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Strategies and scenarios to reduce energy consumption and CO_2 emission in the urban, rural and sustainable neighbourhoods

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ABSTRACT

The building sector has become a major source of worldwide carbon emissions and energy consumption because of rapid population growth and a continuous environmental strain caused by humanity. A lack of consistent data on life-cycle carbon emissions and energy demand at the neighbourhood level has made it difficult to understand the origins of climate change at this scale. A sensitivity analysis brought clarity concerning the extent of environmental impacts on future climate evolution. From this perspective, the authors aimed to evaluate, analyse, compare, and provides recommendations to reduce carbon emissions, as well as the energy required by three types of neighbourhoods (urban, rural, and sustainable) located in and adapted to all countries worldwide. The most important parameters affecting carbon emission and energy consumption were analysed, including the energy mix of countries, local building materials and climate, technological solutions utilised, daily mobility, and occupied spaces. The results indicated that the highest levels of carbon dioxide emissions were produced by countries with prosperous economies, such as China, the United States, India, Germany, and Poland, because of high concentrations of coal in their energy mixes. Modernising cities through the construction of new eco-districts and increasing the use of new techniques for substantial renovations of outdated buildings worldwide could mitigate the amount of greenhouse gases emitted by neighbourhoods 53–97 % by 2050. Moreover, by combining substantial building renovations with the installation of photovoltaic panels on roofs, the objective of 'zero carbon' at the neighbourhood level could be achievable by 2050 in rural neighbourhoods. Radical changes in the judicious choice of construction materials and use of green energy production represent targeted opportunities to resolve the future climate dilemma.

1. Introduction

Nowadays, the building sector is denounced as one of the main sectors that produced an important quantity of carbon which accelerates global warming. Indeed, the various catastrophes that have occurred in many countries have typically been considered as indirect consequences of human actions on nature. In the aftermath of rapid industrialisation, neither the concentration of emitted carbon nor the energy demand stopped increasing (Wang et al., 2011). Between 2000 and 2020, the average concentration of carbon dioxide (CO_2) emitted increased approximately 3 % each year (Zhu et al., 2015). The populations of the least developed and developing countries comprise 80 % of the global population but only had an emission rate of approximately 41 % of the total worldwide emissions in 2004 (Raupach et al., 2007).

In recent years, China has been denounced as the main polluter but also the main force for mitigating carbon emissions and energy consumption worldwide (Liu, Guan et al., 2013). Additionally, China was recognised as the largest consumer of primary energy, consuming approximately half of the coal in the world in 2012 (Liu, Guan et al., 2013); and the 46.7 % in 2018 (according to the BP Energy year book). According to (Peters et al. (2012), China produced approximately 25 % of the entire worldwide carbon emissions in 2011. A significant increase in carbon emissions by countries with strong economies has substantially affected the climate (Jakob & Marschinski, 2013). Carbon

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emissions have varied according to the sources of energy production. Friedlingstein et al. (Friedlingstein et al., 2014) claimed that the efforts, asked by the Intergovernmental Panel on Climate Change (IPCC) to limit climate change below a fixed temperature threshold, required a quota limitation for the most polluting countries in the world. Indeed, according to the Kyoto Protocol, global CO_2 emissions fluctuated from 22.7–33.9 billion tons from 1990 to 2011 (The Kyoto Protocol, 2012). Liu, Xi, and Guan (2013) believed that the substantial carbon emissions margin between the most polluting and least polluting countries in the world could be related to the indifference existing in international climate negotiations.

Nevertheless, efforts to reduce the carbon rate have been observed by the most polluting countries. One strategy in China aimed at increasing energy efficiency in the building sector, as well as in various manufacturing processes (Liu, Guan, Moore et al., 2015). The major objective China had set was to reduce the carbon intensity of its economic production by up to 45 % from 2005 to 2020 (Guan et al., 2014). However, statistical data, published by each country with respect to energy demand and the rate of carbon emitted, have proven erroneous at times. For example, Liu, Xi et al. (2013) found that the energy consumption of China between 2000 and 2012 was actually 10 % higher than that of the value published for the same timeframe by national statistics (Liu, Guan, Wei et al., 2015).

Primary energy demand and CO_2 emissions are two interrelated environmental impacts. According to the IPCC (IPCC et al., 2014), the global energy consumption of buildings corresponds to 8,800 megatons of the total CO_2 emissions worldwide, which represents one-third of the carbon emissions of the total energy consumption. Energy awareness is an effective strategy aimed at encouraging the integration of energy efficiency in buildings (Asensio & Delmas, 2017). The 'square meter' (m^2) is generally the most adopted functional unit used to evaluate the energy efficiency of buildings (Couderc, 2018, Gao et al., 2019). According to Janet and Chester (Reyna & Chester, 2016), climate change is accelerating the demand for energy in buildings. In fact, temperature variation directly modifies the cooling and heating loads. Energy consumption and carbon emissions are dependent upon the behaviour of the occupants of buildings and their living modes (de Meester et al., 2013; Paige et al., 2019). (Paige et al. (2019) claimed that researchers were perplexed for a long time by the behaviour of inhabitants within their residences. In reality, the major goal of energy optimisation in buildings is difficult to achieve because of the lack of total control and the complexity of behaviours exhibited by the occupants. To deal with climate change, more efficient and sustainable energy consumption is required in residential buildings. It is anticipated that occupants can easily adopt energy efficient measures within their environments (Asensio, 2019). More rigorous analysis of the energy consumption of buildings, as well as the effects of climate change by this consumption, requires the use of more recent building data (Allouhi et al., 2015). Many global researchers use the empirical models developed in 1960 to assess the regulation of indoor climate; however, this is mainly based on standards that were developed for an average middle-aged male. It is imperative to assess the behaviours of both sexes to understand the overall behaviours of occupants (Kingma & Wouter van Marken, 2015), as well as the needs of the elderly (de Meester et al., 2013; Paige et al., 2019). In residential neighbourhoods, carbon emissions and energy consumption (in respect to heating and cooling) are increasing rapidly; this is, in part, because of the large variations exhibited in the outdoor climate (Chuan et al., 2019).

The building sector represents a key sector of energy demand and carbon emission, in particular in developed countries. Indeed, the increasing use of air conditioners, heating systems, the absence of passive strategies, and choice of building materials less suited to the climate, because of the high embodied energy and carbon, considerably impact energy demand and emissions of carbon in the building sector. An agreement adopted by the European Council and its Member States created an energy-climate package for 2030 aimed at imposing a reduction of at least 40 % in greenhouse gas emissions, an increase of at least 27 % in renewable energy production, and a reduction of at least 27 % in energy consumption of buildings based on their improved energy efficiencies. These goals will be respected by all Member States only if a sensitivity analysis is conducted in parallel within these states. Many building experts and designers recommend the application of passive strategy techniques and the use of renewable energies for the benefit of fossil fuels in order to reduce energy consumption and carbon concentration emissions from buildings. The introduction of photovoltaic (PV) panels on building envelopes or roofs generates local renewable electrical energy while reducing the load formerly borne by the electrical network (Couderc, 2018). Solar production represents an ecological alternative to generate electricity in a non-polluting way (Couderc, 2018). The majority of solar panels are recyclable. In a study carried out in Slovenia in 2019, Ascencio et al. (Ascencio-V & Topič, 2019) et al. explained that one of the best ways to fight climate change is to massively deploy photovoltaic panels across the whole world. The study conducted by Thomas and Andre (Thomas & André, 2020) in Paris, Lisbon and Stockholm, explained that to minimize the environmental impact and the production of CO2, it is imperative to renovate all the old existing buildings. Parid et al. (2011) Showed the need to use solar panels, explaining that the solar energy received on earth is around 1.8 × 1011 MW, which is much higher than the current rate of demand energy in the buildings and industries. It is very important to notice that other very interesting studies in the same field are detailed in (EPRI, 2010; Eskom, 2012; Groot et al., 2013; Kohle, Kohle, & Joshi, 2021).

These researches assess in detail the costs of installing and producing solar and fossil energy in order to draw a more elaborate table of the most plausible technologies to predict in the growing demand of energy. In addition, this research contains several originalities and new scientific contributions insofar as it attempts to resolve certain questions which have so far remained unanswered. Controlling the rate of carbon emissions and energy consumption at the neighbourhood level is a prerequisite for all nations; however, the literature does not elaborate on the evolution of environmental impacts at the neighbourhood level, which is essential to know and understand.

This study analyses this problem. In addition, although several previous studies have analysed CO_2 emissions and energy consumption at the building and neighbourhood levels, none have compared the various types of neighbourhoods (i.e. urban, rural, and sustainable) located within various countries worldwide, nor have studies examined the factors lying at the origin of life-cycle CO_2 emissions and energy consumption at the neighbourhood level on an international scale. Therefore, uncertainty remains on how to best mitigate the future effects of these emissions and consumption worldwide. Another novelty of this study is assessing the impact of occupants' behaviour on energy demand and carbon emission at the scale of three categories of neighbourhood. The main steps of this work are distributed into sections.

Section 2 will present the methodology used in this study. The results of the analysis will be detailed and discussed elaborately in Sections 3, and 4 will provide the major conclusions.

2. Link between climate change, CO_2 emission and energy

Many factors influence the level of GHG emissions. Globally, more than 60 % of greenhouse gas emissions produced by human activities come from the production and consumption of energy (https://www.rncan.gc.ca/science-donnees/donnees-analyse/donnees-analyse-energetiques/faits-saillants-sur-lenergie/energie-emissions-gaz-effet-serre-ges/20074, 2021). This includes activities such as the use of gasoline for transportation, the production of non-renewable electricity, the production of gas and oil, and the heating and cooling of buildings.

More, the concentration of greenhouse gases increases in the atmosphere, more it is effective in trapping infrared radiation, reducing infrared emissions to space, which leads to a warming of the planetary surface and of the lower layers of the atmosphere (https://www.rncan.

gc.ca/science-donnees/donnees-analyse/donnees-analyse-energetiques/-faits-saillants-sur-lenergie/energie-emissions-gaz-effet-serre-ges/20074, 2021). An increase in the concentration of greenhouse gases therefore results in an accumulation of energy in the climate system, which results in changes in the temperature of the oceans, surface air, and changes in the climate cycle of water, certain extreme events (heat waves, heavy precipitation), melting ice, and rising sea levels (https://www.rncan.gc.ca/science-donnees/donnees-analyse/donnees-analyse-energetiques/faits-saillants-sur-lenergie/energie-emissions-gaz-effet-serre-ges/20074, 2021; Liu, Guan, Wei et al., 2015).

This is how our energy consumption contributes to the phenomenon of global warming measured by meteorological and oceanographic data, and which is also called "climate change" to emphasize the fact that it is not only a question of warming but also changes in other aspects (cycle of water, atmospheric circulation, ocean acidification, sea level, extreme events) (https://www.rncan.gc.ca/science-donnees/donnees-analyse/-donnees-analyse-energetiques/faits-saillants-sur-lenergie/energie-emissions-gaz-effet-serre-ges/20074, 2021).

3. Methodology

According to the United Nations, the European Commission, and other international organizations, more than one-third of the total energy consumption and CO_2 emissions currently comes from the built environment. Buildings, therefore, can play a major role in the battle against global warming. To support this approach, we studied three types of neighbourhoods (urban, rural, and sustainable) and adapted them to various countries worldwide. Subsequently, we quantified the energy required and carbon rate emitted in these three neighbourhood types for each country over a period of 100 years. Aware that unique characteristics exist in each neighbourhood of the countries investigated, we identified parameters having a major influence on GHG emissions and adapted them according to the local context of each country; such as: energy mix, local climate, typical building materials utilised, development level of each country, occupant mobility, built space occupied by each inhabitant, and overall behaviours of the occupants in their habitats (cultural habits). Overall, this research was divided into five major stages.

(a) Modelling of the three neighbourhoods (urban, rural, and sustainable) by Pleiades ACV software.
(b) Quantification of the energy consumption and carbon emission rate of the three neighbourhood types in each country.
(c) Analysing different sources of CO_2 emissions and energy demand.
(d) Introduction of solar panels and substantial renovations of existing buildings for urban and rural areas by 2050.
(e) Analysis of the behaviours of the three neighbourhoods in 2030 and 2050.

3.1. Neighbourhood descriptions

The three neighbourhoods modelled and studied had different characteristics. The district showed in Fig. 1b presented all the criteria of a sustainable neighbourhood, regarding the references published by the experts of the University of Liege and other international Organizations Teller, Marique, Loiseau, Godard, and Delbar (2014). The sustainable neighbourhood consisted of dwellings with two, three, and four facades. The built-up area was mainly dedicated to housing, but it also offered commercial and dedicated spaces for small businesses. There were 40 small apartments, 11 duplex single-family homes, and 45 large dwellings, gardens, and private parking places. The net built density reached 40 dwellings per hectare. The outdoor space consisted of more than 30 % of green areas. Several rainwater recovery systems and reservoirs were in place. This research analysed only the residential part of the neighbourhood, which covered approximately 3.5 ha, with 1 ha of parking lots, roads, and alleys; 19,740 m^2 of living space; and 17,800 m^2

Fig. 1. Map of three neighborhoods studied in this research.
The district showed in figure (1b) presented all the criteria of a sustainable neighborhood, regarding the references published by the experts of the University of Liege and other international Organizations (Kohle et al. (2002); Nematchoua, Teller et al., 2019).

of green space. Other information regarding this neighbourhood was detailed by the authors (Nematchoua et al., 2019). This neighbourhood is located in a suburb of the capital city of each country studied.

The main technologies used in the design of this sustainable neighborhood are:

- Compact buildings, well oriented, taking into account the direction of the sunrise and sunset.
- Thermally insulated thick walls with air sealing,
- Double glazing with high thermal performance or triple glazing, limiting energy losses,
- Solar shading solutions, high inertia materials for interior wall surfaces, and intensive night ventilation to naturally cool the building,
- Building ventilation system, that is efficient both for the air quality and for reducing energy consumption,
- A high performance heating system associated with a smart thermostat system,
- The use of photovoltaic solar panels for electricity production.The picture of this sustainable neighbourhood is shown in Fig. 1(b).

The studied urban neighbourhood was located in the city centre and built during the 19th century, which was a period of rapid urbanisation in cities around the world. The neighbourhood consisted of several residences distributed around shopping centres and offices, and it spanned an area of 8,726 m^2. In this neighbourhood, the buildings were nearly the same in shape and structure. Details on the characteristics of this neighbourhood were published in 2019 by Nematchoua et al. (2019). Authors located this neighbourhood in the city centre of the capital of each country studied. Most of these buildings had at least two floors. Different geometric shapes. We could observe buildings with 2, 3 and 4 facades with different living areas.

Finally, the simulated rural neighbourhood covered an area of 19,457 m^2. It was a residential area only with a total number of accommodations three times lower than that of the urban area. There were not many roads or public transportation in this area. The buildings were old and typically built during the 19th and 20th centuries. The residences had various characteristics, which were detailed in the research conducted by Nematchoua et al. (2020a). Authors situated the rural neighbourhood in the far north of the capital of each country studied. The rural neighbourhood is shown in Fig. 1(c).

The authors adapted the built space occupied by each resident in each country and region. In the sensitivity analysis, the researchers looked at various reports established by the World Bank. In this study, the living area varied from 10 to 50 m^2 per inhabitant in the majority of the most developed countries (Canada, the United States of America (USA), Australia, the United Kingdom (UK), Germany, France, etc.) and from 5 to 30 m^2 in the least developed countries (Benin, Togo, Madagascar, Cambodia, Libya, etc.). The main characteristics of the three neighbourhoods studied are shown in Table 1.

In the Table 1, we can noticed that in the rural type, the number of inhabitants is lower than the number of buildings, because some of these buildings were unoccupied. The modelling of three neighbourhoods studied is showed in the Fig. 2

Table 1
Main reference characteristics of the three neighbourhoods studied.

Neighbourhood Type	Sustainable	Urban	Rural
Total surface area (m^2)	35,480	8,726	19,457
Total population in the neighbourhood	220	100	30
Number of buildings in the neighbourhood	20	30	40
Detached houses (%)	10 %	7 %	75 %
Semi-detached houses (%)	60 %	17 %	19 %
Terraced houses (%)	25 %	75 %	4 %
Apartments (%)	5 %	1 %	2 %
Net built density (dwellings/hectare)	38 dw/ha	35 dw/ha	20 dw/ha
% of surface area occupied by buildings	18 %	44 %	10 %

3.2. Assumptions for the input data

The authors first had to decide how best to adapt these three neighbourhoods to each country to assess and compare the environmental impacts (i.e. energy demand and greenhouse gases) in an equitable way and with an appropriate functional unit.

Note that we selected only the capitals of each country and their surroundings for the location of these three neighbourhoods. The simulation was based on urban neighbourhoods located in the city centre of each capital, sustainable neighbourhoods located in the suburbs of each capital, and rural neighbourhoods located at the periphery of each capital. Choosing the capital cities as study sites was not random; indeed, various research studies showed that in most countries of the world, the capital was considered the most populous city in the country and generated a high energy demand and carbon emissions. Geolocations of the studied sites are shown in Fig. 3.

For each country, the authors analysed the most significant parameters influencing the energy demand and carbon emissions, such as the energy mix, local climate, typical building materials utilised, and the level of development specific to each country; average space occupied by each inhabitant, and overall behaviours of the occupants in their habitats (cultural habits).

(a) Authors were aware that the situation of a country in times of war was not the same as during times of peace. This could have a significant impact on carbon emissions. To resolve this issue, authors have assumed that all the countries studied were living in a time of peace and that there were no wars between nations.
(b) Authors recognised that the energy mix varied from country to country. Additionally, several countries did not regularly publish their electric mix at the end of each year. In our sensitivity analysis, we used data collected by the International Energy Agency (https://www.eia.gov/international/data/world, 2019) and the energy information system of each country. The various energy sources (in %) of the energy mix and electric mix were considered and evaluated. These sources included nuclear, fuel, coal, gas, and renewable energies.
(c) The different values of the local climatic parameters of each country were evaluated with the most recent version of the American Meteonorm software (Remund et al., 2017). With this software and knowing the geographic coordinates of each city, it was possible to connect to an American satellite and download the climatic data specific to each city. The data provided by the Meteonorm software were reliable and have already contributed to several valuable publications from researchers all over the world. The database of this tool contained more than 6,200 cities and more than 8,325 weather stations worldwide.
(d) The information regarding typical building materials used in each country was assessed based on the building thermal regulation standards of each country for 2018–2020, information found on the UN-Habitat website, and various literature reviews (in the case of countries without construction standards).

Standard data on the daily mobility of occupants were proposed by the simulation tool based on the selected study regions. The different weekly journeys of occupants varied according to the types of neighbourhoods (Nematchoua, Teller et al., 2019; Nematchoua, Orosa et al., 2019; Nematchoua et al., 2020a). The data related to mobility is standard and offered by the software used. We have assumed that the daily mobility rate of occupants is 80 % in developed countries (USA, Japan, Germany, France, United Kingdom, etc.), and 50 % in developing countries (Cameroon, Madagascar, Haiti, Thailand, etc.). The distance of the weekly journey between the house and the shops (1000 m); distance from the public transport network (500 m), distance from home to work

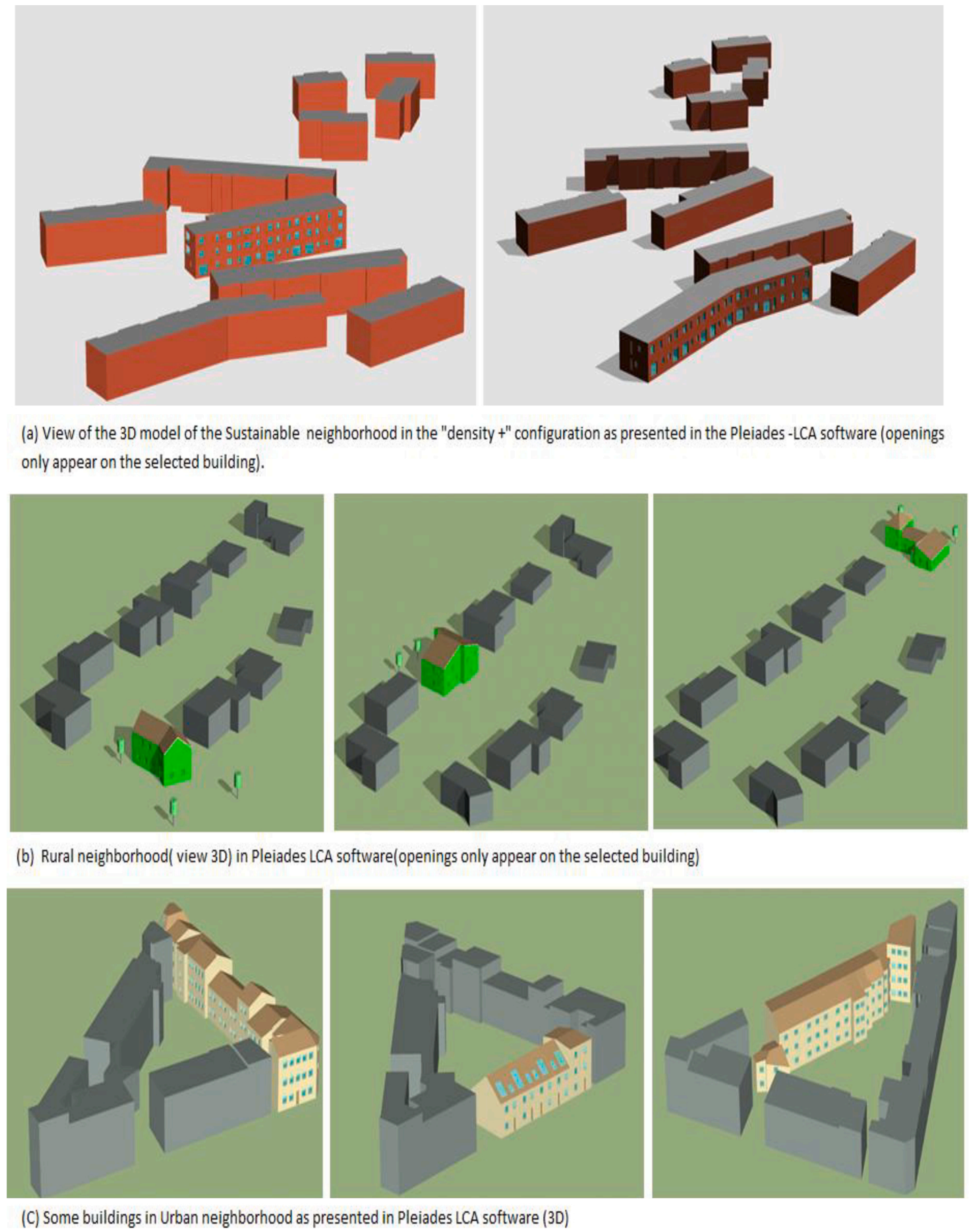

Fig. 2. Modelling of three neighborhoods in the PleiadesLCA software.

(5,000 m- 20,000 m). The trip made during 5 days a week and for 47 weeks a year. The means of public transport are bus, metro, and tram.

The activity of the occupants was considered standard in the different neighbourhoods. Authors assumed that all the occupants were in good health. This was the most favourable case; however, all scientific research has always been based on certain fundamental assumptions. The yield of the water system was fixed at 80 %; the hot water consumption was fixed at 40 L/day/person; while the cold water consumption was fixed at 100 L/day/person (Nematchoua, Teller et al., 2019; Nematchoua, Orosa et al., 2019). The concentration of waste produced by person per day was fixed between 0.6 and 0.9 kg in the case of poor countries, and from 0.8 to 1.2 kg in developed countries (Nematchoua et al., 2020b). Embodied energy is measured as the quantity of non-renewable energy per unit of building material, component or system. It is automatically calculated by the software after modelling of each residence building.

3.3. Environmental database

All the environmental data required for the assessment of the two studied environmental impacts were collected from the database of the Swiss-based ecoinvent, an international leader in the production of data associated with environmental impacts; ecoinvent is also renowned for the transparency of its methods (Ecoinvent Lci database, 2021). The different data for each material contained an inventory of the life-cycle with all the flows of materials and energy entering and leaving the system (Peuportier et al., 2006), which were as follows: (i) resources consumed (water, energy, etc.); (ii) emissions in various natural environments such as air, water, and soil (CO_2 in the air, ammonia in water, metals in the soil, etc.); and (iii) waste created (inert, toxic, or radioactive). We used one of the most recent versions of the database, ecoinvent 3.5.

In this research, we assessed two environmental impacts (life-cycle

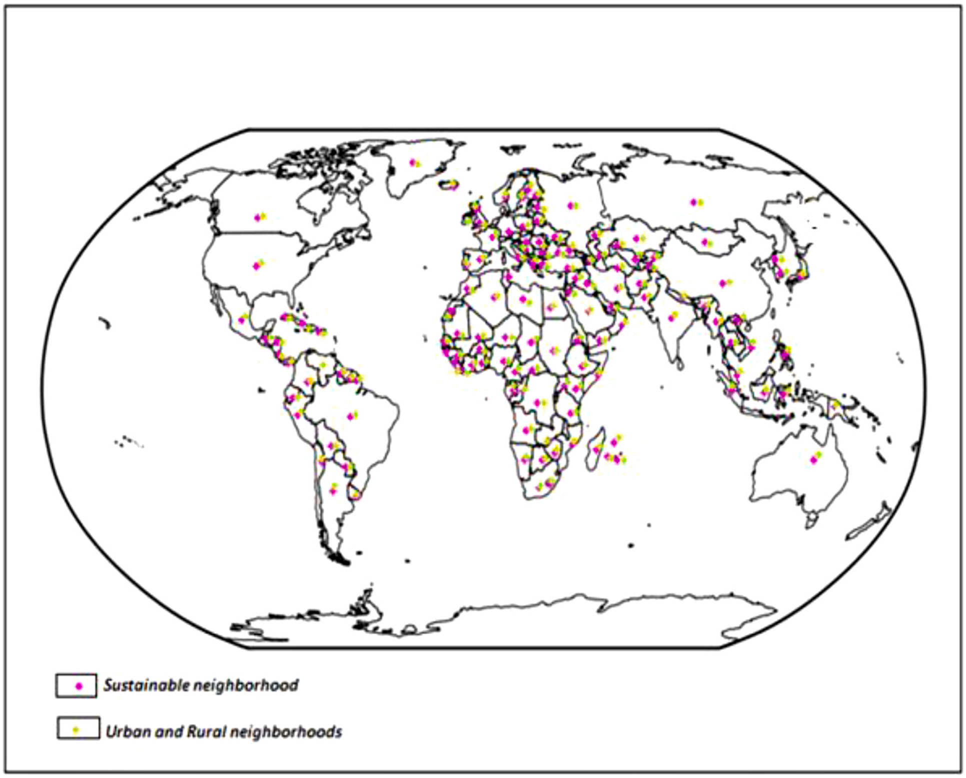

Fig. 3. Geo-location of studied sites of design.

energy demand and life-cycle GHG emissions) on the three types of neighbourhoods, but the methodology could be extended to other environmental indicators (Goedkoop & Spriensma, 2000; Guinée, 2001).

3.4. Simulation

3.4.1. Process

The three neighbourhoods studied were modelled during a period of four months. The duration of the simulation for the applications of the modelled neighbourhoods in all countries of the world was nine months, and the calculations started in January 2019 and ended in September 2019. The simulations were conducted simultaneously by three computer engineers trained in managing life-cycle assessment (LCA) software.

3.4.2. Model

In this research, we used Pleiades LCA software (Izuba Energies, France) as our simulation tool. The interface of version 4.19.1.0 of the Pleiades software consisted of six modules, namely, Library, Modeler, Building Information Modelling, Publisher, Results, and LCA. Each of the modules had a specific function. This simulation tool has been widely recognised for its ability to analyse the life-cycle environmental impacts at the neighbourhood level; it has also been the main modelling tool utilised in several other research studies (Lotteau et al., 2015; Nematchoua, Teller et al., 2019; Nematchoua, Orosa et al., 2019; Nematchoua et al., 2020a).

The Modeler module was considered as the graphical input tool. Indeed, its role was to describe the entire geometry of a building, represent the different solar masks, and identify and define all the compositions of the walls, windows, roof, etc. The Editor module allowed us to conduct the various thermal and dynamic simulations of the building (Colombert et al., 2011). The role of the LCA software was to assess different environmental impacts at both the building and neighbourhood levels based on the results produced by the Modeler.

3.5. Scenarios

With the goal of reaching nearly zero carbon in new neighbourhoods and low carbon emissions in existing neighbourhoods by 2050, we applied two forecast scenarios.

(a) In the first scenario, we conducted major renovations in the different neighbourhoods. This scenario consisted of simultaneously renovating the walls and roofs of existing buildings by insulating the attics, walls, and floors. Moreover, this scenario included the installation of more efficient heating systems (e.g. condensing boilers and heat pumps) in buildings located in temperate zone countries. To this end, the authors conducted simulations and obtained results.

(b) In the second scenario, the authors introduced PV panels that covered one-third of the roof on each building. The solar panels were oriented according to the geographical position of each country. For countries located in the Northern Hemisphere, the panels were oriented towards the south at an optimum angle of 35–37°. Meanwhile, for countries located in the Southern Hemisphere, the panels were oriented towards the north at an angle of 45°. A new simulation was executed.

4. Results and discussion

This section will present, analyse, and briefly discuss the most important, most innovative, and most original results of this study. The data are shown in Figs. 4–11 for more specific details.

4.1. Operational neighbourhood

In this research, it was found that the energy demand was approximately 64.9–284.6 kW h/m^2.year, 27.1–45.4 kW h/m^2.year, and 12.4–106.8 kW h/m^2.year in the urban, sustainable, and rural neighbourhoods, respectively (see Fig. 4). The energy demand was the highest

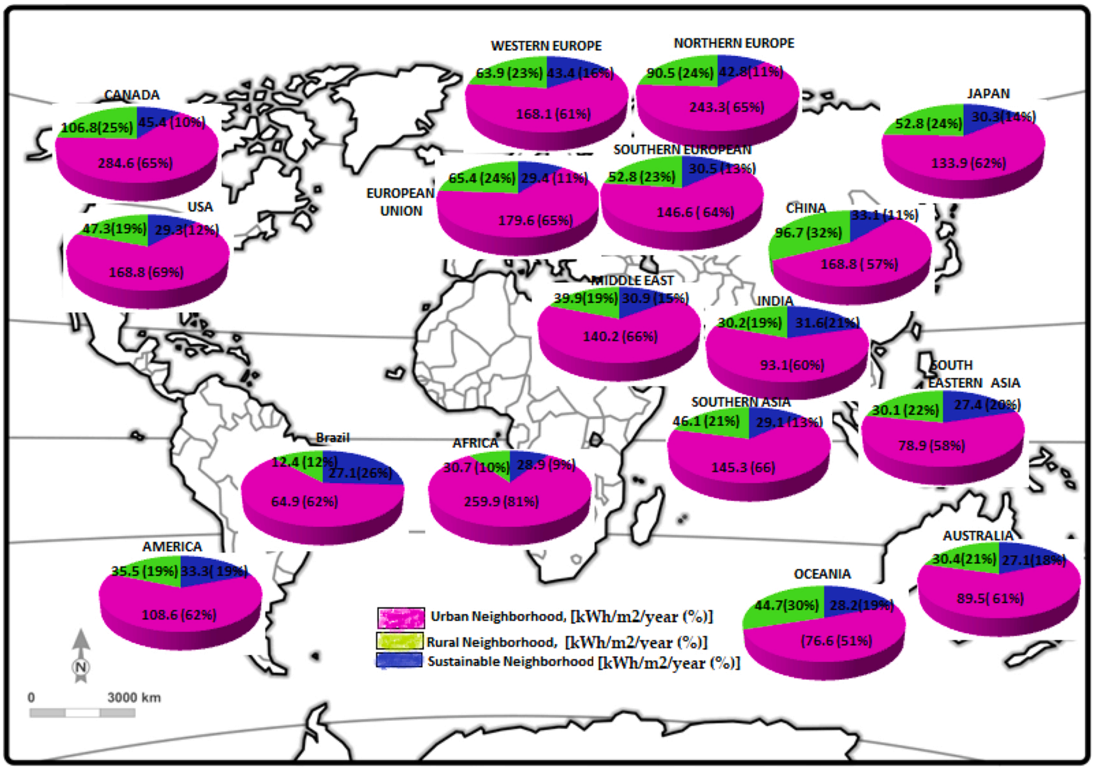

Fig. 4. Distribution of primary energy demand per square meter (net area) during the operational phase of the three (03) neighborhoods designed in several world regions.

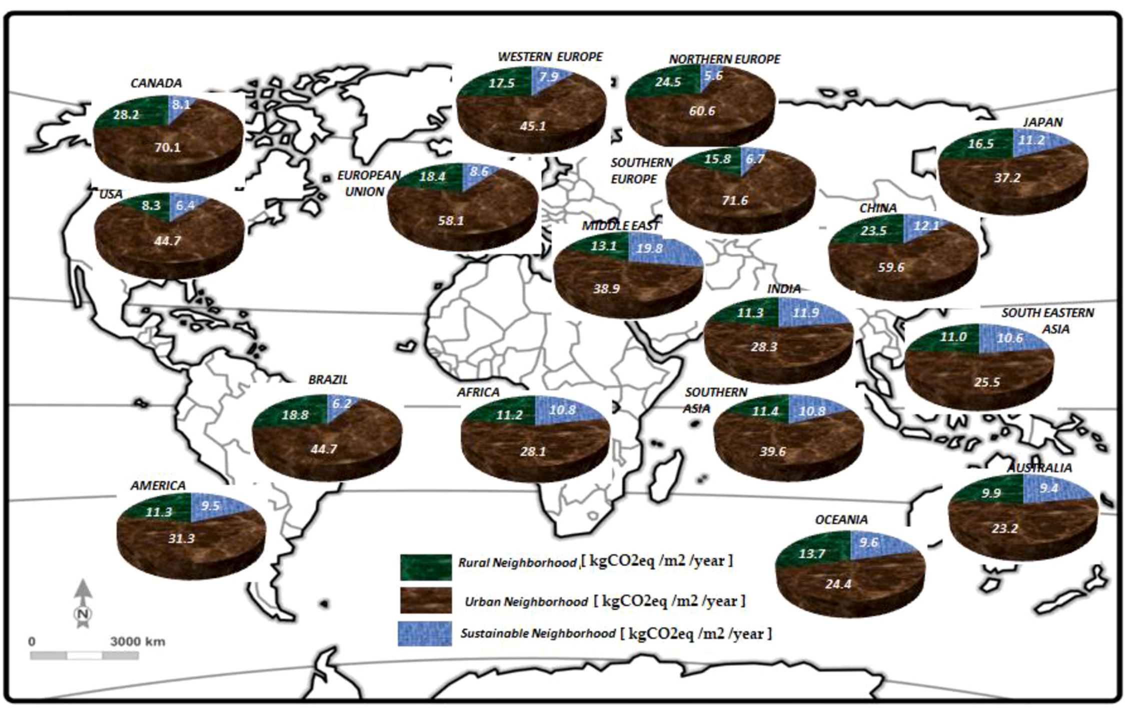

Fig. 5. Carbon emission per square meter (net area) during the operational phase of the three (03) neighborhoods designed in several world regions.

in the urban neighbourhoods, and it was an average of 79.2 % and 70.3 % lower in the sustainable and rural neighbourhoods, respectively. It was interesting to compare the neighbourhoods located on five different continents, and we observed that the energy demand was the highest in Europe and lowest in Africa. Indeed, according to Directive 31 of the European Union (European Union Directive, 2010), the average energy consumption of the buildings was approximately 40 % of the total energy consumption in the European Union. In Africa, this rate remained exceptionally low. Sub-Saharan Africa was one of the regions in the world with the lowest energy consumption (Mohammed et al., 2013).

The energy demand of the three studied neighbourhoods was 30–40 % higher in Canada, the USA, China, and India compared with that of

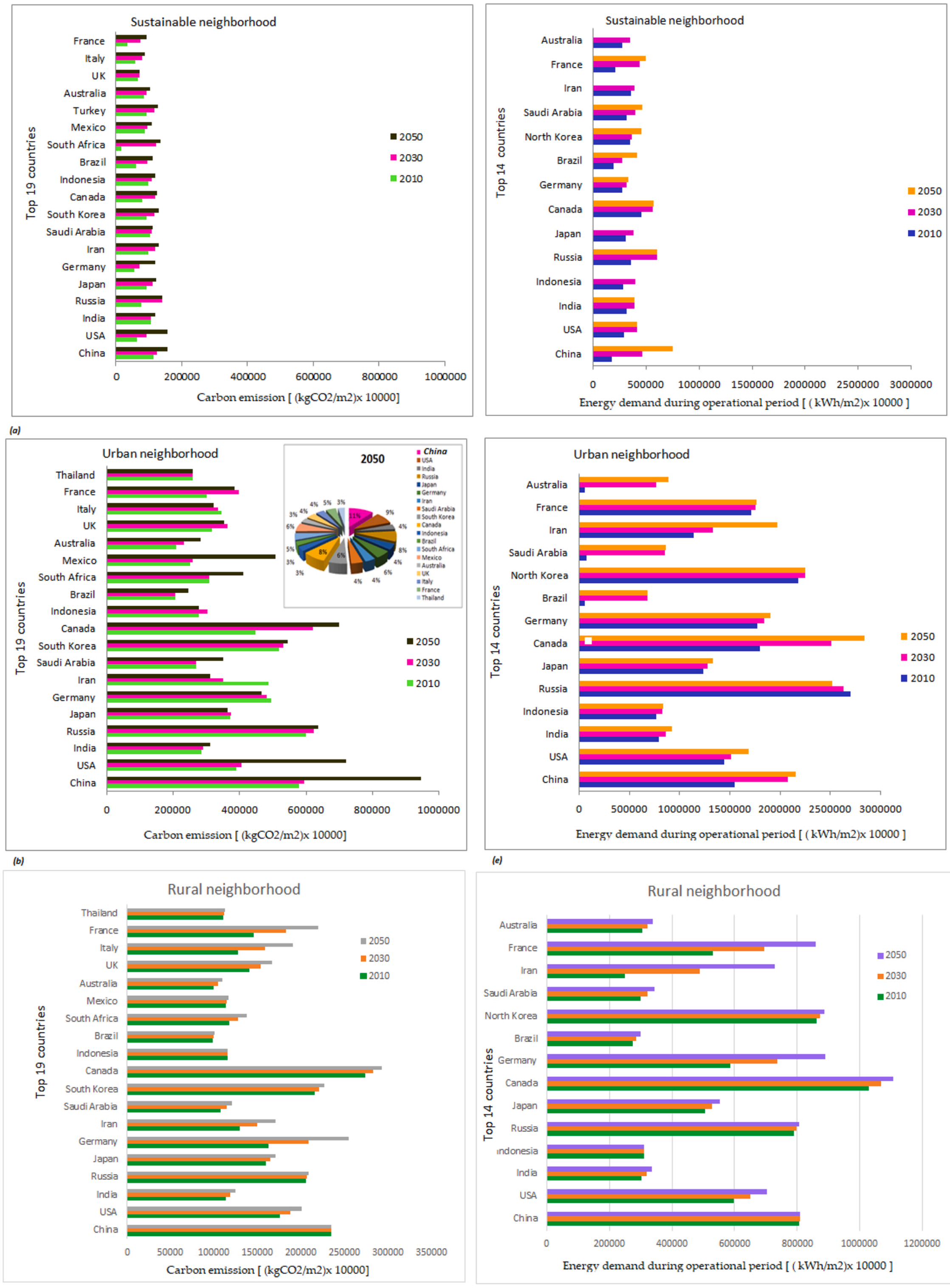

Fig. 6. Primary energy demand in the top 14 countries (d, e,f); and carbon emission in the top 19 countries(a, b,c) in the world during the operational phase of neighborhood per square meter.

the world average. These results were typical in that these countries are among the biggest energy consumers in the world (Shahbaz et al., 2018). Fig. 5 shows the carbon emissions of the studied neighbourhoods in detail during the operational phase by region. The annual carbon emissions by neighbourhood was approximately 24.4–58.1 $kgCO_2/m^2$, 8.5–15.0 $kgCO_2/m^2$, and 11.0–18.4 $kgCO_2/m^2$ in the urban, sustainable, and rural neighbourhoods, respectively. The CO_2 emissions of the urban neighbourhoods were 248 % and 169 % higher compared with those of the sustainable and rural neighbourhoods, respectively. These results proved that CO_2 emissions were the highest in urban neighbourhoods and lowest in sustainable neighbourhoods.

The energy consumption and CO_2 emissions of the cities was maximised, but their consumption of natural soils and other environmental impacts were minimised. The sustainable neighbourhoods represented

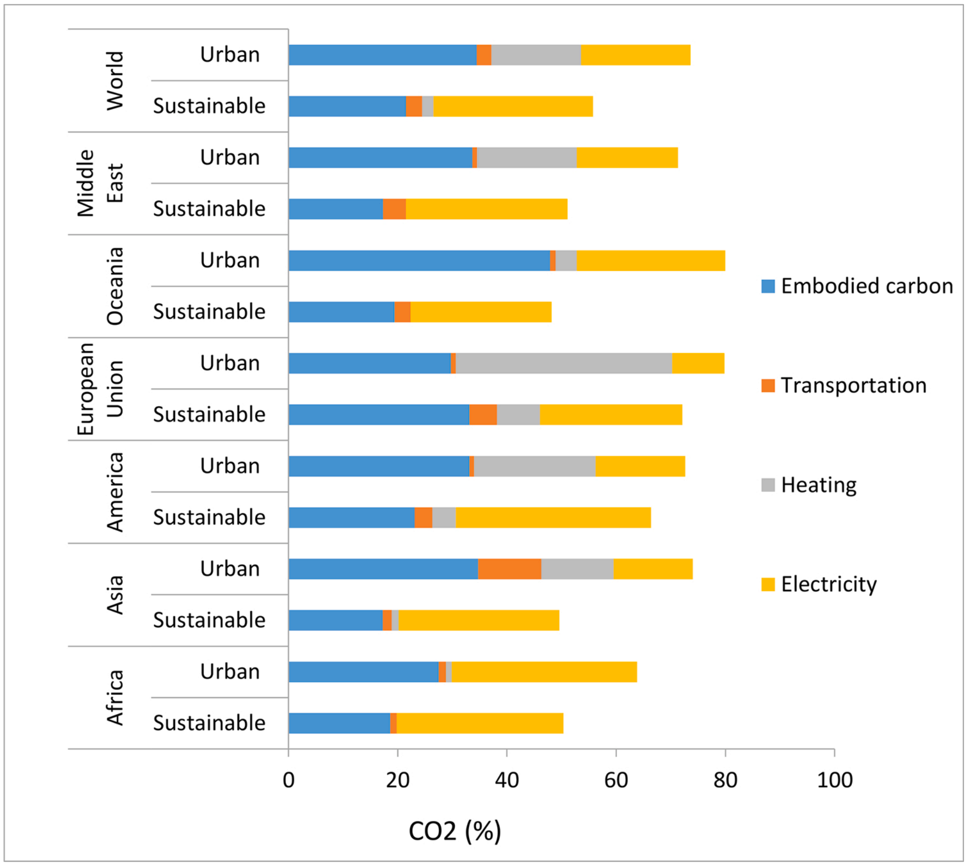

Fig. 7. Analyze of CO2 concentration produces by the building materials, transportation, heating and electricity in the two neighborhoods.

an interesting alternative because they reduced energy consumption and CO_2 emissions while simultaneously achieving reasonable built densities and occupancy rates.

The massive migrations from rural to urban areas that were commonly observed in recent years were accompanied by social transformation and expansion in the urbanised areas. Therefore, the highest CO_2 emissions attributed to neighbourhoods were concentrated in cities. A significant increase in the carbon emissions of cities was a function of strong urban growth; however, it could also be attributed to different economic structures, different urban forms, modes of transport, and infrastructure, as well as a high demand for energy in our accommodations. It was noteworthy that the CO_2 emissions per m^2 of the studied urban neighbourhoods were 15–30 % lower in the majority of African countries (Cameroun, Madagascar, Senegal, Ivory Coast, etc.) compared with the average values of the urban neighbourhoods located in countries worldwide, as well as 35–45 % higher in Canada, the USA, China, India, and Japan compared with the average value of the world. Globally, it was found that 60–70 % of the CO_2 emissions related to the three studied neighbourhoods located within each country of the world come from ten countries, namely, Russia, Japan, Canada, China, the USA, South Korea, Iran, India, Germany, and Poland.

These various conclusions indicated that the residential sector has an important role to play in mitigating the effects of climate change. New zero carbon neighbourhoods could have significant impacts on the reduction of carbon worldwide (Osmani & O'Reilly, 2009). To significantly mitigate climate change worldwide by 2050, a transition towards zero carbon buildings and neighbourhoods must be considered essential (Martiskainen & Kivima, 2018; Yangang et al., 2011). In this section, only the most significant results were presented; however, certain countries could have a more significant impact upon carbon emissions and energy demand than other countries. It became imperative for us to understand why such a large difference exists among the emissions of similar neighbourhoods located in different countries. In the next subsection, the carbon emissions and energy demand of the top countries will be analysed to better understand these results.

4.2. Impacts of the energy mix

Fig. 6 shows the inventory (for 2010) and forecasting (for 2050) of carbon emissions and energy demand of the three studied neighbourhoods per hectare in the 14 countries worldwide that consume the most energy and in the 19 countries worldwide that emit the highest carbon rate, according to a report published in 2018 by the World Bank. In these countries, between 2010 and 2050, the annual carbon emissions per hectare of the neighbourhoods (including buildings, road construction, and daily mobility) could be expected to vary from 78,326.1–117,004.2 $kgCO_2$, 149,309.9–172,165.4 $kgCO_2$, and 363,230.1–441,701.8 $kgCO_2$ in sustainable, rural, and urban neighbourhoods respectively. These results indicated that the concentration of carbon emissions will increase up to 20–25 % by 2050 in all three neighbourhoods compared with the average values reported in 2010.

In 2050, the carbon emission rates of the neighbourhoods per hectare is expected to be up to 277.0 % higher in urban neighbourhoods than those of sustainable neighbourhoods and up to 156.5 % higher in urban neighbourhoods than those of rural neighbourhoods.

It was determined that the carbon emissions of the neighbourhoods located in Germany and Poland were the most substantial in Europe. The amount was approximately 25–45 % higher than the average CO_2 emitted in the neighbourhoods of all the other countries in the European Union. What would cause these significantly higher rates of carbon emissions? Previous studies found that in 2018, Poland produced 122 million metric tons of coal, representing 1.6 % of worldwide coal production, which ranked Poland second in Europe and ninth in the world, just behind Germany (https://www.eia.gov/international/data/world,

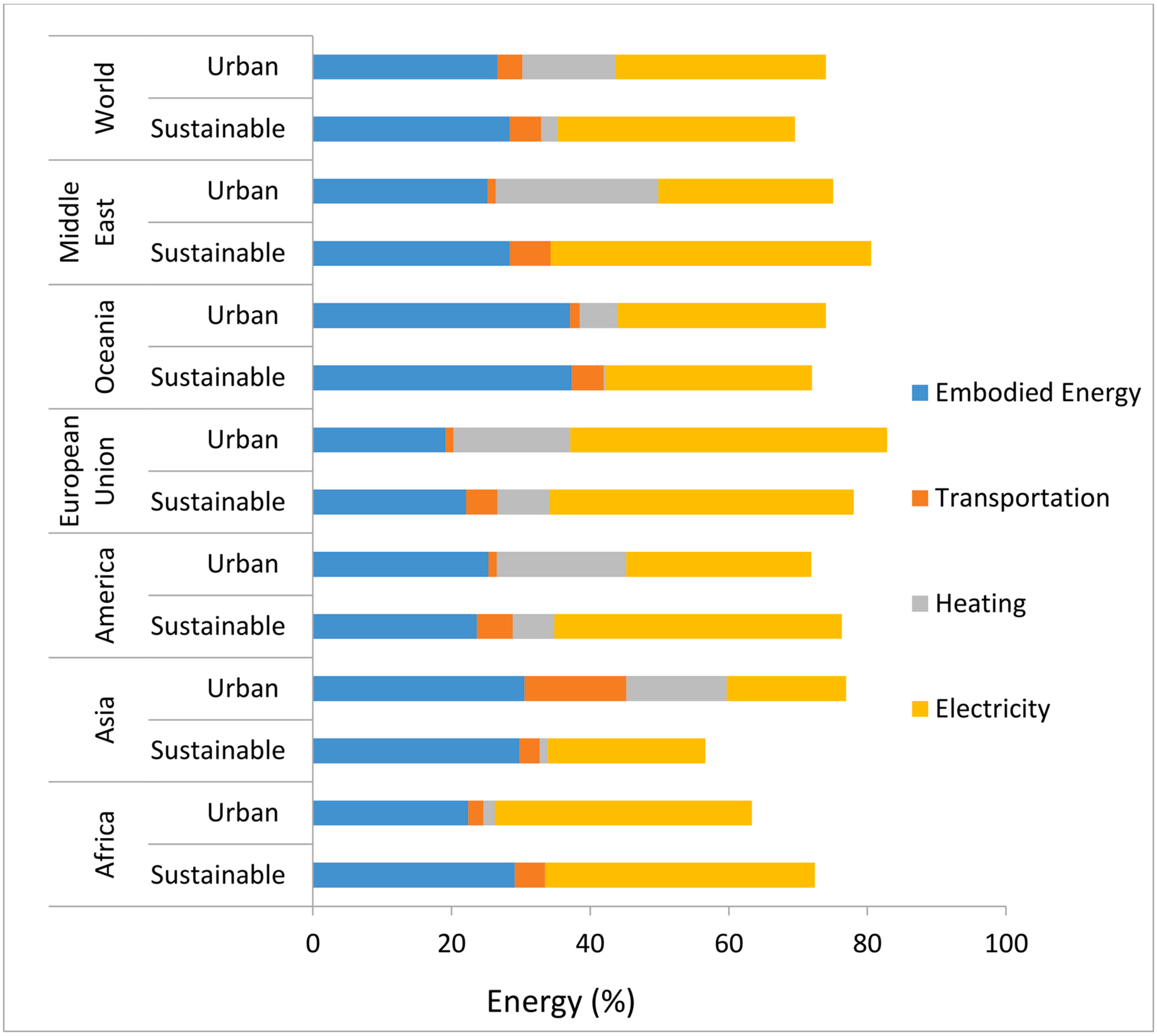

Fig. 8. Energy demand concentration produces by the building materials, transportation, heating and electricity in the two neighborhoods.

2019).

The results also revealed that if China should do nothing to reduce its use of fossil fuels, the three neighbourhoods located in China alone will produce 15–25 % of the total carbon emitted in 2050 by the three studied neighbourhoods located in the 19 most polluting countries of the world. To understand the origin of its carbon emissions, we analysed the energy mix of China. Data published by the World Bank showed that the share of coal in the primary energy mix of China was exceptionally large compared with that of other countries. Indeed, this share was approximately 72 % between 2004 and 2016, but it dropped to 60 % in 2017 and 58 % in 2018. This rate was significant in that it has been one of the main causes of the high CO_2 emissions generated by China. Moreover, the total emissions of CO_2 produced in China underwent a significant increase in recent years (Ullash et al., 2011; Crompton & Yanrui, 2005). This should be of great concern to humanity.

The top 19 CO_2 emitting countries (China, India, the USA, Canada, Russia, Japan, Turkey, Australia, Germany, etc.) represent only 7 % of the total countries on the planet; however, these 19 countries could produce up to 70 % of the global CO_2 emissions in 2050. On the other hand, the least developed countries (Madagascar, Haiti, Comoros, Cameroon, etc.) have been the most vulnerable to impacts generated by the high consumption of fossil fuels in prosperous countries. This situation should not be acceptable in light of the enormous impacts generated by the high concentration of carbon in the atmosphere.

China still belongs to the developing country and the total increase of carbon emission is normal as all developing countries, which means continuous improvement of Chinese living standards. China will peak its carbon emission in 2030 or in-advance, and the great effort of China has been made to continue lowering its carbon intensity per GDP which have lowered by 46 % in 2017 referring to 2005.

In addition, the results of the 14 countries that consumed the most primary energy are shown in Fig. 6(d–f), and their energy demand is expected to increase 20–65 % by 2050 based on neighbourhood type. In 2050, the energy demand of these countries could be 318.6 % and 132.8 % higher in the urban neighbourhoods compared with those of the sustainable and rural neighbourhoods, respectively. The energy demand in 2050 of the three neighbourhoods located in the top 14 consuming countries could represent 65–75 % of the global demand. Although these 14 countries represent only 10 % of the total countries on the planet, the estimated energy demand for each of their three neighbourhoods was approximately 75 % of the total energy demand of the studied neighbourhoods worldwide. Energy demand has continued to increase in the 14 countries studied. In the literature, the authors found that the energy demand increased in China by 4.3 % in 2018, which was higher than the 3.3 % increase in 2017 and the 10-year average increase of 3.9 %. The proposal of solutions aimed at preventing the rapid increase in carbon emissions by 2050 should be imperative.

Table 2 gives the evolution of the percentage of coal in the energy

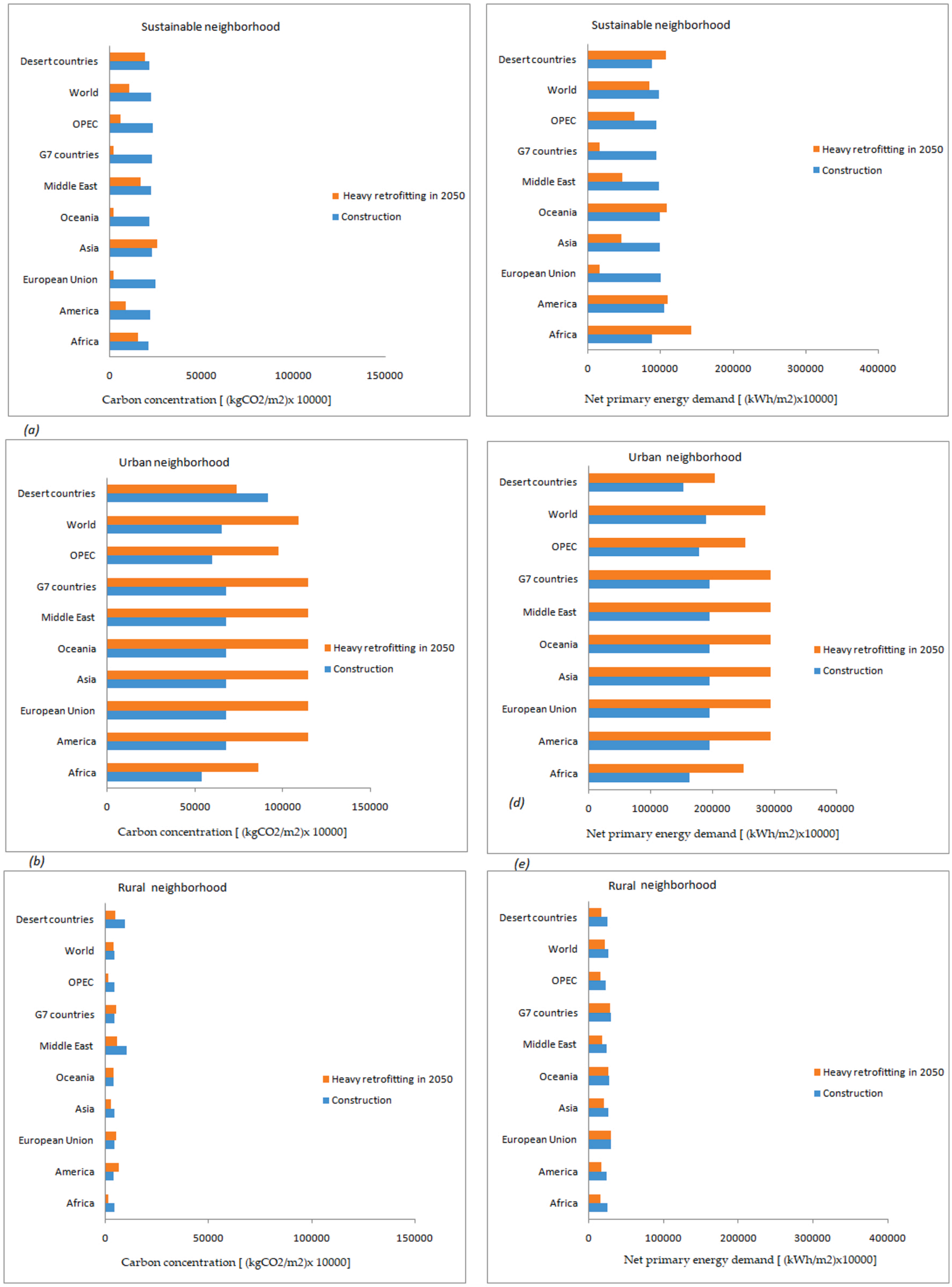

Fig. 9. Quantity of carbon produced (a, b, c), and primary energy demand (d, e, f) after retrofitting of three neighborhoods distributed in many regions per square meter.

mix of various countries from 1980 to 2018 (https://www.eia.gov/international/data/world, 2019). The percentage of coal in the energy mix was extremely high in China, India, and Poland and quite high in South Korea, Japan, Germany, the USA, Russia, and Canada. Although the percentage of coal appeared low in the energy mix of Iran, it had a very high oil concentration (greater than 50 %) in its energy mix, according to the International Energy Agency (https://www.eia.gov/international/data/world, 2019), which explained its high CO_2 emissions.

The effects of the energy mix on the environmental impacts of different countries have become an innovative subject in recent research. These effects have been evaluated at the national level and considered with respect to various economic problems of different countries, variations in the energy supply, and changes in the profile of

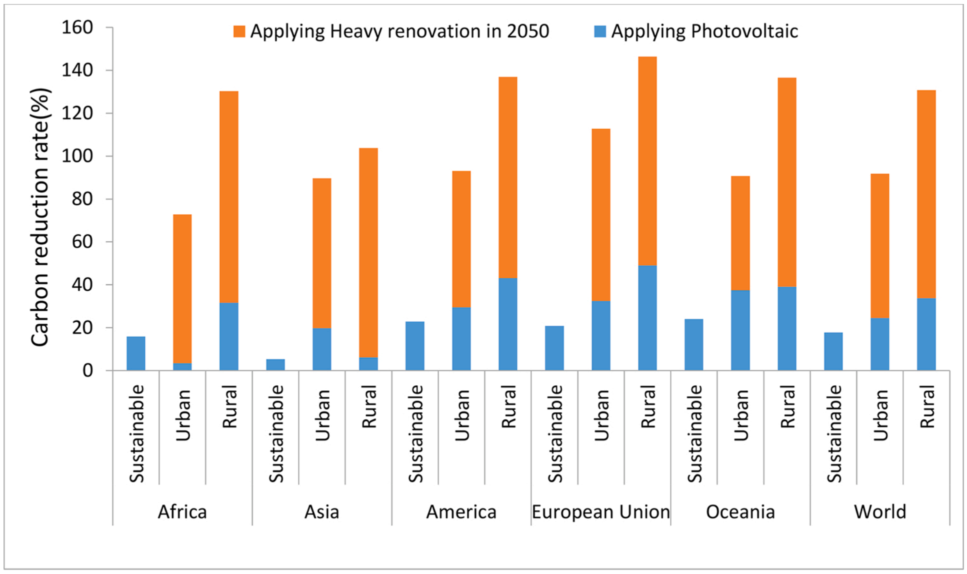

Fig. 10. Comparison of carbon reduction concentration after applying heavy renovation and PV.

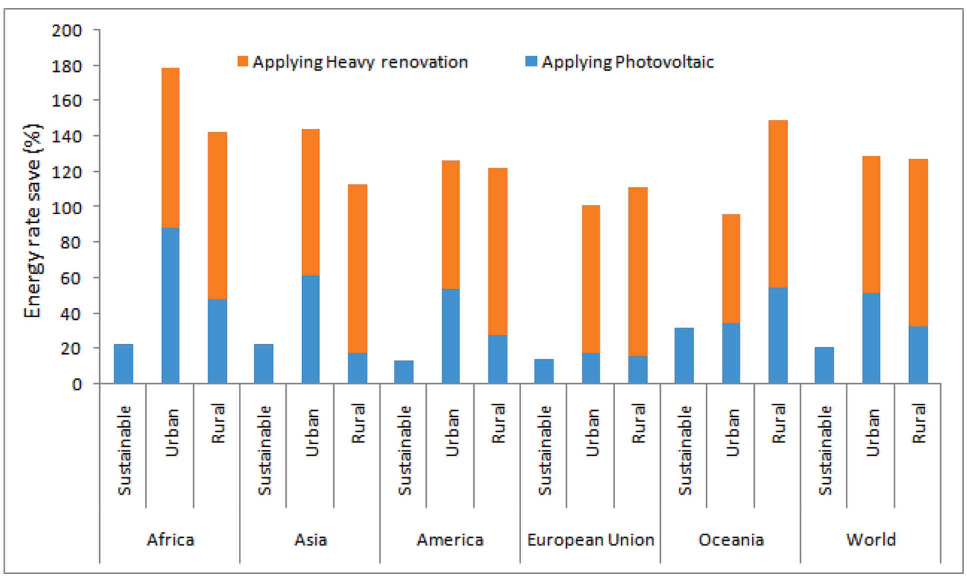

Fig. 11. Energy rate save after applying heavy renovation and PV in the three districts.

Table 2
Percentage of coal in the energy mix of the top 10 biggest CO_2 emitting countries in the world from 1980 to 2018 (https://www.eia.gov/international/data/world, 2019).

Countries	1980	2000	2002	2004	2006	2008	2010	2012	2014	2016	2018
China (%)	73.27	70.65	70.17	71.38	73.46	72.44	71.46	71.23	68.26	65.45	58.0
USA (%)	19.76	22.87	22.45	22.46	22.58	22.66	21.36	18.41	18.31	14.61	19.0
India (%)	48.57	48.42	48.83	49.81	49.32	50.32	50.36	54.84	57.25	54.42	55.0
Russia (%)	–	19.75	18.87	17.49	16.92	17.23	15.46	16.18	14.01	15.24	–
Japan (%)	14.33	17.21	18.78	19.66	19.88	70.76	20.97	22.58	23.98	24.47	28.30
Germany (%)	55.44	20.7	14.27	22.07	21.92	21.94	21.64	23.73	24.19	23.28	21.6
South Korea (%)	35.80	21.34	22.92	23.31	23.66	26.70	28.29	28.35	29.27	27.22	28.9
Iran (%)	3.11	0.95	0.80	0.70	0.57	0.54	0.4	0.26	0.3	0.35	0.32
Canada (%)	8.10	9.84	9.67	8.82	8.50	8.43	6.89	5.58	5.01	4.84	9.1
Poland (%)	71.91	64.73	63.15	62.33	60.23	58.50	58.29	56.13	58.65	55.45	49.3
World (quaBtu)	79.24	98.29	102.94	119.84	135.38	144.27	154.27	169.74	172.35	166.14	

demand (Burke, 2010; Gustavsson & Joelsson, 2010; Hennicke, 2004). Other studies conducted in European countries clarified how a sudden change in the energy mix (because of a change in the supply of fossil energy sources) would lead to significant increases in emissions per occupant, both nationally and globally, even without increases in actual energy consumption (Luickx et al., 2008; Marrero, 2010). The strong industrialisation observed in recent years in various Sub-Saharan African countries has contributed significantly to the increase in the rate of carbon emissions in this region of the world (Steckel et al., 2020).

In this section, the authors analysed the impacts of the energy mix on the carbon emissions of the studied neighbourhoods. It was shown that all fossil fuel energy sources (coal, oil, etc.) do not have the same impact on CO_2 emissions. It was noteworthy that the type of fossil fuel energy source used to produce energy greatly influenced CO_2 emissions. Nevertheless, they all have a negative impact on the environment.

It is showed in this research that the Carbon emissions will increase from 20 to 25 % in 2050 in conventional neighbourhoods. It could be due to the increase of population. The energy transition policies should be performed such as replacing coal thermal plants by renewable electricity production, insulating buildings, replacing cars with alternative transport in cities, etc. for stopping this raise of carbon. It is crucial to identify the other elements that impact carbon emissions and energy demand at the neighbourhood level, which is the objective of Section 3.3. Figs. 7 and 8 showed an comparison between CO2 concentration emission and Energy demand concentration produces by the building materials, transportation, heating and electricity in the urban and sustainable neighborhoods.The case of analysis of rural neighbourhood will be apply in a future research.

4.3. Environmental components

Some of the major components that generate greenhouse gases at the neighbourhood level are shown in Fig. 7. In our research, we found that the four main sources of greenhouse gases globally are embodied carbon (i.e. the quantity of carbon generated for construction materials), heating, electricity, and transportation. The mean distributions of greenhouse gas emissions in the neighbourhoods were 27.9 % for embodied carbon and 24.6 % for electricity. Heating also had a significant impact on the CO_2 emissions in the urban and rural neighbourhoods worldwide (17 %) with wide variations (from 40 % in the European Union to 1% in Africa), and its influence was reduced to 2% in sustainable neighbourhoods. The results showed that among the G20 members (South Africa, Germany, Saudi Arabia, Argentina, Australia, Brazil, Canada, China, South Korea, the USA, France, India, Indonesia, Italy, Japan, Mexico, the UK, Russia, and Turkey), 20–35 % of the carbon emissions at the neighbourhood level were produced in the transport sector. However, the impact of transportation on the mean carbon emissions of the three neighbourhoods located in all countries of the world was reduced to 4 %.

Additionally, it was noteworthy that embodied carbon was the most significant of the four main sources of CO_2 emissions in urban neighbourhoods. From these results, we deduced that construction materials play a major role in the carbon emissions generated by neighbourhoods. In 2012, a research study (Olivier et al., 2012) claimed that the production of cement generates approximately 8% of the global CO_2 emissions. This should bring about questions of concern by governments and environmental specialists. The various objectives aimed at reducing emissions on a global scale should not only be oriented towards the practice of efficiency of emissions, but also the option of using the least polluting construction materials (Milford et al., 2013). Currently, carbon emissions from the transport sector appeared to be the lowest in Africa compared with those of the other continents. It was interesting to note that the global quantity of carbon emissions was expected to increase by 20–30 % in 2050 because of the transport sector. This could be caused by rapid population growth, which is estimated at 9 billion in 2050, with more than 75 % of the population living in urban areas (Bongaarts, 2009, Wolfgang et al., 1997).

The studied buildings in the sustainable neighbourhoods had a high energy performance, and thus, low heating consumption compared with the buildings in the urban and rural neighbourhoods, in which the heating and cooling energy demand was significantly high. Energy consumption for heating was 45–65 % of the total energy used in the urban neighbourhoods of the European Union countries, and heating was the form of energy demand that increased most rapidly in the European Union and North America. On the other hand, the demand for cooling was the most widespread form of energy used in the desert countries, Middle Eastern countries, Sub-Saharan Africa, and Australia. As shown in Fig. 8, electricity consumption was the main component of energy demand in the three studied neighbourhoods (approximately 33.7 %) in all the countries of the three studied zones (temperate, hot, and cold). It was interesting that the embodied energy demand varied from 22 to 47 % of the global energy consumption of the three neighbourhoods (including buildings, road construction, and transportation) in Africa, the USA, and Europe.

Only 4.0 % of the total energy demand of the studied neighbourhoods was associated with transportation. However, between 2010 and 2050, the energy demand will increase in the transport sector. For example, the predicted increase will reach 14–25 % in the urban regions of Asia (China, Japan, Korea, and India). Globally, the results in this section have proven that most of the environmental impacts generated by neighbourhoods (including buildings, road construction, and transportation) come from construction materials and electricity production. These results could be debatable and vary according to different regions. Some of these results were obtained by Blengini (Blengini, 2009).

These results showed that in all the neighbourhoods studied, electricity demand and construction materials were two essential components that influenced the two environmental impacts studied, namely, energy demand and CO_2 emissions. According to (Christen et al. (2011), density, shape, types of buildings, transport networks, vegetation, and land use were determined as responsible for approximately 50 % of the CO_2 emissions of cities. It is crucial to recommend various methods to reduce these impacts, which will comprise the aims of Section 3.4.

4.4. Mitigation strategies

4.4.1. Impact of construction and retrofitting stages

As shown in Fig. 9, during the construction phase of neighbourhoods, the annual concentration of greenhouse gas emissions per square meter was approximately 4.32 $kgCO_2$, 22.45 $kgCO_2$, and 65.08 $kgCO_2$ in rural, sustainable, and urban neighbourhoods, respectively. These results showed that during the construction stage of neighbourhoods, the greenhouse gas emissions were estimated to be 15 times higher in the urban neighbourhoods than those of the rural neighbourhoods, and three times higher in the urban neighbourhoods than those of the sustainable neighbourhoods. This can be due to choosing building materials, indeed, it was noticed more concrete, cement fibre in the urban-type, which is recognized to produce more carbon dioxide. However, further materials having a low concentration of CO_2 in the rural and sustainable neighbourhoods, such as wood, expanded polystyrene.

Globally, it was found that the carbon emitted during the construction phase of neighbourhoods was 28.3 % higher in desert countries (Algeria, Libya, Chad, Mauritania, Morocco, Tunisia, Sudan, Niger, Mali, etc.), 14.8 % higher in Middle Eastern countries (Cyprus, Lebanon, Syria, Turkey, Saudi Arabia, Bahrain, etc.), and 3.9 % higher in G7 countries (Germany, France, the UK, Italy, Japan, Canada, and the USA), compared with the average of all countries in the world.

In the case of substantial renovations of buildings during the retrofitting phase that would occur until 2050, the energy demand and CO_2 emissions of the urban neighbourhoods located in various regions would remain higher than the energy demand and CO_2 emissions during the construction phase, with the exception of the desert countries, in which the construction phase would persist as the largest emitter of CO_2. It has been typical for the carbon emissions of the construction phase to be significantly high in desert countries. Indeed, the construction of new neighbourhoods in a desert region has required a total transformation of nature. The different stages of this mechanism could generate significant amounts of greenhouse gas emissions. Moreover, the carbon emission rate of the retrofitting phase in desert countries would remain above the carbon emission rate of the construction phase of the same neighbourhoods located in all the other regions, including high emitters in Asian countries, such as China, Japan, and India, as well as in the European Union countries. Fig. 9(d– f) shows that the primary energy demand was 3–7% higher in G7 countries than that of desert countries and 2–3% higher in the Organization of the Petroleum Exporting Countries than that of desert countries. This would also be considered typical because the demand for energy could depend on the level of development of a country.

Additionally, Fig. 9(e) shows that the neighbourhood retrofitting phase for substantial renovations of all buildings in an urban neighbourhood in 2050 would present a higher primary energy demand per hectare in all regions of the world compared with that of the primary energy demand for the construction phase of the same neighbourhoods.

4.4.2. Heavy retrofitting and photovoltaic panels

To reduce the two studied environmental impacts, we used two scenarios (as described in Section 2.5). Detailed results are presented in Figs. 10 and 11. Fig. 10 shows that the heavy retrofitting of all the neighbourhoods would allow for the mitigation of the greenhouse effect by 53–97 % in 2050, while the introduction of PV panels on the roofs of all neighbourhood buildings would allow for the reduction of carbon by 3–37 %, 6–49 %, and 5–24 % in urban, rural, and sustainable neighbourhoods, respectively. The performance of the solar panels would vary according to performance, maintenance, and angle of inclination.

These results indicated that the PV yield in carbon was approximately 5–9% higher in the rural areas compared with that of the urban areas. It must be due to the ratio of the roof which is higher in the rural type because the number of stories is lower.

By combining renovation with the installation of PV panels, the objective, 'zero carbon at the neighbourhood level by 2050', would be achieved in rural areas. These results also showed that the yield associated with the rate of carbon reduction was 15–20 % greater in the European Union and the USA than that of Africa. This might be because most of the PV panels used in Africa were manufactured by European Union countries and China. The reason also could be due to a lower electricity consumption in Africa.

Additionally, it was found that each kilowatt hour of energy produced by PV panels in the three neighbourhoods allowed for savings of 0.003–0.007 $kgCO_2$ compared with that of the existing energy mix.

As shown in Fig. 11, it would be possible to save 61–95 % of the total energy demand with a heavy retrofitting of all buildings in the three neighbourhoods. Furthermore, the introduction of PV panels would reduce the energy demand by 13–31 %, 15–85 %, and 17–55 % in the sustainable, urban, and rural neighbourhoods, respectively.

The use of solar PV panels has been the main strategy applied in hot zones (desert zones, Sub-Saharan Africa, etc.). The PV panels have easily compensated for the cooling demand of the hot zones. The PV energy yield was 35–55 % higher in Africa than that of Europe and 17–24 % higher in Africa than that of the USA. The energy savings incurred by the introduction of PV panels on the roofs of buildings in the urban neighbourhoods was 14–19 % in the European Union and 60–85 % in Africa. The energy yield could reach up to 170 % of the energy demand of a neighbourhood in certain regions of Sub-Saharan Africa by combining heavy retrofitting and PV panels. In general, all the countries located in the Sub-Saharan region have a significant capacity for renewable resources, and the various investments in renewable technologies have been known as essential for the growth of their economies. The introduction of PV solar panels or wind turbines at the neighbourhood level, as well as the encouragement of clean technologies could be an exceptionally helpful policy with respect to the reduction of carbon emission levels and the fight against global warming (Christen et al., 2011).

Even after the application of these strategies, the energy demand and greenhouse gas emissions would remain the highest in urban neighbourhoods. To compensate for the different increases in the energy observed as a result of climate change, we strongly recommend the practice of energy efficiency associated with different sources of energy production that have exceptionally low carbon emissions (solar, wind turbine, geothermal, hydro-electric power, etc.).

5. Global strategy adapted in this research and limitations

5.1. Strategy adapted

In summary, in this study, we have applied several strategies to reduce energy consumption such as :

(a) Apply passive strategies: Insulation, natural ventilation, day lighting…
(b) Apply energy efficiency: Lighting, appliances, domestic hot water…
(c) Apply RE generation systems: photovoltaic,
(d) Apply the heavy renovation.

Some strategies to reduce CO_2 emission applied are : selection of materials with low embodied carbon during the renovation of residence building, introduction of PV in all the roof of building, reused and recycled materials…

5.2. Limitations

This scientific research has several limitations, as several studies published in the literature. For example, the climate is changing and at-least one or more climate scenarios based on CIMP5 or CIMP6 should be considered in 2050 scenarios development in future research. The evolution or growth rate of the population by 2050 in each country has not been fully taken into account due to a lack of recent data covering all of the 194 countries studied.

The morphology of neighbourhoods varies from one environment to another. With regard to the number of countries evaluated, we did not study the case of all countries. It is very difficult when comparing countries with different climates and levels of development. This is why in future studies, we will study these different countries according to the type of climate, by emphasizing the social and economic aspects. In this research, we have considered some parameters according to the international standard, such as: the activity of occupants, water system, and water consumption. These conditions should slightly varied in function of countries with different climates and levels of development. Despite that, it is interesting to notice that the approach applied in this study allows us to have a global idea of energy consumption and carbon emissions in the world.

Nevertheless, these results can already be the subject of a publication that could clarify or serve as a reference for future researchers in this field.

6. Conclusion

In conclusion, this study analysed the carbon emissions and energy demand of three types of residential neighbourhoods that were adapted to all countries worldwide. The results demonstrated that the CO_2 emissions of the three studied neighbourhood types located in the top 19 CO_2 emitting countries accounted for 60–70 % of the total carbon emissions worldwide. This percentage could increase up to 80 % by 2050 because of climate change. There is a considerable opportunity to improve this situation at present. Indeed, by increasing the renewable energy quantity in the energy mix of each country by up to 20 %, it would be possible to mitigate the concentration of CO_2 emissions by 10–25 %. These results demonstrated how reorienting the energy mix of each country towards different renewable resources would automatically lead to a significant reduction in greenhouse gas emissions. Reducing the impacts that affect climate change remains a major concern of all governments. It is time to raise global awareness with respect to the harmful and secondary effects that result from a high concentration of carbon emissions in daily life.

Retrofitted and modern sustainable neighbourhoods require higher investment costs than older existing neighbourhoods; however, they are ultimately one of the major solutions that could mitigate global warming. It was demonstrated that substantial building renovations in urban and rural areas allow for the possibility of reducing the energy demand and CO_2 emissions of buildings in a neighbourhood, depending on the region, by up to 95 %. Construction materials and electricity production were revealed as the two most important components responsible for the emission of carbon at the neighbourhood level worldwide, while heating and transportation also had high impacts in some regions. Therefore, it was recommended to choose environmental and energy-efficient construction materials that are most suited to the climate, as well as new environmentally friendly techniques of electrical production. Finally, to mitigate the effects of climate change in the future, we recommend the renovation of the majority of existing residential neighbourhoods and to build a multiplicity of sustainable neighbourhoods throughout the world. Some implications of the location, e.g. transportation of food don't have been taken into account, they can served of basis of future research in this field. In addition, only the residence buildings were studied in these neighbourhoods. In the future research, we will study the case of offices and shopping centres. We will studied the case of all the cities in the large countries like Russia, China, US and India.

Data availability

The data that support this research study and other findings of this study are available from the corresponding author upon reasonable request of each reader.

Declaration of Competing Interest

The authors declare no competing interests.

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