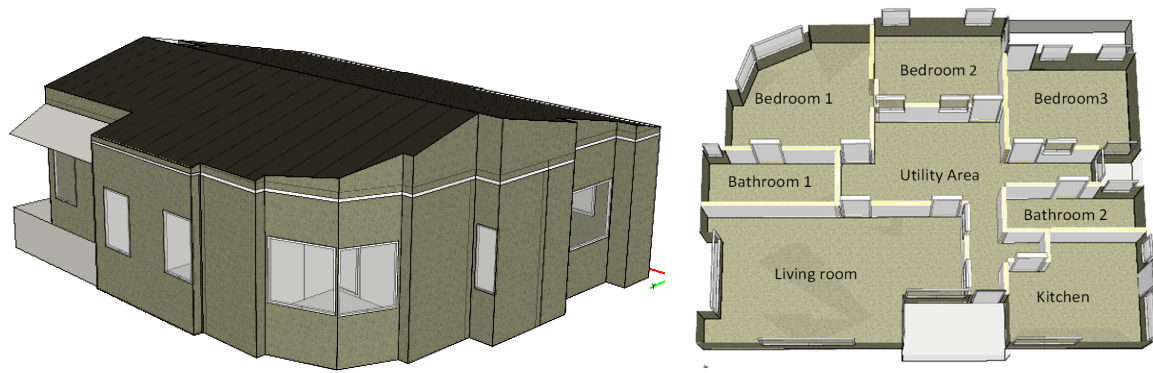


Figure 4. Illustration from the north-east direction and layout of the analyzed building in Kumasi, Ghana.

Table 4. Key architectural and design characteristics of the second single-family house, in Kumasi.

Description	Detail
Net floor area (m ²)	128.1
Total ventilated volume (m ³)	333.1
Overall thermal envelope area (m ²)	436.8
Exterior wall area (m ²)	135.9
Windows area (m ²) [South/ North/East/West]	5.9/4.6/6.9/7.9
Window/floor area (%)	19.7
Window/envelope area (%)	5.8
Envelope area per volume (m ² /m ³)	1.0
Average thermal transmittance (W/m ² K)	2.272

4. Results

4.1. Simulated Building

Monthly simulated final cooling energy demands of the building for the recent and future climates are shown in Figure 5. The cooling energy demands increase considerably under the projected future climates compared to the recent climate, particularly between June and September. Overall, the annual total final cooling energy demands for the building are 10590.2, 13967.0, and 15980.1 kWh for the recent, 2030, and 2050 climates, respectively. These correspond to specific final cooling energy demands of 113.9, 150.2 and 171.8 kWh/m², respectively.

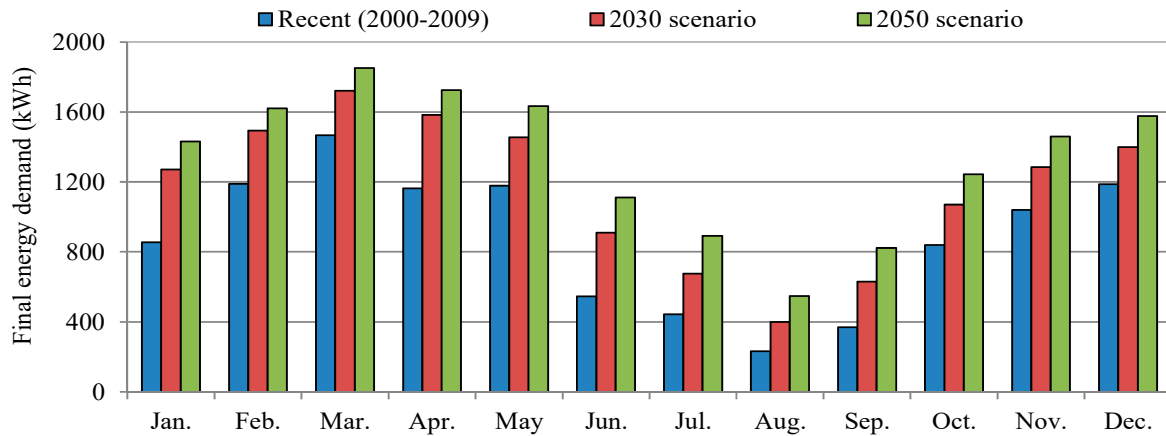


Figure 5. Monthly cooling energy demands for the building under recent and projected future climates.

Specific peak cooling loads of the building as simulated by the IDA-ICE software are shown in Figure 6. These show that the increase of the specific loads under the projected future climates are small (0.7%–3.3%) in contrast to the increase in the specific annual final cooling energy demands, all compared to the recent climate. Compared to the recent climate, the specific annual final cooling energy demands increase by 31% and 50% for the 2030 and 2050 projected future climates, respectively.

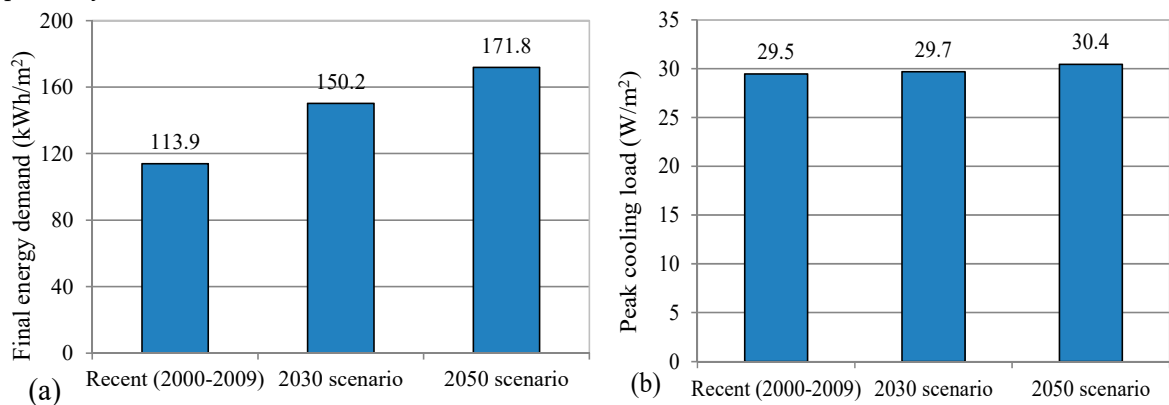


Figure 6. Specific annual cooling energy demands (a) and peak cooling loads (b) for the building under recent and projected future climates.

Profiles of monthly mean indoor air and operative temperatures for the individual zones in the building when simulated with the recent climate data are compared in Figure 7a and b, which also shows the profile of the outdoor air temperature. The temperature profiles are fairly similar for the individual zones. Overall, the mean indoor air and operative temperatures for the whole building are 27.8 and 28.1 °C, respectively, while the mean outdoor air temperature is 27.2 °C.

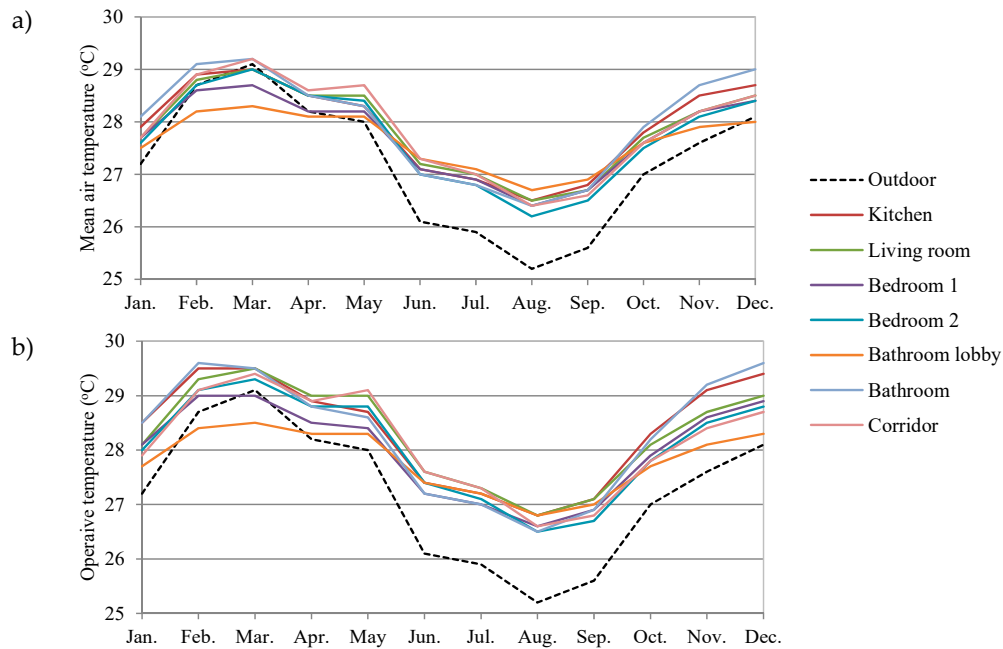


Figure 7. Profiles of monthly mean indoor air (a) and operative temperatures (b) for the individual zones of the building when simulated with the recent climate data.

Figure 8a shows the hourly profiles of the mean indoor air and operative temperatures for the living room of the building when simulated with the recent climate dataset, and Figure 8b shows the same profiles arranged in ascending order of temperatures, as duration curves. The lowest temperatures occur in January while the highest occurs in February and also in December.

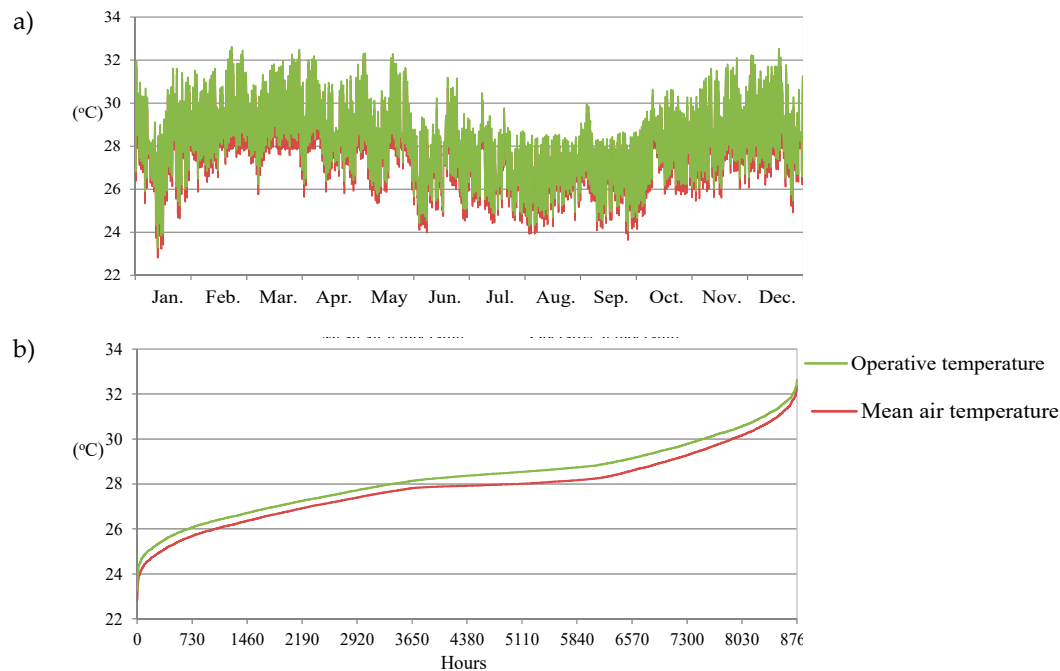


Figure 8. Annual hourly profiles of mean indoor air and operative temperatures for the living room simulated with the recent climate (a), and the same profiles arranged in ascending order (b)

Table 5 presents summaries of the monthly mean outdoor air temperature and indoor air, as well as the operative temperatures for the whole building when simulated with the recent and the

future climate datasets. The simulated mean monthly indoor air and operative temperatures are about 0.7 and 1.1 °C higher for the 2030 and 2050 climates, respectively, compared to the recent climate. However, the mean monthly outdoor air temperatures increase between 1.1 and 1.7 °C for the future climates, compared to the recent climate.

Table 5. Monthly mean outdoor air temperatures, and indoor air and operative temperatures for the whole building when simulated with the recent and future climate datasets.

Month	Recent			2030 scenario			2050 scenario		
	Outdoor air	Indoor air	Operative	Outdoor air	Indoor air	Operative	Outdoor air	Indoor air	Operative
Jan.	27.2	27.7	28.1	28.7	28.7	29.1	29.3	29.1	29.5
Feb.	28.7	28.7	29.1	29.9	29.5	29.8	30.4	29.9	30.3
Mar.	29.1	28.9	29.2	30.0	29.5	29.9	30.5	29.9	30.3
Apr.	28.2	28.4	28.7	29.6	29.3	29.7	30.3	29.8	30.1
May	28.0	28.4	28.7	28.9	28.9	29.3	29.5	29.4	29.8
Jun.	26.1	27.1	27.4	27.4	27.9	28.2	28.0	28.3	28.6
Jul.	25.9	26.9	27.2	26.8	27.6	27.8	27.4	27.9	28.2
Aug.	25.2	26.4	26.7	26.1	27.1	27.3	26.7	27.5	27.7
Sep.	25.6	26.7	26.9	26.8	27.5	27.7	27.4	27.8	28.1
Oct.	27.0	27.7	28.0	27.8	28.2	28.5	28.4	28.5	28.9
Nov.	27.6	28.3	28.7	28.5	28.8	29.2	29.1	29.1	29.5
Dec.	28.1	28.5	29.0	28.9	28.9	29.3	29.5	29.3	29.7
Mean	27.2	27.8	28.1	28.3	28.5	28.8	28.9	28.9	29.2

Table 6 shows the indoor comfort and environmental conditions of the building under the different climates. Compared to the recent climate, the shares of total occupant hours with thermal dissatisfaction and the hours with an operative temperature above 27 °C in an average (typical) zone increase significantly when the building is simulated with the future climates. Thus, the building's indoor environmental conditions deteriorate, with increased thermal discomfort under climate change conditions.

Table 6. Indoor comfort and environmental performances of the building under different climate regimes.

Comfort reference	Recent	2030 scenario	2050 scenario
Share of hours with operative temperature above 27 °C in average zone	78%	90%	95%
Share of total occupant hours with thermal dissatisfaction	37%	46%	52%

4.2. Parametric Study

The effects of various strategies on the cooling energy demands and peak loads of the building under the different climates are summarized in Table 7. Overall, the strategies have noticeable impact on the energy demands and minor impact on the peak loads. The strategies result in decreased energy demands with the exception of a 20% window area increase, and east as well as west orientations. The biggest single energy demand decrease is achieved with 100 mm insulation for walls and roofs. This is followed by external window shading and installation of improved windows with 1.8 W/m² K U-value. Comparatively, small amounts of cooling energy demand decrease are achieved with a 20% window area reduction and with a south, instead of the original north, orientation.

Table 7. Impacts of various strategies on final cooling energy demands and peak load of the building under different climate regimes.

Strategy	Climate	Cooling energy use		Peak cooling load	
		kWh/m ²	Change from reference (%)	W/m ²	Change from reference (%)
Reference	Recent	113.9	-	29.5	-
	2030 scenario	150.2	-	29.7	-
	2050 scenario	171.8	-	30.4	-
South orientation	Recent	112.5	-1.2	29.5	0.0
	2030 scenario	149.1	-0.7	29.7	0.0
	2050 scenario	170.9	-0.5	30.4	0.0
East orientation	Recent	129.0	13.3	29.5	0.0
	2030 scenario	163.5	8.9	29.8	0.4
	2050 scenario	183.5	6.8	30.4	0.0
West orientation	Recent	127.9	12.3	29.5	0.0
	2030 scenario	162.2	8.0	29.8	0.4
	2050 scenario	182.4	6.2	30.5	0.4
Shading	Recent	107.0	-6.1	29.5	0.0
	2030 scenario	143.8	-4.3	29.7	0.0
	2050 scenario	165.9	-3.4	30.4	0.0
+20% window area (increase)	Recent	115.9	1.8	29.6	0.4
	2030 scenario	152.5	1.5	29.8	0.4
	2050 scenario	173.8	1.2	30.5	0.4
-20% window area (decrease)	Recent	111.0	-2.5	29.5	0.0
	2030 scenario	146.0	-2.8	29.7	0.0
	2050 scenario	168.5	-1.9	30.4	0.0
1.8 W/m ² K window	Recent	107.2	-5.9	29.5	0.0
	2030 scenario	144.4	-3.9	29.7	0.0
	2050 scenario	166.7	-3.0	30.4	0.0
100 mm insulation	Recent	100.4	-11.9	29.5	0.0
	2030 scenario	137.1	-8.7	29.7	0.0
	2050 scenario	159.5	-7.2	30.4	0.0

Table 8 shows the impacts of the strategies on the indoor comfort and environmental conditions of the building under the different climates. Similar to the effects on the energy performance, the addition of 100 mm insulation gives the most comfortable indoor environmental conditions, while a west or east orientation gives the worse indoor environmental conditions. The operative temperatures of the building decrease between 0.1 and 0.3 °C or increase between 0.4 and 0.8 °C with the different strategies explored. In general, the impact of the strategies on the indoor comfort and environmental performance of the building is small, compared to the impact on the energy performance as noted in Table 7.

Table 8. Impacts of various strategies on the indoor comfort and environmental conditions of the building under different climate regimes.

Strategy	Climate	Operative	Operative	Thermal
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		temperature (°C)		temperature above 27 °C ^a (%)		dissatisfaction ^b (%)	
		Value	Change from reference	Value	Change from reference	Value	Change from reference
Reference	Recent	28.1	-	78	-	37	-
	2030 scenario	28.8	-	90	-	46	-
	2050 scenario	29.2	-	95	-	52	-
South orientation	Recent	28.1	−0.1	77	−1	37	0
	2030 scenario	28.8	0.0	90	0	46	0
	2050 scenario	29.2	0.0	95	0	52	0
East orientation	Recent	28.5	0.3	83	5	42	5
	2030 scenario	29.2	0.3	92	2	51	5
	2050 scenario	29.6	0.4	96	1	57	5
West orientation	Recent	28.9	0.8	83	5	42	5
	2030 scenario	29.2	0.4	92	2	51	5
	2050 scenario	29.6	0.4	96	1	57	5
Shading window	Recent	27.9	−0.2	75	−3	35	−2
	2030 scenario	28.6	−0.2	89	−1	44	−2
	2050 scenario	29.0	−0.2	94	−1	50	−2
+20% window area (increase)	Recent	27.8	−0.3	76	−2	38	1
	2030 scenario	28.9	0.1	88	−2	48	2
	2050 scenario	29.3	0.1	94	−1	54	2
−20% window area (decrease)	Recent	28.1	0.0	81	3	36	−1
	2030 scenario	28.7	−0.1	92	2	45	−1
	2050 scenario	29.1	−0.1	96	1	51	−1
1.8 W/m ² K window	Recent	28.0	−0.2	76	−2	35	−2
	2030 scenario	28.6	−0.2	89	−1	44	−2
	2050 scenario	29.0	−0.2	95	0	50	−2
100 mm insulation	Recent	27.9	−0.3	74	−4	34	−3
	2030 scenario	28.5	−0.3	88	−2	43	−3
	2050 scenario	28.9	−0.3	94	−1	49	−3

^a Share of hours with operative temperature above 27 °C in average (typical) zone.

^b Share of total occupant hours with thermal dissatisfaction.

4.3. Improved Building

Tables 9 and 10 show the implications of implementing all the strategies which result in reduced energy demands and improved indoor environmental performances for the building, respectively. These strategies include a south orientation, external window shading, a 20% decrease in window area, improved window with 1.8 W/m² K U-value, and addition of 100 mm insulations to walls and roof of the building. In the tables, “base case” denotes the building as-built, while “improved” denotes the building with the improvement strategies. The cooling energy demands and peak loads are 17%–27% and 0%–0.4% lower, respectively, for the improved building compared to the as-built building. Annual cooling energy savings of about 2753–2883 kWh and CO₂ emissions reductions of about 1184–1240 kg CO₂ are achieved when all the improvement strategies are applied for the

building. Furthermore, implementation of all the improvement strategies reduced the building's operative temperatures by 0.6–0.7 °C, while also significantly decreasing the percentage of total occupant hours with thermal dissatisfaction by margins of 8.0%–9.0%.

Table 9. Energy performances of the building as-built and with improvement strategies (see text above).

Climate	Final energy demand (kWh/m ²)		Peak load (W/m ²)		Annual total energy & carbon reductions (base case – improved)	
	Base case	Improved	Base case	Improved	Energy (kWh)	Carbon (kgCO ₂)
Recent	113.9	83.4	29.5	29.4	2836.5	1219.7
2030 scenario	150.2	119.2	29.7	29.7	2883.0	1239.7
2050 scenario	171.8	142.2	30.4	30.4	2752.8	1183.7

Table 10. Indoor comfort and environmental performances of the building as-built and with improvement strategies.

Climate	Operative temperature (°C)		Absolute difference (°C)	Thermal dissatisfaction ^a (%)		Absolute difference (%)
	Base case	Improved		Base case	Improved	
Recent	28.1	27.6	0.6	37.0	29.0	8.0
2030 scenario	28.8	28.1	0.7	46.0	37.0	9.0
2050 scenario	29.2	28.5	0.7	52.0	43.0	9.0

^a Share of total occupant hours with thermal dissatisfaction

As shown in Table 11, PMV and PPD at 1% occupant improve when all the strategies are implemented for the improved building under the different climates, compared to the as-built building. The average PMV and PPD of the improved building are 1.0 and 29.1 under the recent climate. In contrast, the corresponding values for the 2050 climate are 1.3 and 42.5, respectively. Thus, discomfort of the building's occupant increases under the climate change conditions.

Table 11. Predicted mean vote (PMV) and predicted percentage dissatisfied (PPD) at 1% occupant for the building as-built and with improvement strategies with the recent and 2050 climate datasets.

Month	Recent				2050 climate			
	PMV		PPD		PMV		PPD	
	Base case	Improved	Base case	Improved	Base case	Improved	Base case	Improved
Jan.	1.1	0.9	34.7	25.9	1.6	1.3	54.8	41.8
Feb.	1.5	1.3	49.9	38.4	1.9	1.5	68.4	53.9
Mar.	1.5	1.3	53.1	42.5	1.9	1.6	69.0	56.0
Apr.	1.4	1.3	46.2	38.3	1.9	1.6	68.0	56.3
May	1.4	1.2	45.0	35.9	1.8	1.5	61.0	48.7
Jun.	1.0	0.9	27.6	22.1	1.4	1.2	45.0	37.2
Jul.	0.9	0.8	23.9	19.0	1.2	1.1	36.5	31.8
Aug.	0.8	0.6	18.0	14.1	1.0	1.0	28.7	25.8
Sep.	0.8	0.7	21.8	17.9	1.2	1.1	35.6	31.5
Oct.	1.1	1.0	34.2	27.7	1.5	1.3	48.0	38.1

Nov.	1.3	1.1	44.0	32.7	1.7	1.4	58.0	44.6
Dec.	1.4	1.2	47.5	35.7	1.7	1.4	59.1	44.9
Mean	1.2	1.0	37.1	29.1	1.5	1.3	52.6	42.5

5. Impact of Building Design and Location

Tables 12 and 13 provide an overview of the energy and indoor environmental performances of the building in Kumasi when simulated with the recent and future climates for the Ashanti region. The performances are shown for the building as-built (base case) and with improvement strategies as noted in Section 4.3 (improved). Compared to the recent climate, the as-built building's specific annual cooling energy demands increase by 6% and 15% for the 2030 and 2050 climates, respectively. On average, the cooling energy demands decrease by 29%, while peak loads decrease by 43% for the improved building compared to the as-built building. Thus, the cooling energy demands and peak loads are significantly lower for the improved building version compared to the as-built building. The strategies applied to achieve the improved building version give annual cooling energy savings of 4193 kWh and CO₂ emissions reductions of 1803 kgCO₂, both on average.

When comparing the improved and the as-built building versions under both the recent and the future climate conditions, operative temperatures decrease between 0.3 and 0.5 °C, while the percentage of total occupant hours with thermal dissatisfaction reduce between 3% and 5%.

Table 12. Energy performances of the building as-built and with improvement strategies.

Kumasi climate	Final energy demand (kWh/m ²)		Peak load (W/m ²)		Annual total energy & carbon reductions (Base case –Improved)	
	Base case	Improved	Base case	Improved	Energy (kWh)	Carbon (kg CO ₂)
Recent	104.4	74.4	26.9	15.4	3843.0	1652.5
2030 scenario	110.9	78.4	26.9	15.4	4163.3	1790.2
2050 scenario	120.3	84.6	29.1	16.5	4573.2	1966.5

Table 13. Indoor comfort and environmental performances of the building as-built and with improvement strategies.

Kumasi climate	Operative temperature (°C)		Absolute difference (°C)	Thermal dissatisfaction ^a (%)		Absolute difference (%)
	Base case	Improved		Base case	Improved	
Recent	28.6	28.3	0.3	32	29	3
2030 scenario	28.7	28.3	0.4	33	29	4
2050 scenario	28.8	28.3	0.5	34	29	5

^a Share of total occupant hours with thermal dissatisfaction

Table 14 shows PMV and PPD at 1% occupant for the as-built and improved building versions under the recent and 2050 climates scenarios for the Ashanti region. The simulations show that indoor thermal comfort is enhanced in the improved building version and that thermal discomfort increases under the 2050 climate scenario.

Table 14. PMV and PPD at 1% occupant for the building as-built and with improvement strategies when simulated with the recent and 2050 climate datasets for the Ashanti region.

Month	Recent				2050 climate			
	PMV		PPD		PMV		PPD	
	Base case	Improved	Base case	Improved	Base case	Improved	Base case	Improved

Jan.	1.1	1.1	31.9	28.4	1.2	1.1	32.5	28.5
Feb.	1.2	1.1	34.6	29.1	1.2	1.1	35.3	28.9
Mar.	1.2	1.1	35.2	29.3	1.2	1.1	36.9	29.4
Apr.	1.2	1.1	34.4	29.3	1.2	1.1	36.2	29.4
May	1.2	1.1	33.9	29.3	1.2	1.1	36.5	29.5
Jun.	1.1	1.1	31.2	29.0	1.2	1.1	33.8	29.2
Jul.	1.1	1.0	29.5	28.7	1.1	1.1	31.5	28.9
Aug.	1.0	1.0	27.3	28.1	1.1	1.0	29.6	28.6
Sep.	1.1	1.0	28.7	28.4	1.1	1.1	30.4	28.7
Oct.	1.1	1.1	31.6	28.9	1.2	1.1	33.2	28.9
Nov.	1.2	1.1	33.8	29.1	1.2	1.1	34.5	29.0
Dec.	1.2	1.1	33.2	29.0	1.2	1.1	33.1	28.9
Mean	1.2	1.1	32.1	28.9	1.2	1.1	33.6	29.0

6. Discussion and Conclusions

This paper presented an analysis of energy and indoor climate performances of Ghanaian residential buildings under projected future climate conditions and demonstrated adaptation and mitigation strategies that could be applied to improve the thermal performance of buildings under such a context. The analysis was based on dynamic simulations, considering recent climate, as well as SRES A1B projected future climates, for two major regions in Ghana. Few studies have explored strategies for improvement of buildings' thermal performance in Ghana, as noted by Koranteng and Mahdavi [17]. Still, previous works have not comprehensively addressed the implications of climate change for Ghanaian buildings and strategies to improve buildings' performance under such the context that was explored in this study. The findings of this study suggest that climate change will significantly influence energy and indoor climate performances of residential buildings in Ghana, and that thermal performance of buildings could be improved with effective design and construction strategies.

The calculations for the analyzed building in Greater Accra show that cooling energy demand increases by 31% for the year 2030 and by 50% for the year 2050, both compared to the recent conditions. The calculated cooling energy demand increase for the mid-century is consistent with estimates presented for Burkina Faso for a similar period by Ouedraogo et al. [32]. The cooling peak loads are about similar under the recent and future climate conditions for Greater Accra, differing between 0.7% and 3.3%. The indoor climate analysis shows that thermal discomfort levels increases under the future climate conditions, compared to the recent climate conditions. For the analyzed building, operative temperatures increase by 0.7 and 1.1 °C for the 2030 and for the 2050 climates, respectively, compared to the recent climate for Greater Accra. Furthermore, the PPD- and PMV-index for the buildings are significantly higher under the future climates compared to the recent climate conditions. Overall, the percentage of total occupant hours with thermal dissatisfaction increases by factors of 1.24 and 1.41 for the years 2030 and 2050, respectively, compared to the period 2000–2009 for the building in Greater Accra.

The parametric simulations show that, with combined improvement strategies, the overall cooling energy demands could be reduced by 27%, 21%, and 17% for the recent, 2030, and 2050 climates in Accra, respectively. The improvement strategies also give significant reduction in CO₂ emission, besides enhanced indoor environmental conditions, and include building thermal envelope insulation, installation of external window-shading devices, improved glazed windows, reduced windows area, and a south orientation of the biggest windows. When the building in the Greater Accra is simulated with a south, instead of the original north, orientation, the cooling energy demands decrease between 0.5% and 1.2%, suggesting that the as-built building's orientation is about optimal from an energy performance perspective. When comparing the building as-built to the

improved version with the applied strategies, the operative temperature is reduced between 0.6–0.7 °C under the different climates for the Greater Accra. The difference in the percentage of total occupant hours with thermal dissatisfaction for the as-built and notional improved building versions is 8% under the recent climate, and 9% under both the 2030 and 2050 climate scenarios for the Greater Accra. For the analyzed building, installation of 100 mm insulation on the walls and roofs gives the largest single decrease in cooling energy demands, followed by external window shading and improved windows with a U-value of 1.8 W/m² K. However, east and west orientations of the building and a 20% increase in the overall glazed-window area increased the cooling energy demands. Buildings with large glazed windows are increasingly becoming the trend in tropical African countries [32], including Ghana [50], where residential buildings are typically ventilated naturally. This analysis demonstrates that the tendency could lead to increased cooling energy use and thermal discomfort under both current and future climate conditions.

The simulations for the analyzed building with a different design in the Ashanti region further confirms that energy demand will increase while thermal performance deteriorates under projected climate change conditions for Ghanaian buildings. On average, the building's annual cooling energy demands are predicted to increase by 6% and 15% for the years 2030 and 2050, respectively, compared to the recent climate for the Ashanti region. Overall, the calculations show that the extent of changes in energy demand, and also thermal performance of buildings under climate change conditions, will vary depending on building design and location in Ghana.

The analyses presented in this study were based on two differently designed single-family residential buildings with construction materials and systems typically used in Ghana. Moreover, the simulations were based on the conditions of two major cities with the largest amounts of settlements in Ghana. The climate of Ghana is characteristically tropical and was comparatively stable over the recent years. Hence, the findings and trends demonstrated in the results may be generally applicable for the building stock in Ghana. Nevertheless, further studies may be conducted for other cities and building typologies in Ghana to increase the understanding of climate change impacts for buildings. The analyses show that significant CO₂ emission reductions could be achieved from the climate adaptation and mitigation strategies explored. However, costs per unit of energy and carbon savings of the strategies were not analyzed in this study and should be further studied. Furthermore, the thermal comfort analyses could be extended to explore the implications of the examined strategies for airflow rate and pattern in the buildings, as comfort is a function of a complex set of interconnected parameters.

In this study, the impacts of building envelope design on energy and thermal performance were considered through variations of insulations for exterior walls, as well as roofs, and also variations of windows' thermal properties, as well as sizes for the analyzed buildings. Besides its impact on thermal comfort and space conditioning energy demand, as demonstrated in this study, building thermal envelope design has implications for embodied energy and climate impact of buildings (e.g., through materials used for the construction). Several life cycle analyses (LCA) suggest that the embodied energy and carbon of buildings can account for large shares of the total impacts of buildings, depending on factors like material choice, service life, energy systems, and climatic location of buildings [53–55]. The study presented in this paper focused on the implication of thermal envelope design for the operation energy and carbon emission of buildings rather than for the embodied energy and associated climate impact, which are important issues that need further studies to improve the overall performance of buildings. The issue of embodied energy and associated climate impact is beyond the scope of this paper, and an ongoing research project and complementary LCA paper [54] aims to address this issue in detail.

In summary, this study shows that climate change will significantly affect buildings' energy performance and indoor climate conditions in Ghana. Effective adaptation and mitigation strategies, as demonstrated in this study, could significantly improve thermal performances of Ghanaian buildings under both current and projected future climate conditions. The findings of this study increase the understanding of climate change effects for the building construction industry in Ghana

and add to the limited body of existing literature on climate change implications for buildings in tropical developing countries.

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