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Article

Transition to Zero Energy and Low Carbon Emission in Residential Buildings Located in Tropical and Temperate Climates

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Abstract: Different methods to achieve zero-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. Being aware of this fact, a study was carried out to analyse the design of new buildings respecting the "zero-energy and low carbon emission" concept in tropical climatic regions when they are compared with a base case of temperate regions. To reach this objective, the comparison between real and simulated data from the different buildings studied was developed. The results showed that the renovation of existing residential buildings allows for reducing up to 35% of energy demand and a great quantity of CO_2 emissions in both climate types. Despite this, the investment rate linked to the construction of zero-energy buildings in tropical zones is 12 times lower than in temperate zones and the payback was double. In particular, this effect can be related to the efficiency of photovoltaic panels, which is estimated to be, at least, 34% higher in tropical zones than temperate zones. Finally, this study highlights the interest and methodology to implement zero-energy buildings in tropical regions.

Keywords: zero-energy; low carbon; residential buildings; tropical; temperate climate

1. Introduction

Between 2000 and 2020, the average concentration of carbon dioxide (CO_2) emitted increased by approximately 2–3% each year [1]. In 2018, China (29.7%), the United States (13.9%), India (6.9%), the EU28 (9.1%), Russia, (4.6%) and Japan (3.2%)—the world's largest CO_2 emitters—together accounted for 51% of the population, 80% of total fossil fuel consumption, and 67.5% of total fossil CO_2 emissions in the world [2]. Nevertheless, efforts to reduce the carbon rate have been observed by the most polluting countries with activities like reducing building energy consumption. In this sense, a net-zero-energy building (ZEB) means that the total amount of energy used, calculated on an annual basis, is roughly equal to the amount of renewable energy created on the site [3].

Nowadays, in European Union countries (Belgium, France, Italy), primary energy demand in the building sector represents almost 40% of total energy [4]. Moreover, for the past ten years, it has been noticed that the building sector emitted up to 36% of greenhouse

gas, and produced 38% of wastes [4]. In particular, in Brussels, construction and operation represent 98% of the water flow, 75% of energy demand, 65% of greenhouse gas emissions and about 33% of waste generated each year [5]. In consequence, this city has set itself the ambition of reducing energy consumption up to 30% by 2030 and up to 40% of carbon emissions in the construction sector [5]. Another example of a European city is Paris, where the building sector (residential and tertiary) accounts for 80% of the region's energy consumption, and 20% of the emission of greenhouse gas. In consequence, the city of Paris aims to reduce energy consumption by 1/3 by 2030, and by 50% by 2050. To reach this objective, a new climate plan provides for massive renovations of social and tertiary housing in this city [6]. Another example of non-European cities is Washington, where the carbon emission intensity decreased by 4.9% in 2019 [7]. Finally, in Sub-Saharan Africa (Senegal, Cameroon, and Madagascar), the building sector consumes more than 25% of total primary energy, which is generated by fossil fuels and emitting thousands of tons of carbon into the atmosphere each year. This CO_2 concentration is almost negligible compared to those produced in developed countries.

In general, it is interesting to highlight that, although most of these countries have a lot of potential resources (solar, hydro, wind), they are exploited at less than 5%. This situation remains very serious due to how strongly carbon emissions have a negative impact on global warming and, in consequence, it is important to take action to protect the environment. In this sense, the energy renovation of old buildings and the design of new buildings, mainly powered by renewable energy, can contribute enormously to the reduction of greenhouse gas emissions. What is more, stand-alone buildings can be the start of the solution but there are few guides to reach this objective.

Different recent research works aim to be examples of standalone buildings. Some of them evaluated the possibility to reach zero-energy and low carbon in buildings, yet the regulations and objectives set by several international organizations are not enough to be applied on a large scale [8].

In this sense, it is interesting to highlight that, although zero-energy building is more favourable in tropical and hot zones due to more favourable climatic factors, it was observed that countries located in temperate zones are more involved in the implementation of this new technology. In particular, most of the zero-energy buildings use the power grid for energy storage, but some are grid independent [9].

The development of zero-energy buildings has become possible not only thanks to advances in new energy technologies and construction techniques like solar panels, heat pumps, and low-emissivity triple glazing, but also thanks to researchers, who collect precise data on the energy performance of traditional and experimental buildings and provide parameters for advanced computer models to predict the efficiency of engineering designs [10]. In this sense, some recent research works were carried out in this field in the temperate region. For instance, after a strong study on one residential building located in Boston city in 2006, Szejnwald et al. [11] showed that renovation is the best technique for allowing the reduction of the significant part of energy demand. In 2017, the results of studies conducted by Yi et al. [12] explained that although the studies detail step-by-step the different processes of implementing zero-energy in new constructions, it is often difficult in practice to make this objective, because of the variety of outdoor climates according to the seasons. The results of studies conducted by Szalay and Zold [13] aiming to design zero-energy buildings showed that it is easier to achieve the ZEB by grouping buildings according to their geometrical shape and age. The research conducted by Zhou et al. [14] in an office building in China showed that the choice of HVAC systems has a significant impact on the implementation of zero-energy in buildings in temperate zones. This study recommended adopting energy efficiency techniques according to the local climate of each region. With the aim of increasing the energy performance of buildings over their entire life cycle, in order to increase the possibilities of achieving zero-energy building, Srinivasan et al. [15] found a new method aimed at optimizing the production of energy generated by renewable sources. The research carried out by Robert and Kummert [16]

based on the "Morphing" method made it possible to analyse, on the basis of hourly data for the last 50 years and a general circulation model, the impacts of global warming on the implementation of NZEB in the temperate zone. The results showed that global warming significantly impacted zero-energy buildings. The study carried out by Pikas et al. [17] aimed to estimate the optimal cost of the energy performance of the residential building with almost zero energy consumption. The results explained that very few methods allow estimating the optimal cost of the energy used in these residences.

Despite these previous works about temperature regions, there is a lack of information about tropical cities and the possibilities to improve the energy consumption in their buildings. In this sense, tropical cities are some of the most favourable regions for the implementation of ZEB but the rate of buildings respecting the zero-energy concept is very low in this region of the world. In this sense, the study carried out in 2019 by Nematchoua and Sigrid [18] aimed to assess the different possibilities for the implementation of residential buildings with zero-energy and low carbon emissions in sub-Saharan Africa. The results showed that the most efficient solution to consider a zero-energy building in the city of Antananarivo requires an additional expenditure estimated at 40% of the initial cost of the building. This will result in savings of $475 per year starting in 2030, and also about a 99% reduction in carbon emissions.

In consequence, the objective of this study is to assess and analyse the cost and energy use with the implementation of residential buildings with zero-energy and low carbon emissions in tropical regions (sub-Saharan Africa), taking as reference this same analysis in temperate zones. In particular, paying special attention to the energy production generated by photovoltaic panels in hot zones and then the impact of heating on energy demand in temperate zones. The final objective is to show to architects, engineers, urban planners, investors, politicians, even non-specialists in energy and the environment, a simple methodology to analyse the energetic and economic interest into building new zero-energy and low carbon buildings in different climate regions.

To reach this objective, the present work is constituted of several parts: an analysis of some keywords in the second part; a methodology, results, and discussion, and finally the conclusions.

2. Keywords Analysis

The systematic structure of this manuscript is shown in Figure 1.

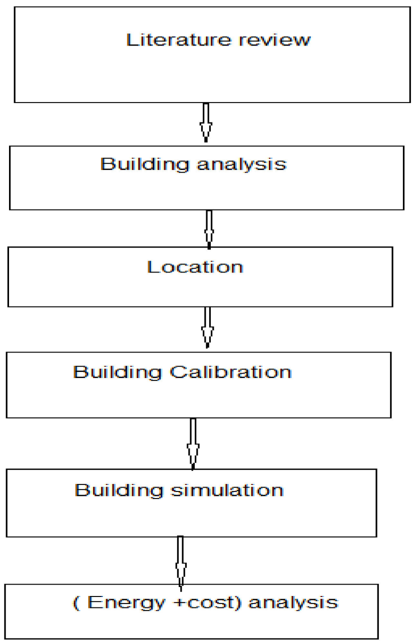

Figure 1. Research conceptual framework.

2.1. Buildings and Zero-Energy Concept

Before carrying out different research works and case studies about zero-energy and low-carbon buildings, it is important to do a previous analysis about the different concepts of existing low environmental impact housing in order to make more understandable some practical cases which will be presented in this research.

2.1.1. Nearly Zero-Energy Building

A nearly zero-energy building is economical in primary energy. The nearly zero quantity required for heating, cooling, lighting, domestic hot water, and ventilation is thus covered by solar heat or by renewable energy sources as well as by reasonable technical installations. In this sense, in the European Union, a building energy performance requirement was set between 2014 and 2021 as shown in Table 1.

Table 1. Evolution of the energy performance requirements of buildings from 2014 to 2021 for the residential and commercial buildings in some European Union countries [19].

Type of Building Construction	Building Energy Performance (2014)	Building Energy Performance (2017)	Nearly Zero-Energy Building (2021)
Overall level of thermal insulation (kWh/m^{2}year)	≤35	≤35	≤35
Overall energy performance of the building (residential building) (kWh/m^{2}year)	≤80	≤65	≤45
Overall energy performance of the building (commercial building) (kWh/m^{2}year)	≤80	€ (65–90)	€ (45–90)
Primary energy demand (kWh/m^{2}year)	≤130	≤115	≤85

2.1.2. Passive Building

The objective of a passive house is to consume very little energy while ensuring high thermal comfort in summer and winter as well as good air quality. Once again, in the European Union, some criteria must be respected to obtain the label "passive building", as shown in Table 2.

Table 2. Criteria for a passive building [20].

Passive Building	Criteria
Heating energy (kWh/m^{2}year)	≤15
Primary energy (kWh/m^{2}year)	≤120
Air tightness (vol/h)	≤0.6
Annual overheating hours (>25 °C)	≤5%

It is interesting to highlight that heating requirements of less than 15 kWh per m^2 and year are four to six times less than a new conventional building and up to ten times less than an existing building over ten years old.

2.2. Zero-Energy Building

It is a building that produces all the energy that it needs. It is interesting to note that a zero-energy building does not necessarily meet the criteria for a passive building. We must distinguish a building called energetically sufficient from a building called energetically autonomous.

(i) An energy-efficient building is capable of producing, over a year, an amount of energy proportional to the amount of energy it consumes. However, it will not necessarily consume the energy it needs when it produces it. Example: consider a building for which we install photovoltaic panels. During sunny periods (in summer), the panels will generate electricity at their optimum efficiency [21], and the house will supply energy to the grid. During the rest of the time or during a dead period such as in winter, the panels will not always supply enough electricity. Consequently, the dwelling cannot do without the electrical network. However, the total annual balance is zero since the excess production in summer compensates for the lack in winter.

(ii) An energetically autonomous building must not be connected to the electrical distribution network. When the panels cannot produce as much electricity as needed, the batteries used to store the excess electricity produced during sunny periods provide the electricity. To achieve energy independence, the building has above-average levels of insulation.

The principle of the zero-energy building, therefore, differs from that of the passive house, since it consists of compensating for total consumption, whatever it is, and not in optimizing the conditions favouring the energy sobriety of the house.

2.3. Positive-Energy Building

A building is said to be positive energy when it produces more energy than it consumes. A positive-energy building can be a passive building with enough renewable energy sources, or a building that does not meet the criteria to be a passive building, but still has a surplus of overall energy production.

3. Methodology

As it was shown before, the present paper aims to show a methodology for designing new buildings respecting the zero-energy concept, adding, as original consideration, the climatic regions where the buildings are placed and taking as reference the temperate regions. To reach this objective, three temperate countries and three tropical countries, with their typical building constructions, were selected. In consequence, weather data and simulations were employed to define the energy consumption and economical investment needed in each case study and its comparison will let define the more interesting region to implement the zero-energy concept. All these items will be described in the next sections.

3.1. Location

This study was carried out in three developed countries (Belgium, France, and the United States) located in a temperate climate, and three developing countries (Cameroon, Senegal, and Antananarivo) located in Sub-Sahara Africa (tropical climate).

The study took place in the capital of each country, as these study locations were chosen based on their environmental (climatic), energy, and social differences. The three cities selected in this study, and placed in Sub-Saharan Africa, are of very high solar potential (which is favourable to the supply of PV) and also the wind speed, which is favourable to the installation of wind turbines (speed between 5 m/s and 10 m/s).

The countries located in temperate zones such as Belgium, France, and the United States, have climatic conditions less favourable to zero-energy objectives because of the low sunshine in winters. However, important reforms are being carried out in these countries with the objective of achieving zero-energy and low carbon in 2050. This study aims to support this approach.

3.1.1. Studied Locations

Sub-Saharan Africa is made up of 48 countries with varying climates. It is one of the regions of the world that is very rich in biodiversity, and, above all, one of the most vulnerable to climate change. More than 80% of the population from this region are under 35 years old. Three of the cities in this study are located in this region: the city of Douala located in Cameroon, the city of Antananarivo in Madagascar, and Dakar in Senegal.

(1) Located between 4°03′ N and 9°4′ E, the city of Douala is the economic capital of Cameroon. Douala covers 923 km^2 and is strongly dominated by the tropical climate essentially made up of two seasons: the dry season from November to April and the rainy season from April to November.

(2) Dakar is the main city of Senegal. It is a coastal city located on the edge of the Atlantic Ocean. This city is dominated by the tropical climate and crossed by the monsoon coming from the southwest which is a humid wind bringing rain, and also a dry wind (the Harmattan). Dakar is one of the largest metropolises in Africa with a very high growth rate.

(3) Located 1435 m above the sea, the city of Antananarivo, the political capital of Madagascar, is spread over 350 km of surface. The city of Antananarivo is strongly dominated by the tropical climate of such an altitude. It has notably cool, mild winters and very rainy summers. Figure 2 gives the geographical location of these different cities studied, while Table 3 shows some climatic characteristics.

(4) Brussels is the capital of Belgium, the French Community of Belgium, the Flemish Community, and the seat of several European Union institutions. The climate of Brussels is temperate and influenced by the Gulf Stream. The proximity to the sea has a strong influence on this climate. The climate of Brussels is generally characterized by mild and rainy winters and relatively cool and humid summers.

(5) Washington DC is one of the world's largest cities, located in the mid-Atlantic region of the East Coast of the United States, between Virginia and Maryland. The nation's capital is around 40 miles south of Baltimore, 30 miles west of Annapolis and the Chesapeake Bay, and 108 miles north of Richmond. Founded in 1791, Washington DC is the place where the seat of the American congress is located [22]. Major factors determining Washington's climate include the large semi-permanent high-pressure and low-pressure systems of the North Pacific Ocean, the continental air masses of North America, and the Olympic and Cascade Mountains [22]. In spring and summer, a high-pressure anticyclone system dominates the North Pacific Ocean, causing air to spiral out in a clockwise fashion [22].

(6) Paris is the capital city of France, and the largest city in France. The area is 105 km^2. Paris is also the centre of the French economy, politics, traffic, and culture. The climate of Paris is said to be a warm temperate. The rainfall in Paris is significant, with precipitation even during the driest month. The average annual temperature in Paris is 11.3 °C. Figure 3 shows location of some cities studied in this research.

Figure 2. Location of three studied cities.

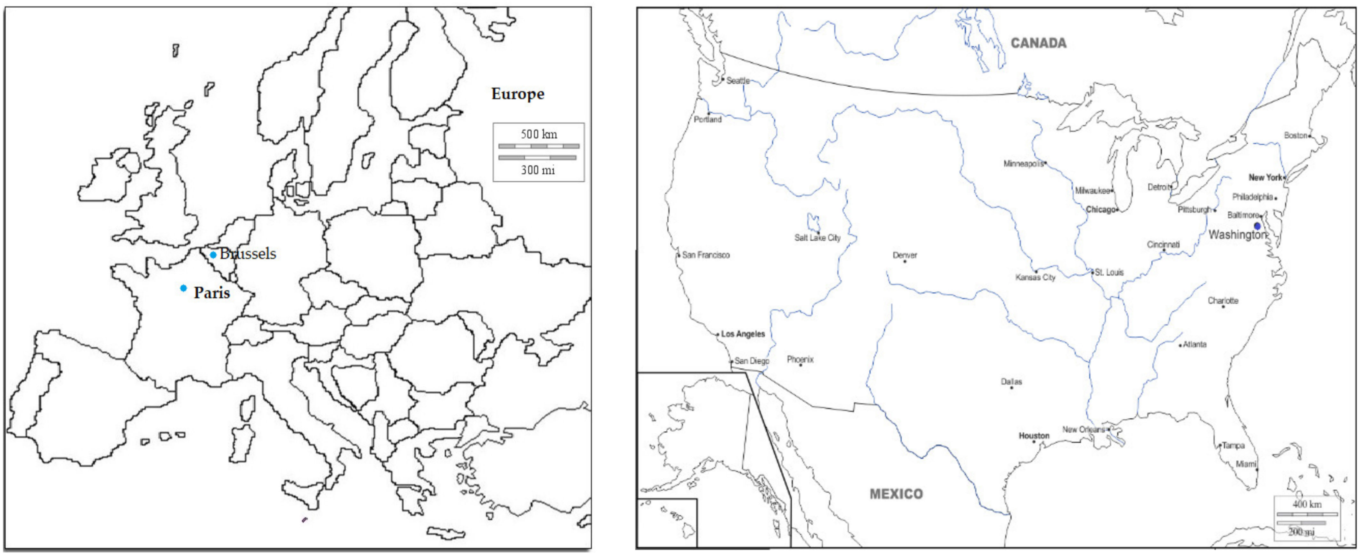

Figure 3. Location of Brussels and Paris (**on right**) and Washington DC (**on left**).

3.1.2. Climatic Data

In this research, all the climate data for simulations are downloaded from American Meteonorm software (Version 7.3.3, Meteotest AG (Bern, Switzerland)), based on the geographical coordinates of each city. The software provided the possibility to download data in hours, days, or months according to our requirements. Hourly data of temperature, relative humidity, airspeed, solar radiation, and precipitation for the last 30 years were collected for all the climate regions.

3.2. Buildings

This research was carried out about residential buildings. The type of building and construction materials varied according to the countries and this is why there were two categories of residential buildings (one more adapted in a temperate climate and another in a tropical climate). In this sense, the different buildings have different shapes with different structure materials and different areas, which can accommodate several people as shown in Table 4.

- The first residential building designed for this project, and located in the tropical region, was a simple one-floor family house consisting of four bedrooms, a shower room, and a kitchen. The building materials mainly consisted of Earth bricks and essentially glazed windows (glass thickness: 5.5 cm).
- The second residential building designed for this project, and located in the temperate region, was a familiar residence composed of two bedrooms, a living room, kitchen, and restroom. The different building materials are detailed in Table 4.

Table 3. Information regarding the six selected representative countries.

No	Country	City	Climate	Location	Temp.(°C)		RH (%)	
					Min	Max.	Min.	Max.
1	Belgium	Brussels	temperate	50.85° N, 4.35° E	−1	30	30	90
2	Cameroon	Douala	tropical	4.05° N, 9.76° E	18	37	30	90
3	France	Paris	temperate	48.85° N, 2.35° E	−10	31	30	90
4	Madagascar	Antananarivo	tropical	18.87° S, 47.50° E	10	35	55	90
5	Senegal	Dakar	tropical	14.72° N, 17.46° W	15	35	30	100
6	United States	Washington	temperate	38.90° N, 77.03° W	−2	33	30	98

From this Table 4, it can be observed that most of the materials chosen in the case of renovated residence buildings have low thermal conductivity and embodied carbon almost equal to zero. The goal is to select the materials that are more sustainable (low conductivity and embodied carbon). The lower the thermal conductivity of a material, the more this material has a huge capacity to limit heat transfer.

3.3. Simulation Tools

In this study, version (5.5.2) of the Design Builder software (Stroud, UK) was employed. This software is highly renowned in this field and has served as the basis for thousands of works of scientific research. Design Builder software, the same as TRNSYS, DOE, Pleiades, Helios, etc. software, is very well known in the field of simulation, optimization, modelling, BIM (Building Information Modelling), LCC (Life Cycle Cost), LCA (Life Cycle Assessment), etc.

This software is coupled with the Energy Plus (version 8.2, funded by the U.S. Department of Energy's (DOE) Building Technologies Of-fice (BTO)) tool to assess the consumption and energy demand of a building [23] and offers the most building materials with their physical thermal property. The modelling of the building selected is shown in Figure 4.

Table 4. Thermal characteristics of building constructions.

Region	Building Category	Building Clement	Layer	Component	Thickness (m)	Thermal Conductivity (W/mK)	Density (kg/m^3)	Specific Heat Capacity (J/kg K)	Embodied Carbon (kg CO_2/kg)	U-Value (W/(m^{2}K))
Tropical region	Residence in the initial state	Exterior wall	Layer1	Plaster	0.025	0.500	1300	1000	0.12	2.750
			Layer2	Concrete block	0.120	1.630	2300	1000	0.08	
			Layer3	Plaster	0.050	0.500	1300	1000	0.12	
		Partition wall	Layer	Concrete block	0.120	1.630	2300	1000	0.08	5.850
		Roof	Layer1	Clay Tile	0.025	1.000	2000.0	800	0.46	0.160
			Layer2	Stone Wool	0.242	0.040	30.0	840	1.05	
			Layer3	Roofing felt	0.005	0.190	960.0	837	-	
	Residence after renovation	Exterior wall	Layer	Wood	0.153	0.040	110	1800	0.00	0.250
		Partition wall	Layer	Wood	0.070	0.040	110	1800	0.00	0.250
		Roof	Layer1	Clay Tile	0.025	1.000	2000.0	800	0.46	0.160
			Layer2	Stone Wool	0.242	0.040	30.0	840	1.05	
			Layer3	Roofing felt	0.005	0.190	960.0	837	-	
Temperate region	Residence in the initial state	Exterior wall	Layer1	Plaster	0.030	0.500	1300	1000	0.12	0.330
			Layer2	Concrete	0.140	0.510	1400	1000	0.08	
			Layer3	Extruded polystyrene	0.120	0.034	35	1400	2.88	
			Layer4	Facing brick	0.090	0.620	1700	800	0.22	
		Partition wall	Layer1	Plaster	0.030	0.500	1300	1000	0.12	1.570
			Layer2	Brick	0.140	0.720	1920	840	0.22	
			Layer3	Plaster	0.030	0.500	1300	1000	0.12	
		Roof	Layer1	Roof tiles	0.030	0.550	1900	837	0.05	0.180
			Layer2	Wooden lathing	0.038	0.130	2800	896	0.45	
			Layer3	Air gap	0.025	-	-	-	-	
			Layer4	Wood	0.042	0.120	510	1380	0.45	
			Layer5	Rock wool	0.400	0.100	500	1000	0.98	
			Layer6	composite wood	0.018	0.040	160	1888	0.19	

Table 4. *Cont.*

Region	Building Category	Building Clement	Layer	Component	Thickness (m)	Thermal Conductivity (W/mK)	Density (kg/m^3)	Specific Heat Capacity (J/kg K)	Embodied Carbon (kg CO_2/kg)	U-Value (W/(m^{2}K))
	Residence after renovation	Exterior wall	Layer1	Plaster	0.030	0.500	1300	1000	0.12	0.350
			Layer2	Concrete	0.140	0.510	1400	1000	0.08	
			Layer3	Wood frame	0.030	0.120	510	1380	0.45	
			Layer4	ISOCELL cellulose	0.020	0.100	400	1360	-	
			Layer5	Composite wood panel	0.020	0.250	900	1000	0.12	
			Layer6	Wooden cladding	0.022	0.130	160	1800	0.05	-
		Partition wall	Layer1	Plaster	0.030	0.50	1300	1000	0.12	1.570
			Layer2	Brick	0.140	0.720	1920	840	0.22	
			Layer3	Plaster	0.030	0.500	1300	1000	0.12	
		Roof	Layer1	Roof tiles	0.030	0.550	1900	837	0.05	0.180
			Layer2	Wooden lathing	0.038	0.130	2800	896	0.45	
			Layer3	Air gap	0.025	-	-	-	-	
			Layer4	Wood	0.042	0.120	510	1380	0.45	
			Layer5	Hemp wool	0.400	0.037	800	1000	0.00	
			Layer6	Composite wood	0.018	0.130	1000	1000	0.01	

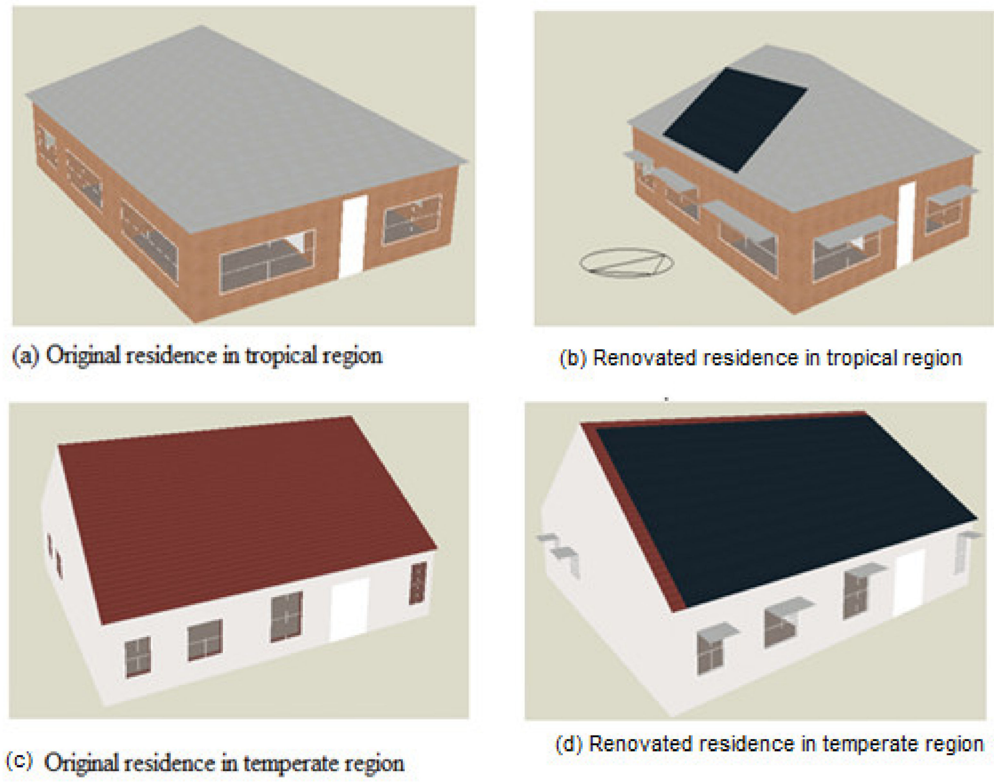

Figure 4. Case of (**a**,**b**) renovated residence building in the tropical region and (**c**,**d**) temperate climate.

In this sense, it is interesting to highlight that the design builder software automatically gives the embodied carbon of each type of material used during the construction of the building, as well as the quantity of carbon produced during the operational phase of the building. As a consequence, the total carbon emission rate during the life cycle assessment of the building can be freely obtained.

In the case of a building located in the tropical climate, the efficiency of the solar panels is very high due to the high concentration of solar radiation throughout the year, and it is not needed to add another source of energy such as a wind turbine to achieve the "Zero-Energy Building" objective. In contrast, in the case of a building located in a temperate climate, it was necessary to associate the photovoltaic panels (PV) and wind turbines to reach the "Zero-Energy Building" to maintain the same area of PV installed in a building located in the tropical region. Indeed, in the temperate region, the sunshine is high only in summer, which is why the PV has a low yield in this region. The input data of the simulation software is shown in Table 5.

Table 5. Input data for the simulations.

Parameters (Renovated Residence = After Applying Renovation, Passive Strategy, and Green Energy)	Building Located in the Tropical Region		Building Located in the Temperate Region	
	Initial State	After Renovation	Initial State	After Renovation
Height (m)	3.5	3.5	3.5	3.5
Area (m^2)	342.0	342.0	342.0	342.0
Activity template	Domestic House	Domestic House	TM_3-Bed Living Kitchen	TM_3-Bed Living Kitchen
Occupancy density (people/m^2)	0.0230	0.0230	0.0303	0.0303

Table 5. *Cont.*

Parameters (Renovated Residence = After Applying Renovation, Passive Strategy, and Green Energy)	Building Located in the Tropical Region		Building Located in the Temperate Region	
	Initial State	After Renovation	Initial State	After Renovation
Activity (met)	0.9	0.9	0.9	0.9
Clothing (Clo)	0.5–1.0	0.5–1.0	0.5–1.0	0.5–1.0
DHW: consumption rate (l/m^2-day)	0.53	0.53	0.72	0.52
Fresh air (l/s-person)	10	10	10	10
Lighting: target luminance (lux)	100	100	125	100
Computer: power density(W/m^2)	0.200	0.180	0.200	0.105
Other equipment: power density (W/m^2)	3.58	3.58	3.58	3.58
Occupancy schedule	24/7	24/7	24/7	24/7
Construction template	Project construction template	Project-construction template	Project construction template	Project construction template
Air tightness (vol/h)	0.5	0.5	0.5	0.5
Glazing template	Project glazing template	Project glazing template	Project glazing template	Project glazing template
Glazing type	Preferred height 1.5 m, 30% glazed Thickness: 5.5 cm	Preferred height 1.5 m, 30% glazed Thickness: 5.5 cm	Preferred height 1.5 m, 30% glazed Thickness: 5.5 cm	Preferred height 1.5 m, 30% glazed Thickness: 5.5 cm
Local shading	No	1.0 m overhang	No	1.0 m overhang
Lighting template	Incandescent	LED	Incandescent	LED
Lighting control	No	Yes	No	Yes
Lighting schedule	24/7	Mon.–Sun. 6 p.m.–7 a.m.	24/7	Mon.–Sun. 6 p.m.–7 a.m.
HVAC template	Fan coil unit (4-pipe) Air Cooler chiller	Fan coil unit (4-pipe) with district cooling	Oil heating	Fan coil unit (4-pipe) with district heating+ cooling
HVAC Schedule	12/7	6/7	24/7	24/7
Heating: Fuel	No	No	Natural gas, COP = 0.9	Natural gas, COP = 0.9
Cooling: Fuel	Electricity from grid	Electricity from green energy	Electricity from grid	Electricity from green energy
Other ventilation	Natural ventilation (NV)	Natural ventilation (NV)	Natural ventilation (NV)	Natural ventilation (NV)

3.4. Description of the Photovoltaic Panel

In this study, photovoltaic panels with different areas, according to the cities, placed on the roof of a building located in the tropical and temperate climates, were introduced. The different cells were made of polycrystalline, with a base load of direct current by an inverter. Its optimal inclination was fixed at 37°, oriented toward the south in the case of Paris, Brussels, and Washington and 45° oriented toward the north in Douala, Dakar, and Antananarivo cities [24].

3.5. Model Validation

Validation is applied by comparing simulation and measured data. We analysed two parameters: monthly energy consumption and hourly air temperature. In this study, two formulas mentioned in ASHRAE guideline 14 [25] were applied: coefficient of variation of

square root error (RMSE) and mean bias error (MBE). The different RMSE and MBE values were evaluated, taking into account the two Equations (1) and (2) [25].

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

$$\text{MBE}(\%) = \frac{\sum_{i=1}^{N}(Mi - Si)}{\sum_{i=1}^{N} Mi} \tag{2}$$

where Si and Mi were simulated data and measured data over a given interval I, respectively, the total number of data implemented, M is the total number of measured data.

In Guideline 14 of ASHRAE [26], it is recommended that a simulation model can be considered calibrated if the following conditions are fulfilled:

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

The present research work is a continuation of a previous study [23] where a comparison between measurement and simulation data is shown and a small difference and negligible error between these two categories of data are concluded.

The various results of the calculations carried out show that the MBE value found is 0.6%, and that of RMSE is 0.2%. However, the values required in the ASHRAE-14 directive are between (−10%; +10%), counting as (MBE), and (−30%; +30%), counting as (RMSE). By observing these results, we deduce that the hourly values of MBE and RMSE found in this research are within the range requested by ASHRAE. On the basis of the previous results, we conclude that this simulation model is calibrated with different hourly data. In addition, a comparison between the monthly energy values was made. The value of the MBE obtained is −4.6%, while that of the RMSE obtained after the calculation is 0.7%. In accordance with ASHRAE, the various acceptable limits are between (−5%; +5%) representing the (MBE) and (−15%; +15%) representing the (RMSE). By comparing these results, it can easily be deduced that the MBE and RMSE values for the various monthly data are within the range recommended by ASHRAE (2002). Thus, the new simulation model can be considered as calibrated with the different monthly data and, therefore, the set of these two results shows that the new model can be validated.

3.6. Experiment

Before analysing the developed experiment, it is of interest to highlight that the building studied in the case of countries located in the tropical region is a copy of a residential building designed in Antananarivo city.

As it was shown before, it is of interest to comment that an experiment in this building in 2017 [27] was carried out. In this experiment, 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, and wind speed, between other variables. Finally, the measurement data and response of occupants allowed us to evaluate the comfort rate of residential buildings, as was described in reference [27].

4. Results and Discussion

4.1. Case of Residence Building Located in the Tropical Region

In this section, the simulation results of buildings placed in the tropical regions are showed and the sum-up is in Tables 6 and 7. In particular, Table 6 shows a comparison of monthly air temperature (°C) before and after the building revision.

Table 6. Variation of indoor air temperature in tropical regions.

Month		January	February	March	April	May	June	July	August	September	October	November	December
Original Residence building	Antananarivo	25.21	24.83	25.47	24.64	23.45	21.74	20.75	21.10	23.27	24.51	25.56	25.12
	Douala	26.66	26.59	26.36	26.13	26.17	25.80	25.35	25.04	25.10	25.62	26.05	26.54
	Dakar	24.66	24.84	25.18	25.19	26.00	26.64	27.04	26.98	27.20	27.20	26.91	25.90
Residence after renovation	Antananarivo	25.25	25.02	25.33	24.48	23.27	21.75	20.75	21.03	23.08	24.56	25.44	25.21
	Douala	26.19	26.24	26.10	25.88	25.89	25.49	25.14	24.96	25.08	25.41	25.52	26.04
	Dakar	24.78	24.96	25.21	25.30	25.82	26.46	26.92	26.91	27.05	27.02	26.71	25.75

Table 7. Annual operational carbon and energy demand in the residential building of tropical regions.

Cities		Antananarivo	Douala	Dakar	Total
Residence in the initial state	Energy demand (kWh)	3149.31	10,276.65	21,593.81	
	Carbon emission rate (kg CO_2)	1722.95	7366.85	13,085.86	
Renovated residence (applying: renovation + passive strategies + PV)	Surface of installed photovoltaic panels (m^2)	16	34	58	
	Cooling energy (kWh)	0.00	0.00	0.00	
	Energy demand (kWh)	2564.80	6944.28	13,874.95	0
	Green energy generated (kWh)	−2565.00	−6944.30	−13,875.01	
	Carbon emission rate (kg CO_2)	−3149.30	−140.51	3278.49	

4.1.1. Analysis of Indoor Conditions and Energy Consumption in Tropical Regions

First of all, it must be explained that indoor conditions are dependent on outdoor conditions, which were obtained from the Meteonorm tool. In particular, in Figure 5, it can be observed that Antananarivo has a wet tropical climate with a range of air temperature, relative humidity, and Predicted Mean Vote (PMV) [28] of 20.99 °C to 26.04 °C, 45% to 75%, and −2.07 to 0, respectively. At the same time, in Douala, the air temperature was between 25.45 °C and 27.37 °C and the relative humidity varied from 68.81% to 73.65%. From these results, it was concluded that, despite the fact that they have the same building construction, it is less comfortable in Douala than Antananarivo, which is located on several mountains. Indeed, climate conditions seem to be more favourable in the cities located in an altitude than in the coastal cities [25], which are dominated by heat [27].

In Antananarivo:

$$PMV = 0.106Top - 4.11, (R = 0.43); Rh = 1.208Top + 24.19, (R = 0.42) \quad (3)$$

In Dakar:

$$PMV = 0.286Top - 7.99, (R = 0.57); Rh = 3.993Top - 43.78, (R = 0.73) \quad (4)$$

In Douala:

$$PMV = 0.980Top - 26.41, (R = 0.85); Rh = - 2.199Top + 128.8, (R = 0.88) \quad (5)$$

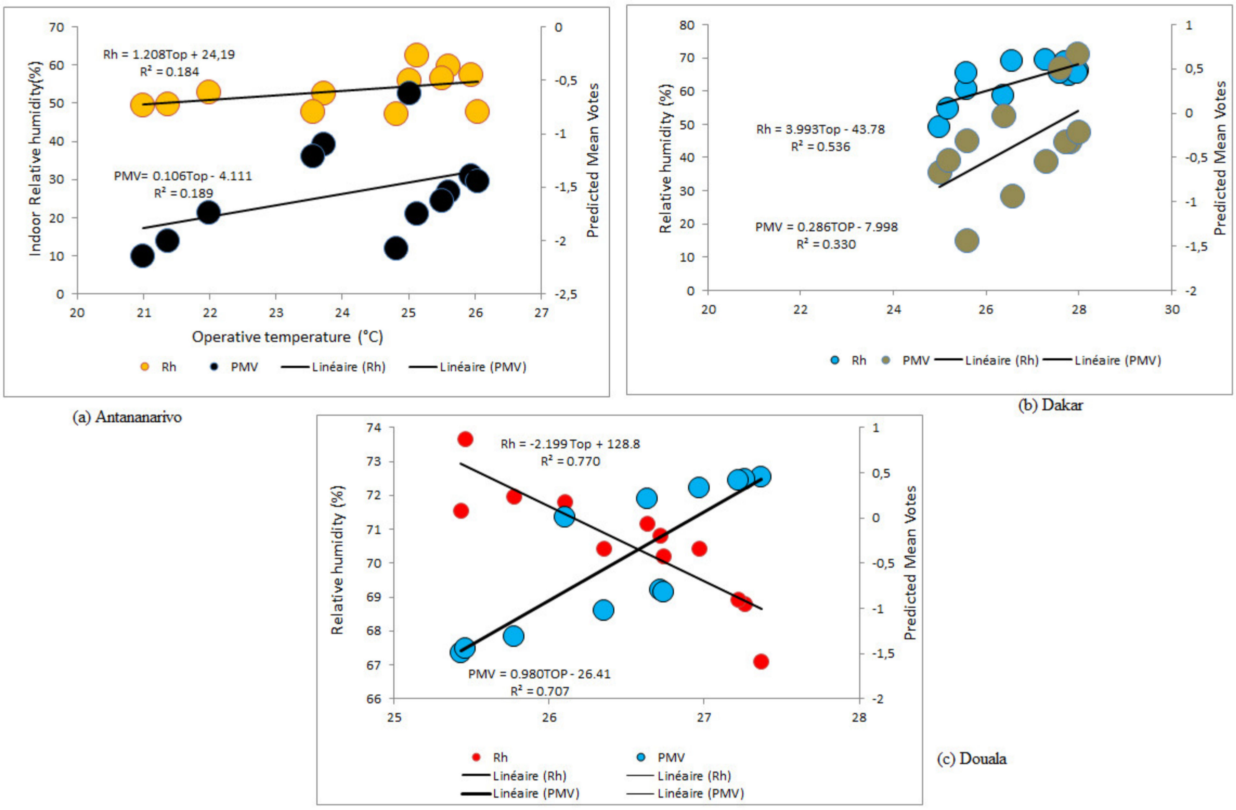

Figure 5. Variation of relative humidity and Predicted Mean Votes function of operative temperature in: (**a**) Douala; (**b**) Antananarivo; (**c**) Dakar.

The average indoor air temperature in the residence building placed in three Sub-Sahara Africa cities is given in Table 6.

In Table 6, the average indoor air temperature before and after the revision process can be observed. From this table, it can be concluded that the temperature decreases in the renovated residence when it is compared with the existing one. As a consequence, the cooling energy demand showed in Figure 5 and Table 7 was equal to zero after a renovation. This result shows that the choice of the most adapted materials to the local climate can significantly reduce the cooling energy demand. From this table, it was observed that renovation allows reducing the energy consumption between 9.7% and 35.5% in these three cities. Furthermore, the energy demand is 63% higher in the coastal region than in high altitude regions, which confirms the previous study carried out by Nematchoua et al. [29–32]. In particular, in Table 7, it can be observed that, after the revision process, the zero-energy objective is respected (the sum of the energy demand and the green energy generated by some photovoltaic panels (PV) is equal to zero).

At the time of analysing the energy savings, it is of interest to pay special attention to PV behaviour. In this sense, it is important to note that the size of the PV varies according to the region. Figure 5 shows that the PV is more efficient in Antananarivo than in Douala and Dakar cities. For these two cities, the solution to PV's inability, to meet monthly energy, is to store the excess electricity produced during sunny periods. At the same time, it was obtained that the energy generated by photovoltaic panels is the most efficient in the dry season. Indeed, it decreases from 8% to 23% in the three cities between rainy (May–September) and dry seasons (Figure 6a–c).

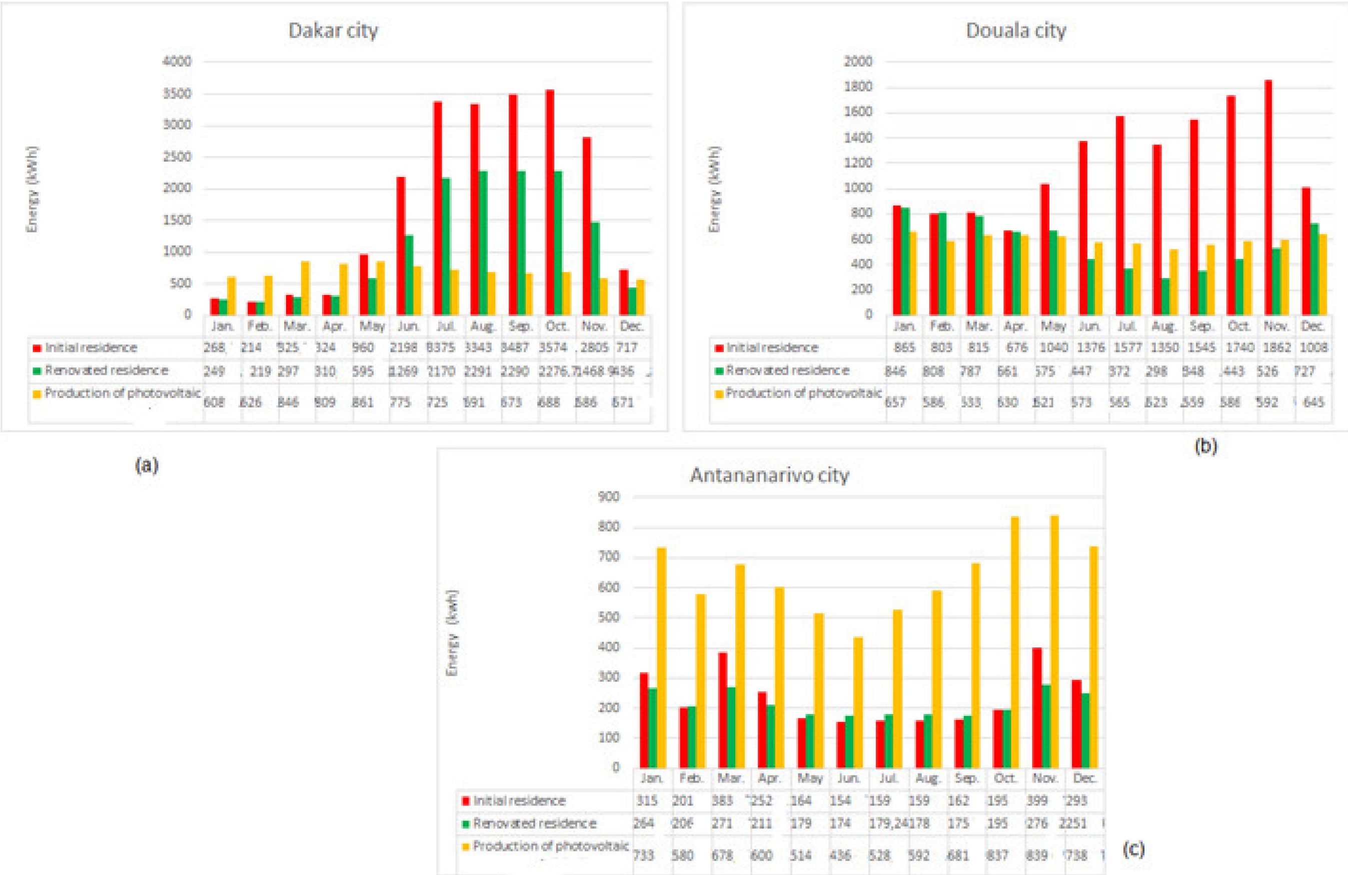

Figure 6. Monthly energy demand and production by photovoltaic panels in Dakar city (**a**); Douala (**b**); and Antananarivo (**c**).

This energy saving has some implications. In this sense, the carbon emission rate is negative in Antananarivo and Douala, which means that these residences remove more CO_2 than it emits into the atmosphere. Furthermore, it was observed that this rate is very low in Dakar (9.58 kg CO_2/m^2) compared to the initial concentration of carbon set to 38.26 kg CO_2/m^2. This reduction of carbon, estimated to be 74.96%, may be due to the implementation of sustainable materials and the application of passive strategy techniques [29].

Finally, from these results, it can be concluded that the renovation of the building requires an additional cost, but it improves indoor air quality [33]. Due to its related effect, in the next subsection, the impact of renovation by analysing investment cost will in turn be analysed.

Similar to air temperature, relative humidity has a significant effect on energy use in the buildings. Indeed, as explained by Aktas et al. [34], improving thermal comfort while reducing energy consumption in a building requires careful management of humidity levels, as well as careful selection of building materials.

4.1.2. Cost Analysis

At the time of evaluating the economic investment, it must be considered that the standards show an estimated investment of a low energy building from 35% to 55% higher than a conventional residential building. In this particular case study, the analysis of the cost is based on many assumptions, as detailed in Tables 8 and 9. In this sense, an increase between 40% and 70% was observed when compared to the basic price to reach the standard building with zero-energy and a payback period of 6.3 years. Furthermore, it is of interest to highlight that the transition between traditional structural work, respecting the energy performance of the building, and structural work respecting the low energy standard, leads to an increase in costs, which can vary from 35 to 55%.

Table 8. The average cost parameter applied at the building level in Sub-Saharan Africa [35].

Currency and Exchange Rate	
Currency Symbol	**$**
Applicable construction labour Hours and local cost index	
Regional material cost index	0.06
Hourly labour rate worker	$0.23–3.01
Hourly labour rate craftsman	$0.21–1.9
Discount factor (capital cost) and inflation	
Discount rate (cost of capital)	18.0%
General inflation rate	8.0%
Energy inflation rate	6.2%
Water inflation rate	5.2%
EOL as % of capex	1.5%

Table 9. Evaluation of residential building cost.

	Parameters	Values
Initial state of the building	Residence area	342 m^2
	Annual heating requirements	0
	building life cycle	50 years
	Price of the closed building structural work	30,000 € including VAT
	Electricity price	0.15 € per kWh
	Electricity consumption	2564.8 kWh per year
	Electricity cost	19,236 € for 50 years
Residence building+ PV installed	The price of the closed building structural work	32,400 € including VAT
	PV cost	2400 €
	Saving cost	16,836 € for 50 years
	Payback	6.23 years

4.2. Case of Residence Building Located in the Temperate Region

4.2.1. Analysis of Indoor Conditions and Energy Consumption

As a base case, to be compared with the results obtained in the tropical region, the building placed in the temperate climate region was analysed. In this sense, three cities located in the countries of France, Belgium, and the United States were chosen. The building placed in this new climatic region shows some differences in morphology and occupation in accordance with its typical design. In particular, the occupation rate is 0.0303, which means a person for 33 m^2 of area. Finally, it is important to notice that, at the time of the revision process, the PV area varied depended on micro-climate.

The main results were summed up in Tables 10 and 11 shown. In the revised building, there is a more comfortable indoor air temperature. In particular, Figure 7 shows the comparison of heating energy demand in the temperate region before and after the revision process. After renovating this residential building, it was noticed that the heating energy decreases to 31.4% (from 89.45 kWh/m^2 to 61.37 kWh/m^2) in Paris; to 33.3% (between 93.3 kWh/m^2 and 62.2 kWh/m^2) in Washington; and to 30.4% (between 95.7 kWh/m^2 and

66.6 kWh/m^2) in Brussels. Finally, from Table 11, it can be deduced that, in the three cities, green energy generated is equal to the energy demand. Furthermore, the results showed that the heating energy represents between 60% and 91% of total energy consumption in a residential building in the temperate region, which confirms the results found by Olonscheck et al. [36]. In this sense, in order to produce green electricity equal to the building energy demand, it is necessary to combine two different renewable technologies: gas cogeneration and photovoltaic panels. The required PV area is 58 m^2 in Brussels, 45 m^2 in Paris, and 42 m^2 in Washington DC with this combined cogeneration solution, but would extend to 194 m^2 in Brussels, 151 in Paris, and 141 m^2 in Washington DC without the cogeneration. This combined solution produces nearly zero annual operational carbon in the three cities, so an economical study will be shown in the next section.

Table 10. Comparison of indoor air temperature (in °C) in one residence building located in three cities.

Month		**Jan.**	**Feb.**	**Mar**	**Apr**	**May**	**Jun.**	**Jul.**	**Aug**	**Sep.**	**Oct.**	**Nov**	**Dec**
Original residence	Brussels	16.42	16.56	17.42	18.09	16.94	18.65	21.56	21.19	17.65	18.57	17.41	16.85
	Paris	16.74	16.81	17.53	18.30	18.20	20.33	22.53	23.12	19.50	18.69	17.53	16.87
	Washington	15.90	16.66	17.83	18.60	20.72	23.80	25.02	24.32	22.23	20.08	17.78	16.60
Renovated residence	Brussels	15.87	15.93	16.61	17.36	15.75	17.63	20.55	20.00	16.53	17.94	16.78	16.24
	Paris	16.11	16.05	16.74	17.62	17.02	19.24	21.64	22.16	18.12	18.03	16.76	16.03
	Washington	16.13	16.26	16.89	17.45	14.16	16.87	21.10	21.19	19.19	17.70	16.23	16.18

Table 11. Annual operational carbon and electricity demand in the residential buildings located in temperate climates.

	Cities	**Brussels**	**Paris**	**Washington**
Initial building	Cooling electricity (kWh/m^2)	1.02	2.46	2.48
	Heating and domestic hot water (Gas) (kWh/m^2)	37.71	34.96	33.20
	Electricity demand (kWh/m^2)	25.46	24.90	22.06
	Carbon emission rate (kg CO_2/m^2)	18.64	18.39	16.89
Revised building	Surface of installed photovoltaic panels (m^2) for a building area of 342 m^2	58.00	45.00	42.00
	Green electricity produced by gas cogeneration (kWh/m^2)	40.96	38.99	37.03
	Heating and domestic hot water (Gas cogeneration) (kWh/m^2)	37.71	34.96	33.20
	Cooling electricity (kWh/m^2)	0	0	0
	Electricity demand (kWh/m^2)	20.36	18.77	14.54
	Green electricity generated (kWh/m^2)	−17.11	−14.74	−10.71
	Carbon emission rate (kg CO_2/m^2)	−2.60	−0.11	2.17

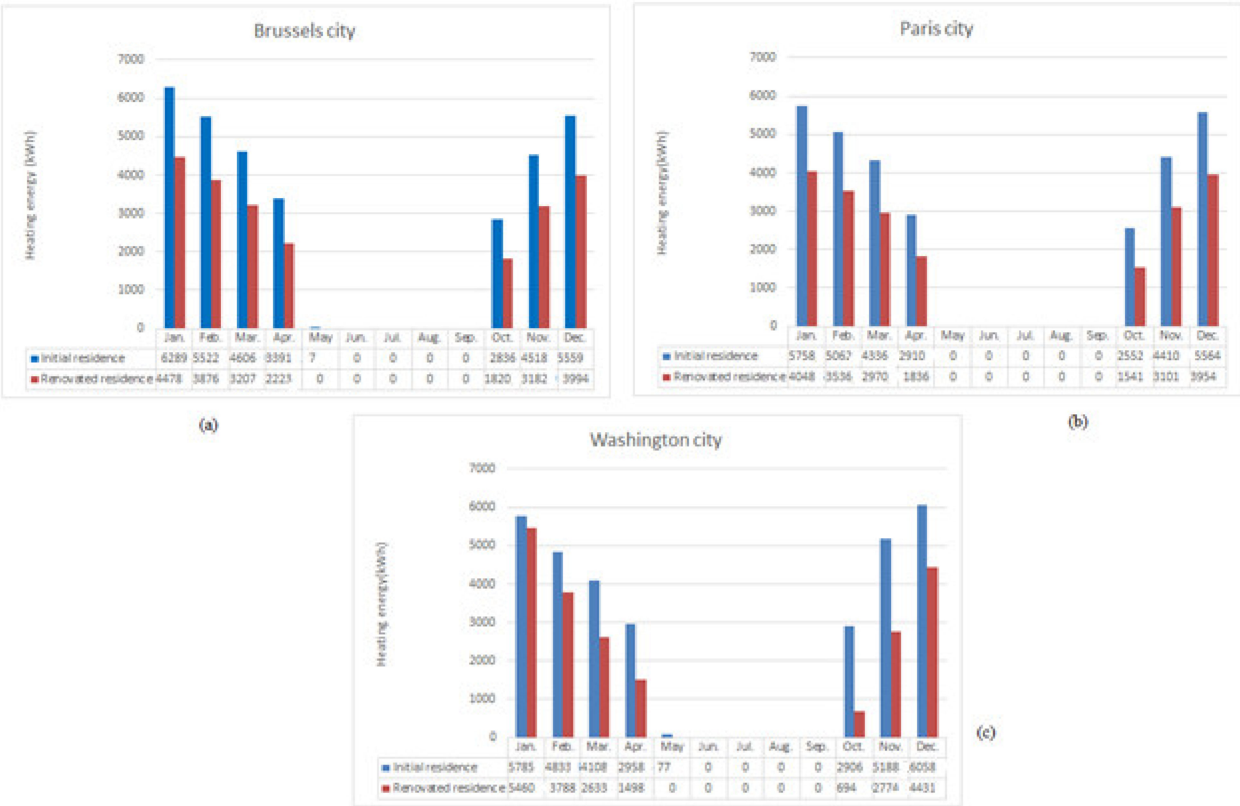

Figure 7. Heating energy in Brussels (**a**), Paris (**b**), and Washington DC (**c**).

4.2.2. Cost Analysis

Some details regarding the evaluation of cost are given in Table 12. From this table, it was concluded that this house meets the criteria of the passive house and a payback period of 3.8 years to amortize the initial economical investment in the revised building.

Table 12. Evaluation of cost.

Buildings	Parameters	Values
Initial state of the building	Initial investment	350,000 € including VAT
	Area	342 m^2
	Annual heating requirements (case of Brussels)	13.81 kWh/m^2
	Electricity price	0.25 €/kWh
Residence building + PV installed	The price of the closed building structural work	385,000 €
	Price of energy demand (cooling+ heating+ electricity+ domestic hot water)	9163.5 € per year
	Payback	3.8 years

Finally, from these results, it can be concluded that the investment cost and energy consumption are more important in a residential building located in temperate rather than in tropical climates. In particular, the energy consumption is around 78.2% higher in temperate than tropical climates and, at the same time, the investment cost is 12 times higher in temperate than tropical climates.

5. Conclusions

With the aim to define the energetic and economic interest of the transition to zero-energy in residential buildings in tropical climates, the energy performance of two standard residential buildings selected in tropical and temperate regions was improved towards zero-energy and low carbon emissions. The results showed that the zero-energy building concept is the most likely in the tropical region in favour of its geographical position. In particular, the zero-energy buildings are reached with an average indoor air temperature between 20.8 °C and 25.6 °C in the continental tropical region; from 24.7 °C to 27.2 °C in the coastal tropical regions; and from 16.4 °C to 25.1 °C in the temperate regions. In consequence, it was obtained that the renovation allowed a reduction of the energy consumption up to 36% in the tropical region with a payback of 6.3 years, whereas heating energy decreases from 30 to 34% in the three cities studied. These results are related to the location of the city and the seasonal efficiency of the PV, between other parameters.

Although a similar energy saving was obtained in temperate and tropical regions, and the investment cost is higher in the temperate region than in the tropical one, it was obtained that the payback is nearly half.

Finally, the results of this study can be applied in other countries with a similar climate. Furthermore, this study can serve as a guide for all those who wish to invest in sustainable construction. Another future, more detailed study will allow us to understand in depth the impact of the choice of construction materials in green buildings.

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Transition to Zero Energy and Low Carbon Emission in Residential Buildings Located in Tropical and Temperate Climates

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Abstract: Different methods to achieve zero-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. Being aware of this fact, a study was carried out to analyse the design of new buildings respecting the "zero-energy and low carbon emission" concept in tropical climatic regions when they are compared with a base case of temperate regions. To reach this objective, the comparison between real and simulated data from the different buildings studied was developed. The results showed that the renovation of existing residential buildings allows for reducing up to 35% of energy demand and a great quantity of CO_2 emissions in both climate types. Despite this, the investment rate linked to the construction of zero-energy buildings in tropical zones is 12 times lower than in temperate zones and the payback was double. In particular, this effect can be related to the efficiency of photovoltaic panels, which is estimated to be, at least, 34% higher in tropical zones than temperate zones. Finally, this study highlights the interest and methodology to implement zero-energy buildings in tropical regions.

Keywords: zero-energy; low carbon; residential buildings; tropical; temperate climate

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1. Introduction

Between 2000 and 2020, the average concentration of carbon dioxide (CO_2) emitted increased by approximately 2–3% each year [1]. In 2018, China (29.7%), the United States (13.9%), India (6.9%), the EU28 (9.1%), Russia, (4.6%) and Japan (3.2%)—the world's largest CO_2 emitters—together accounted for 51% of the population, 80% of total fossil fuel consumption, and 67.5% of total fossil CO_2 emissions in the world [2]. Nevertheless, efforts to reduce the carbon rate have been observed by the most polluting countries with activities like reducing building energy consumption. In this sense, a net-zero-energy building (ZEB) means that the total amount of energy used, calculated on an annual basis, is roughly equal to the amount of renewable energy created on the site [3].

Nowadays, in European Union countries (Belgium, France, Italy), primary energy demand in the building sector represents almost 40% of total energy [4]. Moreover, for the past ten years, it has been noticed that the building sector emitted up to 36% of greenhouse

gas, and produced 38% of wastes [4]. In particular, in Brussels, construction and operation represent 98% of the water flow, 75% of energy demand, 65% of greenhouse gas emissions and about 33% of waste generated each year [5]. In consequence, this city has set itself the ambition of reducing energy consumption up to 30% by 2030 and up to 40% of carbon emissions in the construction sector [5]. Another example of a European city is Paris, where the building sector (residential and tertiary) accounts for 80% of the region's energy consumption, and 20% of the emission of greenhouse gas. In consequence, the city of Paris aims to reduce energy consumption by 1/3 by 2030, and by 50% by 2050. To reach this objective, a new climate plan provides for massive renovations of social and tertiary housing in this city [6]. Another example of non-European cities is Washington, where the carbon emission intensity decreased by 4.9% in 2019 [7]. Finally, in Sub-Saharan Africa (Senegal, Cameroon, and Madagascar), the building sector consumes more than 25% of total primary energy, which is generated by fossil fuels and emitting thousands of tons of carbon into the atmosphere each year. This CO_2 concentration is almost negligible compared to those produced in developed countries.

In general, it is interesting to highlight that, although most of these countries have a lot of potential resources (solar, hydro, wind), they are exploited at less than 5%. This situation remains very serious due to how strongly carbon emissions have a negative impact on global warming and, in consequence, it is important to take action to protect the environment. In this sense, the energy renovation of old buildings and the design of new buildings, mainly powered by renewable energy, can contribute enormously to the reduction of greenhouse gas emissions. What is more, stand-alone buildings can be the start of the solution but there are few guides to reach this objective.

Different recent research works aim to be examples of standalone buildings. Some of them evaluated the possibility to reach zero-energy and low carbon in buildings, yet the regulations and objectives set by several international organizations are not enough to be applied on a large scale [8].

In this sense, it is interesting to highlight that, although zero-energy building is more favourable in tropical and hot zones due to more favourable climatic factors, it was observed that countries located in temperate zones are more involved in the implementation of this new technology. In particular, most of the zero-energy buildings use the power grid for energy storage, but some are grid independent [9].

The development of zero-energy buildings has become possible not only thanks to advances in new energy technologies and construction techniques like solar panels, heat pumps, and low-emissivity triple glazing, but also thanks to researchers, who collect precise data on the energy performance of traditional and experimental buildings and provide parameters for advanced computer models to predict the efficiency of engineering designs [10]. In this sense, some recent research works were carried out in this field in the temperate region. For instance, after a strong study on one residential building located in Boston city in 2006, Szejnwald et al. [11] showed that renovation is the best technique for allowing the reduction of the significant part of energy demand. In 2017, the results of studies conducted by Yi et al. [12] explained that although the studies detail step-by-step the different processes of implementing zero-energy in new constructions, it is often difficult in practice to make this objective, because of the variety of outdoor climates according to the seasons. The results of studies conducted by Szalay and Zold [13] aiming to design zero-energy buildings showed that it is easier to achieve the ZEB by grouping buildings according to their geometrical shape and age. The research conducted by Zhou et al. [14] in an office building in China showed that the choice of HVAC systems has a significant impact on the implementation of zero-energy in buildings in temperate zones. This study recommended adopting energy efficiency techniques according to the local climate of each region. With the aim of increasing the energy performance of buildings over their entire life cycle, in order to increase the possibilities of achieving zero-energy building, Srinivasan et al. [15] found a new method aimed at optimizing the production of energy generated by renewable sources. The research carried out by Robert and Kummert [16]

based on the "Morphing" method made it possible to analyse, on the basis of hourly data for the last 50 years and a general circulation model, the impacts of global warming on the implementation of NZEB in the temperate zone. The results showed that global warming significantly impacted zero-energy buildings. The study carried out by Pikas et al. [17] aimed to estimate the optimal cost of the energy performance of the residential building with almost zero energy consumption. The results explained that very few methods allow estimating the optimal cost of the energy used in these residences.

Despite these previous works about temperature regions, there is a lack of information about tropical cities and the possibilities to improve the energy consumption in their buildings. In this sense, tropical cities are some of the most favourable regions for the implementation of ZEB but the rate of buildings respecting the zero-energy concept is very low in this region of the world. In this sense, the study carried out in 2019 by Nematchoua and Sigrid [18] aimed to assess the different possibilities for the implementation of residential buildings with zero-energy and low carbon emissions in sub-Saharan Africa. The results showed that the most efficient solution to consider a zero-energy building in the city of Antananarivo requires an additional expenditure estimated at 40% of the initial cost of the building. This will result in savings of $475 per year starting in 2030, and also about a 99% reduction in carbon emissions.

In consequence, the objective of this study is to assess and analyse the cost and energy use with the implementation of residential buildings with zero-energy and low carbon emissions in tropical regions (sub-Saharan Africa), taking as reference this same analysis in temperate zones. In particular, paying special attention to the energy production generated by photovoltaic panels in hot zones and then the impact of heating on energy demand in temperate zones. The final objective is to show to architects, engineers, urban planners, investors, politicians, even non-specialists in energy and the environment, a simple methodology to analyse the energetic and economic interest into building new zero-energy and low carbon buildings in different climate regions.

To reach this objective, the present work is constituted of several parts: an analysis of some keywords in the second part; a methodology, results, and discussion, and finally the conclusions.

2. Keywords Analysis

The systematic structure of this manuscript is shown in Figure 1.

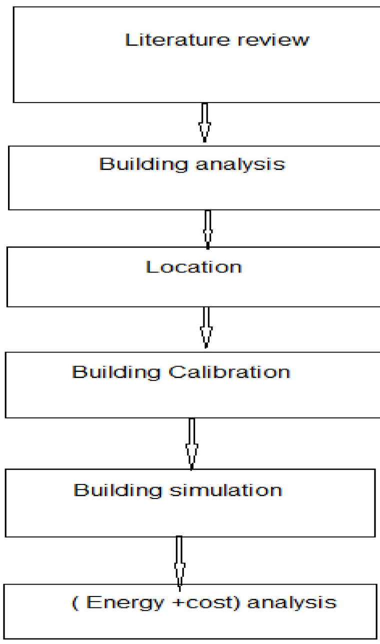

Figure 1. Research conceptual framework.

2.1. Buildings and Zero-Energy Concept

Before carrying out different research works and case studies about zero-energy and low-carbon buildings, it is important to do a previous analysis about the different concepts of existing low environmental impact housing in order to make more understandable some practical cases which will be presented in this research.

2.1.1. Nearly Zero-Energy Building

A nearly zero-energy building is economical in primary energy. The nearly zero quantity required for heating, cooling, lighting, domestic hot water, and ventilation is thus covered by solar heat or by renewable energy sources as well as by reasonable technical installations. In this sense, in the European Union, a building energy performance requirement was set between 2014 and 2021 as shown in Table 1.

Table 1. Evolution of the energy performance requirements of buildings from 2014 to 2021 for the residential and commercial buildings in some European Union countries [19].

Type of Building Construction	Building Energy Performance (2014)	Building Energy Performance (2017)	Nearly Zero-Energy Building (2021)
Overall level of thermal insulation (kWh/m^{2}year)	≤35	≤35	≤35
Overall energy performance of the building (residential building) (kWh/m^{2}year)	≤80	≤65	≤45
Overall energy performance of the building (commercial building) (kWh/m^{2}year)	≤80	€ (65–90)	€ (45–90)
Primary energy demand (kWh/m^{2}year)	≤130	≤115	≤85

2.1.2. Passive Building

The objective of a passive house is to consume very little energy while ensuring high thermal comfort in summer and winter as well as good air quality. Once again, in the European Union, some criteria must be respected to obtain the label "passive building", as shown in Table 2.

Table 2. Criteria for a passive building [20].

Passive Building	Criteria
Heating energy (kWh/m^{2}year)	≤15
Primary energy (kWh/m^{2}year)	≤120
Air tightness (vol/h)	≤0.6
Annual overheating hours (>25 °C)	≤5%

It is interesting to highlight that heating requirements of less than 15 kWh per m^2 and year are four to six times less than a new conventional building and up to ten times less than an existing building over ten years old.

2.2. Zero-Energy Building

It is a building that produces all the energy that it needs. It is interesting to note that a zero-energy building does not necessarily meet the criteria for a passive building. We must distinguish a building called energetically sufficient from a building called energetically autonomous.

(i) An energy-efficient building is capable of producing, over a year, an amount of energy proportional to the amount of energy it consumes. However, it will not necessarily consume the energy it needs when it produces it. Example: consider a building for which we install photovoltaic panels. During sunny periods (in summer), the panels will generate electricity at their optimum efficiency [21], and the house will supply energy to the grid. During the rest of the time or during a dead period such as in winter, the panels will not always supply enough electricity. Consequently, the dwelling cannot do without the electrical network. However, the total annual balance is zero since the excess production in summer compensates for the lack in winter.

(ii) An energetically autonomous building must not be connected to the electrical distribution network. When the panels cannot produce as much electricity as needed, the batteries used to store the excess electricity produced during sunny periods provide the electricity. To achieve energy independence, the building has above-average levels of insulation.

The principle of the zero-energy building, therefore, differs from that of the passive house, since it consists of compensating for total consumption, whatever it is, and not in optimizing the conditions favouring the energy sobriety of the house.

2.3. Positive-Energy Building

A building is said to be positive energy when it produces more energy than it consumes. A positive-energy building can be a passive building with enough renewable energy sources, or a building that does not meet the criteria to be a passive building, but still has a surplus of overall energy production.

3. Methodology

As it was shown before, the present paper aims to show a methodology for designing new buildings respecting the zero-energy concept, adding, as original consideration, the climatic regions where the buildings are placed and taking as reference the temperate regions. To reach this objective, three temperate countries and three tropical countries, with their typical building constructions, were selected. In consequence, weather data and simulations were employed to define the energy consumption and economical investment needed in each case study and its comparison will let define the more interesting region to implement the zero-energy concept. All these items will be described in the next sections.

3.1. Location

This study was carried out in three developed countries (Belgium, France, and the United States) located in a temperate climate, and three developing countries (Cameroon, Senegal, and Antananarivo) located in Sub-Sahara Africa (tropical climate).

The study took place in the capital of each country, as these study locations were chosen based on their environmental (climatic), energy, and social differences. The three cities selected in this study, and placed in Sub-Saharan Africa, are of very high solar potential (which is favourable to the supply of PV) and also the wind speed, which is favourable to the installation of wind turbines (speed between 5 m/s and 10 m/s).

The countries located in temperate zones such as Belgium, France, and the United States, have climatic conditions less favourable to zero-energy objectives because of the low sunshine in winters. However, important reforms are being carried out in these countries with the objective of achieving zero-energy and low carbon in 2050. This study aims to support this approach.

3.1.1. Studied Locations

Sub-Saharan Africa is made up of 48 countries with varying climates. It is one of the regions of the world that is very rich in biodiversity, and, above all, one of the most vulnerable to climate change. More than 80% of the population from this region are under 35 years old. Three of the cities in this study are located in this region: the city of Douala located in Cameroon, the city of Antananarivo in Madagascar, and Dakar in Senegal.

(1) Located between 4°03′ N and 9°4′ E, the city of Douala is the economic capital of Cameroon. Douala covers 923 km^2 and is strongly dominated by the tropical climate essentially made up of two seasons: the dry season from November to April and the rainy season from April to November.
(2) Dakar is the main city of Senegal. It is a coastal city located on the edge of the Atlantic Ocean. This city is dominated by the tropical climate and crossed by the monsoon coming from the southwest which is a humid wind bringing rain, and also a dry wind (the Harmattan). Dakar is one of the largest metropolises in Africa with a very high growth rate.
(3) Located 1435 m above the sea, the city of Antananarivo, the political capital of Madagascar, is spread over 350 km of surface. The city of Antananarivo is strongly dominated by the tropical climate of such an altitude. It has notably cool, mild winters and very rainy summers. Figure 2 gives the geographical location of these different cities studied, while Table 3 shows some climatic characteristics.
(4) Brussels is the capital of Belgium, the French Community of Belgium, the Flemish Community, and the seat of several European Union institutions. The climate of Brussels is temperate and influenced by the Gulf Stream. The proximity to the sea has a strong influence on this climate. The climate of Brussels is generally characterized by mild and rainy winters and relatively cool and humid summers.
(5) Washington DC is one of the world's largest cities, located in the mid-Atlantic region of the East Coast of the United States, between Virginia and Maryland. The nation's capital is around 40 miles south of Baltimore, 30 miles west of Annapolis and the Chesapeake Bay, and 108 miles north of Richmond. Founded in 1791, Washington DC is the place where the seat of the American congress is located [22]. Major factors determining Washington's climate include the large semi-permanent high-pressure and low-pressure systems of the North Pacific Ocean, the continental air masses of North America, and the Olympic and Cascade Mountains [22]. In spring and summer, a high-pressure anticyclone system dominates the North Pacific Ocean, causing air to spiral out in a clockwise fashion [22].
(6) Paris is the capital city of France, and the largest city in France. The area is 105 km^2. Paris is also the centre of the French economy, politics, traffic, and culture. The climate of Paris is said to be a warm temperate. The rainfall in Paris is significant, with precipitation even during the driest month. The average annual temperature in Paris is 11.3 °C. Figure 3 shows location of some cities studied in this research.

Figure 2. Location of three studied cities.

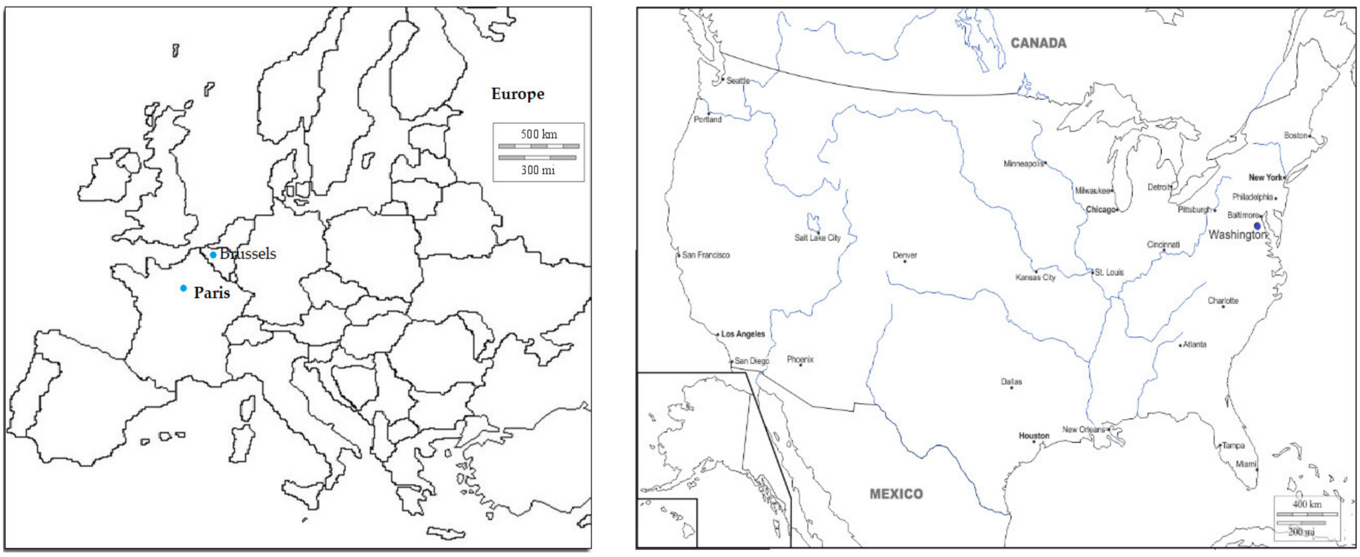

Figure 3. Location of Brussels and Paris (**on right**) and Washington DC (**on left**).

3.1.2. Climatic Data

In this research, all the climate data for simulations are downloaded from American Meteonorm software (Version 7.3.3, Meteotest AG (Bern, Switzerland)), based on the geographical coordinates of each city. The software provided the possibility to download data in hours, days, or months according to our requirements. Hourly data of temperature, relative humidity, airspeed, solar radiation, and precipitation for the last 30 years were collected for all the climate regions.

3.2. Buildings

This research was carried out about residential buildings. The type of building and construction materials varied according to the countries and this is why there were two categories of residential buildings (one more adapted in a temperate climate and another in a tropical climate). In this sense, the different buildings have different shapes with different structure materials and different areas, which can accommodate several people as shown in Table 4.

- The first residential building designed for this project, and located in the tropical region, was a simple one-floor family house consisting of four bedrooms, a shower room, and a kitchen. The building materials mainly consisted of Earth bricks and essentially glazed windows (glass thickness: 5.5 cm).
- The second residential building designed for this project, and located in the temperate region, was a familiar residence composed of two bedrooms, a living room, kitchen, and restroom. The different building materials are detailed in Table 4.

Table 3. Information regarding the six selected representative countries.

No	Country	City	Climate	Location	Temp.(°C)		RH (%)	
					Min	Max.	Min.	Max.
1	Belgium	Brussels	temperate	50.85° N, 4.35° E	−1	30	30	90
2	Cameroon	Douala	tropical	4.05° N, 9.76° E	18	37	30	90
3	France	Paris	temperate	48.85° N, 2.35° E	−10	31	30	90
4	Madagascar	Antananarivo	tropical	18.87° S, 47.50° E	10	35	55	90
5	Senegal	Dakar	tropical	14.72° N, 17.46° W	15	35	30	100
6	United States	Washington	temperate	38.90° N, 77.03° W	−2	33	30	98

From this Table 4, it can be observed that most of the materials chosen in the case of renovated residence buildings have low thermal conductivity and embodied carbon almost equal to zero. The goal is to select the materials that are more sustainable (low conductivity and embodied carbon). The lower the thermal conductivity of a material, the more this material has a huge capacity to limit heat transfer.

3.3. Simulation Tools

In this study, version (5.5.2) of the Design Builder software (Stroud, UK) was employed. This software is highly renowned in this field and has served as the basis for thousands of works of scientific research. Design Builder software, the same as TRNSYS, DOE, Pleiades, Helios, etc. software, is very well known in the field of simulation, optimization, modelling, BIM (Building Information Modelling), LCC (Life Cycle Cost), LCA (Life Cycle Assessment), etc.

This software is coupled with the Energy Plus (version 8.2, funded by the U.S. Department of Energy's (DOE) Building Technologies Of-fice (BTO)) tool to assess the consumption and energy demand of a building [23] and offers the most building materials with their physical thermal property. The modelling of the building selected is shown in Figure 4.

Table 4. Thermal characteristics of building constructions.

Region	Building Category	Building Clement	Layer	Component	Thickness (m)	Thermal Conductivity (W/mK)	Density (kg/m^3)	Specific Heat Capacity (J/kg K)	Embodied Carbon (kg CO_2/kg)	U-Value (W/(m^{2}K))
Tropical region	Residence in the initial state	Exterior wall	Layer1	Plaster	0.025	0.500	1300	1000	0.12	2.750
			Layer2	Concrete block	0.120	1.630	2300	1000	0.08	
			Layer3	Plaster	0.050	0.500	1300	1000	0.12	
		Partition wall	Layer	Concrete block	0.120	1.630	2300	1000	0.08	5.850
		Roof	Layer1	Clay Tile	0.025	1.000	2000.0	800	0.46	0.160
			Layer2	Stone Wool	0.242	0.040	30.0	840	1.05	
			Layer3	Roofing felt	0.005	0.190	960.0	837	-	
	Residence after renovation	Exterior wall	Layer	Wood	0.153	0.040	110	1800	0.00	0.250
		Partition wall	Layer	Wood	0.070	0.040	110	1800	0.00	0.250
		Roof	Layer1	Clay Tile	0.025	1.000	2000.0	800	0.46	0.160
			Layer2	Stone Wool	0.242	0.040	30.0	840	1.05	
			Layer3	Roofing felt	0.005	0.190	960.0	837	-	
Temperate region	Residence in the initial state	Exterior wall	Layer1	Plaster	0.030	0.500	1300	1000	0.12	0.330
			Layer2	Concrete	0.140	0.510	1400	1000	0.08	
			Layer3	Extruded polystyrene	0.120	0.034	35	1400	2.88	
			Layer4	Facing brick	0.090	0.620	1700	800	0.22	
		Partition wall	Layer1	Plaster	0.030	0.500	1300	1000	0.12	1.570
			Layer2	Brick	0.140	0.720	1920	840	0.22	
			Layer3	Plaster	0.030	0.500	1300	1000	0.12	
		Roof	Layer1	Roof tiles	0.030	0.550	1900	837	0.05	0.180
			Layer2	Wooden lathing	0.038	0.130	2800	896	0.45	
			Layer3	Air gap	0.025	-	-	-	-	
			Layer4	Wood	0.042	0.120	510	1380	0.45	
			Layer5	Rock wool	0.400	0.100	500	1000	0.98	
			Layer6	composite wood	0.018	0.040	160	1888	0.19	

Table 4. *Cont.*

Region	Building Category	Building Clement	Layer	Component	Thickness (m)	Thermal Conductivity (W/mK)	Density (kg/m^3)	Specific Heat Capacity (J/kg K)	Embodied Carbon (kg CO_2/kg)	U-Value (W/(m^{2}K))
	Residence after renovation	Exterior wall	Layer1	Plaster	0.030	0.500	1300	1000	0.12	0.350
			Layer2	Concrete	0.140	0.510	1400	1000	0.08	
			Layer3	Wood frame	0.030	0.120	510	1380	0.45	
			Layer4	ISOCELL cellulose	0.020	0.100	400	1360	-	
			Layer5	Composite wood panel	0.020	0.250	900	1000	0.12	
			Layer6	Wooden cladding	0.022	0.130	160	1800	0.05	-
		Partition wall	Layer1	Plaster	0.030	0.50	1300	1000	0.12	1.570
			Layer2	Brick	0.140	0.720	1920	840	0.22	
			Layer3	Plaster	0.030	0.500	1300	1000	0.12	
		Roof	Layer1	Roof tiles	0.030	0.550	1900	837	0.05	0.180
			Layer2	Wooden lathing	0.038	0.130	2800	896	0.45	
			Layer3	Air gap	0.025	-	-	-	-	
			Layer4	Wood	0.042	0.120	510	1380	0.45	
			Layer5	Hemp wool	0.400	0.037	800	1000	0.00	
			Layer6	Composite wood	0.018	0.130	1000	1000	0.01	

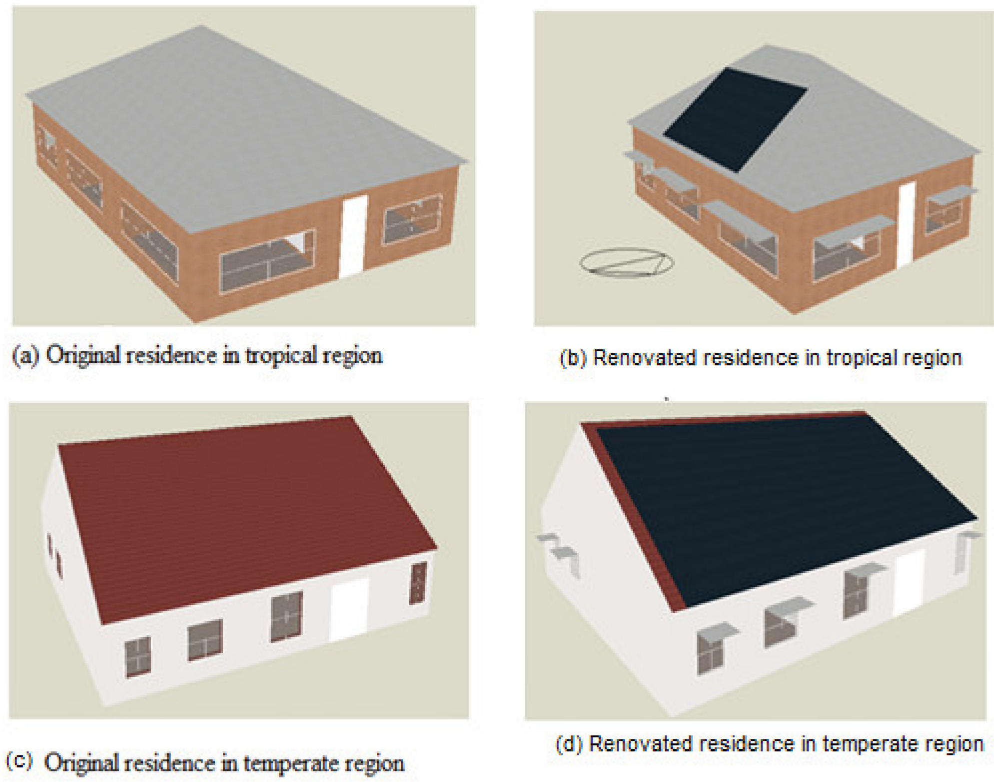

Figure 4. Case of (**a**,**b**) renovated residence building in the tropical region and (**c**,**d**) temperate climate.

In this sense, it is interesting to highlight that the design builder software automatically gives the embodied carbon of each type of material used during the construction of the building, as well as the quantity of carbon produced during the operational phase of the building. As a consequence, the total carbon emission rate during the life cycle assessment of the building can be freely obtained.

In the case of a building located in the tropical climate, the efficiency of the solar panels is very high due to the high concentration of solar radiation throughout the year, and it is not needed to add another source of energy such as a wind turbine to achieve the "Zero-Energy Building" objective. In contrast, in the case of a building located in a temperate climate, it was necessary to associate the photovoltaic panels (PV) and wind turbines to reach the "Zero-Energy Building" to maintain the same area of PV installed in a building located in the tropical region. Indeed, in the temperate region, the sunshine is high only in summer, which is why the PV has a low yield in this region. The input data of the simulation software is shown in Table 5.

Table 5. Input data for the simulations.

Parameters (Renovated Residence = After Applying Renovation, Passive Strategy, and Green Energy)	Building Located in the Tropical Region		Building Located in the Temperate Region	
	Initial State	**After Renovation**	**Initial State**	**After Renovation**
Height (m)	3.5	3.5	3.5	3.5
Area (m^2)	342.0	342.0	342.0	342.0
Activity template	Domestic House	Domestic House	TM_3-Bed Living Kitchen	TM_3-Bed Living Kitchen
Occupancy density (people/m^2)	0.0230	0.0230	0.0303	0.0303

Table 5. *Cont.*

Parameters (Renovated Residence = After Applying Renovation, Passive Strategy, and Green Energy)	Building Located in the Tropical Region		Building Located in the Temperate Region	
	Initial State	After Renovation	Initial State	After Renovation
Activity (met)	0.9	0.9	0.9	0.9
Clothing (Clo)	0.5–1.0	0.5–1.0	0.5–1.0	0.5–1.0
DHW: consumption rate (l/m^2-day)	0.53	0.53	0.72	0.52
Fresh air (l/s-person)	10	10	10	10
Lighting: target luminance (lux)	100	100	125	100
Computer: power density(W/m^2)	0.200	0.180	0.200	0.105
Other equipment: power density (W/m^2)	3.58	3.58	3.58	3.58
Occupancy schedule	24/7	24/7	24/7	24/7
Construction template	Project construction template	Project-construction template	Project construction template	Project construction template
Air tightness (vol/h)	0.5	0.5	0.5	0.5
Glazing template	Project glazing template	Project glazing template	Project glazing template	Project glazing template
Glazing type	Preferred height 1.5 m, 30% glazed Thickness: 5.5 cm	Preferred height 1.5 m, 30% glazed Thickness: 5.5 cm	Preferred height 1.5 m, 30% glazed Thickness: 5.5 cm	Preferred height 1.5 m, 30% glazed Thickness: 5.5 cm
Local shading	No	1.0 m overhang	No	1.0 m overhang
Lighting template	Incandescent	LED	Incandescent	LED
Lighting control	No	Yes	No	Yes
Lighting schedule	24/7	Mon.–Sun. 6 p.m.–7 a.m.	24/7	Mon.–Sun. 6 p.m.–7 a.m.
HVAC template	Fan coil unit (4-pipe) Air Cooler chiller	Fan coil unit (4-pipe) with district cooling	Oil heating	Fan coil unit (4-pipe) with district heating+ cooling
HVAC Schedule	12/7	6/7	24/7	24/7
Heating: Fuel	No	No	Natural gas, COP = 0.9	Natural gas, COP = 0.9
Cooling: Fuel	Electricity from grid	Electricity from green energy	Electricity from grid	Electricity from green energy
Other ventilation	Natural ventilation (NV)	Natural ventilation (NV)	Natural ventilation (NV)	Natural ventilation (NV)

3.4. Description of the Photovoltaic Panel

In this study, photovoltaic panels with different areas, according to the cities, placed on the roof of a building located in the tropical and temperate climates, were introduced. The different cells were made of polycrystalline, with a base load of direct current by an inverter. Its optimal inclination was fixed at 37°, oriented toward the south in the case of Paris, Brussels, and Washington and 45° oriented toward the north in Douala, Dakar, and Antananarivo cities [24].

3.5. Model Validation

Validation is applied by comparing simulation and measured data. We analysed two parameters: monthly energy consumption and hourly air temperature. In this study, two formulas mentioned in ASHRAE guideline 14 [25] were applied: coefficient of variation of

square root error (RMSE) and mean bias error (MBE). The different RMSE and MBE values were evaluated, taking into account the two Equations (1) and (2) [25].

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

$$\mathrm{MBE}(\%) = \frac{\sum_{i=1}^{N}(Mi - Si)}{\sum_{i=1}^{N} Mi} \quad (2)$$

where Si and Mi were simulated data and measured data over a given interval I, respectively, the total number of data implemented, M is the total number of measured data.

In Guideline 14 of ASHRAE [26], it is recommended that a simulation model can be considered calibrated if the following conditions are fulfilled:

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

The present research work is a continuation of a previous study [23] where a comparison between measurement and simulation data is shown and a small difference and negligible error between these two categories of data are concluded.

The various results of the calculations carried out show that the MBE value found is 0.6%, and that of RMSE is 0.2%. However, the values required in the ASHRAE-14 directive are between (−10%; +10%), counting as (MBE), and (−30%; +30%), counting as (RMSE). By observing these results, we deduce that the hourly values of MBE and RMSE found in this research are within the range requested by ASHRAE. On the basis of the previous results, we conclude that this simulation model is calibrated with different hourly data. In addition, a comparison between the monthly energy values was made. The value of the MBE obtained is −4.6%, while that of the RMSE obtained after the calculation is 0.7%. In accordance with ASHRAE, the various acceptable limits are between (−5%; +5%) representing the (MBE) and (−15%; +15%) representing the (RMSE). By comparing these results, it can easily be deduced that the MBE and RMSE values for the various monthly data are within the range recommended by ASHRAE (2002). Thus, the new simulation model can be considered as calibrated with the different monthly data and, therefore, the set of these two results shows that the new model can be validated.

3.6. Experiment

Before analysing the developed experiment, it is of interest to highlight that the building studied in the case of countries located in the tropical region is a copy of a residential building designed in Antananarivo city.

As it was shown before, it is of interest to comment that an experiment in this building in 2017 [27] was carried out. In this experiment, 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, and wind speed, between other variables. Finally, the measurement data and response of occupants allowed us to evaluate the comfort rate of residential buildings, as was described in reference [27].

4. Results and Discussion

4.1. Case of Residence Building Located in the Tropical Region

In this section, the simulation results of buildings placed in the tropical regions are showed and the sum-up is in Tables 6 and 7. In particular, Table 6 shows a comparison of monthly air temperature (°C) before and after the building revision.

Table 6. Variation of indoor air temperature in tropical regions.

Month		January	February	March	April	May	June	July	August	September	October	November	December
Original Residence building	Antananarivo	25.21	24.83	25.47	24.64	23.45	21.74	20.75	21.10	23.27	24.51	25.56	25.12
	Douala	26.66	26.59	26.36	26.13	26.17	25.80	25.35	25.04	25.10	25.62	26.05	26.54
	Dakar	24.66	24.84	25.18	25.19	26.00	26.64	27.04	26.98	27.20	27.20	26.91	25.90
Residence after renovation	Antananarivo	25.25	25.02	25.33	24.48	23.27	21.75	20.75	21.03	23.08	24.56	25.44	25.21
	Douala	26.19	26.24	26.10	25.88	25.89	25.49	25.14	24.96	25.08	25.41	25.52	26.04
	Dakar	24.78	24.96	25.21	25.30	25.82	26.46	26.92	26.91	27.05	27.02	26.71	25.75

Table 7. Annual operational carbon and energy demand in the residential building of tropical regions.

Cities		Antananarivo	Douala	Dakar	Total
Residence in the initial state	Energy demand (kWh)	3149.31	10,276.65	21,593.81	
	Carbon emission rate (kg CO_2)	1722.95	7366.85	13,085.86	
Renovated residence (applying: renovation + passive strategies + PV)	Surface of installed photovoltaic panels (m^2)	16	34	58	
	Cooling energy (kWh)	0.00	0.00	0.00	
	Energy demand (kWh)	2564.80	6944.28	13,874.95	0
	Green energy generated (kWh)	−2565.00	−6944.30	−13,875.01	
	Carbon emission rate (kg CO_2)	−3149.30	−140.51	3278.49	

4.1.1. Analysis of Indoor Conditions and Energy Consumption in Tropical Regions

First of all, it must be explained that indoor conditions are dependent on outdoor conditions, which were obtained from the Meteonorm tool. In particular, in Figure 5, it can be observed that Antananarivo has a wet tropical climate with a range of air temperature, relative humidity, and Predicted Mean Vote (PMV) [28] of 20.99 °C to 26.04 °C, 45% to 75%, and −2.07 to 0, respectively. At the same time, in Douala, the air temperature was between 25.45 °C and 27.37 °C and the relative humidity varied from 68.81% to 73.65%. From these results, it was concluded that, despite the fact that they have the same building construction, it is less comfortable in Douala than Antananarivo, which is located on several mountains. Indeed, climate conditions seem to be more favourable in the cities located in an altitude than in the coastal cities [25], which are dominated by heat [27].

In Antananarivo:

$$\mathrm{PMV} = 0.106\mathrm{Top} - 4.11,\ (R = 0.43);\ \mathrm{Rh} = 1.208\mathrm{Top} + 24.19,\ (R = 0.42) \quad (3)$$

In Dakar:

$$\mathrm{PMV} = 0.286\mathrm{Top} - 7.99,\ (R = 0.57);\ \mathrm{Rh} = 3.993\mathrm{Top} - 43.78,\ (R = 0.73) \quad (4)$$

In Douala:

$$\mathrm{PMV} = 0.980\mathrm{Top} - 26.41,\ (R = 0.85);\ \mathrm{Rh} = -\ 2.199\mathrm{Top} + 128.8,\ (R = 0.88) \quad (5)$$

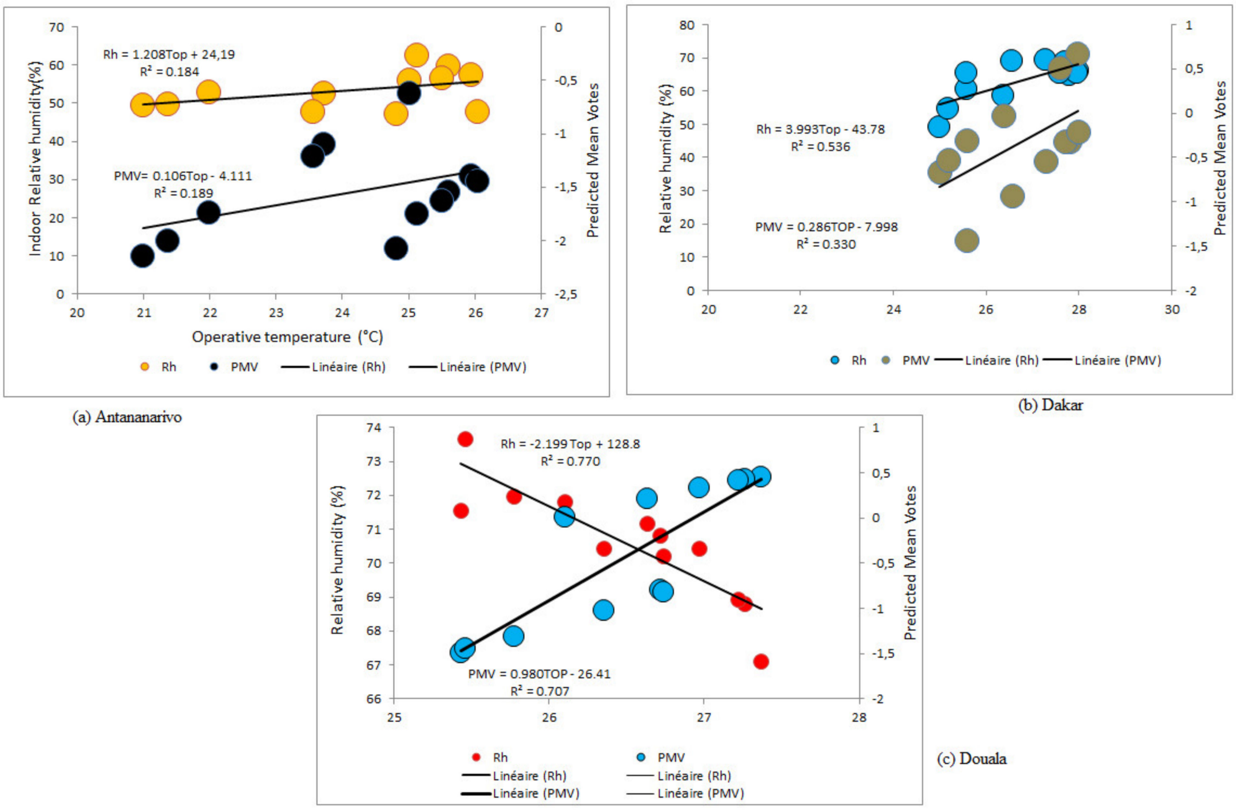

Figure 5. Variation of relative humidity and Predicted Mean Votes function of operative temperature in: (**a**) Douala; (**b**) Antananarivo; (**c**) Dakar.

The average indoor air temperature in the residence building placed in three Sub-Sahara Africa cities is given in Table 6.

In Table 6, the average indoor air temperature before and after the revision process can be observed. From this table, it can be concluded that the temperature decreases in the renovated residence when it is compared with the existing one. As a consequence, the cooling energy demand showed in Figure 5 and Table 7 was equal to zero after a renovation. This result shows that the choice of the most adapted materials to the local climate can significantly reduce the cooling energy demand. From this table, it was observed that renovation allows reducing the energy consumption between 9.7% and 35.5% in these three cities. Furthermore, the energy demand is 63% higher in the coastal region than in high altitude regions, which confirms the previous study carried out by Nematchoua et al. [29–32]. In particular, in Table 7, it can be observed that, after the revision process, the zero-energy objective is respected (the sum of the energy demand and the green energy generated by some photovoltaic panels (PV) is equal to zero).

At the time of analysing the energy savings, it is of interest to pay special attention to PV behaviour. In this sense, it is important to note that the size of the PV varies according to the region. Figure 5 shows that the PV is more efficient in Antananarivo than in Douala and Dakar cities. For these two cities, the solution to PV's inability, to meet monthly energy, is to store the excess electricity produced during sunny periods. At the same time, it was obtained that the energy generated by photovoltaic panels is the most efficient in the dry season. Indeed, it decreases from 8% to 23% in the three cities between rainy (May–September) and dry seasons (Figure 6a–c).

Figure 6. Monthly energy demand and production by photovoltaic panels in Dakar city (**a**); Douala (**b**); and Antananarivo (**c**).

This energy saving has some implications. In this sense, the carbon emission rate is negative in Antananarivo and Douala, which means that these residences remove more CO_2 than it emits into the atmosphere. Furthermore, it was observed that this rate is very low in Dakar (9.58 kg CO_2/m^2) compared to the initial concentration of carbon set to 38.26 kg CO_2/m^2. This reduction of carbon, estimated to be 74.96%, may be due to the implementation of sustainable materials and the application of passive strategy techniques [29].

Finally, from these results, it can be concluded that the renovation of the building requires an additional cost, but it improves indoor air quality [33]. Due to its related effect, in the next subsection, the impact of renovation by analysing investment cost will in turn be analysed.

Similar to air temperature, relative humidity has a significant effect on energy use in the buildings. Indeed, as explained by Aktas et al. [34], improving thermal comfort while reducing energy consumption in a building requires careful management of humidity levels, as well as careful selection of building materials.

4.1.2. Cost Analysis

At the time of evaluating the economic investment, it must be considered that the standards show an estimated investment of a low energy building from 35% to 55% higher than a conventional residential building. In this particular case study, the analysis of the cost is based on many assumptions, as detailed in Tables 8 and 9. In this sense, an increase between 40% and 70% was observed when compared to the basic price to reach the standard building with zero-energy and a payback period of 6.3 years. Furthermore, it is of interest to highlight that the transition between traditional structural work, respecting the energy performance of the building, and structural work respecting the low energy standard, leads to an increase in costs, which can vary from 35 to 55%.

Table 8. The average cost parameter applied at the building level in Sub-Saharan Africa [35].

Currency and Exchange Rate	
Currency Symbol	**$**
Applicable construction labour Hours and local cost index	
Regional material cost index	0.06
Hourly labour rate worker	$0.23–3.01
Hourly labour rate craftsman	$0.21–1.9
Discount factor (capital cost) and inflation	
Discount rate (cost of capital)	18.0%
General inflation rate	8.0%
Energy inflation rate	6.2%
Water inflation rate	5.2%
EOL as % of capex	1.5%

Table 9. Evaluation of residential building cost.

	Parameters	Values
Initial state of the building	Residence area	342 m^2
	Annual heating requirements	0
	building life cycle	50 years
	Price of the closed building structural work	30,000 € including VAT
	Electricity price	0.15 € per kWh
	Electricity consumption	2564.8 kWh per year
	Electricity cost	19,236 € for 50 years
Residence building+ PV installed	The price of the closed building structural work	32,400 € including VAT
	PV cost	2400 €
	Saving cost	16,836 € for 50 years
	Payback	6.23 years

4.2. Case of Residence Building Located in the Temperate Region

4.2.1. Analysis of Indoor Conditions and Energy Consumption

As a base case, to be compared with the results obtained in the tropical region, the building placed in the temperate climate region was analysed. In this sense, three cities located in the countries of France, Belgium, and the United States were chosen. The building placed in this new climatic region shows some differences in morphology and occupation in accordance with its typical design. In particular, the occupation rate is 0.0303, which means a person for 33 m^2 of area. Finally, it is important to notice that, at the time of the revision process, the PV area varied depended on micro-climate.

The main results were summed up in Tables 10 and 11 shown. In the revised building, there is a more comfortable indoor air temperature. In particular, Figure 7 shows the comparison of heating energy demand in the temperate region before and after the revision process. After renovating this residential building, it was noticed that the heating energy decreases to 31.4% (from 89.45 kWh/m^2 to 61.37 kWh/m^2) in Paris; to 33.3% (between 93.3 kWh/m^2 and 62.2 kWh/m^2) in Washington; and to 30.4% (between 95.7 kWh/m^2 and

66.6 kWh/m^2) in Brussels. Finally, from Table 11, it can be deduced that, in the three cities, green energy generated is equal to the energy demand. Furthermore, the results showed that the heating energy represents between 60% and 91% of total energy consumption in a residential building in the temperate region, which confirms the results found by Olonscheck et al. [36]. In this sense, in order to produce green electricity equal to the building energy demand, it is necessary to combine two different renewable technologies: gas cogeneration and photovoltaic panels. The required PV area is 58 m^2 in Brussels, 45 m^2 in Paris, and 42 m^2 in Washington DC with this combined cogeneration solution, but would extend to 194 m^2 in Brussels, 151 in Paris, and 141 m^2 in Washington DC without the cogeneration. This combined solution produces nearly zero annual operational carbon in the three cities, so an economical study will be shown in the next section.

Table 10. Comparison of indoor air temperature (in °C) in one residence building located in three cities.

Month		Jan.	Feb.	Mar	Apr	May	Jun.	Jul.	Aug	Sep.	Oct.	Nov	Dec
Original residence	Brussels	16.42	16.56	17.42	18.09	16.94	18.65	21.56	21.19	17.65	18.57	17.41	16.85
	Paris	16.74	16.81	17.53	18.30	18.20	20.33	22.53	23.12	19.50	18.69	17.53	16.87
	Washington	15.90	16.66	17.83	18.60	20.72	23.80	25.02	24.32	22.23	20.08	17.78	16.60
Renovated residence	Brussels	15.87	15.93	16.61	17.36	15.75	17.63	20.55	20.00	16.53	17.94	16.78	16.24
	Paris	16.11	16.05	16.74	17.62	17.02	19.24	21.64	22.16	18.12	18.03	16.76	16.03
	Washington	16.13	16.26	16.89	17.45	14.16	16.87	21.10	21.19	19.19	17.70	16.23	16.18

Table 11. Annual operational carbon and electricity demand in the residential buildings located in temperate climates.

	Cities	Brussels	Paris	Washington
Initial building	Cooling electricity (kWh/m^2)	1.02	2.46	2.48
	Heating and domestic hot water (Gas) (kWh/m^2)	37.71	34.96	33.20
	Electricity demand (kWh/m^2)	25.46	24.90	22.06
	Carbon emission rate (kg CO_2/m^2)	18.64	18.39	16.89
Revised building	Surface of installed photovoltaic panels (m^2) for a building area of 342 m^2	58.00	45.00	42.00
	Green electricity produced by gas cogeneration (kWh/m^2)	40.96	38.99	37.03
	Heating and domestic hot water (Gas cogeneration) (kWh/m^2)	37.71	34.96	33.20
	Cooling electricity (kWh/m^2)	0	0	0
	Electricity demand (kWh/m^2)	20.36	18.77	14.54
	Green electricity generated (kWh/m^2)	−17.11	−14.74	−10.71
	Carbon emission rate (kg CO_2/m^2)	−2.60	−0.11	2.17

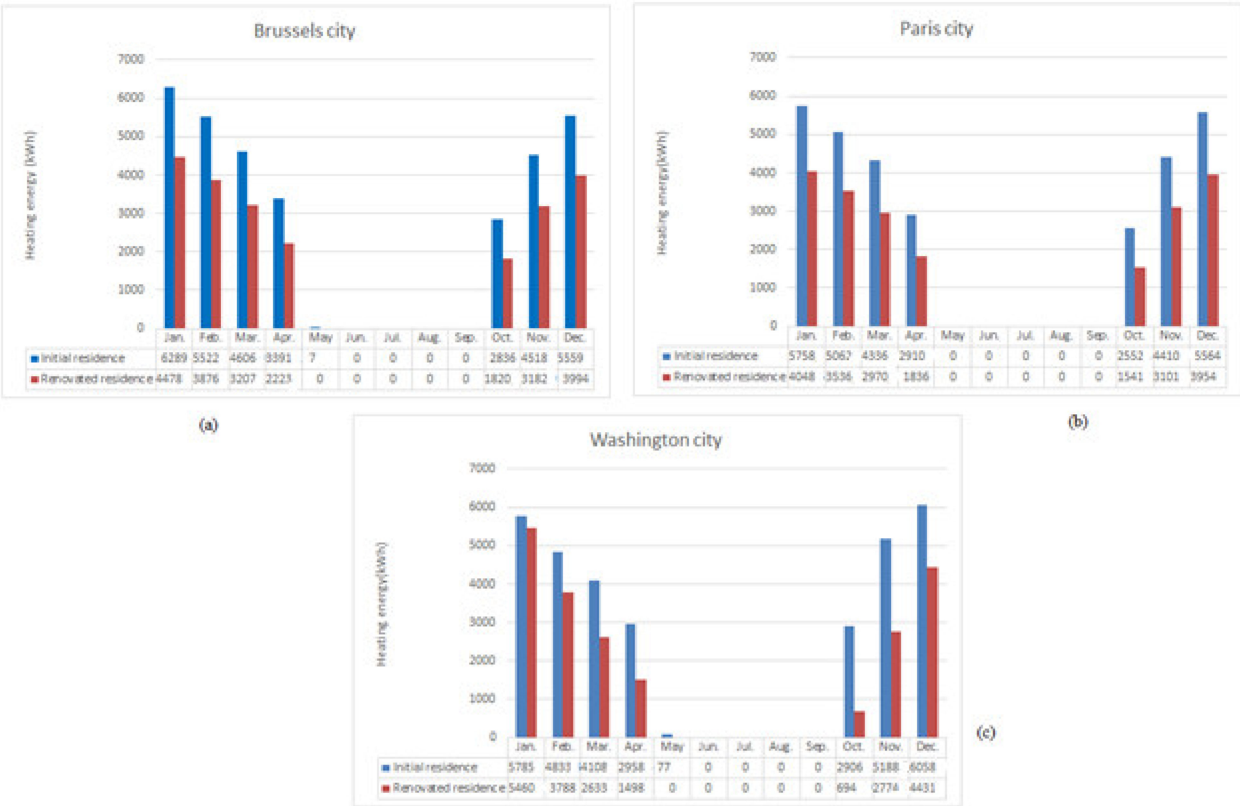

Figure 7. Heating energy in Brussels (**a**), Paris (**b**), and Washington DC (**c**).

4.2.2. Cost Analysis

Some details regarding the evaluation of cost are given in Table 12. From this table, it was concluded that this house meets the criteria of the passive house and a payback period of 3.8 years to amortize the initial economical investment in the revised building.

Table 12. Evaluation of cost.

Buildings	Parameters	Values
Initial state of the building	Initial investment	350,000 € including VAT
	Area	342 m^2
	Annual heating requirements (case of Brussels)	13.81 kWh/m^2
	Electricity price	0.25 €/kWh
Residence building + PV installed	The price of the closed building structural work	385,000 €
	Price of energy demand (cooling+ heating+ electricity+ domestic hot water)	9163.5 € per year
	Payback	3.8 years

Finally, from these results, it can be concluded that the investment cost and energy consumption are more important in a residential building located in temperate rather than in tropical climates. In particular, the energy consumption is around 78.2% higher in temperate than tropical climates and, at the same time, the investment cost is 12 times higher in temperate than tropical climates.

5. Conclusions

With the aim to define the energetic and economic interest of the transition to zero-energy in residential buildings in tropical climates, the energy performance of two standard residential buildings selected in tropical and temperate regions was improved towards zero-energy and low carbon emissions. The results showed that the zero-energy building concept is the most likely in the tropical region in favour of its geographical position. In particular, the zero-energy buildings are reached with an average indoor air temperature between 20.8 °C and 25.6 °C in the continental tropical region; from 24.7 °C to 27.2 °C in the coastal tropical regions; and from 16.4 °C to 25.1 °C in the temperate regions. In consequence, it was obtained that the renovation allowed a reduction of the energy consumption up to 36% in the tropical region with a payback of 6.3 years, whereas heating energy decreases from 30 to 34% in the three cities studied. These results are related to the location of the city and the seasonal efficiency of the PV, between other parameters.

Although a similar energy saving was obtained in temperate and tropical regions, and the investment cost is higher in the temperate region than in the tropical one, it was obtained that the payback is nearly half.

Finally, the results of this study can be applied in other countries with a similar climate. Furthermore, this study can serve as a guide for all those who wish to invest in sustainable construction. Another future, more detailed study will allow us to understand in depth the impact of the choice of construction materials in green buildings.

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Transition to Zero Energy and Low Carbon Emission in Residential Buildings Located in Tropical and Temperate Climates

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Abstract: Different methods to achieve zero-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. Being aware of this fact, a study was carried out to analyse the design of new buildings respecting the "zero-energy and low carbon emission" concept in tropical climatic regions when they are compared with a base case of temperate regions. To reach this objective, the comparison between real and simulated data from the different buildings studied was developed. The results showed that the renovation of existing residential buildings allows for reducing up to 35% of energy demand and a great quantity of CO_2 emissions in both climate types. Despite this, the investment rate linked to the construction of zero-energy buildings in tropical zones is 12 times lower than in temperate zones and the payback was double. In particular, this effect can be related to the efficiency of photovoltaic panels, which is estimated to be, at least, 34% higher in tropical zones than temperate zones. Finally, this study highlights the interest and methodology to implement zero-energy buildings in tropical regions.

Keywords: zero-energy; low carbon; residential buildings; tropical; temperate climate

1. Introduction

Between 2000 and 2020, the average concentration of carbon dioxide (CO_2) emitted increased by approximately 2–3% each year [1]. In 2018, China (29.7%), the United States (13.9%), India (6.9%), the EU28 (9.1%), Russia, (4.6%) and Japan (3.2%)—the world's largest CO_2 emitters—together accounted for 51% of the population, 80% of total fossil fuel consumption, and 67.5% of total fossil CO_2 emissions in the world [2]. Nevertheless, efforts to reduce the carbon rate have been observed by the most polluting countries with activities like reducing building energy consumption. In this sense, a net-zero-energy building (ZEB) means that the total amount of energy used, calculated on an annual basis, is roughly equal to the amount of renewable energy created on the site [3].

Nowadays, in European Union countries (Belgium, France, Italy), primary energy demand in the building sector represents almost 40% of total energy [4]. Moreover, for the past ten years, it has been noticed that the building sector emitted up to 36% of greenhouse

gas, and produced 38% of wastes [4]. In particular, in Brussels, construction and operation represent 98% of the water flow, 75% of energy demand, 65% of greenhouse gas emissions and about 33% of waste generated each year [5]. In consequence, this city has set itself the ambition of reducing energy consumption up to 30% by 2030 and up to 40% of carbon emissions in the construction sector [5]. Another example of a European city is Paris, where the building sector (residential and tertiary) accounts for 80% of the region's energy consumption, and 20% of the emission of greenhouse gas. In consequence, the city of Paris aims to reduce energy consumption by 1/3 by 2030, and by 50% by 2050. To reach this objective, a new climate plan provides for massive renovations of social and tertiary housing in this city [6]. Another example of non-European cities is Washington, where the carbon emission intensity decreased by 4.9% in 2019 [7]. Finally, in Sub-Saharan Africa (Senegal, Cameroon, and Madagascar), the building sector consumes more than 25% of total primary energy, which is generated by fossil fuels and emitting thousands of tons of carbon into the atmosphere each year. This CO_2 concentration is almost negligible compared to those produced in developed countries.

In general, it is interesting to highlight that, although most of these countries have a lot of potential resources (solar, hydro, wind), they are exploited at less than 5%. This situation remains very serious due to how strongly carbon emissions have a negative impact on global warming and, in consequence, it is important to take action to protect the environment. In this sense, the energy renovation of old buildings and the design of new buildings, mainly powered by renewable energy, can contribute enormously to the reduction of greenhouse gas emissions. What is more, stand-alone buildings can be the start of the solution but there are few guides to reach this objective.

Different recent research works aim to be examples of standalone buildings. Some of them evaluated the possibility to reach zero-energy and low carbon in buildings, yet the regulations and objectives set by several international organizations are not enough to be applied on a large scale [8].

In this sense, it is interesting to highlight that, although zero-energy building is more favourable in tropical and hot zones due to more favourable climatic factors, it was observed that countries located in temperate zones are more involved in the implementation of this new technology. In particular, most of the zero-energy buildings use the power grid for energy storage, but some are grid independent [9].

The development of zero-energy buildings has become possible not only thanks to advances in new energy technologies and construction techniques like solar panels, heat pumps, and low-emissivity triple glazing, but also thanks to researchers, who collect precise data on the energy performance of traditional and experimental buildings and provide parameters for advanced computer models to predict the efficiency of engineering designs [10]. In this sense, some recent research works were carried out in this field in the temperate region. For instance, after a strong study on one residential building located in Boston city in 2006, Szejnwald et al. [11] showed that renovation is the best technique for allowing the reduction of the significant part of energy demand. In 2017, the results of studies conducted by Yi et al. [12] explained that although the studies detail step-by-step the different processes of implementing zero-energy in new constructions, it is often difficult in practice to make this objective, because of the variety of outdoor climates according to the seasons. The results of studies conducted by Szalay and Zold [13] aiming to design zero-energy buildings showed that it is easier to achieve the ZEB by grouping buildings according to their geometrical shape and age. The research conducted by Zhou et al. [14] in an office building in China showed that the choice of HVAC systems has a significant impact on the implementation of zero-energy in buildings in temperate zones. This study recommended adopting energy efficiency techniques according to the local climate of each region. With the aim of increasing the energy performance of buildings over their entire life cycle, in order to increase the possibilities of achieving zero-energy building, Srinivasan et al. [15] found a new method aimed at optimizing the production of energy generated by renewable sources. The research carried out by Robert and Kummert [16]

based on the "Morphing" method made it possible to analyse, on the basis of hourly data for the last 50 years and a general circulation model, the impacts of global warming on the implementation of NZEB in the temperate zone. The results showed that global warming significantly impacted zero-energy buildings. The study carried out by Pikas et al. [17] aimed to estimate the optimal cost of the energy performance of the residential building with almost zero energy consumption. The results explained that very few methods allow estimating the optimal cost of the energy used in these residences.

Despite these previous works about temperature regions, there is a lack of information about tropical cities and the possibilities to improve the energy consumption in their buildings. In this sense, tropical cities are some of the most favourable regions for the implementation of ZEB but the rate of buildings respecting the zero-energy concept is very low in this region of the world. In this sense, the study carried out in 2019 by Nematchoua and Sigrid [18] aimed to assess the different possibilities for the implementation of residential buildings with zero-energy and low carbon emissions in sub-Saharan Africa. The results showed that the most efficient solution to consider a zero-energy building in the city of Antananarivo requires an additional expenditure estimated at 40% of the initial cost of the building. This will result in savings of $475 per year starting in 2030, and also about a 99% reduction in carbon emissions.

In consequence, the objective of this study is to assess and analyse the cost and energy use with the implementation of residential buildings with zero-energy and low carbon emissions in tropical regions (sub-Saharan Africa), taking as reference this same analysis in temperate zones. In particular, paying special attention to the energy production generated by photovoltaic panels in hot zones and then the impact of heating on energy demand in temperate zones. The final objective is to show to architects, engineers, urban planners, investors, politicians, even non-specialists in energy and the environment, a simple methodology to analyse the energetic and economic interest into building new zero-energy and low carbon buildings in different climate regions.

To reach this objective, the present work is constituted of several parts: an analysis of some keywords in the second part; a methodology, results, and discussion, and finally the conclusions.

2. Keywords Analysis

The systematic structure of this manuscript is shown in Figure 1.

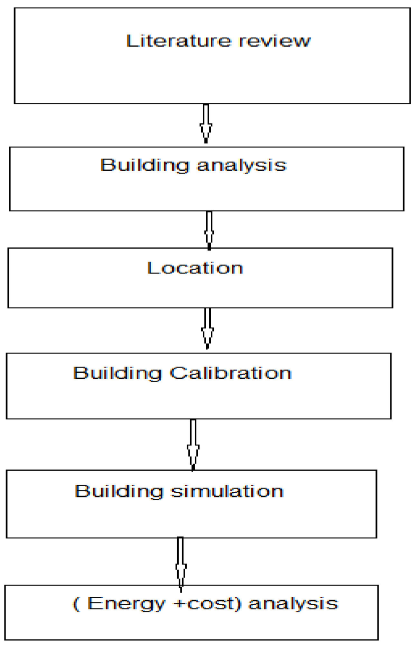

Figure 1. Research conceptual framework.

2.1. Buildings and Zero-Energy Concept

Before carrying out different research works and case studies about zero-energy and low-carbon buildings, it is important to do a previous analysis about the different concepts of existing low environmental impact housing in order to make more understandable some practical cases which will be presented in this research.

2.1.1. Nearly Zero-Energy Building

A nearly zero-energy building is economical in primary energy. The nearly zero quantity required for heating, cooling, lighting, domestic hot water, and ventilation is thus covered by solar heat or by renewable energy sources as well as by reasonable technical installations. In this sense, in the European Union, a building energy performance requirement was set between 2014 and 2021 as shown in Table 1.

Table 1. Evolution of the energy performance requirements of buildings from 2014 to 2021 for the residential and commercial buildings in some European Union countries [19].

Type of Building Construction	Building Energy Performance (2014)	Building Energy Performance (2017)	Nearly Zero-Energy Building (2021)
Overall level of thermal insulation (kWh/m^{2}year)	≤35	≤35	≤35
Overall energy performance of the building (residential building) (kWh/m^{2}year)	≤80	≤65	≤45
Overall energy performance of the building (commercial building) (kWh/m^{2}year)	≤80	€ (65–90)	€ (45–90)
Primary energy demand (kWh/m^{2}year)	≤130	≤115	≤85

2.1.2. Passive Building

The objective of a passive house is to consume very little energy while ensuring high thermal comfort in summer and winter as well as good air quality. Once again, in the European Union, some criteria must be respected to obtain the label "passive building", as shown in Table 2.

Table 2. Criteria for a passive building [20].

Passive Building	Criteria
Heating energy (kWh/m^{2}year)	≤15
Primary energy (kWh/m^{2}year)	≤120
Air tightness (vol/h)	≤0.6
Annual overheating hours (>25 °C)	≤5%

It is interesting to highlight that heating requirements of less than 15 kWh per m^2 and year are four to six times less than a new conventional building and up to ten times less than an existing building over ten years old.

2.2. Zero-Energy Building

It is a building that produces all the energy that it needs. It is interesting to note that a zero-energy building does not necessarily meet the criteria for a passive building. We must distinguish a building called energetically sufficient from a building called energetically autonomous.

(i) An energy-efficient building is capable of producing, over a year, an amount of energy proportional to the amount of energy it consumes. However, it will not necessarily consume the energy it needs when it produces it. Example: consider a building for which we install photovoltaic panels. During sunny periods (in summer), the panels will generate electricity at their optimum efficiency [21], and the house will supply energy to the grid. During the rest of the time or during a dead period such as in winter, the panels will not always supply enough electricity. Consequently, the dwelling cannot do without the electrical network. However, the total annual balance is zero since the excess production in summer compensates for the lack in winter.

(ii) An energetically autonomous building must not be connected to the electrical distribution network. When the panels cannot produce as much electricity as needed, the batteries used to store the excess electricity produced during sunny periods provide the electricity. To achieve energy independence, the building has above-average levels of insulation.

The principle of the zero-energy building, therefore, differs from that of the passive house, since it consists of compensating for total consumption, whatever it is, and not in optimizing the conditions favouring the energy sobriety of the house.

2.3. Positive-Energy Building

A building is said to be positive energy when it produces more energy than it consumes. A positive-energy building can be a passive building with enough renewable energy sources, or a building that does not meet the criteria to be a passive building, but still has a surplus of overall energy production.

3. Methodology

As it was shown before, the present paper aims to show a methodology for designing new buildings respecting the zero-energy concept, adding, as original consideration, the climatic regions where the buildings are placed and taking as reference the temperate regions. To reach this objective, three temperate countries and three tropical countries, with their typical building constructions, were selected. In consequence, weather data and simulations were employed to define the energy consumption and economical investment needed in each case study and its comparison will let define the more interesting region to implement the zero-energy concept. All these items will be described in the next sections.

3.1. Location

This study was carried out in three developed countries (Belgium, France, and the United States) located in a temperate climate, and three developing countries (Cameroon, Senegal, and Antananarivo) located in Sub-Sahara Africa (tropical climate).

The study took place in the capital of each country, as these study locations were chosen based on their environmental (climatic), energy, and social differences. The three cities selected in this study, and placed in Sub-Saharan Africa, are of very high solar potential (which is favourable to the supply of PV) and also the wind speed, which is favourable to the installation of wind turbines (speed between 5 m/s and 10 m/s).

The countries located in temperate zones such as Belgium, France, and the United States, have climatic conditions less favourable to zero-energy objectives because of the low sunshine in winters. However, important reforms are being carried out in these countries with the objective of achieving zero-energy and low carbon in 2050. This study aims to support this approach.

3.1.1. Studied Locations

Sub-Saharan Africa is made up of 48 countries with varying climates. It is one of the regions of the world that is very rich in biodiversity, and, above all, one of the most vulnerable to climate change. More than 80% of the population from this region are under 35 years old. Three of the cities in this study are located in this region: the city of Douala located in Cameroon, the city of Antananarivo in Madagascar, and Dakar in Senegal.

(1) Located between 4°03′ N and 9°4′ E, the city of Douala is the economic capital of Cameroon. Douala covers 923 km^2 and is strongly dominated by the tropical climate essentially made up of two seasons: the dry season from November to April and the rainy season from April to November.
(2) Dakar is the main city of Senegal. It is a coastal city located on the edge of the Atlantic Ocean. This city is dominated by the tropical climate and crossed by the monsoon coming from the southwest which is a humid wind bringing rain, and also a dry wind (the Harmattan). Dakar is one of the largest metropolises in Africa with a very high growth rate.
(3) Located 1435 m above the sea, the city of Antananarivo, the political capital of Madagascar, is spread over 350 km of surface. The city of Antananarivo is strongly dominated by the tropical climate of such an altitude. It has notably cool, mild winters and very rainy summers. Figure 2 gives the geographical location of these different cities studied, while Table 3 shows some climatic characteristics.
(4) Brussels is the capital of Belgium, the French Community of Belgium, the Flemish Community, and the seat of several European Union institutions. The climate of Brussels is temperate and influenced by the Gulf Stream. The proximity to the sea has a strong influence on this climate. The climate of Brussels is generally characterized by mild and rainy winters and relatively cool and humid summers.
(5) Washington DC is one of the world's largest cities, located in the mid-Atlantic region of the East Coast of the United States, between Virginia and Maryland. The nation's capital is around 40 miles south of Baltimore, 30 miles west of Annapolis and the Chesapeake Bay, and 108 miles north of Richmond. Founded in 1791, Washington DC is the place where the seat of the American congress is located [22]. Major factors determining Washington's climate include the large semi-permanent high-pressure and low-pressure systems of the North Pacific Ocean, the continental air masses of North America, and the Olympic and Cascade Mountains [22]. In spring and summer, a high-pressure anticyclone system dominates the North Pacific Ocean, causing air to spiral out in a clockwise fashion [22].
(6) Paris is the capital city of France, and the largest city in France. The area is 105 km^2. Paris is also the centre of the French economy, politics, traffic, and culture. The climate of Paris is said to be a warm temperate. The rainfall in Paris is significant, with precipitation even during the driest month. The average annual temperature in Paris is 11.3 °C. Figure 3 shows location of some cities studied in this research.

Figure 2. Location of three studied cities.

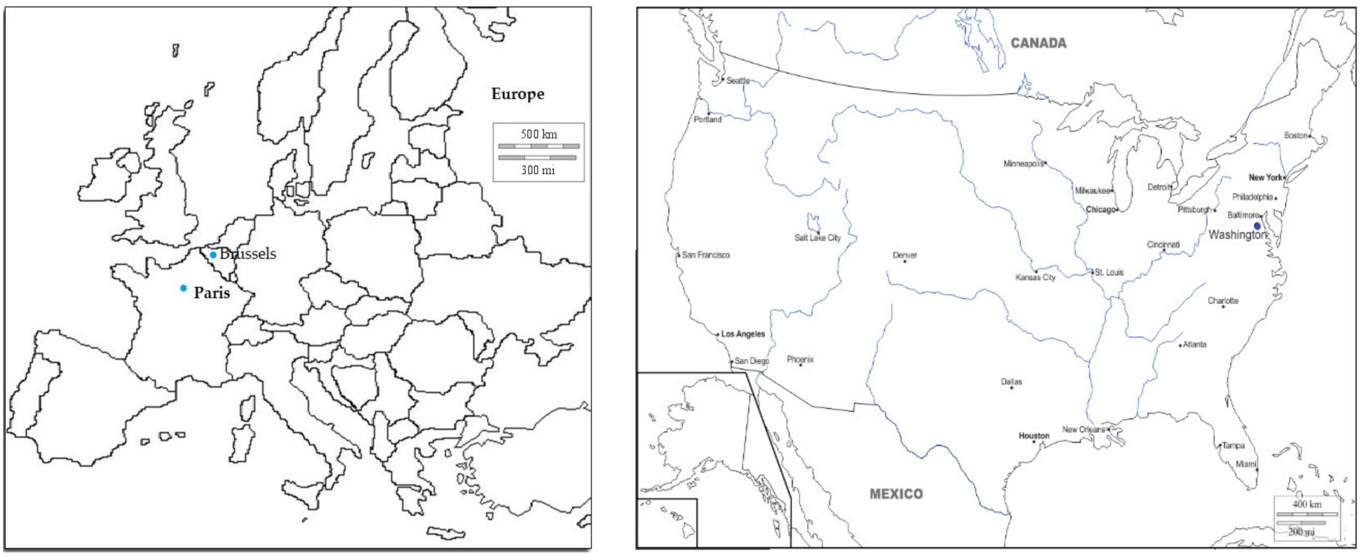

Figure 3. Location of Brussels and Paris (**on right**) and Washington DC (**on left**).

3.1.2. Climatic Data

In this research, all the climate data for simulations are downloaded from American Meteonorm software (Version 7.3.3, Meteotest AG (Bern, Switzerland)), based on the geographical coordinates of each city. The software provided the possibility to download data in hours, days, or months according to our requirements. Hourly data of temperature, relative humidity, airspeed, solar radiation, and precipitation for the last 30 years were collected for all the climate regions.

3.2. Buildings

This research was carried out about residential buildings. The type of building and construction materials varied according to the countries and this is why there were two categories of residential buildings (one more adapted in a temperate climate and another in a tropical climate). In this sense, the different buildings have different shapes with different structure materials and different areas, which can accommodate several people as shown in Table 4.

- The first residential building designed for this project, and located in the tropical region, was a simple one-floor family house consisting of four bedrooms, a shower room, and a kitchen. The building materials mainly consisted of Earth bricks and essentially glazed windows (glass thickness: 5.5 cm).
- The second residential building designed for this project, and located in the temperate region, was a familiar residence composed of two bedrooms, a living room, kitchen, and restroom. The different building materials are detailed in Table 4.

Table 3. Information regarding the six selected representative countries.

No	Country	City	Climate	Location	Temp.(°C)		RH (%)	
					Min	Max.	Min.	Max.
1	Belgium	Brussels	temperate	50.85° N, 4.35° E	−1	30	30	90
2	Cameroon	Douala	tropical	4.05° N, 9.76° E	18	37	30	90
3	France	Paris	temperate	48.85° N, 2.35° E	−10	31	30	90
4	Madagascar	Antananarivo	tropical	18.87° S, 47.50° E	10	35	55	90
5	Senegal	Dakar	tropical	14.72° N, 17.46° W	15	35	30	100
6	United States	Washington	temperate	38.90° N, 77.03° W	−2	33	30	98

From this Table 4, it can be observed that most of the materials chosen in the case of renovated residence buildings have low thermal conductivity and embodied carbon almost equal to zero. The goal is to select the materials that are more sustainable (low conductivity and embodied carbon). The lower the thermal conductivity of a material, the more this material has a huge capacity to limit heat transfer.

3.3. Simulation Tools

In this study, version (5.5.2) of the Design Builder software (Stroud, UK) was employed. This software is highly renowned in this field and has served as the basis for thousands of works of scientific research. Design Builder software, the same as TRNSYS, DOE, Pleiades, Helios, etc. software, is very well known in the field of simulation, optimization, modelling, BIM (Building Information Modelling), LCC (Life Cycle Cost), LCA (Life Cycle Assessment), etc.

This software is coupled with the Energy Plus (version 8.2, funded by the U.S. Department of Energy's (DOE) Building Technologies Of-fice (BTO)) tool to assess the consumption and energy demand of a building [23] and offers the most building materials with their physical thermal property. The modelling of the building selected is shown in Figure 4.

Table 4. Thermal characteristics of building constructions.

Region	Building Category	Building Clement	Layer	Component	Thickness (m)	Thermal Conductivity (W/mK)	Density (kg/m^3)	Specific Heat Capacity (J/kg K)	Embodied Carbon (kg CO_2/kg)	U-Value (W/(m^{2}K))
Tropical region	Residence in the initial state	Exterior wall	Layer1	Plaster	0.025	0.500	1300	1000	0.12	2.750
			Layer2	Concrete block	0.120	1.630	2300	1000	0.08	
			Layer3	Plaster	0.050	0.500	1300	1000	0.12	
		Partition wall	Layer	Concrete block	0.120	1.630	2300	1000	0.08	5.850
		Roof	Layer1	Clay Tile	0.025	1.000	2000.0	800	0.46	0.160
			Layer2	Stone Wool	0.242	0.040	30.0	840	1.05	
			Layer3	Roofing felt	0.005	0.190	960.0	837	-	
	Residence after renovation	Exterior wall	Layer	Wood	0.153	0.040	110	1800	0.00	0.250
		Partition wall	Layer	Wood	0.070	0.040	110	1800	0.00	0.250
		Roof	Layer1	Clay Tile	0.025	1.000	2000.0	800	0.46	0.160
			Layer2	Stone Wool	0.242	0.040	30.0	840	1.05	
			Layer3	Roofing felt	0.005	0.190	960.0	837	-	
Temperate region	Residence in the initial state	Exterior wall	Layer1	Plaster	0.030	0.500	1300	1000	0.12	0.330
			Layer2	Concrete	0.140	0.510	1400	1000	0.08	
			Layer3	Extruded polystyrene	0.120	0.034	35	1400	2.88	
			Layer4	Facing brick	0.090	0.620	1700	800	0.22	
		Partition wall	Layer1	Plaster	0.030	0.500	1300	1000	0.12	1.570
			Layer2	Brick	0.140	0.720	1920	840	0.22	
			Layer3	Plaster	0.030	0.500	1300	1000	0.12	
		Roof	Layer1	Roof tiles	0.030	0.550	1900	837	0.05	0.180
			Layer2	Wooden lathing	0.038	0.130	2800	896	0.45	
			Layer3	Air gap	0.025	-	-	-	-	
			Layer4	Wood	0.042	0.120	510	1380	0.45	
			Layer5	Rock wool	0.400	0.100	500	1000	0.98	
			Layer6	composite wood	0.018	0.040	160	1888	0.19	

Table 4. *Cont.*

Region	Building Category	Building Clement	Layer	Component	Thickness (m)	Thermal Conductivity (W/mK)	Density (kg/m^3)	Specific Heat Capacity (J/kg K)	Embodied Carbon (kg CO_2/kg)	U-Value (W/(m^{2}K))
	Residence after renovation	Exterior wall	Layer1	Plaster	0.030	0.500	1300	1000	0.12	0.350
			Layer2	Concrete	0.140	0.510	1400	1000	0.08	
			Layer3	Wood frame	0.030	0.120	510	1380	0.45	
			Layer4	ISOCELL cellulose	0.020	0.100	400	1360	-	
			Layer5	Composite wood panel	0.020	0.250	900	1000	0.12	
			Layer6	Wooden cladding	0.022	0.130	160	1800	0.05	-
		Partition wall	Layer1	Plaster	0.030	0.50	1300	1000	0.12	1.570
			Layer2	Brick	0.140	0.720	1920	840	0.22	
			Layer3	Plaster	0.030	0.500	1300	1000	0.12	
		Roof	Layer1	Roof tiles	0.030	0.550	1900	837	0.05	0.180
			Layer2	Wooden lathing	0.038	0.130	2800	896	0.45	
			Layer3	Air gap	0.025	-	-	-	-	
			Layer4	Wood	0.042	0.120	510	1380	0.45	
			Layer5	Hemp wool	0.400	0.037	800	1000	0.00	
			Layer6	Composite wood	0.018	0.130	1000	1000	0.01	

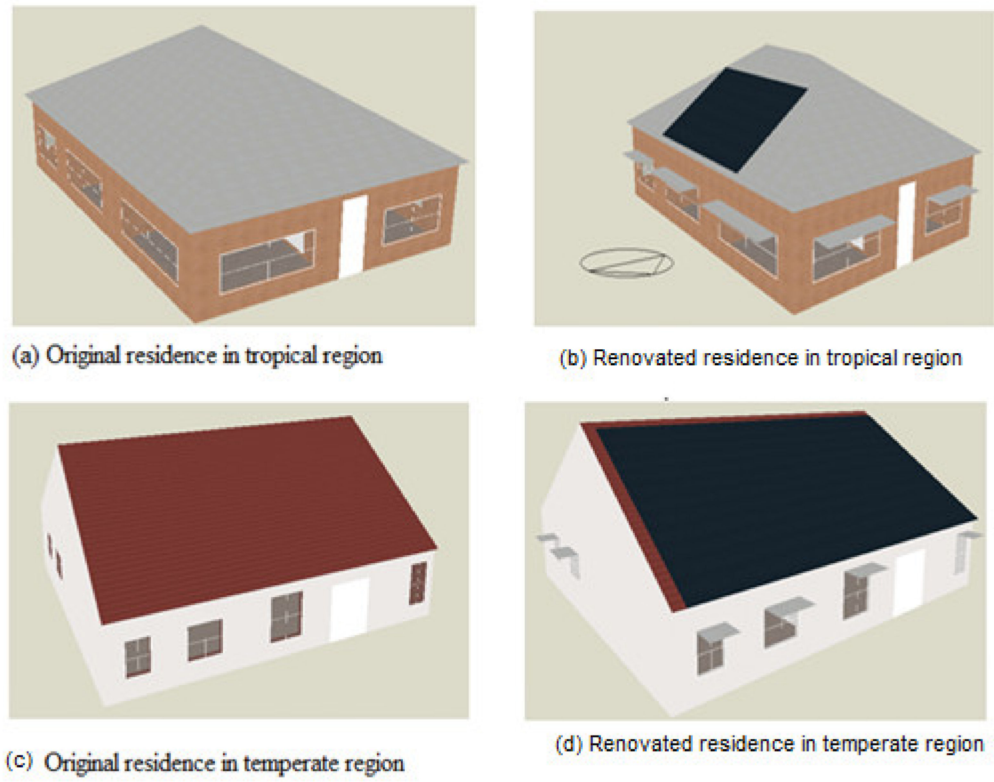

Figure 4. Case of (**a**,**b**) renovated residence building in the tropical region and (**c**,**d**) temperate climate.

In this sense, it is interesting to highlight that the design builder software automatically gives the embodied carbon of each type of material used during the construction of the building, as well as the quantity of carbon produced during the operational phase of the building. As a consequence, the total carbon emission rate during the life cycle assessment of the building can be freely obtained.

In the case of a building located in the tropical climate, the efficiency of the solar panels is very high due to the high concentration of solar radiation throughout the year, and it is not needed to add another source of energy such as a wind turbine to achieve the "Zero-Energy Building" objective. In contrast, in the case of a building located in a temperate climate, it was necessary to associate the photovoltaic panels (PV) and wind turbines to reach the "Zero-Energy Building" to maintain the same area of PV installed in a building located in the tropical region. Indeed, in the temperate region, the sunshine is high only in summer, which is why the PV has a low yield in this region. The input data of the simulation software is shown in Table 5.

Table 5. Input data for the simulations.

Parameters (Renovated Residence = After Applying Renovation, Passive Strategy, and Green Energy)	Building Located in the Tropical Region		Building Located in the Temperate Region	
	Initial State	**After Renovation**	**Initial State**	**After Renovation**
Height (m)	3.5	3.5	3.5	3.5
Area (m^2)	342.0	342.0	342.0	342.0
Activity template	Domestic House	Domestic House	TM_3-Bed Living Kitchen	TM_3-Bed Living Kitchen
Occupancy density (people/m^2)	0.0230	0.0230	0.0303	0.0303

Table 5. *Cont.*

Parameters (Renovated Residence = After Applying Renovation, Passive Strategy, and Green Energy)	Building Located in the Tropical Region		Building Located in the Temperate Region	
	Initial State	After Renovation	Initial State	After Renovation
Activity (met)	0.9	0.9	0.9	0.9
Clothing (Clo)	0.5–1.0	0.5–1.0	0.5–1.0	0.5–1.0
DHW: consumption rate (l/m^2-day)	0.53	0.53	0.72	0.52
Fresh air (l/s-person)	10	10	10	10
Lighting: target luminance (lux)	100	100	125	100
Computer: power density(W/m^2)	0.200	0.180	0.200	0.105
Other equipment: power density (W/m^2)	3.58	3.58	3.58	3.58
Occupancy schedule	24/7	24/7	24/7	24/7
Construction template	Project construction template	Project-construction template	Project construction template	Project construction template
Air tightness (vol/h)	0.5	0.5	0.5	0.5
Glazing template	Project glazing template	Project glazing template	Project glazing template	Project glazing template
Glazing type	Preferred height 1.5 m, 30% glazed Thickness: 5.5 cm	Preferred height 1.5 m, 30% glazed Thickness: 5.5 cm	Preferred height 1.5 m, 30% glazed Thickness: 5.5 cm	Preferred height 1.5 m, 30% glazed Thickness: 5.5 cm
Local shading	No	1.0 m overhang	No	1.0 m overhang
Lighting template	Incandescent	LED	Incandescent	LED
Lighting control	No	Yes	No	Yes
Lighting schedule	24/7	Mon.–Sun. 6 p.m.–7 a.m.	24/7	Mon.–Sun. 6 p.m.–7 a.m.
HVAC template	Fan coil unit (4-pipe) Air Cooler chiller	Fan coil unit (4-pipe) with district cooling	Oil heating	Fan coil unit (4-pipe) with district heating+ cooling
HVAC Schedule	12/7	6/7	24/7	24/7
Heating: Fuel	No	No	Natural gas, COP = 0.9	Natural gas, COP = 0.9
Cooling: Fuel	Electricity from grid	Electricity from green energy	Electricity from grid	Electricity from green energy
Other ventilation	Natural ventilation (NV)	Natural ventilation (NV)	Natural ventilation (NV)	Natural ventilation (NV)

3.4. Description of the Photovoltaic Panel

In this study, photovoltaic panels with different areas, according to the cities, placed on the roof of a building located in the tropical and temperate climates, were introduced. The different cells were made of polycrystalline, with a base load of direct current by an inverter. Its optimal inclination was fixed at 37°, oriented toward the south in the case of Paris, Brussels, and Washington and 45° oriented toward the north in Douala, Dakar, and Antananarivo cities [24].

3.5. Model Validation

Validation is applied by comparing simulation and measured data. We analysed two parameters: monthly energy consumption and hourly air temperature. In this study, two formulas mentioned in ASHRAE guideline 14 [25] were applied: coefficient of variation of

square root error (RMSE) and mean bias error (MBE). The different RMSE and MBE values were evaluated, taking into account the two Equations (1) and (2) [25].

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

$$\mathrm{MBE}(\%) = \frac{\sum_{i=1}^{N}(Mi - Si)}{\sum_{i=1}^{N} Mi} \tag{2}$$

where Si and Mi were simulated data and measured data over a given interval I, respectively, the total number of data implemented, M is the total number of measured data.

In Guideline 14 of ASHRAE [26], it is recommended that a simulation model can be considered calibrated if the following conditions are fulfilled:

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

The present research work is a continuation of a previous study [23] where a comparison between measurement and simulation data is shown and a small difference and negligible error between these two categories of data are concluded.

The various results of the calculations carried out show that the MBE value found is 0.6%, and that of RMSE is 0.2%. However, the values required in the ASHRAE-14 directive are between (−10%; +10%), counting as (MBE), and (−30%; +30%), counting as (RMSE). By observing these results, we deduce that the hourly values of MBE and RMSE found in this research are within the range requested by ASHRAE. On the basis of the previous results, we conclude that this simulation model is calibrated with different hourly data. In addition, a comparison between the monthly energy values was made. The value of the MBE obtained is −4.6%, while that of the RMSE obtained after the calculation is 0.7%. In accordance with ASHRAE, the various acceptable limits are between (−5%; +5%) representing the (MBE) and (−15%; +15%) representing the (RMSE). By comparing these results, it can easily be deduced that the MBE and RMSE values for the various monthly data are within the range recommended by ASHRAE (2002). Thus, the new simulation model can be considered as calibrated with the different monthly data and, therefore, the set of these two results shows that the new model can be validated.

3.6. Experiment

Before analysing the developed experiment, it is of interest to highlight that the building studied in the case of countries located in the tropical region is a copy of a residential building designed in Antananarivo city.

As it was shown before, it is of interest to comment that an experiment in this building in 2017 [27] was carried out. In this experiment, 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, and wind speed, between other variables. Finally, the measurement data and response of occupants allowed us to evaluate the comfort rate of residential buildings, as was described in reference [27].

4. Results and Discussion

4.1. Case of Residence Building Located in the Tropical Region

In this section, the simulation results of buildings placed in the tropical regions are showed and the sum-up is in Tables 6 and 7. In particular, Table 6 shows a comparison of monthly air temperature (°C) before and after the building revision.

Table 6. Variation of indoor air temperature in tropical regions.

Month		January	February	March	April	May	June	July	August	September	October	November	December
Original Residence building	Antananarivo	25.21	24.83	25.47	24.64	23.45	21.74	20.75	21.10	23.27	24.51	25.56	25.12
	Douala	26.66	26.59	26.36	26.13	26.17	25.80	25.35	25.04	25.10	25.62	26.05	26.54
	Dakar	24.66	24.84	25.18	25.19	26.00	26.64	27.04	26.98	27.20	27.20	26.91	25.90
Residence after renovation	Antananarivo	25.25	25.02	25.33	24.48	23.27	21.75	20.75	21.03	23.08	24.56	25.44	25.21
	Douala	26.19	26.24	26.10	25.88	25.89	25.49	25.14	24.96	25.08	25.41	25.52	26.04
	Dakar	24.78	24.96	25.21	25.30	25.82	26.46	26.92	26.91	27.05	27.02	26.71	25.75

Table 7. Annual operational carbon and energy demand in the residential building of tropical regions.

Cities		Antananarivo	Douala	Dakar	Total
Residence in the initial state	Energy demand (kWh)	3149.31	10,276.65	21,593.81	
	Carbon emission rate (kg CO_2)	1722.95	7366.85	13,085.86	
Renovated residence (applying: renovation + passive strategies + PV)	Surface of installed photovoltaic panels (m^2)	16	34	58	
	Cooling energy (kWh)	0.00	0.00	0.00	
	Energy demand (kWh)	2564.80	6944.28	13,874.95	0
	Green energy generated (kWh)	−2565.00	−6944.30	−13,875.01	
	Carbon emission rate (kg CO_2)	−3149.30	−140.51	3278.49	

4.1.1. Analysis of Indoor Conditions and Energy Consumption in Tropical Regions

First of all, it must be explained that indoor conditions are dependent on outdoor conditions, which were obtained from the Meteonorm tool. In particular, in Figure 5, it can be observed that Antananarivo has a wet tropical climate with a range of air temperature, relative humidity, and Predicted Mean Vote (PMV) [28] of 20.99 °C to 26.04 °C, 45% to 75%, and −2.07 to 0, respectively. At the same time, in Douala, the air temperature was between 25.45 °C and 27.37 °C and the relative humidity varied from 68.81% to 73.65%. From these results, it was concluded that, despite the fact that they have the same building construction, it is less comfortable in Douala than Antananarivo, which is located on several mountains. Indeed, climate conditions seem to be more favourable in the cities located in an altitude than in the coastal cities [25], which are dominated by heat [27].

In Antananarivo:

$$\text{PMV} = 0.106\text{Top} - 4.11, (R = 0.43); \text{Rh} = 1.208\text{Top} + 24.19, (R = 0.42) \quad (3)$$

In Dakar:

$$\text{PMV} = 0.286\text{Top} - 7.99, (R = 0.57); \text{Rh} = 3.993\text{Top} - 43.78, (R = 0.73) \quad (4)$$

In Douala:

$$\text{PMV} = 0.980\text{Top} - 26.41, (R = 0.85); \text{Rh} = -2.199\text{Top} + 128.8, (R = 0.88) \quad (5)$$

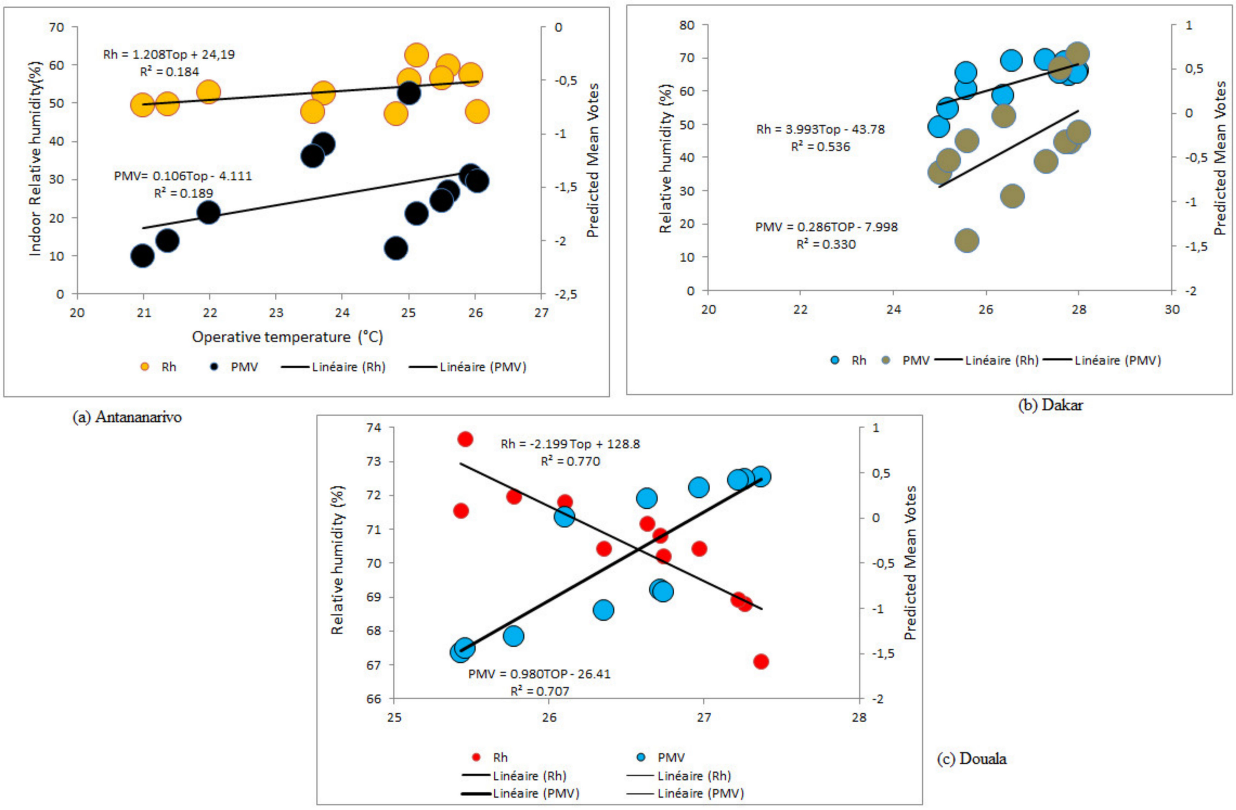

Figure 5. Variation of relative humidity and Predicted Mean Votes function of operative temperature in: (**a**) Douala; (**b**) Antananarivo; (**c**) Dakar.

The average indoor air temperature in the residence building placed in three Sub-Sahara Africa cities is given in Table 6.

In Table 6, the average indoor air temperature before and after the revision process can be observed. From this table, it can be concluded that the temperature decreases in the renovated residence when it is compared with the existing one. As a consequence, the cooling energy demand showed in Figure 5 and Table 7 was equal to zero after a renovation. This result shows that the choice of the most adapted materials to the local climate can significantly reduce the cooling energy demand. From this table, it was observed that renovation allows reducing the energy consumption between 9.7% and 35.5% in these three cities. Furthermore, the energy demand is 63% higher in the coastal region than in high altitude regions, which confirms the previous study carried out by Nematchoua et al. [29–32]. In particular, in Table 7, it can be observed that, after the revision process, the zero-energy objective is respected (the sum of the energy demand and the green energy generated by some photovoltaic panels (PV) is equal to zero).

At the time of analysing the energy savings, it is of interest to pay special attention to PV behaviour. In this sense, it is important to note that the size of the PV varies according to the region. Figure 5 shows that the PV is more efficient in Antananarivo than in Douala and Dakar cities. For these two cities, the solution to PV's inability, to meet monthly energy, is to store the excess electricity produced during sunny periods. At the same time, it was obtained that the energy generated by photovoltaic panels is the most efficient in the dry season. Indeed, it decreases from 8% to 23% in the three cities between rainy (May–September) and dry seasons (Figure 6a–c).

Figure 6. Monthly energy demand and production by photovoltaic panels in Dakar city (**a**); Douala (**b**); and Antananarivo (**c**).

This energy saving has some implications. In this sense, the carbon emission rate is negative in Antananarivo and Douala, which means that these residences remove more CO_2 than it emits into the atmosphere. Furthermore, it was observed that this rate is very low in Dakar (9.58 kg CO_2/m^2) compared to the initial concentration of carbon set to 38.26 kg CO_2/m^2. This reduction of carbon, estimated to be 74.96%, may be due to the implementation of sustainable materials and the application of passive strategy techniques [29].

Finally, from these results, it can be concluded that the renovation of the building requires an additional cost, but it improves indoor air quality [33]. Due to its related effect, in the next subsection, the impact of renovation by analysing investment cost will in turn be analysed.

Similar to air temperature, relative humidity has a significant effect on energy use in the buildings. Indeed, as explained by Aktas et al. [34], improving thermal comfort while reducing energy consumption in a building requires careful management of humidity levels, as well as careful selection of building materials.

4.1.2. Cost Analysis

At the time of evaluating the economic investment, it must be considered that the standards show an estimated investment of a low energy building from 35% to 55% higher than a conventional residential building. In this particular case study, the analysis of the cost is based on many assumptions, as detailed in Tables 8 and 9. In this sense, an increase between 40% and 70% was observed when compared to the basic price to reach the standard building with zero-energy and a payback period of 6.3 years. Furthermore, it is of interest to highlight that the transition between traditional structural work, respecting the energy performance of the building, and structural work respecting the low energy standard, leads to an increase in costs, which can vary from 35 to 55%.

Table 8. The average cost parameter applied at the building level in Sub-Saharan Africa [35].

Currency and Exchange Rate	
Currency Symbol	**$**
Applicable construction labour Hours and local cost index	
Regional material cost index	0.06
Hourly labour rate worker	$0.23–3.01
Hourly labour rate craftsman	$0.21–1.9
Discount factor (capital cost) and inflation	
Discount rate (cost of capital)	18.0%
General inflation rate	8.0%
Energy inflation rate	6.2%
Water inflation rate	5.2%
EOL as % of capex	1.5%

Table 9. Evaluation of residential building cost.

	Parameters	Values
Initial state of the building	Residence area	342 m^2
	Annual heating requirements	0
	building life cycle	50 years
	Price of the closed building structural work	30,000 € including VAT
	Electricity price	0.15 € per kWh
	Electricity consumption	2564.8 kWh per year
	Electricity cost	19,236 € for 50 years
Residence building+ PV installed	The price of the closed building structural work	32,400 € including VAT
	PV cost	2400 €
	Saving cost	16,836 € for 50 years
	Payback	6.23 years

4.2. Case of Residence Building Located in the Temperate Region

4.2.1. Analysis of Indoor Conditions and Energy Consumption

As a base case, to be compared with the results obtained in the tropical region, the building placed in the temperate climate region was analysed. In this sense, three cities located in the countries of France, Belgium, and the United States were chosen. The building placed in this new climatic region shows some differences in morphology and occupation in accordance with its typical design. In particular, the occupation rate is 0.0303, which means a person for 33 m^2 of area. Finally, it is important to notice that, at the time of the revision process, the PV area varied depended on micro-climate.

The main results were summed up in Tables 10 and 11 shown. In the revised building, there is a more comfortable indoor air temperature. In particular, Figure 7 shows the comparison of heating energy demand in the temperate region before and after the revision process. After renovating this residential building, it was noticed that the heating energy decreases to 31.4% (from 89.45 kWh/m^2 to 61.37 kWh/m^2) in Paris; to 33.3% (between 93.3 kWh/m^2 and 62.2 kWh/m^2) in Washington; and to 30.4% (between 95.7 kWh/m^2 and

66.6 kWh/m^2) in Brussels. Finally, from Table 11, it can be deduced that, in the three cities, green energy generated is equal to the energy demand. Furthermore, the results showed that the heating energy represents between 60% and 91% of total energy consumption in a residential building in the temperate region, which confirms the results found by Olonscheck et al. [36]. In this sense, in order to produce green electricity equal to the building energy demand, it is necessary to combine two different renewable technologies: gas cogeneration and photovoltaic panels. The required PV area is 58 m^2 in Brussels, 45 m^2 in Paris, and 42 m^2 in Washington DC with this combined cogeneration solution, but would extend to 194 m^2 in Brussels, 151 in Paris, and 141 m^2 in Washington DC without the cogeneration. This combined solution produces nearly zero annual operational carbon in the three cities, so an economical study will be shown in the next section.

Table 10. Comparison of indoor air temperature (in °C) in one residence building located in three cities.

Month		Jan.	Feb.	Mar	Apr	May	Jun.	Jul.	Aug	Sep.	Oct.	Nov	Dec
Original residence	Brussels	16.42	16.56	17.42	18.09	16.94	18.65	21.56	21.19	17.65	18.57	17.41	16.85
	Paris	16.74	16.81	17.53	18.30	18.20	20.33	22.53	23.12	19.50	18.69	17.53	16.87
	Washington	15.90	16.66	17.83	18.60	20.72	23.80	25.02	24.32	22.23	20.08	17.78	16.60
Renovated residence	Brussels	15.87	15.93	16.61	17.36	15.75	17.63	20.55	20.00	16.53	17.94	16.78	16.24
	Paris	16.11	16.05	16.74	17.62	17.02	19.24	21.64	22.16	18.12	18.03	16.76	16.03
	Washington	16.13	16.26	16.89	17.45	14.16	16.87	21.10	21.19	19.19	17.70	16.23	16.18

Table 11. Annual operational carbon and electricity demand in the residential buildings located in temperate climates.

	Cities	Brussels	Paris	Washington
Initial building	Cooling electricity (kWh/m^2)	1.02	2.46	2.48
	Heating and domestic hot water (Gas) (kWh/m^2)	37.71	34.96	33.20
	Electricity demand (kWh/m^2)	25.46	24.90	22.06
	Carbon emission rate (kg CO_2/m^2)	18.64	18.39	16.89
Revised building	Surface of installed photovoltaic panels (m^2) for a building area of 342 m^2	58.00	45.00	42.00
	Green electricity produced by gas cogeneration (kWh/m^2)	40.96	38.99	37.03
	Heating and domestic hot water (Gas cogeneration) (kWh/m^2)	37.71	34.96	33.20
	Cooling electricity (kWh/m^2)	0	0	0
	Electricity demand (kWh/m^2)	20.36	18.77	14.54
	Green electricity generated (kWh/m^2)	−17.11	−14.74	−10.71
	Carbon emission rate (kg CO_2/m^2)	−2.60	−0.11	2.17

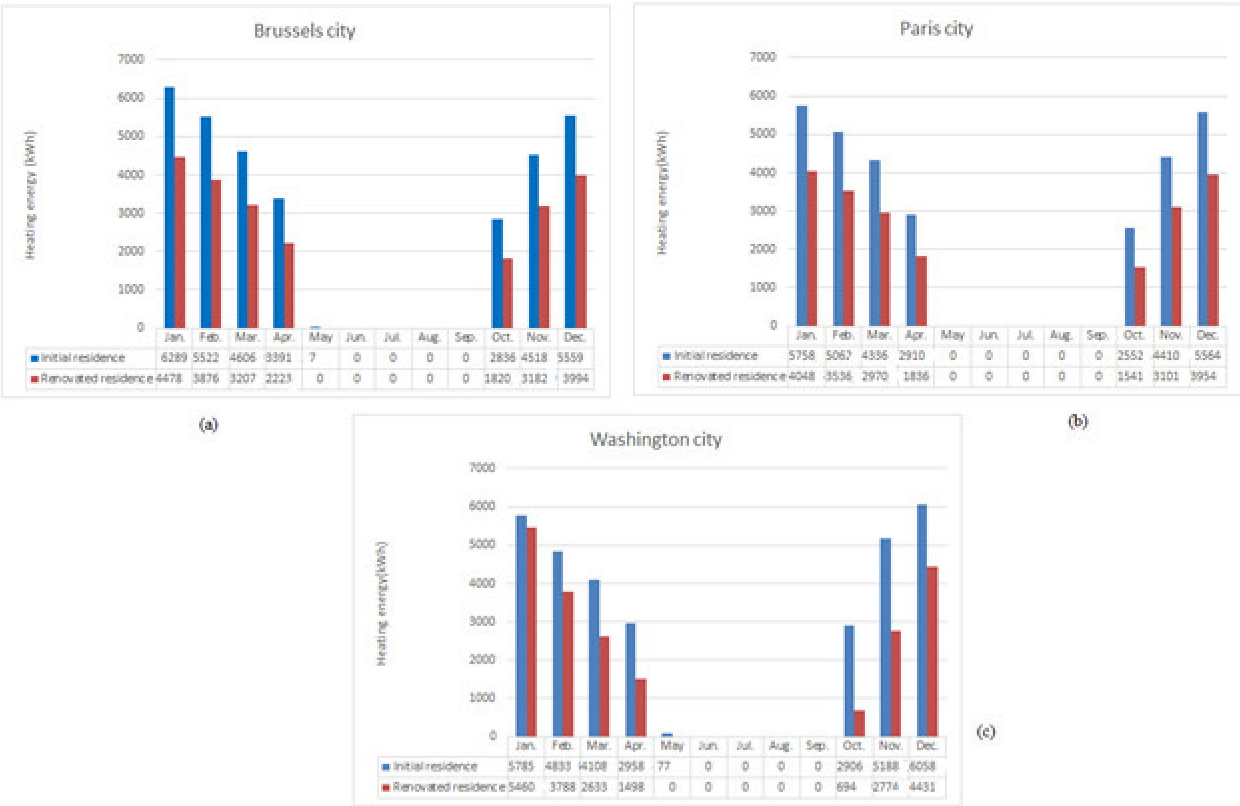

Figure 7. Heating energy in Brussels (**a**), Paris (**b**), and Washington DC (**c**).

4.2.2. Cost Analysis

Some details regarding the evaluation of cost are given in Table 12. From this table, it was concluded that this house meets the criteria of the passive house and a payback period of 3.8 years to amortize the initial economical investment in the revised building.

Table 12. Evaluation of cost.

Buildings	Parameters	Values
Initial state of the building	Initial investment	350,000 € including VAT
	Area	342 m^2
	Annual heating requirements (case of Brussels)	13.81 kWh/m^2
	Electricity price	0.25 €/kWh
Residence building + PV installed	The price of the closed building structural work	385,000 €
	Price of energy demand (cooling+ heating+ electricity+ domestic hot water)	9163.5 € per year
	Payback	3.8 years

Finally, from these results, it can be concluded that the investment cost and energy consumption are more important in a residential building located in temperate rather than in tropical climates. In particular, the energy consumption is around 78.2% higher in temperate than tropical climates and, at the same time, the investment cost is 12 times higher in temperate than tropical climates.

5. Conclusions

With the aim to define the energetic and economic interest of the transition to zero-energy in residential buildings in tropical climates, the energy performance of two standard residential buildings selected in tropical and temperate regions was improved towards zero-energy and low carbon emissions. The results showed that the zero-energy building concept is the most likely in the tropical region in favour of its geographical position. In particular, the zero-energy buildings are reached with an average indoor air temperature between 20.8 °C and 25.6 °C in the continental tropical region; from 24.7 °C to 27.2 °C in the coastal tropical regions; and from 16.4 °C to 25.1 °C in the temperate regions. In consequence, it was obtained that the renovation allowed a reduction of the energy consumption up to 36% in the tropical region with a payback of 6.3 years, whereas heating energy decreases from 30 to 34% in the three cities studied. These results are related to the location of the city and the seasonal efficiency of the PV, between other parameters.

Although a similar energy saving was obtained in temperate and tropical regions, and the investment cost is higher in the temperate region than in the tropical one, it was obtained that the payback is nearly half.

Finally, the results of this study can be applied in other countries with a similar climate. Furthermore, this study can serve as a guide for all those who wish to invest in sustainable construction. Another future, more detailed study will allow us to understand in depth the impact of the choice of construction materials in green buildings.

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