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CASE STUDY

Evaluation of energy consumption and CO_2 emission in a standard traditional building located in tropical region, a case of Madagascar Island

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Abstract: Energy demand varies depending on the location chosen for construction. There are very few studies related to the analysis and reduction of energy consumption in the more traditional buildings in the tropical regions, moreover, until now, no standard on energy efficiency exists in the literature related to this region. It is necessary to conduct regular research in this region in order to propose new construction rules more adapted to the new climate. It is in this sense that this study was built with as main objective to analyze the bioclimatic potential of different climatic zones in different regions of Madagascar. In addition, this research assesses and compares the indoor air temperature, the energy requirement, the carbon emission and the relative humidity in a traditional building commonly found in cities in sub-Saharan Africa, which was designed to be placed in four cities unevenly distributed in four climatic zones of Madagascar. In order to achieve this goal, hourly meteorological data for the past thirty years has been analyzed for two seasons (dry season and rainy season). At the same time, the adaptive comfort model defined by ASHRAE 55 served as a reference for evaluating the different potentials of passive design. The results showed that by 2030 the need for energy is expected to increase globally in these different cities studied. Like other countries around the world, it is recommended that countries in Sub-Saharan Africa conduct more of this kind of energy. Study in order to establish a construction standard specific to this region of the world.

Keywords: energy consumption, traditional building, Madagascar, tropical region

1 Introduction

Currently, the building sector consumes up to 40% of total energy and produces almost 35% of the carbon dioxide emitted into the atmosphere [1, 2]. However, the increase in average temperatures on the earth's surface is the direct consequence of massive greenhouse gas emissions [3]. Based on this value, it is easy to deduce that this sector plays an important role in the evolution of the external climate. In the context of current and future energy, tools and methods for designing buildings and associated energy and thermal systems are evolving rapidly [4]. New buildings require the indoor temperature to be within a comfortable range with minimal temperature fluctuation during the day [5, 6]. In today's world, in the world and especially in developed countries, the construction of ecological buildings adapted to their climates is in great demand. Demographic, social and economic growth in the city and urbanization is increasing day by day. By 2030, it is likely that 6 in 10 people will live in urban areas [7], or 90% of this growth estimate will occur in the African continent and or other underdeveloped countries. In this case, a bad impact of this urbanization can occur due to bad urban planning [7]. For many years, humanity has been faced with a high demand for energy [8]. It is a direct consequence of world population growth and the gradual transformation of many primary economies [9]. Predicting the energy consumption of residential buildings is fundamental in proposing strategies for improving their energy performance with the aim of saving energy and reducing the environmental impacts of buildings [10].

The housing situation in Madagascar is characterized, both in quality and in quantity, by an absolute insufficiency, which is explained both by demographic factors (population growth, rapid urbanization) and by the socio-economic factors involved (underdevelopment of the productive forces) [11]. The island of Madagascar ranks among the countries most vulnerable to the effects of climate change [12] and it is ranked among the top ten countries in the world for the cyclone mortality risk index [12]. Since the 1970s, the country has been rocked by four political crises (in 1972, in 1996 in 2002 and in 2009), plunging it into an economic recession marked by a drop in the rate of growth of products (GDP) [13]. To date, no urban plan has been applied in Madagascar. Considering the current behavior of human beings, it is obvious that it is easier to reduce the energy consumption in a building than to limit the rate of carbon emission [11]. The impact of embodied and operational carbon is very significant in the building class. In 2012, Rossi *et al*. [14] did the study on the three major European cities Brussels, Coimbra and Lulea and found that carbon emissions are very high during the operation phase of the building. In 2019, Nematchoua *et al*. [15] found that carbon dioxide emissions were up to 37% lower in green buildings than in older buildings. As in all coastal regions of the world, Madagascar is highly exposed to the adverse effects of climate change. Consequently, it is very difficult to propose a common standard relating to all regions of Madagascar because of the great variability of the type of climate. The big island is one of the regions of the world where biodiversity and buildings are strongly impacted by seasonal climate variability [10]. Several other important researches have been carried out in recent years for example, an innovative technology of microbial electro-synthesis has been recently developed that can sequester CO_2 with little electrical energy to produce biofuels thus alleviating the problem of global warming [16]. There are not enough studies in Sub-Saharan Africa that propose techniques to evaluate and reduce the amount of energy consumed and the rate of carbon emissions in traditional buildings. Data for this region are lacking in the literature. Different methods to achieve low energy and low carbon on the scale of a building are shown by most of the research works. Despite this, the recommendations generally offered by researchers do not always correspond to the realities found during the construction of new buildings in a determined region. Therefore, a standard may not be valid in all climate regions of the world. This study analyzes and compares cooling energy consumption, and operational carbon emissions in four cities of the selected large island (Antsiranana, Mahajanga, Antanarivo and Toamasina). (see in Table 1)

Table 1 Some information concerning the four selected cities in Madagascar

No.	Cities	Latitude	Longitude	Altitude	Temp.(°C)		RH (%)		Wind speed		Type of climate
					Max.	Min.	Max.	Min.	Max.	Min.	
1	Antananarivo	18°54'S	47°31'E	1270	25.25	10.00	90.00	55.50	6.50	0.00	Altitude tropical
2	Antsiranana	12°16'S	49°17'E	40	33.50	20.00	85.00	60.00	9.00	4.50	Transitional tropical
3	Mahajanga	15°43'S	46°19'E	20	37.50	15.00	90.00	40.00	8.50	0.10	Hot tropical
4	Toamasina	18°09'S	49°24'E	6	35.50	17.00	80.00	50.00	8.50	0.00	Humid tropical

2 Materials and Methods

In this research, we assessed the bioclimatic potential of different cities in Madagascar using the most recent data. On those, we used the psychometric map taking into account the global climate of each city selected to be able to analyze the bioclimatic potential, the temperature of the indoor air, the consumption of cooling energy and electricity, relative humidity and operational carbon. This method was previously applied in research conducted by Khambadkone and Jain in 2017 [17].

2.1 Climate data

For this research, the current climatic data on Antananarivo, Mahajanga, Toamasina and Antsiranana were downloaded with the most recent version of the Meteonorm software. This tool has been used by many researchers [11] because it is possible to have meteorological data for more than 2100 meteorological sites around the world [11]. For this software we can have data such as the external hourly parameter of each city selected in the form of "epw" files and which can be used directly by the Energy-Plus software. Since the results provided by the Meteonorm software have been verified by the United States Department of Energy, Energy Efficiency and Renewable Energy. In this research, our data is divided into two groups: present and future (2030).

2.2 Assessment of the annual bioclimatic potential

In this research, the ASHRAE 55-2017 adaptive comfort model will be used and associated with the psychometric map to assess the bioclimatic potential of the four selected cities. To properly conduct our study, all the remarks and recommendations that were made by some researchers previously in some selected cities are all considered. In 2009 Rakoto-Joseph *et* *al*. [18] has defined several zonings in Madagascar. However, one of the limitations of this study was that certain essential parameters such as solar radiation and humidity which have a considerable impact on the comfort of the habitat were not taken into account [11]. Attia Shady *et al*. in 2019 [19] continued this study, with very innovative results but it is limited to two cities in Madagascar only (Antananarivo and Toamasina). Madagascar consists of six main climatic zones [12] and each region has its own microclimate. But overall it is dominated by the tropical climate. In addition we have noticed that in the psychometric map each point found represents each hour of the day; and that all the plots observed on the curve used two design strategies (Natural Ventilation and Direct Evaporative Cooling) [11]. Attia Shady, *et al*. in 2019 [19]; Khoukhi M, *et al*. in 2012 [20] and Fezzioui N et al. in 2019 [21] carried out research and obtained a very innovative result that the two strategies listed above are the most effective and the most adapted to the coastal regions of Madagascar. In the psychometric graph, we can find that the thermal comfort zone is crossed by the direct cooling zone. In 1992, Givoni B [22] recommended that in hot and dry countries, the maximum temperature of the dry thermometer was around 45°C and that of the wet thermometer in summer be set at around 25°C. Finally, according to his statement, it's worth pointing out that the building design has a significant effect on the cooling area and passive solar heating.

2.3 Buildings studied

In general, in Madagascar the traditional building is all constructed from local materials. Either in wood clad in sheets (Aluminum) or in wood made with earth mortar and the cover is in sheet. However, our research is focused on a wooden building clad in sheets (Aluminum), that is to say the frame is in wood and the roof is in aluminum sheet (Fig. 3). Sheet metal was the most demanded, for local construction because of its very low market purchase cost [11]. Some characteristics of this building are detailed in Table 2. This type of building which will be built in the city of Antsiranana and also which will be rebuilt in three other cities of the big island; including two coastal towns which are Mahajanga and Toamasina and a high plateau town which is the capital of Madagascar is the town of Antananarivo. These three cities were chosen as a benchmark for several reasons. The town of Antsiranana is a coastal, tourist town, with habitats built to African and European standards. The city of Diego-Suarez or Antsiranana is the largest city in the north of the country; it is the capital of the DIANA Region. It is considered to be the 2nd most beautiful and largest bay in the world, (after that of Rio de Janeiro Brazil). The city of Mahajanga is a port city on the northeast coast of the Big Island in the Mozambique Channel and the capital of the BOENY region. It is a tourist town that attracts many national and international tourists by the seafront promenade called “the Edge or on the tourist village” punctuated by a Baobab emblematic of the city with a circumference of 14 meters. The city of Toamasina is the economic capital of the large island, the capital of the ANTSINANA region. The city is located between one side of the Indian Ocean, and classified the first port of Madagascar. The city of Toamasina or the ANTSINANA region attracts a lot of strange investors thanks to its wealth in mineral resources, such as Nickel and Cobalt which are exploited by strange company called Sheritt Ambatovy. And for the city of Antananarivo, it is the capital of Madagascar which is the capital of the ANALAMANGA region. It is the most populous city in Madagascar. It is located on the high plateau with an altitude of about 1270 m, overlooking the city, the Rova Palace of Manjakamiadana was the heart of the Merina kingdom from the 17th century. It houses wooden houses and royal tombs. The city is located approximately 350 km from the east coast of the island and 550 km from its west coast. Each of the cities selected for this study have its own climatic characteristic, and which had a significant impact on cooling energy consumption, indoor air temperature and operational carbon emission as well as relative humidity in this said building.

2.4 Model simulation and validation

To properly conduct our study, the chosen building was designed and modeled by Design-Builder software, which is a reference software in this field. Since this simulation tool integrates the Energy-Plus software, which is software widely used today for improving the thermal performance of buildings [23]. The 3D model of the building drawn and simulated in this software is shown in Figure 3. On the other hand, the geometry and shape of the building are shown in Figure 5; and its constituents detailed in Table 2 and 3 served all input parameters in this software. The air conditioning systems were implemented on the basis of an audit of the building in accordance with the occupancy, lighting and air conditioning schedules [24].

Table 2 Input parameters depending on the model

	Age (year)	Height (m)	Area (m^2)	Occupant/m^2	schedule	Ventilation	Activity (met)	Clothing (Clo)	
								Dry season	Rainy season
Traditional Building	Over 80	3.5	120	0.4	24H/7	NV	1	0.5	1

Table 3 Thermal properties of construction materials of each building selected

No.		Building material	Layer	Composite	Thickness (m)	Thermal conductivity (W/m-K)	Density (kg/m^3)	Specific heat capacity (J/kg K)	U-Value (W/m^2-K)
1	Traditional residence	External wall	Layer e1	Aluminum	0.003	230.00	2700.00	880.00	5.882
		Partition	Layer e2	Aluminum	0.003	230.00	2700.00	880.00	5.882
		Roof	Layer e3	Aluminum	0.003	230.00	2700.00	880.00	5.882

2.5 Experimental campaign and measurement instruments

The experimental study was carried out in 2019 in nine (9) Districts located in the northern region of the big island by nine (9) students trained for three days in this circumstance, each of whom is responsible for a District. The study took place over two seasons (dry season and rainy season). During this great experimental campaign forty-five (45) traditional buildings were investigated. The new adaptive approach was applied consisting of performing physical measurements of certain climatic parameters inside the building and simultaneously distributing the questionnaires. In total, more than 250 people were interviewed through 842 questionnaires. The results obtained were analyzed, interpreted and integrated into the literature [11]. The different stages of the experimental study are detailed according to the study conducted by Nematchoua Kameni *et al.* in 2017 and 2019. [24, 25]. (see in Figure 1)

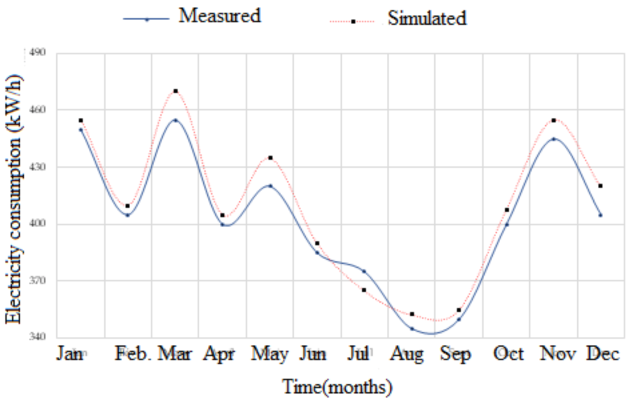


Figure 1 Monthly confrontations of monitored and simulated energy consumption

2.6 Validation

In any simulation and data projection study, calibration is considered one of the most important steps to validate the data. In this study, the calibration is based on the comparison of simulation results with those measured in buildings. Calibration is carried out on the basis of recurrent energy consumption patterns and conditions arising from the physical behavior of buildings. There are several guidelines in the literature for calibrating a new model. In this study, two recommendations mentioned in ASHRAE guideline 14 [26] were applied: the coefficient of variation or square root error (RMSE) and the mean error of bias (MBE). The different RMSE and MBE values were evaluated on the basis of two equations mentioned below [26].

$$RMSE(\%) = \frac{1}{m}\sqrt{\frac{\sum_{i-1}^{n}(m_i - s_i)^2}{n}} \tag{1}$$

$$MBE(\%) = \frac{\sum_{i-1}^{n}(m_i - s_i)}{\sum_{i-1}^{n} m_i} \tag{2}$$

With $s_i$and m_i, which respectively represent simulated and measured data over a given interval. The “n” is considered to be the total number of data implemented. In guideline 14 presented by ASHRAE [26], it is recommended that a simulation model can be considered calibrated if the following guidelines are followed:

(1) Hourly MBE between ±10% and hourly RMSE less than 30%.

(2) Monthly MBE between ±5% and monthly RMSE less than 15%.

In this study, the simulation model was calibrated using as reference the average indoor air temperatures and the electricity consumed. Other physical parameters such as relative humidity are also used to validate this model. In this research, several calibrations were performed on the reference model to detect possible errors. The different air conditioning, lighting, occupancy schedules; airtightness data; and the temperature set points for the building were adapted during the calibration. After each simulation, the different values of RMSE and MBE were evaluated and compared to the standard referenced in Guide 14, ASHRAE. Table 2 and 4 detail the final values of this model. The more detailed results of the validation of the adopted simulation model are presented after section 3.1. (see in Figure 2, 3, 4, and 5)

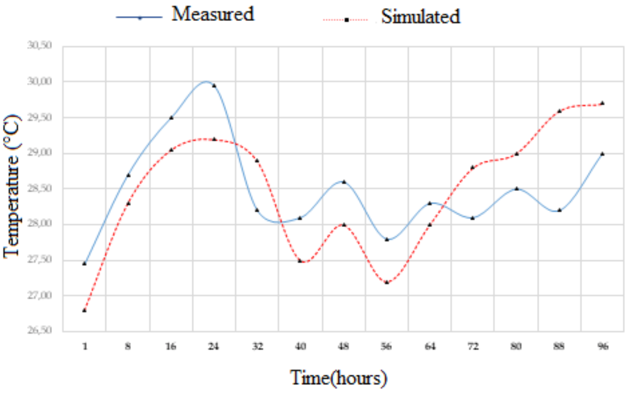


Figure 2 Comparison between simulated and measured indoor air temperatures

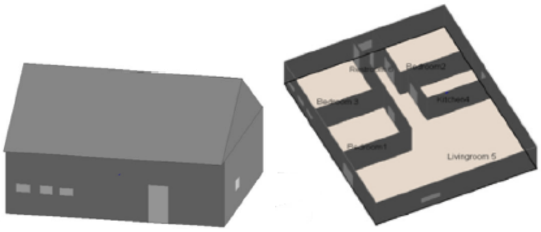


Figure 3 Building modeling (3D) and simulation using Design-Builder software

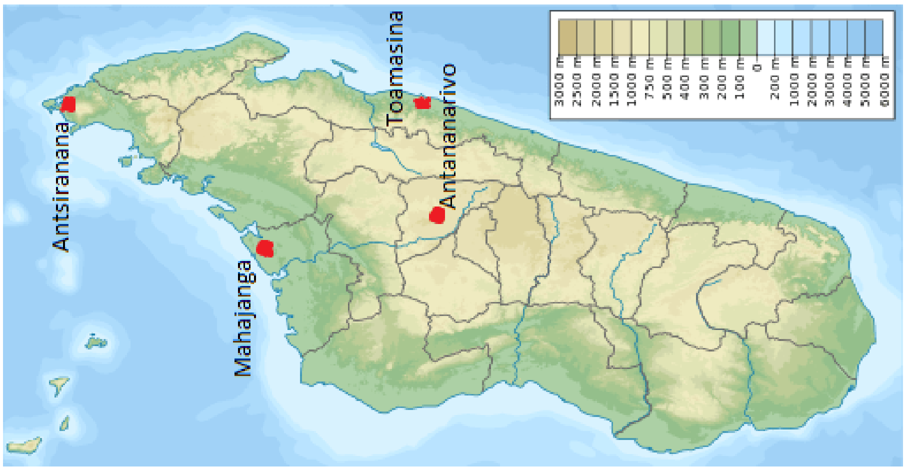


Figure 4 Map of Madagascar showing the four selected cities

Figure 5 Traditional house

2.7 Data evaluation

After a comparison between the measured and simulated values, the model was validated and the different values of cooling energy consumption, indoor air temperature, incorporated carbon and relative humidity were evaluated for the four cities from Madagascar selected. (see in Table 4)

Table 4 Summary of the validation of the new simulation model

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

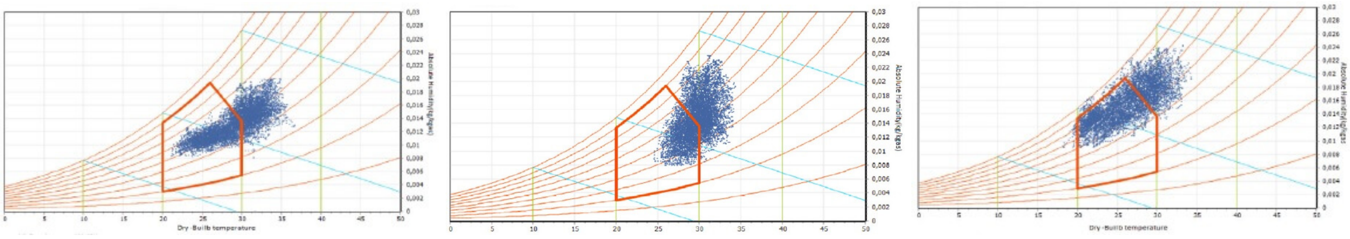
3 Results and discussions

3.1 Bioclimatic potential and thermal comfort parameters

In this research, we calculated the different adaptive comfort temperature ranges for the four cities selected in these different regions (DIANA, BOENY, ANALAMANGA and ANTSINANANA) which is located in different climatic zones by the adaptive model ASHRAE 55-2004 [27]. Monthly meteorological data from the last ten years was used. In Table 5, it can be seen that each of the cities presented has its own monthly comfort ranges. Figure 6 shows the bioclimatic diagrams of some cities of Madagascar studied. These diagrams are derived from hourly weather data for each selected city. (see in Figure 6)

Table 5 Average indoor temperatures for adaptive comfort in the various cities selected

No.	City	90 % of acceptability	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1	Antsiranana	Max (°C)	28.6	29.1	29.3	29.2	29.3	28.8	28.6	28.7	29.0	29.2	29.4	29.6	29.1
		Min (°C)	23.5	24.0	24.2	24.0	24.2	23.7	23.5	23.7	23.9	24.2	24.3	24.5	24.0
2	Antananarivo	Max (°C)	27.5	27.5	27.7	27.5	24.7	27.0	26.8	26.6	26.8	27.1	27.6	27.5	27.0
		Min (°C)	22.4	22.5	22.6	22.5	19.5	21.9	21.8	21.6	21.5	22.0	22.6	22.5	22.0
3	Mahajanga	Max (°C)	28.5	28.7	29.0	29.1	29.1	28.8	28.7	28.7	28.8	28.9	29.0	29.1	28.9
		Min (°C)	23.5	23.6	23.9	24.1	24.0	23.8	23.7	23.5	23.8	23.9	24.0	24.0	23.8
4	Toamasina	Max (°C)	28.5	28.6	28.7	28.6	28.4	27.9	27.7	27.6	27.8	28.1	28.4	28.8	28.3
		Min (°C)	23.5	23.6	23.7	23.6	23.3	22.9	22.7	22.6	22.6	23.0	23.4	23.8	23.2

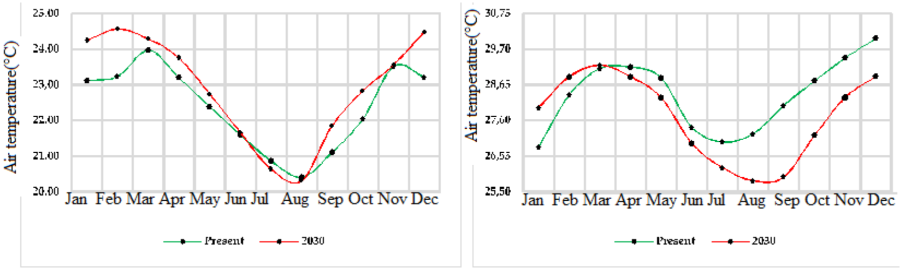


(a) Antananarivo (b) Antsiranana (c) Mahajanga

Figure 6 Bioclimatic diagram of some selected city

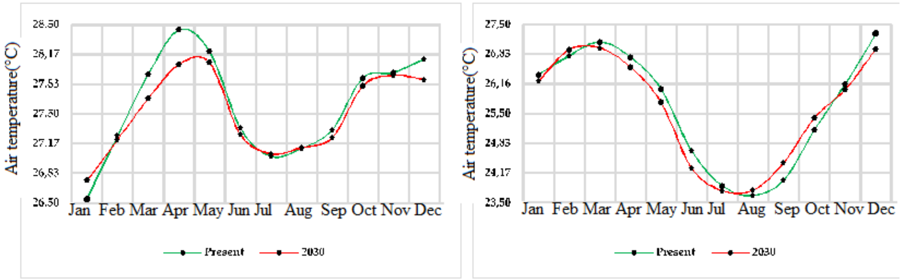
3.2 Air temperature

Figure 7 shows the shape of the indoor air temperature curve for the present year and for the year 2030 for each month in a year for the four selected cities. In these figures, we see that for the city of Antananarivo, the temperature rise by 2030 is unavoidable during the hot season and can exceed the value of 24.50°C. In the cold season, that is to say between the month of May in the month of October, the air temperature drop is heard up to 20.50°C also for the year 2030. For the other coastal towns of Madagascar, like the case of Antsiranana, Mahajanga and Toamasina, great climatic variability will be observed by 2030, during the hot and cold seasons. The Antsiranana city is well known for the drop in temperature during the cold season.



(a) Antananarivo

(b) Antsiranana



(c) Mahajunga

(d) Toamassina

Figure 7 Indoor air temperature for each city

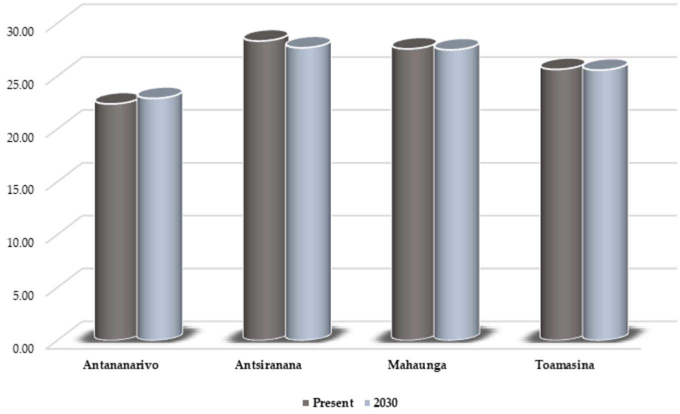


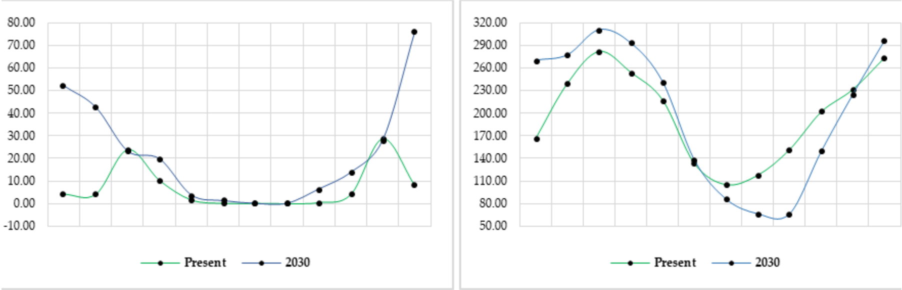
Figure 8 Annual indoor air temperature for the four cities

On the other hand, by analyzing Figure 8, we see that for each city selected, the annually air temperature will change slightly. The case of the capital of Madagascar Antananarivo, by 2030 we see that there is a difference of 0.52°C. The city the most vulnerable to climate change is Mahajanga, may be because of its geographical position.

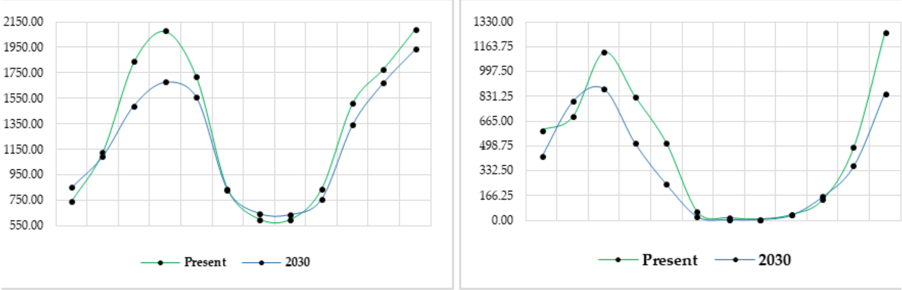
The increase of the air temperature is very significant in 2030, in all the cities evaluated. Important strategies should be taken for reducing the strong pressure of human on the environment.

3.3 Cooling energy consumption

Since here the traditional residence has been ventilated naturally. To assess its cooling energy consumption, a simple ventilation system of the same type was installed. Figure 9 shows the cooling energy consumption in the building for the four selected cities for two time periods (present and in 2030). From this curve we can deduce that the city of Mahajanga which is located in a hot tropical climate consumes more cooling energy, the highest currently is the month of December 2089.17 kWh and in 2030 it can reach up to at 1931.97 kWh. On the other hand, the city of Antananarivo which is located in an altitude of tropical climate shows the lowest consumption of cooling energy in all times. Currently the highest is the month of November which displays the value of 28.71 kWh and in 2030 it is the month of December which has a value of 75.81 kWh.



(a)Cooling energy in Antananarivo Cooling energy in Antsiranana



Cooling energy in Mahajanga Cooling energy in Toamasina

Figure 9 Cooling energy for each city

For the annual average value of cooling energy consumption, Figure 10 below, shows that for the four cities selected it is always the city of Mahajanga that consumes more cooling energy. Currently, from this figure we can deduce that the annual average value for the city of Mahajanga is 1313.07 kWh and in 2030 it will show the value of 1208.75 kWh. However, it is still the city of Antananarivo that consumes less cooling energy, currently it shows us the highest average annual consumption value is 7.16 kWh and for the year 2030 it is 22.35 kWh.

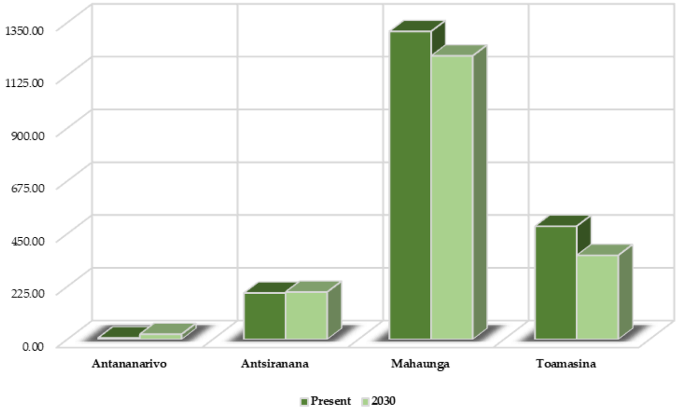


Figure 10 Cooling energy for the four cities

3.4 Energy consumption

Figure 11 shows the electricity consumption in this building for the four selected cities. Based on the results obtained, it can be deduced that it is always the hottest city that consumes more electricity. This figure shows directly that the city of Mahajanga consumes more than

1,870 kWh of electricity now in a year. In addition, it is in Antananarivo, which consumes less electricity in a year. The current average value is 571.17 kWh. By 2030, if nothing is done to slow down the evolution of the external climate, it could reach the value of 586.61 kWh. On the other hand, for the other two cities, the average annual consumption is between 762.67 kWh and 922.56 kWh at present, and will be between 766.67 kWh and 1042.62 kWh in 2030. These results can be completed those found in [28].

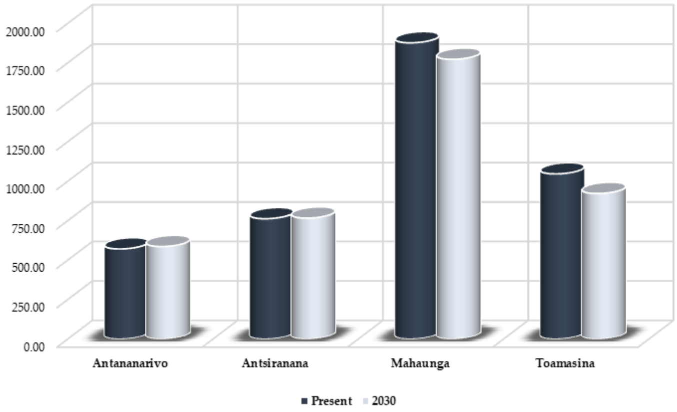
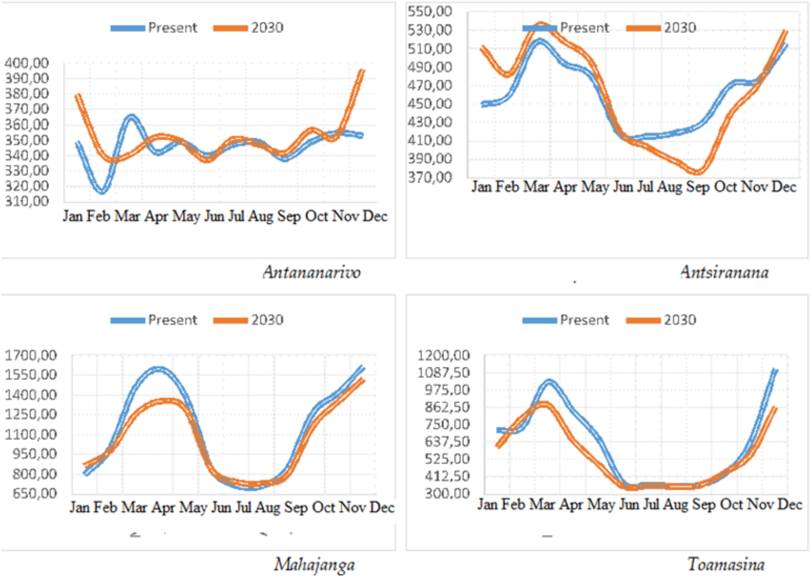


Figure 11 Electricity for the four cities

3.5 Operational carbon

Figure 12 shows the detailed monthly operational carbon for the same buildings in different selected cities. The city of Mahajanga, which is located in a hot tropical climate, has the highest concentration of operational carbon. Currently the operational carbon value of this city is between 1597.1 kg CO_2 and 1616.04 kg CO_2 and which extend into the month of December and the month of April. The city of Antananarivo has the lowest concentration of operational carbon among all the cities selected. The current maximum value is 364.85 kg CO_2 (ontenue in March); and the minimum value is 340.5 kg CO_2 (in February). For the year 2030, we see that there is a huge increase in operational carbon concentration in January and December. During this period, the CO_2 rate varies between 379.96 kg and 395.95 kg. The two cities: Antsiranana and Toamasina, have a maximum value of 517.79 kg CO_2 (in March), and 1114.19 kg CO_2 in December. On the other hand in 2030, we see that the CO_2 rate will increase in the city of Antsiranana in March (up to 535.31 kg). The strong variation of the carbon rate, is perhaps due especially to the behavior of the occupants. In the literature, several studies showed the important of occupant's behavior on the increase of CO_2 in a residential building [3].



Antananarivo *Antsiranana*

Mahajanga *Toamasina*

Figure 12 CO_2 emission for each city

By analyzing Figure 13, below, we can see that in one year the average value in operational carbon concentration for each selected city is between 346.21kgCO2 and 1137.71 kg CO_2 currently. The city of Mahajanga produces the most carbon while the city of Antananarivo emits the lowest. In Antananarivo, the average value is estimated at 353.78 kg CO_2, which is the minimum value. Compared to the present, we can deduce that there is an increase of 2.18%. However, it is the city of Mahajanga that shows the maximum value with an average quantity of 1074.50 kg CO_2 in a year. If we compare this value with the present, we can see that there is a slight increase of 5.55%. Very interesting results have been found in this study. The most of findings confirmed the results found in [3].

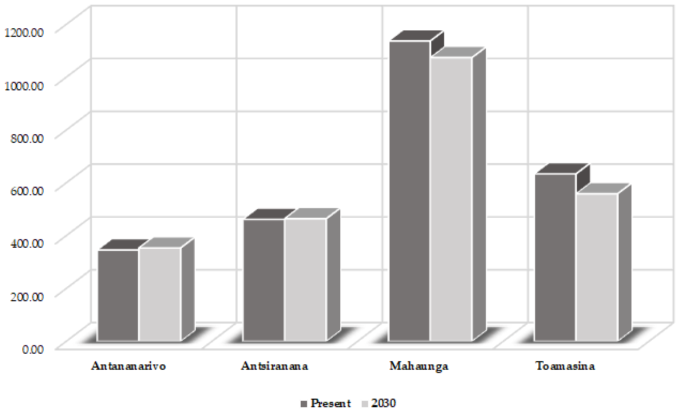


Figure 13 CO_2 emission for the four cities

These different results show that the air temperature has a strong impact on the energy consumption. The concentration of CO_2 varied in function of geo-localisation of city.

4 Conclusion

In this research we have analyzed the results of the bioclimatic potential of some climatic zones of Madagascar. For this purpose, four cities in different climatic zones were selected. This study included the analysis of psychometric diagrams as well as performance simulations of a traditional building that is commonly built in Madagascar. Additionally, energy requirement, indoor air temperature, and operational carbon concentration are all assessed in this research. It was very interesting to notice that the cooling energy and CO_2 emission in all the selected cities are very high in hot tropical region compare to others regions. In Antsiranana, a slight increase is observed of around 2.02% for the year 2030. The CO_2 rate will increase in Antananarivo and Antsiranana from 2.18% to 0.52%; respectively, in 2030. To reduce the demand for cooling energy and the operational carbon concentration in these cities, it is recommended to use local materials more suited to the micro-climate of the region. This study can serve as a guide for those who would like to work in this field in the future.

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