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Evaluation of bioclimatic potential, energy consumption, CO_2-emission, and life cycle cost of a residential building located in Sub-Saharan Africa; a case study of eight countries

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ABSTRACT

Nowadays, one of the current concerns of the United Nations and the European Union is to offer more reliable mechanisms aimed at reducing energy consumption and carbon emissions on a building scale. The new required recommendations can be applied to all countries of the world. The main objective of this study is to evaluate, analyse and compare the indoor air condition (comfort rate and CO_2 concentration), and energy consumption, prevailing in a family building built in eight cities (Douala, Kinshasa, Abidjan, Lagos, Pretoria, Dakar, Antananarivo and Addis Ababa), located in eight countries (Cameroon, DRC, Cote d'Ivoire, Nigeria, South Africa, Senegal, Madagascar and Ethiopia) in Sub-Saharan Africa. In addition, this study assesses the total cost of the life cycle of a new building over a period of 50 years in each country. Parameter simulations and optimizations are carried out over three periods (current, 2030 and 2050) with Design Builder software renowned in this area. The results showed that the comfort potential is around 10–21% higher in the residential buildings located at altitude compare to those ones in coastal regions. The thermal comfort range is found between 20 °C and 29 °C in these different cities. The preferred thermal environment in altitude regions, where it makes cold, should be "slightly warm", corresponding to around 1 °C above the neutral temperature, in order to satisfy the majority of the building occupant. In addition, the preferred thermal environment in coastal regions, where it makes warm, should be "slightly cold", corresponding to around 1 °C below the neutral temperature, in order to satisfy the majority of the occupants of the building. Finally, the building's Life cycle cost (LCC) ranges between 25% and 35% for construction cost; from 30%to 40%, for operation cost; between 2% and 3% for maintenance cost; between 9% and 15% for energy cost on the whole LCC in Sub-Saharan-Africa.

1. Introduction

The building is any construction intended for housing or constituting a shelter. Buildings are denounced as one of the main sectors for carbon emission and energy consumption. A human spends more than 70% of his time inside a building (Modeste et al., 2014), it is important to adapt new constructions to new climates. The building is recognized as the privileged sector where carbon neutrality objectives will be applied in the countries of the European Union in 2050 (Kitio, 2013). Nowadays, the building is at the heart of the Government's strategy for the energy transition. Buildings are at the centre of the economic, social and environmental challenges of our societies. Globally and according to the latest report from the Intergovernmental Panel on Climate Change (IPCC), the building is thus responsible for one-third of greenhouse gas (GHG) emissions. In Africa, it is vital to anticipate the infrastructure and resource needs and to limit the environmental and societal degradations associated with the urbanization process, particularly with regard to the long lifespan of urban constructions. Sustainable building is part of this perspective and also aims to offer elements of responses to the difficulties encountered by some countries in the fight against poverty and inequality, access to energy and a sustainable and sober energy supply in carbon, natural resource management and adaptation to climate change.

Climate change has a strong impact on the interior comfort of the building (Andrea and Enedir, 2016; Modeste et al., 2019). Residential building is a place par excellence that can respond to the challenges posed by climate change, since mitigation and adaptation measures can

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be implemented there quite easily. Over consumption of energy in residential and commercial buildings is noticed in developed countries (USA, France, Canada Switzerland etc.), although a growing number of researches show that these different problems could be reduced. Researchers explain that developing countries are likely to fall into the same trap, as their demographic and economic growth, so that if the current situation continues, the final energy consumption of buildings on a scale global and corresponding emissions are expected to double or even triple by 2050 (Changement climatique, 2014).

Africa is experiencing rapid urbanization which should continue over the next decades, fuelled by high demographic growth, it is likely that its population will reach 2.4 billion inhabitants by 2050 (ONU Habitat, 2014), including 1.34 billion urban dwellers (55%), against 455 million at present (http://www.un.org/en/development/desa/population/publications/pdf/trends/WPP_Wallchart.pdf2012, 2019). The continent already brings together more than a quarter of the 100 cities experiencing the highest urban growth and should have three megalopolises by 2025: Lagos (Nigeria) with 18.9 million inhabitants, Cairo (Egypt, 14.7 million) and Kinshasa (Democratic Republic of the Congo, 14.5 million) (World Urbanization Prospects, 2012). In parts of Sub-Saharan Africa, the current building stock could increase fourfold by 2050 (Kitio, 2013).

The notion of thermal comfort is closely linked to the energy performance of the building (Lavoye and Thellier, 2015). This concept is difficult to grasp given its subjective nature (Modeste et al., 2014). Givoni's research has broadened the comfort zone for developing countries located in warm climates, where populations are more acclimatized to the heat and where a higher temperature can be compensated by natural ventilation (Givoni, 1998). This enlargement, also responds to a higher energy constraint in developing countries. Certain architectural trends ultimately support an extension of the discomfort temperature threshold to 30–32 °C, in order to increase the margin for the implementation of a passive bioclimatic strategy (Solener, 2014). Research on the bioclimatic of a region was conducted by several researchers. The bioclimatic diagram of a place can make it possible to verify whether the conditions of interior comfort are fully respected. There are generally three research groups in this area. The first group explained the functioning of the buildings under the base of the old bioclimatic maps (De Wilde, 2018; La Roche and Liggett, 2001). The second group was more oriented towards the simulation approach (Osman and Sevinc, 2019); and the third, considered to be the most recent, showed a new approach combining habitat performance simulations and analyses of bioclimatic maps (Pajek and Košir, 2018). Santy et al. (2017) carried out a bioclimatic Analysis of a Passive House in Indonesia with application of Olgyay Bioclimatic Chart, Givoni Bioclimatic Chart and Mahoney Table. The results showed a similarity between data found in Bioclimatic chart of Givoni and those of Olgyay. An opening of about 20% to 35% was recommended for good ventilation. Other researches on the bioclimatic were developed either for assessing the thermal comfort (Hyde et al., 2016; Rohles et al., 1975); or either to study the cooling and heating potential (Galaso et al., 2016; Kartal and Chousein, 2016).

The incorporated carbon from construction is estimated between 10 and 20% of the total carbon footprint, over the entire life cycle of a building. In new buildings, the structure of the building covers almost 50% of the initial embodied carbon (Kaethner (Arup) and Burridge, 2012). In 2015, Peng (2016) found that up to85.4% of the total carbon emissions was produced during the operational stage of building. These results were again confirmed later by Nematchoua et al. (Modeste et al., 2019; Nematchoua et al., 2019). Eleftheriadis et al. (2018) explained that a poor interpretation of the optimization results can lead to a poor choice of materials and structural designs which could directly impact the carbon emission of buildings. Other studies showing CO_2 emission at the building scale are given in Zhang et al. (2019) and Kayaçetin and horTanyer (2020).

Large construction projects require an analysis and detail on the investment cost and the duration of profitability. These help investors in their decision-making. More advanced research in this area is presented in the literature (Mahajan et al., 2014; Nematchoua et al., 2020).

The main objective of this work is to evaluate, analyse, compare and optimize thermal comfort, energy consumption and carbon emission on the scale of a residential building located in eight countries located in Sub Saharan Africa. This research has several novelties/originalities: Up to now, no in-depth research in this area, covering simultaneously these eight countries, has yet been conducted in Sub Saharan Africa; Up to now, no research comparing energy consumption and operational carbon in coastal and altitude regions in Sub-Saharan Africa; Up to now no research assessed Life Cycle Cost combining five regions located in Sub Saharan Africa (Central Africa, West Africa, East Africa, South Africa and Indian Ocean).

This study can therefore serve as a basis for future researchers who would like to orient themselves in this area. The different stages of this research detail in the following paragraphs.

2. Objective

Global objective of this research is to assess the future impacts that climate change will have on the indoor air quality and energy consumption in a residential building designed in eight countries located in Africa (Cameroon, Senegal, Madagascar, South Africa, Ethiopia, Nigeria Ivory coast and DRC). In addition, in this study, we simultaneously assessed embodied carbon and the average of Life Cycle Cost (LCC) in the eight countries.

3. Methods

The studies regarding analysis of bioclimatic potential, thermal comfort and energy consumption etc. are not new. However, the results depend of each region and can be very interesting to establish a data base. With the case of this study, psychometrics charts considering global climate of each city were associated several approaches showed in Milne and Givoni (1979), Katafygiotou and Serghides (2015), and Attia et al. (2019). The different steps of this study are shown in the next sub-sections.

3.1. Studied locations

Sub-Saharan Africa is the extent of the African continent south of the Sahara, ecologically separated from the countries of the north by the harsh climate of the largest warm desert in the world. It is home to forty-eight states, whose borders stem from decolonization. Its climates are distinguished by annual rainfall variations rather than by temperature variations. It is a very rich area in terms of biodiversity, although vulnerable to climate change. Sub-Saharan Africa is the most dynamic part of the planet in terms of population. The subcontinent is the least economically developed area.

The eight studied cities are located in central Africa (Douala and Kinshasa); West Africa (Lagos, Dakar, Abidjan); East Africa (Addis Ababa); in South Africa (Pretoria), and in The Indian Ocean (Antananarivo).

(1) The city of Douala, located around 13 m above sea level, between 4°03′N and 9° 4′E, is considered a port city. It is the economic capital of Cameroon; it is also the main business centre and one of the largest cities in Cameroon. Its area is estimated around 923 km^2. Douala is dominated by the tropical climate with two main climatic seasons: a rainy season (April to November) and a dry season (November to April).

(2) The Kinshasa city is located between 4° 19′S, and 15° 19′E, it is the capital and the largest city of the Democratic Republic of Congo (DRC). With an estimated population for 2017 of 17,071,000 inhabitants over an area of 9965 km^2. It is the third

Fig. 1. Africa map showing the eight selected locations.

most populous city in Africa after Cairo and Lagos, and it is considered to be the largest French-speaking city in the world and is among the most populous cities. Located on the south bank of the Congo River, at the level of the Pool Malebo, it has as main border the capital of the Republic of Congo, Brazzaville. The city of Kinshasa is dominated by the equatorial climate made up of four seasons: from January to February a short dry season; from March to May a short rainy season; from June to September a long dry season and from October to December a long rainy season.

(3) The Lagos city covering an area of 999.6 km^2, located between 6° 27′N and 3° 23′E, is the largest city in Nigeria and the African continent. It surpassed Cairo and Kinshasa in the 2000 s, during which it experienced a strong demographic surge. Lagos has a warm Mediterranean climate with a dry summer.

(4) Dakar is located in the far west of the Cape Verde Peninsula, on the edge of the Atlantic Ocean. It is the political, economic and cultural capital of Senegal. It alone concentrates 80% of industrial and commercial companies and around 1/4 of the country's total population. Dakar, like the rest of the country, has a tropical climate. It is thus strongly influenced by the southwest monsoon, a wind coming from the Atlantic Ocean, very humid which brings rain and the Harmattan, dry tempered wind. At the same time, temperatures vary with the seasons: Dakar experiences a very mild climate from November to April with an average temperature of around 20 °C. Finally, Dakar is one of the largest cities in Africa and its demographic growth is significant and increasing rapidly.

(5) Abidjan is the economic capital of Ivory Coast. It is also the most populous city in French-speaking West Africa, and the second largest city and third largest agglomeration within the Francophone. The city of Abidjan covers an area of 422 km^2. The city enjoys a sub-equatorial climate, hot and humid, which includes a long rainy season (May-June-July), a short rainy season (September-November) and two dry seasons. The long dry season begins from December and ends in late March. Rainfall is abundant with more than 1500 mm of water per year.

(6) Addis Ababa is the capital of Ethiopia, it is located in the centre of the country, on a plateau at an altitude between 2300 and 2600 m, which makes it the highest capital of Africa and the fifth worldwide. Located in the dry tropical zone, Addis Ababa escapes the hot temperatures of Djibouti in the east, or Sudan in the west, thanks to the altitude which allows relatively pleasant temperatures all year round. The main rainy season is from June to September. Finally, it is interesting to highlight that the area of Addis Ababa is 526.47 km^{2}and that the capital is divided into ten districts.

(7) The city of Pretoria, located at 1350 m above sea level, is considered the administrative capital of South Africa. It is one of the largest cities in the country. This city is located around 50 km north of Johannesburg, precisely in the northeast region of South Africa. Its area is estimated at 1644 km^2. This city is surrounded by several hills of the mountain range. The city of Pretoria is known for its apartheid days. The city currently has different races and communities. Pretoria's climate is humid subtropical where the summer season is often hot and rainy while the winters are rather short, cold and dry.

(8) Antananarivo is the capital of the island of Madagascar. It occupies the slopes of a rocky ridge culminating at approximately 1435 m. The city is about 350 km from the east coast of the island and 550 km from its west coast. Antananarivo has a tropical altitude climate. The average temperature over the year is moderated by the effects of altitude. The climate is characterized

Table 1
Information regarding the eight selected representative countries in Africa.

No.	Cities	Countries	Latitude	Longitude	Altitude (m)	Temp.(C°)		RH (%)		Wind speed (m/s)		Climate
						Max.	Min.	Max	Min.	Max.	Min.	
1	Douala	Cameroon	4°03′	9°4′	13	37	18	90	30	3.0	0.3	Wet & hot tropical
2	Kinshasa	DRC	4°19S	15°19′E	240	35	15	92	20	4.5	0.6	Equatorial
3	Dakar	Senegal	14° 41′N	17° 26′W	10	35	15	100	30	7.7	1.9	Tropical
4	Abidjan	Ivory Coast	5°18′N	4°04O	18	32	20	96	4	5.5	0.5	Sub-equatorial
5	Addis Ababa	Ethiopia	9°1′N	38°44′E	2355	31	9	80	20	5.0	0	Altitude Tropical
6	Pretoria	South Africa	25°44′S	28°11′E	1544	31	5	80	5	4.1	0.5	warm humid subtropical climate
7	Lagos	Nigeria	6°27′N	3°23′E	10	32	10	92	30	5.5	1.3	Tropical
8	Antananarivo	Madagascar island	18°54S	47°31E	1270	35.0	10.0	90.0	55.5	4.5	0.0	Altitude tropical

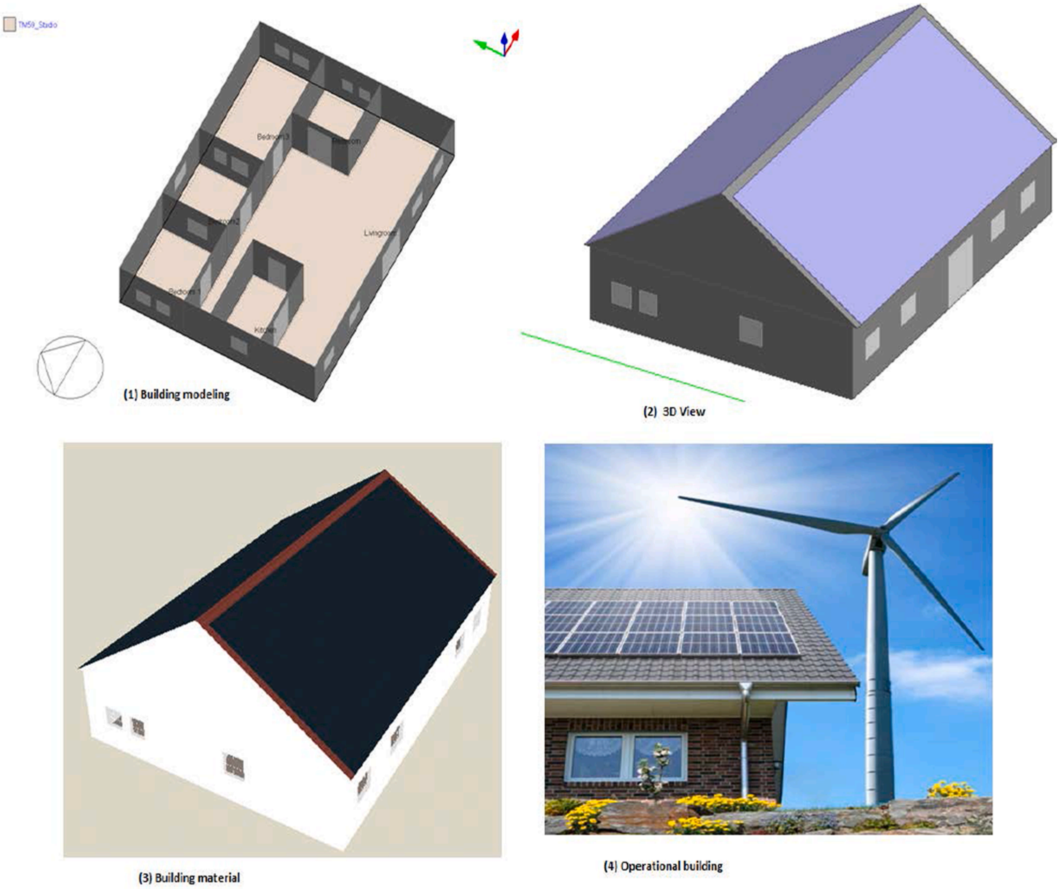


Fig. 2. Modelling and operational building.

by cool, very dry winters and mild, very rainy summers. Fig. 1 shows the geographic location of these 8 cities studied, while Table 1 reveals some climatic characteristics.

3.2. *Climate data*

In this research, the hourly external data for the last thirty years were downloaded with the most recent version (version 7.7.3) of Meteonorm. This tool is known to be a reference in meteorological data. With the Meteonorm software, it is possible to download the climatic data of many regions in the world. As input, the altitude is requested, latitude and longitude of the study area.

Data can be downloaded on three categories: the past (1961–1990), the present, and the future with the implementation of scenarios A2, A1B, and B1, RCP 4.5 and RCP 8.5; of the IPCC.

3.3. *Evaluation of annual bioclimatic potential*

We applied the ASHRAE 55-2017 adaptive comfort model combined with a psychometric chart to study the bioclimatic potential of different cities. Several researches were conducted in these regions aiming to establish the bioclimatic potential with better known data (Attia et al., 2019; Fezzioui et al., 2009; Khambadkone and Jain, 2017; Khoukhi and Fezzioui, 2012; Modeste et al., 2017). More than 80% of this research is based on a simulation study. One of the advantages of this study is that it combines simulation and experimentation. The 70% of the cities studied in this research are located in the coastal zone (Douala, Lagos, Abidjan, Dakar …). These cities have very different macro climates due to their proximity to the Ocean. On a bioclimatic diagram, each point represents each hour of the day. However, the different plots observed on the curve show two design strategies (natural ventilation and direct evaporative cooling). On the psychometric diagram, the thermal comfort zone is

Table 2
Materials and their characteristics.

	Layer	Component	Thickness (m)	Thermal conductivity (W/m-K)	Density (kg/m3	Specific heat capacity (J/kg K)	EmbodiedCarbon (kgCO$_2$)	Cost (\$/m^2)	U-value (W/m^2-K)
External walls	Layer1	Ceiling	0.02	0.056	380.0	1000.0	1.2	6.6	0.348
	Layer2	Hemp	0.09	0.04	25.0	1000.0	0.0	2.5	
	Layer3	Brick	0.14	0.72	1920	840	0.22	2.2	
	Layer4	Ceiling tiles	0.02	0.056	380.0	1000.0	1.2	6.6	
Roof	Layer1	Roof tiles	0.03	0.84	1900	800	0.46	7.5	0.294
	Layer2	Polyurethane	0.05	0.042	8.0	3470	0.00	1.00	
	Layer3	wood	0.04	0.04	1000	1000	0.00	2.5	
Internal partitions	Layer1	Ceiling	0.02	0.056	380.0	1000.0	1.2	6.6	0.310
	Layer2	Hemp	0.09	0.04	25.0	1000.0	0.0	2.5	
	Layer3	Stone Basalt	0.10	3.49	2880	840	0.01	10.0	

crossed by the direct cooling zone. According to Givoni (1992), in hot and dry countries, the maximum temperature of the dry thermometer is around 45° C and that of the wet thermometer is around 25 °C.

3.4. Studied building

The building analysed in this study is a copy of a family house built on an area of 273 m^2, and consisting of three bedrooms, a shower, a living room and a kitchen. This residence is occupied by 5 people (a young couple and their three children). An overall view of this building is shown in Fig. 2.Residence occupancy calendar: 24/7; height 4 m, occupant activity is sedentary; clothing is 1Clo in the rainy season and 0.5Clo in the dry season. The building is analysed in mechanical and also natural ventilation conditions. The different materials making up this building and their characteristics are shown in Table 2.

3.5. Software

The building modelling and simulation tool used in this research is the Design-Builder software. Design Builder software is one of the most renowned software in building optimization and modelling. This software has several features. It offers different types of materials with variable properties. In addition, this tool makes it possible to calculate the thermal losses/gains of the envelope in winter/summer; Dynamic simulation (STD) restoring comfort data, balance, etc. The duration of each simulation depends enormously on the capacity of your simulator. A more detailed view of this software is shown on the website: https://designbuilder.co.uk/.

3.6. Calibration of the model

Calibration is the most important step for data validation. In this research, calibration is applied by comparing simulation and measured data. We analysed two parameters: monthly electricity consumption and hourly air temperature.

There are several requested methods and guidelines in the literature for calibrating a model. In this research, two ways mentioned in ASHRAE guideline 14 (ASHRAE, 2002) were used: Coefficient of variation or square root error (RMSE) and mean bias error (MBE). The different RMSE and MBE values were evaluated taking into account the two equations reported below (ASHRAE, 2002).

$$RMSE(\%) = \frac{1}{M}\sqrt{\frac{\sum_{i=1}^{N}(Mi - Si)^2}{N}}$$

and

$$MBE(\%) = \frac{\sum_{i=1}^{N}(Mi - Si)}{\sum_{i=1}^{N}Mi}$$

Where S_i and M_i main simulated and measured data over a given interval I, respectively the total number of data implemented.

In Guideline 14 by ASHRAE (2002), it is recommended that a simulation model can be considered calibrated if the following conditions are followed:

- Hourly MBE between ± 10% and hourly RMSE smaller than 30%.
- Monthly MBE between ± 5% and monthly RMSE less than 15%.

3.7. Experimental study

The building studied is a copy of a residence building encountered in Antananarivo city. It was a standard residence in Madagascar. We carried out an experiment in this building, such as in several other residential buildings located in Antananarivo, and in several other cities located in Madagascar. This large experimental study took place in 2017 and covered several types of buildings as described in Modeste et al. (2017). Overall, more than 1000 people were interviewed during this study. The new adaptive approach recommended in the ASHRAE-55 standard was applied, consisting of distributing questionnaires and simultaneously taking physical measurements of air temperature, relative humidity, wind speed, etc.

The measurement data and response of occupants allowed us to evaluate the comfort rate of residential buildings.

A detailed description of the experimental study is given in references (Modeste et al., 2017; Nematchoua et al., 2019).

3.8. Scenario

Initially, we studied this residential building in natural condition. In fact, this building is a copy (100%) of a family residence located in Antananarivo (Madagascar). This building is under natural ventilation between 6am to 7 pm, and air conditioning between 7 pm and 5 am. It is aired most of the day and supplied with electricity by the electric power distribution company in Madagascar. No water heating is employed. We have therefore applied the A2 scenario proposed by the IPCC, which is considered to be one of the most realistic in Madagascar and in the 7 other cities studied to assess the weather in the future (2030 and 2050). Hourly data from the past 30 years was used in this simulation. Finally, this building was studied on the basis of several hypotheses:

- Scenario1: We solicited and installed photovoltaic panels covering almost three fifths of the surface of the roof. To moderate the heat transfer from the outside to the inside of the building, we increased the thickness of the insulation on the roof as on the different walls by about 2 cm thick. Based on the recommendations found in the literature, we decided according to the geographic position of each city to orient the main façade from south to north, putting sunscreens on each window. The optimal tilt of the solar panels in this region is 45 °C. We have in this case excluded the network from an energy storage system (for example the battery).

Table 3
Average indoor adaptive comfort temperature ranges (°C) with 90% of Acceptability Range in the eight selected cities.

N°	Region	Country	City	Current	2030	2050
1	Central Africa	Cameroon	Douala	23.0–28.2	23.2–28.5	24.0–29.1
2		DRC	Kinshasa	22.5–28.0	22.7–28.5	23.0–29.0
3	West Africa	Senegal	Dakar	22.0–28.3	22.5–28.5	22.5–29.0
4		Ivory Coast	Abidjan	23.0–28.5	23.2–28.8	23.3–29.0
5		Nigeria	Lagos	23.1–28.5	23.3–28.9	23.5–29.0
6	South Africa	South Africa	Pretoria	20.7–27.6	21.0–27.8	21.2–27.9
7	East Africa	Ethiopia	Addis Ababa	21.8–27.1	22.0–27.3	22.5–27.7
8	Indian Ocean	Madagascar island	Antananarivo	21.5–27.3	21.7–27.8	22.0–28.0

- Scenario 2: in this case, we applied all the details presented in the previous scenario (scenario 1) but, however, we had connected the entire electrical network to a storage system. In addition, we installed a wind turbine, the characteristics of which are detailed in the following paragraph. We simulated this building according to each scenario and we found very interesting results.

3.9. Description of wind turbine

The wind speed is considerable in these cities which made the selected cities favourable to the implementation of the wind turbines with following characteristics:

(i) General: operation scheme (base load), electrical bus type(alternating current);
(ii) Generator list: numbers of generators(01), Availability schedule (on 24/7), rotor type (1-Horizontal), power control(3-variable Sp), rotor speed(41 rev/min), rotor diameter(19 m), overall height(31 m), number of blades(03), rated power output(55000 W), rated wind speed(11 m/s), cut in wind speed(3.5 m/s), cut out wind speed(25 m/s), overall wind turbine system(0.835), maximum tip speed ratio(8), maximum power coefficient(0.40), annual local average wind(6.4).

3.10. Common criteria

The eight countries studied are located in Sub-Saharan Africa. In this region of the world the style of construction is almost common with the same local materials (aluminium sheet, earth brick, bamboo, plank, raffia etc.). The activity of the occupants, the hours of occupation, lighting and the density of occupation per inhabitant are almost the same. Despite the fact that the behaviour differentiates from one individual to another, overall, in this region the inhabitants are more attached to nature, the forest and the traditions of the forest. The population activity is sedentary. However, it is recognized that the climate of a place varies according to its geographical position and this is why the different cities studied rarely have the same climate. In the eight countries studied, the energy mix is strongly dominated by the consumption of fossil energy (petroleum, coal, etc.).

4. Results

4.1. Bioclimatic potential and thermal comfort parameters

The adaptive comfort temperature ranges for the eight studied cities located in eight countries were calculated under basic ofASHRAE55-2004 adaptive model (ASHRAE, 2002). Hourly weather data for the last twenty years were applied for this aim. As we can see in the data of the Table 3, it can be deduced that each of these cities has its own monthly comfort ranges. What is more, the climate varied according to the geographic position of each city. In this sense, for the cities located in altitude, as Addis Ababa (2355 m); Pretoria (1544 m) and Antananarivo (1270 m), the climate is milder and peaceful; with a more moderate temperature variation. Global adaptive comfort temperature with more than 90% of acceptable range is between 20.7 °C and29.1°Cin the eight selected cities. Fig. 3. shows the bioclimatic diagrams in 2018 and 2050 of the studied cities. These diagrams are simulated with the hourly meteorological data of each city. The comfort ranges are over this one recommended by several international standards.

The number of hours of comfort is highest in Addis Ababa and lowest in Douala and Lagos.

4.1.1. Annual thermal comfort frequency

The different annual thermal comfort frequencies in each of the cities studied are shown in Fig. 4. This diagram potentially represents the number of hours of comfort without implementing a bioclimatic strategy. The average annual comfort rate is estimated at 30.2% in the eight cities. We find that the weather in the city of Addis Ababa has the most hours within comfort limits (50.5%), compared to other cities studied. Meanwhile, Kinshasa city weather shows the most hours within the limits of discomfort (11.8% in 2018, and 4.9% in 2050). The comfort rate is estimated from 11.8% above the average of the eight cities in Pretoria city, and to 7.8% below the average of the different cities studied in Abidjan.

4.1.2. Predicted mean votes

Predicted Mean Votes were evaluated employing 6 parameters as input data (air temperature, radian temperature, relative humidity, activity, air speed and clothing). The Fig. 5showed the average air temperature in this building on three periods and can be observed that the air temperature was expected to increase between 0.4 °C and 1.8 °C in 2050.

Fig. 6 shows the variation of Predicted Mean Votes (PMV) with uniform air temperatures in the residential building located in the six cities studied. Some good correlations were found between the predicted average vote (PMV) and the operating temperature. Overall, in the six cities, when the uniform indoor air temperatures were between 16.0 °C and 27.0 °C, the PMV varied between −1.1 and 1.4. Finally, when the neutral temperature is evaluated for PMV = 0, it was obtained that the neutral temperature is 24.6 °C in Abidjan; 22.1 °C in Addis Ababa; from 21.9 °C in Dakar; 24.7 °C in Lagos; and 26 °C in Pretoria.

4.2. Validation and calibration of new simulation model

The RMSE and MBE values allow a meticulous comparison of the measured and simulated data. The different results found are reported in Table 4. After calculation, the MBE value found is 0.6%, while that of RMSE is 0.2%. However, the different values recommended in the ASHRAE directive 14 are between [−10%; +10%], counting for (MBE) and, [−30%; +30%], counting for (RMSE). Looking at these results, we can conclude that the different hourly values of MBE and RMSE found in this study are within the range recommended by ASHRAE. We deduce that this simulation model is calibrated with hourly data. In addition, a comparison between the different monthly energy values was conducted. The value of the MBE obtained is −4.6%, while that of the RMSE found is 0.7%. In accordance with ASHRAE, the different acceptable limits are between [−5%; +5%] representing the (MBE) and [−15%; +15% representing the (RMSE). By analysing these results, we can easily

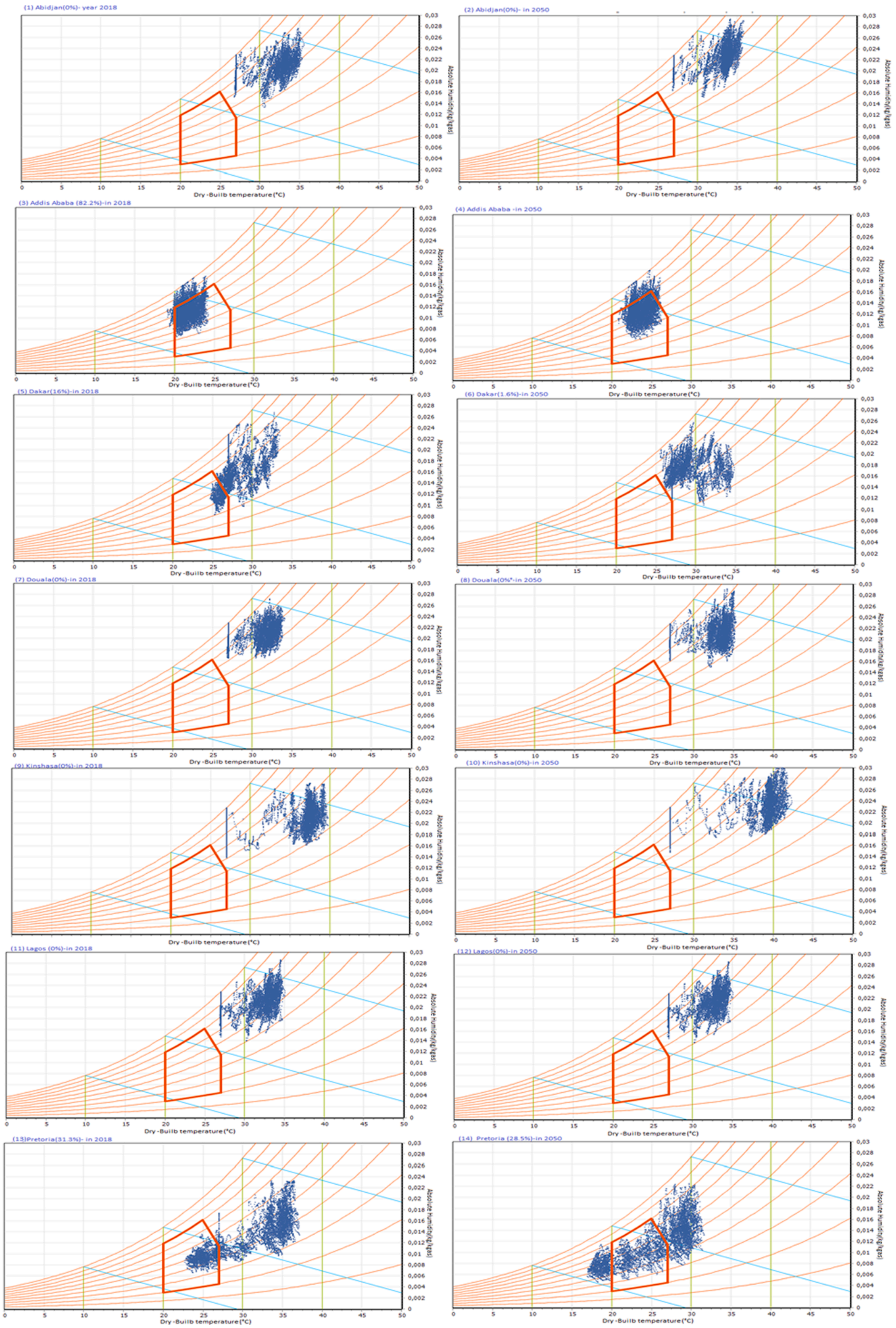


Fig. 3. Bioclimatic diagram for seven selected cities on two periods (2018 and 2050).

deduce that the MBE and RMSE values for the different monthly data are within the range recommended by ASHRAE (2002). After this, the new simulation model was calibrated with the different monthly data and, in consequence, all of these two results show that the new model is calibrated and can be validated.

4.3. *Energy demand*

4.3.1. *Cooling energy*

Fig. 7 shows in detail the different values of cooling energy in the residential building located in the cities studied according to three scenarios (current, 2030 and 2050). Zero cooling energy in Addis Ababa

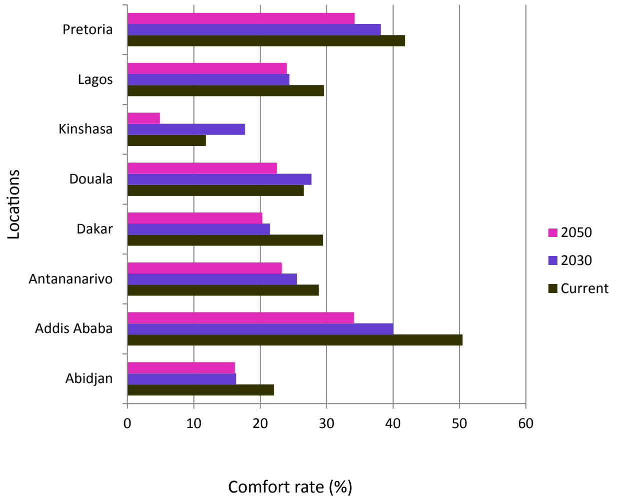


Fig. 4. Annual thermal comfort percentage of the eight selected cities.

and Antananarivo (two cities locatedonseveral mountains). The three coastal cities (Douala, Lagos and Abidjan), located in the tropical zone, showed a very high value of cooling energy: around 41.4% in 2018; around 42.9% in 2030; and around 44.2% in 2050. However, the city of Pretoria, located in a subtropical climate, will show one of the lowest cooling energy rates (from 1.2% in 2018 to 4.5% in 2050). It is interesting to note that the cooling energy decreases up to 11.2% when the thickness of the insulation on the main facade and the roof of the building is increased by 2 cm, combined with the installation of photovoltaic panels on the roofs. Overall, average cooling energy will increase between 1.7 and 15.0% from 2018 to 2030.

4.3.2. *Net site energy*

Fig. 8 shows the net energy residence consumption in each city for a case study of three scenarios (current, 2030 and 2050). We assumed that in each country studied, the energy mix will vary very little in the future. We can notice that the average energy consumed in the eight cities is currently estimated at 39.2 kWh/m^2; and will be 45.6 kWh/m^2 in 2030; and 51.9 kWh/m^2 in 2050. The cities of Douala (79.1 kWh/m^2), Lagos (76.6 kWh/m^2) and Abidjan (72.8 kWh/m^2), show high energy consumption in residential buildings, while other cities such as Addis Ababa (5.3 kWh/m^2),Antananarivo (5.9 kWh/m^2)and Pretoria (6.3 kWh/m^2) show low energy consumption in residential buildings.

It is very interesting to notice that by applying (PV + wind turbine) on the residential building designed in Antananarivo and Addis Ababa cities, annual building energy produced is equal to the annual building energy consumption.

In all the eight cities, the criterion of "Positive Energy Building" (a positive energy building is a building that produces more energy than it consumes) is reached, just after the installation of PV + wind turbine in the residential building.

4.4. *Operational and embodied carbon*

As describe in Design builder help (https://designbuilder.co.uk/helpv6.0/Content/Carbon.htm, 2020), Embodied carbon means all the CO_2 emitted in producing materials. It is estimated from the energy used to extract and transport raw materials as well as emissions from manufacturing processes (https://designbuilder.co.uk/helpv6.0/Content/Carbon.htm, 2020). The embodied carbon of a building can include all the emissions from the construction materials, the building process, all the fixtures and fittings inside as well as from deconstructing and disposing of it at the end of its lifetime (https://designbuilder.co.uk/helpv6.0/Content/Carbon.htm, 2020). It can be used to compare the environmental impacts of different building materials, designs and construction processes. It can help to identify elements which are carbon-intensive and promote alternative options which reduce the amount of CO_2 released (https://designbuilder.co.uk/helpv6.0/Content/Carbon.htm, 2020). It can be used to design policies that reduce the CO_2 emissions from the construction sector. Used together with the operational carbon (i.e. the carbon emitted due to use of the building for heating, cooling, equipment use etc), the embodied carbon can be included as part of a whole life cycle assessment (LCA) to understand the overall impact of the building on the environment over its whole life cycle.

Fig. 9 shows the operational carbon per square meter detailed in the different cities selected. The operational carbon rate is the lowest in Antananarivo and Addis Ababa (around 3.5kgCO$_2$/m^2), and the highest in Douala and Lagos: from 27.3kgCO$_2$/m^2 to 32.7kgCO$_2$/m^2. Globally, in the eight selected cities, carbon concentration varies between 3.6 kgCO$_2$/m^2 and 28.2 kgCO$_2$/m^2 with an average around of 14.8kgCO$_2$/m^2. Carbon dioxide emission is expected to increase between 4.5% and 12.5%, from 2018 to 2050.

Embodied carbon is the rate of carbon produced by each building material. In different cities, embodied carbon produces by this residential building was estimated to be around of 52438.7 kgCO$_2$/year. This concentration of carbon is low compared to other values found in some studies. This is normal because certain materials used in this study, such as Hemp and Limestone silicon, do not emit carbon.

4.5. *Life cycle cost*

In this research, the Life cycle cost of residential building was based on the model suggested by Langdon in 2007 (Langdon, 2007). The Life cycle of a building is assessed into 50 years and evaluated according to the local context, more common to those of Sub-Saharan African countries. It is interesting to notice that the standards of international construction costs are hardly respected in the eight countries selected. The calculation of Life cycle cost is detailed in Nematchoua (2020). The Table 5 shows some cost parameters used to evaluate LCC

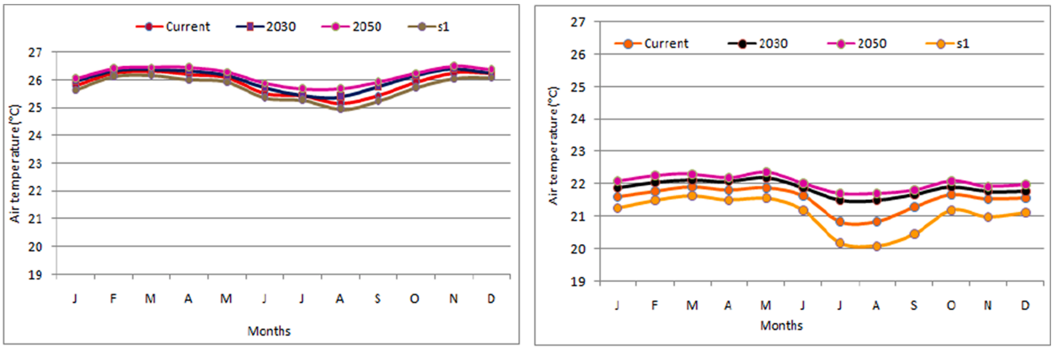
According to the Figs. 10 and 11 it can be seen that, in the eight countries, the building Life cycle cost ranges between 25% and 35% for construction cost; from 30%to 40% for operation cost; between 2% and3%for maintenance cost; from 0 to 1% for demolition cost and between 9% and 15%for energy cost on the whole LCC.

5. Discussions

5.1. *In-depth discussion of main results*

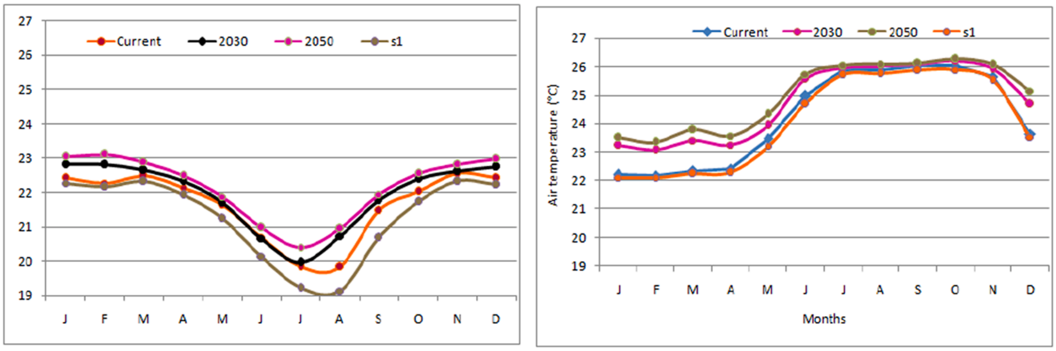
In the case of experimental studies, the results vary from region to region. It is sometimes very difficult to find the results common to several regions. While in the case of research concentrated around the simulation of the data, all the accepted results tend to converge, whatever the place of study.

It is difficult to find in Sub-Saharan Africa a habitat where 90% of the occupants find the environment comfortable, as in most countries of the world. This study reveals a new comfort range relating to the different countries studied which is ranged between 20 °C and 29 °C. This interval found in this study is beyond the recommendations of the international standard (ASHRAE, 2004), which estimates values in the 23–26 °C range. Nevertheless, it is very nearby of comfort range found in several researches carried out in this region (Modeste et al., 2017; Nematchoua et al., 2019; Nematchoua et al., 2020; Ogbonna and Harris, 2008). In Sub-Saharan Africa, buildings found in cities located at altitude are between 10% and 21% more comfortable than those found in cities located in the coastal area. This result is not surprising, Djongyang and Tchinda (2009) shown that the climate is milder at altitude than in the coastal zone. The orientation of the building and construction materials can have a significant effect on indoor air and energy consumption. The neutral temperature range is between 21.9 °C and 26.0 °C and varied of



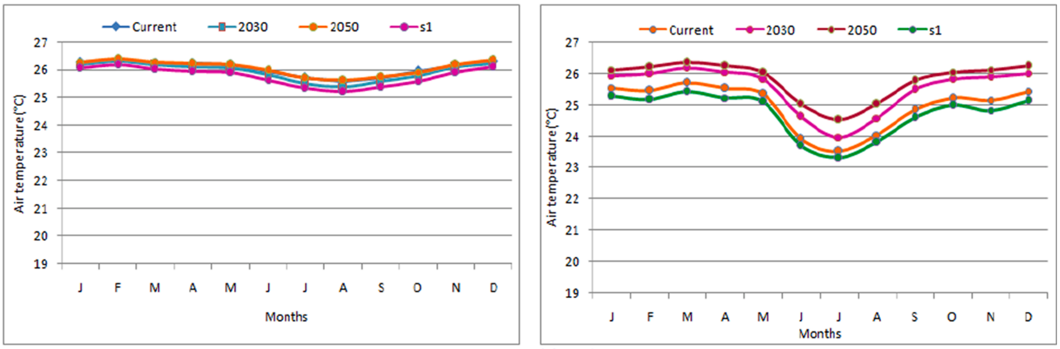
(1) Abidjan

(2) Addis Ababa



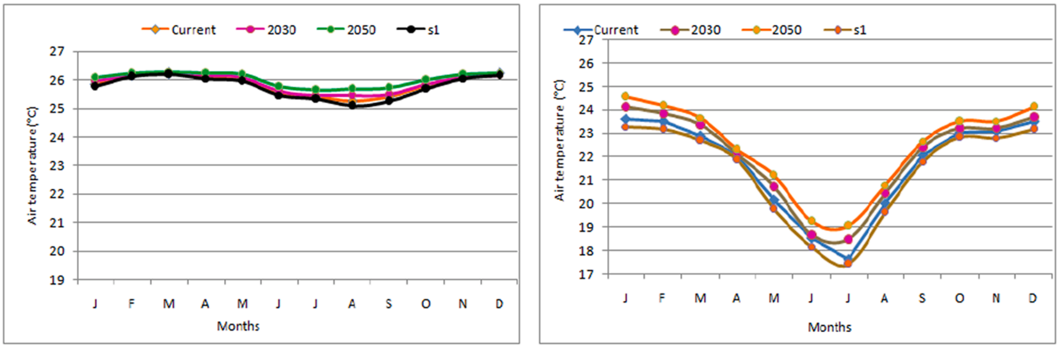
(3) Antananarivo

(4) Dakar



(5) Douala

(6) Kinshasa



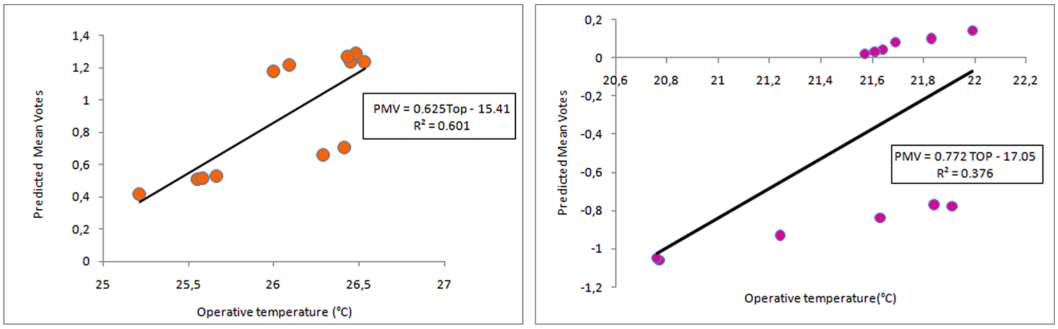
(7) Lagos

(8) Pretoria

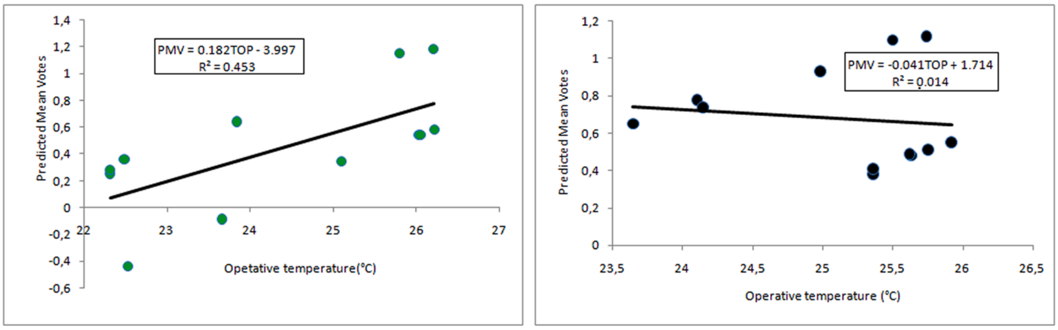
Fig. 5. Monthly air temperature for the eight selected cities applying three periods (current, 2030 and 2050) and one scenario.

a region to another. This included neutrality interval that found by Mui and Wong (2007) in the regions covered by subtropical climates which were 23.6 °C and 21.4 1 °C in summer and winter.

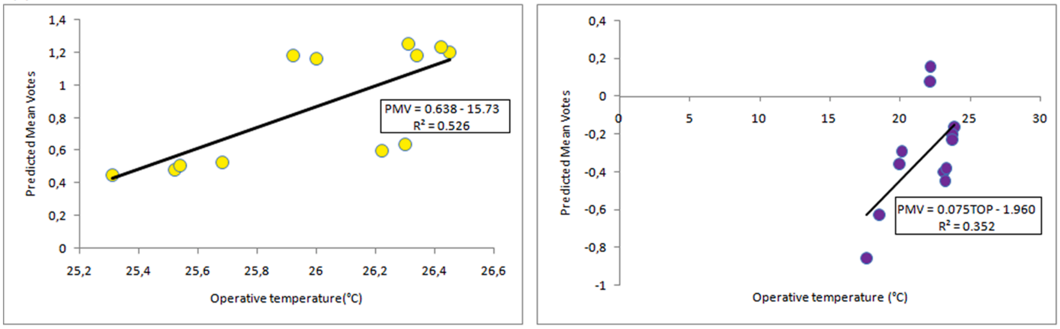
The preferred thermal environment in Antananarivo, Addis Ababa and Pretoria should be slightly warm, corresponding to around 1 °C above the neutral temperature, in order to satisfy the majority of the building occupant. In addition, the preferred thermal environment in Douala, Lagos, Abidjan, and Kinshasa should be slightly cold, corresponding to around 1 °C below the neutral temperature, in order to satisfy the majority of the occupants of the building. In this study, we found that the cost of energy expenditure represented between 9% and 15% of the total cost of expenditure. While cooling energy represents between 4 and 7% of building energy expenditure in the eight countries. The US Department of Energy (DOE) declared in 2005 that most typical households spend between 8 and 14% of their income on expenditure. This indicates that heating and cooling costs represent between 3 and 5% of gross annual income (Zhao et al., 2016). We deduce that our results are close to that recommended by DOE.



(1) Abidjan (2) Addis Ababa



(3) Dakar (4) Kinshasa



(5) Lagos (6) Pretoria

Fig. 6. Predicted Mean Votes versus operative temperature in six selected cities.

Table 4
Calibration of new model.

Parameter	Hourly indoor air temperature	Monthly electricity consumption
MBE (%)	0.6	−4.6
RMSE (%)	0.2	0.7

At the same time, results showed that an increase in the outside temperature will immediately lead to an increase in the demand for energy in the buildings; it is recommended that the occupants take preventive actions aimed at reducing energy consumption. The RT 2012 standard recommends considerably improving the energy efficiency of the building up to the threshold set at 50 kWh/m^2. In this study, the average energy consumed in the eight countries is estimated at 39 kWh/m^2. This means that this studied building model can be adopted for the establishment of low energy consumption residences. Finally, the Table 6 shows a comparison between Operational carbon/energy in ten countries.

By comparing our results to those found in a more conventional building located in Belgium and Portugal (Barbara et al., 2012), we find that the level of carbon emitted during the operational phase of the residential building in Belgium and Portugal is 56.3% greater than that of the eight countries located in Sub-Saharan Africa. Moreover, operational energy is 82.5% higher in residential building in Belgium and Portugal than residential building in Sub Saharan Africa. The carbon rate emitted per square meter in this study is within the range recommended by Lotteau et al. (2015), which was between 11kgCO$_2$/m^2 and 140 kgCO$_2$/m^2.

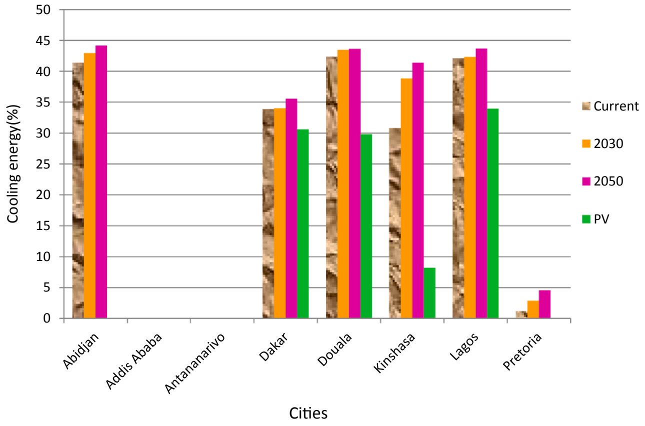


Fig. 7. Cooling energy in the selected locations during three periods (current, 2030 and 2050), and applied scenario PV.

The amount of CO$_2$ emitted per kWh generated is 0.4 kg. Despite

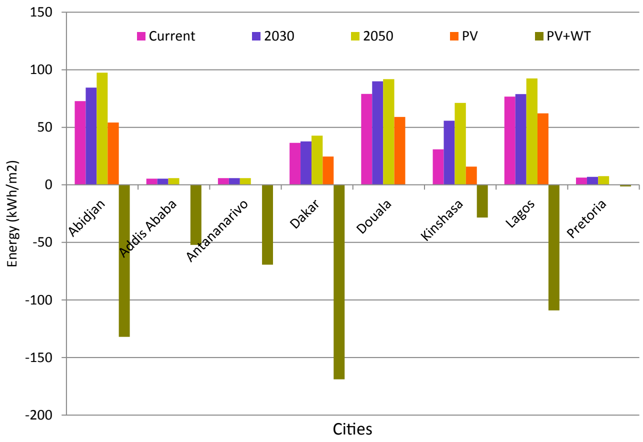


Fig. 8. Total energy (consumed + produced) in the selected locations.

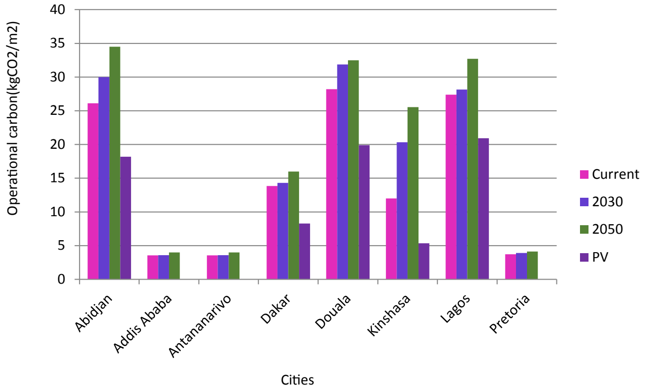


Fig. 9. Annual operational carbon quantity in eight cities located in eight countries.

Table 5

Cost parameter used for the Life Cycle Cost Assessment in the eight countries.

Currency and Exchange Rate Currency symbol	$
Applicable construction labor hours and local cost index	
Regional material cost index	0.06–0.09
Hourly labor rate worker	0.23–5.01$
Hourly labor rate craftsman	0.21–3.9$
Discount factor (capital cost) and inflation	
Discount rate (cost of capital)	15–20%
General inflation rate	5–10%
Energy inflation rate	5.2–11.2%
Water inflation rate	5.2–9.0%
EOL as % of capex	1.5–2.0%

everything, a good government policy applied in each country will allow a significant reduction in carbon levels in the building and city scale. Bhutan remains the only country in the world with a negative carbon footprint. Sub-Saharan African countries (Cameroon, Gabon, DRC), dominated by the immense dense forest should copy this example. The design of the new residential building proposed in this study requires an investment estimated between 45 and 76% greater than that of the more conventional traditional buildings commonly encountered in Sub-Saharan Africa. Such an investment for the construction of this house cannot be considered a loss. Indeed, the amount of electricity produced by this habitat and which can be sold to individuals is estimated on average at 18,946.86 kWh/year. This shows that this house produces about $ 2423/year by selling its own energy produced for individuals.

5.2. Limitations and strength of this scientific research

This scientific research has several novelties and limits as shown in the following subsection.

5.2.1. Originality and novelty

This research analyses and compares the bioclimatic diagram, comfort rate, energy consumption, operational carbon and life cycle cost of a family building built in eight countries located in Sub Saharan Africa. So far, no study grouping these countries has yet been conducted in this area. What is more, all the cities selected in this study are strongly dominated by the impacts linked to climate change following the strong pressure of human in nature. In consequence, present paper assesses the forecast of energy, carbon and comfort in eight countries covering various climates in Africa. So far, no study has yet been conducted in this region with the proposed method.

Finally, this research assesses the total energy generated by the wind turbine and the photovoltaic panels applied to a family building, during two seasons (dry and rainy seasons). So far, no study grouping all these cities and evaluating these data has not carried out.

5.2.2. Limitations

Any scientific study must have limits whatever its content. For instance, this study does not cover all types of climates in Africa, and the results may depend on the type of climate in the region studied. What is more, this study was carried out only in a family residence, why not also studied the cases of hotels, offices, schools etc. and several more familiar typologies of buildings exist in Sub-Saharan Africa, this study applies to a construction with more modern materials.

More other aspects can be improved. On one hand, statistical analysis of the data was not carried out, in depth in this study; only scenario A2 of the IPCC is applied in this study, it would have been better to apply the scenarios RCP 4.5, RCP6 or RCP 8. On the other hand, the different indoor temperature data selected for the calibration of the simulation model do not cover a full year, except in the case of electricity. In consequence, the model should be more reliable, if for example, the internal measurements were spread over at least one or two years, without measurement stop. Nevertheless, this study was carried out with the most available reliable data.

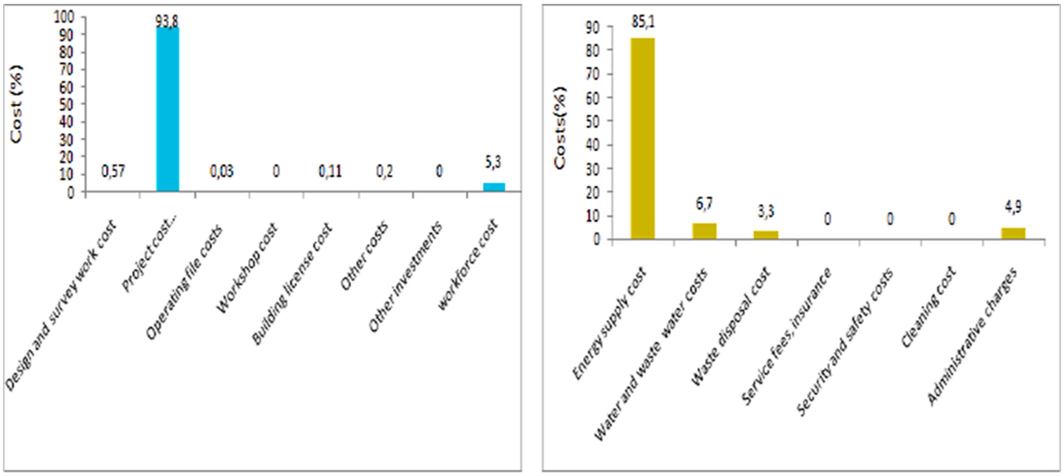
5.3. Practice and global implications

This study is based on the most recent data that makes it possible to update the older bioclimatic design models in this region. Results and conclusions can be applied by designers, engineers and other building specialists provide more sustainable, less consumable and less polluting buildings in these different countries. An equipment threshold is recommended for obtaining Zero energy or positive energy buildings as shown in this study. The results of this research could also, be beneficial to investors, politicians and individuals and be relevant and exploited in other countries.

In general, this research could serve as a guide for all future researchers attracted or fascinated by this field of study. The potential for energy savings in the building sector is considerable and should be harnessed to reduce household energy bills and the sector's greenhouse gas emissions. Finally, future research works will be oriented towards the comparison and statistical analysis of indoor air, energy consumption and carbon levels in traditional habitats and new sustainable habitats in Sub Saharan Africa.

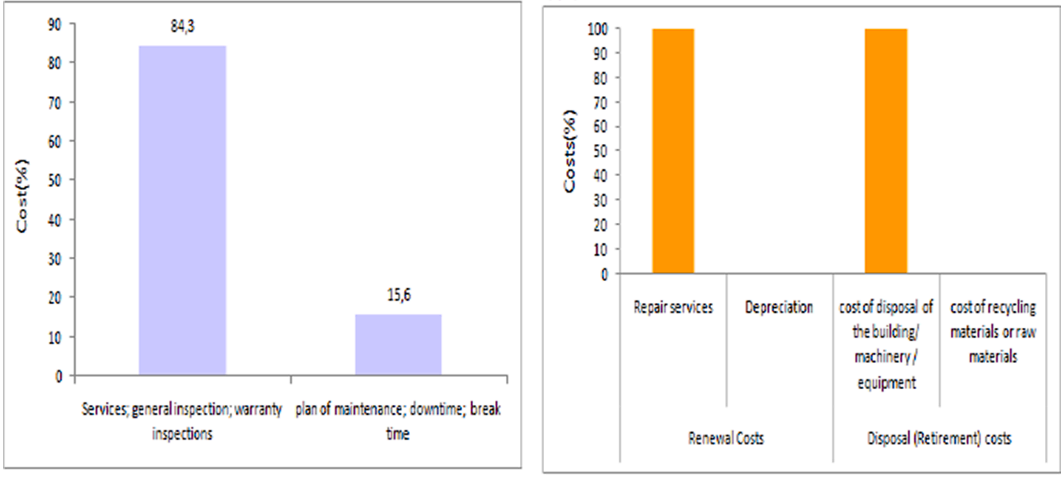
6. Conclusions

This study, conducted in eight countries located in Sub-Saharan Africa (Cameroon, Ethiopia, Nigeria, Ivory Coast, DRC, Senegal, Madagascar, and South Africa) assesses analyses and compares the potential for comfort, energy consumption, carbon emission and LCC over



a) Investment cost

(b) Operational cost



(c) Maintenance cost

(d) Renewal and disposal costs

Fig. 10. Detailed costs in the cities.

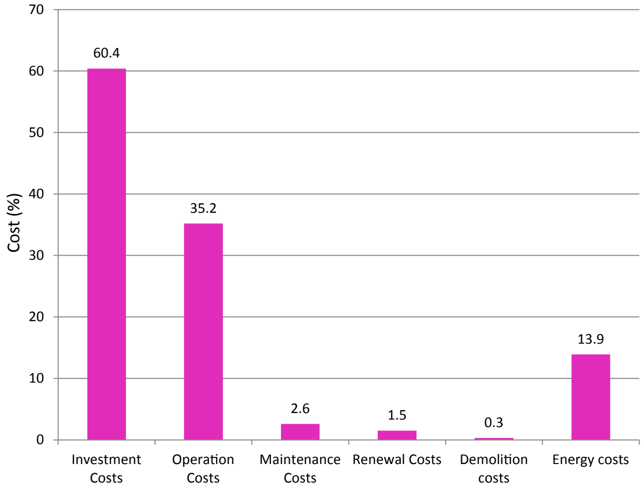


Fig. 11. Average Life Cycle Cost of study building located in the eight selected countries (in natural condition without photovoltaic panel and wind turbine).

50 years, of a residential building originally designed in Antananarivo. The data and results collected vary according to the place of study. The residence buildings are 10–17% more comfortable when they are located altitude than in coastal regions in Sub- Sahara Africa. Indeed, the climate is the most moderated in altitude. Neutral temperature was estimated to be between 21.0 and 26 °C in the eight studied cities. During the operational phase of building energy cost occupies a good part of the expenditure, indeed, energy cost represented between 9% and 15% of the total cost of the expenditure. While cooling energy represents between 4 and 7% of building energy expenditure in the eight countries. At the same time, the old types of more traditional constructions are recognized as more efficient in energy than the new, more modern buildings. Local materials are more suited to micro climates and low carbon producer. Between 6 and 25% of the total carbon emitted during the operation of the building could be avoided with the application of solar panels as one of the sources of energy production in the residential building. Applied technique and materials selected in the design of this building can serve as a guide for architects in the implementation of new, more ecologically buildings due to, for instance, coastal towns require architecture more suited to the climate. Finally, new research works will analyse and compare the different methods of reducing CO_2 on a building scale.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Table 6
Comparison of operational carbon and energy.

	Cameroon	Ethiopia	Ivory Coast	Nigeria	Madagascar	Senegal	South Africa	RDC	Belgium	Portugal
Operational carbon (kg/m^2 yr)	28.2	3.6	26.1	27.4	3.5	13.9	3.7	12.0	29.1	38.7
Operational energy (kWh/m^2 yr)	79.1	5.3	72.8	76.6	5.9	36.4	6.3	30.9	274.4	174.7

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