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ORIGINAL PAPER

Estimation, analysis and comparison of carbon emissions and construction cost of the two tallest buildings located in United States and China

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Abstract
Nowadays, it is noticed that more than a third of the carbon dioxide (CO_2) emitted in the atmosphere comes from the construction sector. This CO_2 concentration has a significant effect on climate change. In the new cities, tall buildings multiply as mushrooms. Some specialists believe that they can be one of the solutions to reduce the carbon content in the atmosphere. The main aim of this study is to simulate, analyze and compare the embodied carbon and operational carbon of the two tallest buildings located in the United States and China, by using Design Builder and Pleiades software: the One World Trade Center in USA and the Shanghai Tower in China. Even if the embodied carbon of these super tall buildings is very high, the operational carbon remains the most important source of carbon emissions on their whole life cycle. Future carbon emissions of these two buildings were estimated in three periods (2030, 2050 and 2080) following the A2 scenario from the Intergovernmental Panel on Climate Change (IPCC). The results show that the operational carbon will increase by 10.6% at One World Trade Center (1WTC, USA) and 7.8% at Shanghai Tower (ST, China) in 2050. In addition, this study analyzed the impacts of the electricity mix and photovoltaic panels on their carbon dioxide emissions. Replacing energy production based on coal by renewable energy sources in the electricity mix of these countries could induce a reduction of 47.5% and 65.6% of total operational carbon emitted by the 1WTC and ST, respectively, by 2050. Finally, 46% of the building construction cost of these skyscrapers is related to their structure and superstructure.

Keywords Dynamic thermal simulation · Embodied and operational carbon · Energy efficient high-rise buildings · Towers · Super tall buildings

Introduction

Climate change is recognized as a natural occurrence, nevertheless current climate change is recognized to be accelerated by humans due to their pressure on nature (Nematchoua et al. 2018; Nematchoua et al. 2019a, b, c, d, e). The high concentration of greenhouse gases released into the atmosphere is mentioned as the main cause of global warming (Nematchoua et al. 2014a, b; Nematchoua et al. 2017). The Intergovernmental Panel on Climate Change (IPCC) showed that carbon dioxide (CO_2) constitutes around 50% of the anthropogenic greenhouse gas emissions (Nematchoua et al. 2019b) and buildings account for about 32% of CO_2 emissions in the world (Dincer and Rosen 1999). Each year, in each continent in the world, thousands of buildings are built on the basis of new technologies adapted to the standards of each country. The building sector is at the heart of all global strategies of development (World Bank 2021). The creation of carbon calculation methodologies and environmental decision support tools are some concerns of new environmental specialists (World Population 2019).

The UN expects two-thirds of the world to live in cities by 2050, which will induce challenges to achieve new cities (World Population 2019). A dense urban population is more likely to walk, bike or use public transport modes than

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suburban or rural populations. Moreover, high-rise buildings can save the land and mitigate urban sprawl, while maximizing the financial performance of real estate in the city. But on the other hand, skyscrapers consume more energy and require high maintenance (Tanya et al. 2017). So, designing green skyscrapers is a potential way to achieve new urban cities. With a height of 88 m, Bolueta in the Spanish city of Bilbao is now the tallest Passive House building in the world, followed by the Passive House students' residence (86 m) at Cornell Tech in Manhattan (New York) which opened to residents in 2017. But, what about the environmental quality of super-tall buildings?

During the process of urbanization and industrialization of the United States and China, the construction sector was recognized as consuming a large amount of electricity and resources and producing a large amount of waste. The consumption of energy and natural resources and the treatment of solid wastes that occur during the construction, use and dismantling phases of buildings produce high carbon dioxide emissions (Kneifel 2010; Peng and Wu 2015). Construction, use and maintenance of buildings in an environmentally responsible way require considering their environmental impacts on their entire life cycle, taking especially into account embodied and operational energy and carbon issues (Peng and Wu 2015). Note also that CO_2 concentrations inside buildings are generally higher than outside because building occupants produce CO_2 when they breathe. However, ventilation allows indoor air to be replaced by outside air, which has the effect of controlling indoor CO_2 levels (Nematchoua et al. 2019c, 2014b).

The most common measures to reduce the building's CO_2 emissions concern mainly the application of thermal insulation in buildings roofs and walls as well as the choice of windows with better thermal performances (Peng and Wu 2015). Building materials are often selected according to their cost of purchase on the market, their structural performances or their esthetic characteristics. But many other characteristics should attract the attention of architects when choosing materials from an environmental point of view: thermal conductivity, carbon content, etc. (Dakwale and Ralegaonkar 2012). Some researchers, such as (Dakwale and Ralegaonkar 2012), explained that it is possible to reduce building carbon emissions by up to 36% by improving the thermal performance of the building envelope and by effectively selecting appropriate U-factors for building materials. Several researchers conducted studies on carbon footprint of construction materials (Hugo et al. 2014; Venkatarama et al. 2010; Gartner 2004). Hugo et al. (2014) explained that it is possible to reduce buildings carbon dioxide emissions by minimizing the use of construction materials. Other studies have already been carried out on CO_2 emissions due to buildings at a larger scale (Chen et al. 2011; Su et al. 2008; Wang et al. 2009; Nematchoua et al. 2019d).

An investigation of the current literature shows that very few studies evaluate or compare the carbon emission related to high-rise buildings, whereas it would be interesting to have reference values for the environmental performance of this specific building type. Currently, among the 100 highest buildings in the world, nine are built as steel structures, 30 as reinforced concrete, 5 as steel and reinforced concrete and 56 as composite structures (Zhao et al. 2015). Previous studies on carbon analysis of tall buildings focus only on the structural system (Zhao et al. 2015; Gan et al. 2019; Mavrokapnidis et al. 2019) or the façade materials (Giordano et al. 2017). The main objective of this study is to estimate, analyze and compare embodied and operational carbon of the two tallest buildings located in the two most polluting countries of the world: the One World Trade Center (1WTC) in the United States of America and the Shanghai Tower (ST) in China. In addition, this study analyses the investment costs of these two high-rise buildings. Future carbon emissions of these two buildings were estimated on three periods (2030, 2050 and 2080) under the basis of the A2 scenario of the Intergovernmental Panel on Climate Change (IPCC).

The structure of this article includes an "Introduction" section, "Materials and methods" section (including the studied buildings, climatic data, simulation software, models and scenarios), a part presenting the "Results and discussion" section, the "Conclusion" and references.

Materials and methods

In this research, the embodied and operational CO_2 of two of the tallest building located in the USA (One World Trade Centre, 1WTC) and in China (Shanghai Tower, ST) were evaluated by using Design Builder and Pleiades LCA software. The life cycle of these two buildings was fixed at 100 years, taking into account the different parameters specific to each of these countries, such as energy mix and climate type. In addition, the study shows the energy consumption and construction costs of these extremely high buildings and a sensitivity analysis on the impacts of the electricity mix and the addition of photovoltaic panels on CO_2 emissions.

Overall, the methodology used in this research is divided into four main sections:

(a) Building selection and building modeling;
(b) LCA of CO_2-emissions of the selected buildings, estimating their embodied and operational CO2 emissions;
(c) Sensitivity analysis on the electricity mix and photovoltaic panels
(d) Analysis of construction costs of the two high-rise buildings.

Assessing impacts in LCA

In this research, the different stages applied by Pleiades software for making LCIA consists:

(1) *Classification*: In this first step LCI data are assigned to the considered impact categories. The selection of these impact categories is based on the expected types of impacts.
(2) *Characterization*: This second step involves the application of weighting factors or equivalence to unify all relevant substances within each impact category (e.g., all contributions to global warming are transformed into kilograms of equivalent CO_2). This step provides a way to directly compare the LCI results within each category.
(3) *Normalization*: The goal of this third step is to establish a common reference to enable the comparison of different environmental impacts. To achieve this aim, a reference quantity is used to make the data 'dimensionless' (e.g., the value of the considered category for the total activity in the world, country, or region).
(4) *Valuation*: The final step is the assessment of the relative importance of the potential environmental impacts identified in the previous steps by assigning them weightage. It consists in determining which impact category is the most damaging and in what intensity in relation with the others: The final aim is to obtain a unique result. Valuation is usually a controversial step, is based on subjective considerations.

Fig. 1 One World Trade Center and other Towers in New York City (USA)

Fig. 2 Shanghai Tower and other Towers in Shanghai city (China)

Studied cities

The 1WTC is located between 40° 42′ 46″ N and 74° 00′ 48″ W in New York City, in the United States of America. New York has a humid continental climate, almost similar to that which governs the north-eastern coast of Asia. Every year, in this city, it is noticed a variation of temperatures ranging from − 15 to 41 °C, according to the seasons. The different variations of seasons in New York during the year are defined in this way: (i) between December and mid-March, it is the winter period; January and February are the coldest months, with temperatures decreasing to − 10 °C. During this season there is an average of 60 to 90 cm of snow. (ii) From mid-March to mid-May, it's spring. The temperatures increase to 22 °C in May. (iii) From mid-May to October, this is the summer period with temperatures ranging from 20 to 25 °C in the morning and 30 °C to 40 °C in the afternoon. (iv) In November, it is short transition autumn; the temperatures drop very quickly, they fall to 12 °C in the afternoon and 5 °C in the morning. Figure 1 shows the One World Trade Center in New York City.

The Shanghai Tower is located between 31° 14′ 08″ N and 121° 30′ 04″ E, in Shanghai city, in China. The city of Shanghai is located in a vast delta, consisting of the Yangtze River that flows into the East China Sea. This city is made up of four seasons: (i) spring between March and May; during this period, the temperature oscillates around 20 °C. (ii) Summer, from June to September, is the longest season of the year. During this season, temperatures are well above 35 °C. (iii) From October to November, it is autumn. (iv) Winter is relatively short, from December to February, with average temperatures between 0 and 10 °C. Shanghai Tower is shown in Fig. 2.

The main climatic characteristics of these two regions can be summarized in Table 1 below.

Climatic data

These two very high buildings are located in two different bioclimatic areas, which are related to different climatic conditions. The weather data used in this research are taken from the latest version of one of the most popular American meteorological data packages (Meteonorm 7.3). This software can provide weather data for more than 2100 weather sites around the world. It has five geostationary satellites regularly updated by many experts in the field. Climate data in Meteonorm are grouped into three broad categories: (a) Radiation period (1981–2010); (b) temperature period, (1961–2009); (c) scenario for future periods: IPCC AR4 B1, IPCC AR4 A1B, IPCC AR4 A2, RCP 4.5, RCP 8.5 (Jump 2000). In this article, the authors used the A2 scenario of IPCC. The choice of this scenario was not randomly undertaken, indeed, it has already been used in other studies forecasting the energy demand in buildings (Nematchoua et al. 2015, 2019e; Al-Kodmany, 2015). It is considered to be one of the most realistic for these cities. Scenario A2 describes a very heterogeneous world (self-sufficiency, preservation of local identities). The population continues to grow as fertility rates move more slowly, while economic development is mainly regional.

Simulation software

In this research, we used two software: Design Builder and Pleiades ACV. The main role of Design Builder software is to model a building and to make different dynamic thermal simulations possible. It is a software with multiple functionalities allowing to make: calculation of the heat losses/gains, dimensioning of heating and cooling, dynamic Simulation (STD), 3D Construction, modeling of the building, management of the occupation, assessment of the energy consumption, calculations related to RT2012 and LEED and calculation of construction costs.

Furthermore, the purpose of the Pleiades ACV software is to model and evaluate the environmental impacts of buildings and neighborhoods. We used this software to calculate the life cycle carbon emissions of the two skyscrapers over 100 years of life for both buildings. The software interface is structured around three axes:

(1) Library: environmental impact data libraries and general calculation characteristics. In this research, we considered a constant value for other materials at the site which is 5%, default typical service life of elements such as interior and exterior doors for 30 years, the life of the equipment was assumed 20 years, glazing 30 years (Nematchoua et al. 2019d). The two studied buildings being located in the heart of big cities (New York and Shanghai). The transport distances are freely selected by using Pleiades ACV. Indeed, the daily distance from home to shop fixed to 500 m, the distance between house and public transportation system 250 m and daily distance from home to workplace 2500 m.

(2) Project manager: project management with LCA data for any type of project and building use with the EQUER engine. In this research, we also assumed constant values for the following variables: loss of electrical network from 5 to 10% according to the country; water distribution efficiency: 90%; cold water consumption: 90 liters/person/day; Hot water consumption: 40 liters/person/day; a selective collection of glass: yes; sorted glass: 90%; incinerated waste 35%; recovery to incineration: yes; substituted energy: gas or fuel oil (depending on the country); recovery yield: 80%; selective collection of paper: yes; sorted paper: 98%(for both cases). For the One World Trade Centre, the distance from the site to the garbage dump: 6 km; the distance from the site to the incinerator: 300 km; the distance from the site to the recycling center: 20 km. For the case of Shanghai Tower: the distance from the site to the garbage dump: 10 km; the distance from the site to the incinerator: 250 km; the distance from the site to the recycling center: 20 km.

(3) Calculation and results: this part allows starting the calculations and consulting the results. The 2D plan of one floor located in each studied building is shown in Figs. 3 and 4.

Table1 Some information regarding the two selected representative cities

Building	Countries	City	Location	Temp. (°C)		RH (%)		Wind speed (m/s)	
				Min.	Max.	Min.	Max.	Min.	Max.
World Trade Centre	United States	New York	40° 42′ N, 74° 0′ W	− 15	41	30	80	0.2	6.9
Shanghai Tower	China	Shanghai	31° 14′ N, 121° 30′ E	− 10	49	30	90	0.0	10.0

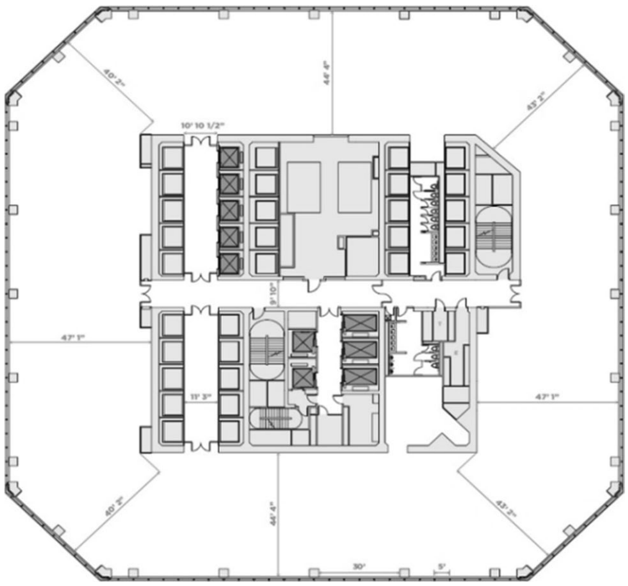

Fig. 3. 2D plan of a floor of the One World Tower Centre [29]

Building description

Choosing these two buildings was not done randomly. Indeed, 1WTC is the tallest building in the USA and ST is the tallest building in China. Both buildings have received a LEED certification (Gold for 1WTC and Platinum for ST). One World Trade Center is an office tower with a hybrid structure combining a massive reinforced concrete core with a peripheral steel frame (Rahimian and Eilon 2015). Its energy performance aims to reach 20 percent better than the US code, using twelve phosphoric acid fuel cells (PAFC), which are among the cleanest sources of energy available today. All the building's materials contain at least 25% of recycled-content materials. The Shanghai Tower includes a double-layer façade, allowing natural ventilation and cooling of the building that reduces energy costs of indoor air conditioning system, and wind turbines that cover the electricity needed for the illumination of the building and other electrical uses (Risen 2015). One of the great advantages of very tall buildings is that they occupy less green space and shelter more people, in this sense, the destruction of fauna and flora is reduced.

The use of these buildings is divided between offices, restaurants, shops, and hotels. Given the size or height of the buildings, it was very difficult to assess the total concentration of CO_2 from each building. For this, more than 200 simulation tests were carried out from the first floor up to the last floor for evaluating the CO_2 rate from the two buildings studied.

The number of people was fixed at a maximum of two by office or room, and a maximum of five in a restaurant or shop, in each building. In this study, we have not studied in depth the effects of the equipment in different areas. Occupant activity fixed by the office has been considered sedentary. In each zone, the heating set point of the day (from 7:00 am to 8:00 pm), was fixed at 20 °C; and of the night (from 9:00 pm to 6:00 am), at 18 °C. Cooling set point temperature was fixed at 27 °C.

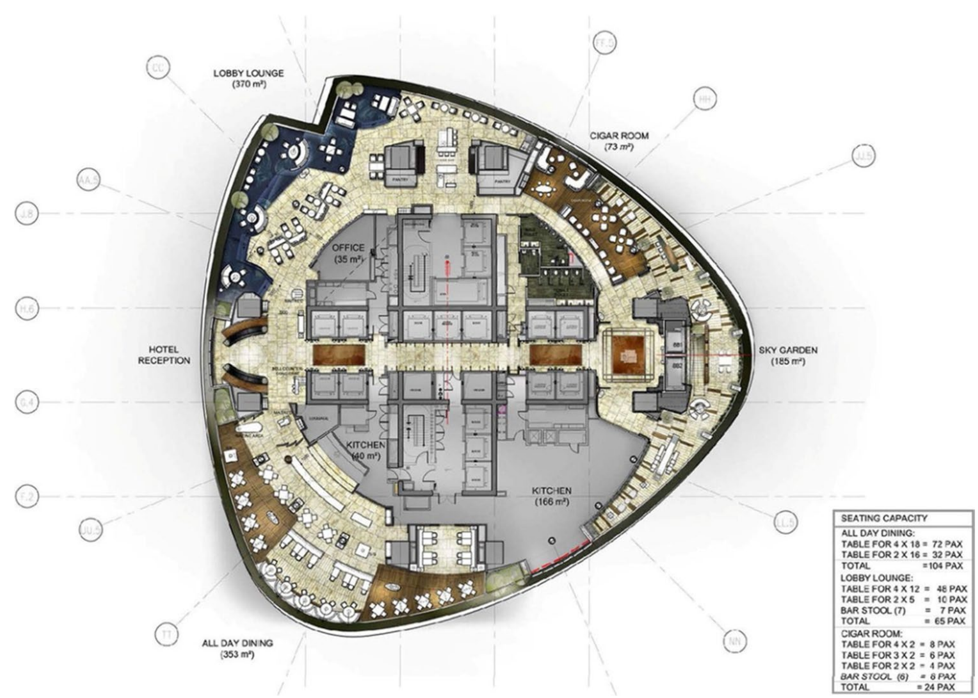

Fig. 4. 2D Plan of a floor of the Shanghai Tower [30]

Models and scenarios

In this research, we used IPCC AR4 A2, as a scenario for future periods (2030, 2050 and 2080). The A2 family of scenarios is characterized by a world of independently operating, self-reliant nations, continuously increasing population (Jump 2000). This scenario was used by many researchers in these two countries. In addition, eleven models are defined as showed in Table 3. These different models allow studying of various scenarios concerning the adaption of renewable energy, climate change and energy mix. The different models were established on the basis of the energy mix of each country, and also taking into account some IPCC recommendations.

Mo is the benchmark model similar to the energy mix of each of the countries studied. Models M_5 to M_{10} are built on the basis of the variability of one or more parameters of M_O.

In this study, several hypotheses or models are applied; the main objective is to understand in which case, the concentration of carbon will be the lowest. In Table 3, there are several tests or models. These examples are taken from the requirements of several international standards. Through these examples, we want to show the population, the importance of using renewable energy sources.

Note that we start by studying the building in its normal state, while carrying out all possible simulations. It is noted that coal is one of the main sources of carbon emission in these two countries. For this, we are gradually reducing the carbon rate in favor of renewable energies. The objective, in this case, is to assess the impact of green energies on carbon emissions.

Results and discussion

Indoor air

Figure 5 presents the Brager diagram in the two buildings studied. The adaptive approach is designed to guide the construction of buildings without centralized air conditioning. It aims to offer a less stringent control of temperatures within buildings, encouraging the user to participate actively in its comfort. For the human being, the notion of comfort integrates many parameters. This notion is essential before dealing with the analysis of the energy/environment/economy balance. The Brager diagram validates the level of comfort in each zone of a naturally ventilated building. Indeed, the Brager diagram shows an image of the evolution of the uniform temperature of the building according to the outside temperature of the moment. Each point represents one hour of study. Comfort is assured for all the points located between the two black lines. Removing the air conditioning systems from the two buildings studied, the calculated comfort rate was 31% in One Word Trade Center (1WTC), and 29.6% in Shanghai Tower with only natural ventilation (see Fig. 4a and b). Outdoor air temperature varied from 4.97 to 37.14 °C, with an average of 21.29 °C, in 1WTC but between 6.12 and 38.94 °C, with 22.82 °C as average in Shanghai Tower. Under the same assumptions, the total comfort concentration is expected to decrease up to 1.6% by 2030, 3.0% by 2050 and 4.2% by 2080 at the 1WTC compared to the current year (see Fig. 4c, e and g). This one is going to decrease up to 0.4% by 2030, 0.7% by 2050 and 1.4% by 2080 at the Shanghai Tower compared to the current climate (see Fig. 4d, f and h). Indoor air and thermal comfort depending directly on outdoor air (Nematchoua et al. 2014b, 2017), it is normal that in a situation of natural ventilation, the rate of comfort will decrease in future, considering the evolution of the outside climate (Nematchoua et al. 2015; Nematchoua et al. 2019a, b, c, d, e). It is thus imperative to use an air conditioning system to improve the level of comfort in these two buildings, mainly consisting of office rooms.

These results show that nowadays under natural ventilation, the 1WTC is slightly more comfortable than the ST. Nevertheless, in 2080, if no action is taken to curb the evolution of the outdoor climate, it is likely that the offices of ST will be more comfortable under natural ventilation than those of the 1WTC.

In these two buildings, it was found that the comfort rate is weak (around 30%) when only natural ventilation is applied. Both buildings must use mechanical ventilation and cooling systems to improve occupant comfort and worker performance. These different systems used to soothe the indoor climate generate carbon dioxide during their operation. The very low comfort rate in these buildings can be due to the altitude effect and also to the choice of construction materials. Indeed, as shown in Table 2, the building materials chosen in this research have thermal conductivity, which facilitates the rapid transfer of heat through the walls of the building.

Operational buildings

Figures 6 and 7 show the carbon concentration emitted in the two buildings during the operational phase. On the basis of this hypothesis, the average rate of carbon emitted is estimated at 7,546,471.8 $kgCO_2$ for 1WTC and 25,544,266.1$kgCO_2$ for the (ST). These results show that during the operational phase of the building, the Shanghai Tower produces 3.38 times the total CO_2 concentration emitted by the One World Trade Centre.

Considering model M1: a total energy amount of 298,147 kWh is produced by solar panels on the case of 1WTC building and 293,533 kWh on the case of ST building. In this case, the CO_2 rate decreases up to 50% in the case of the

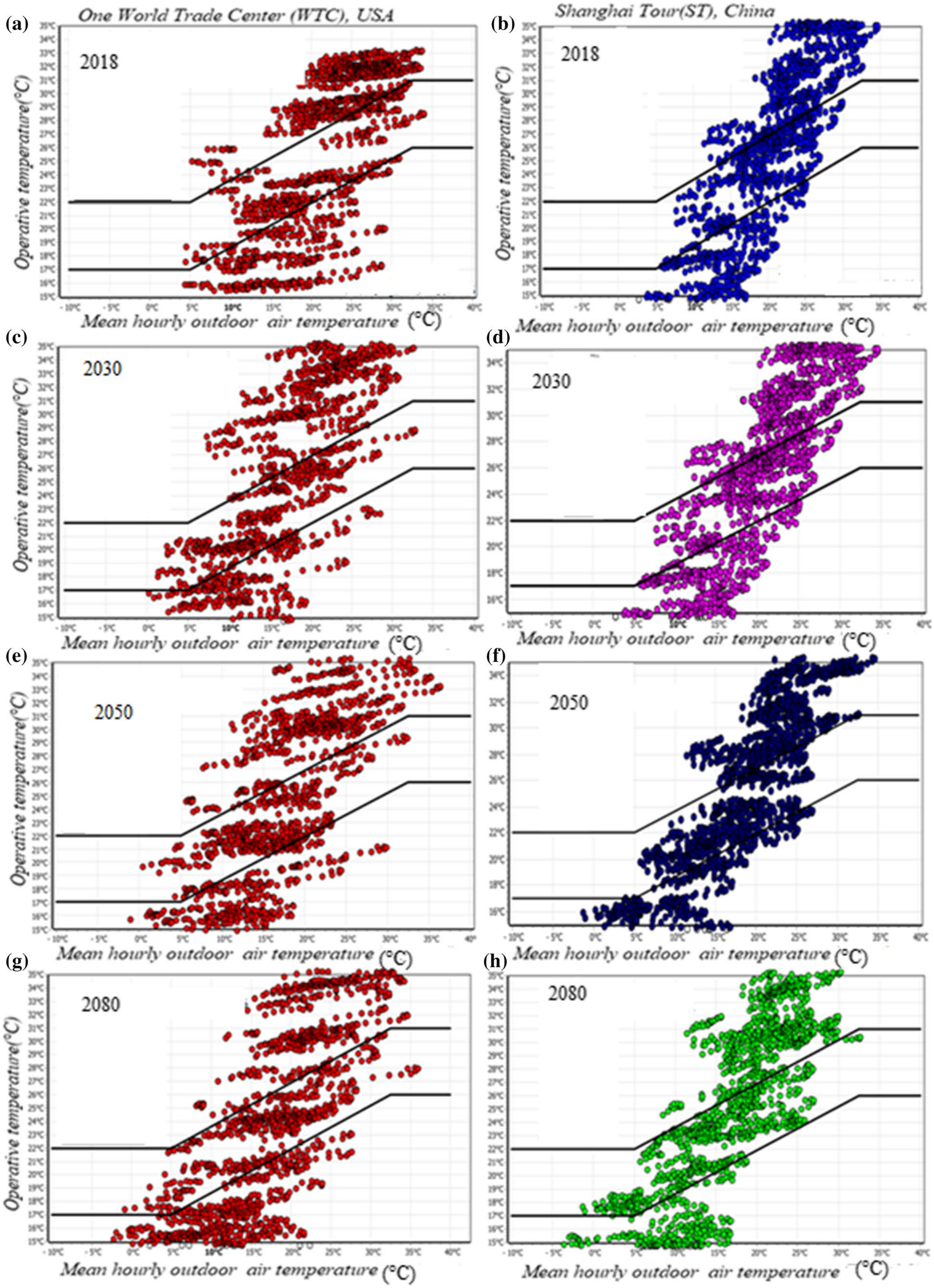

Fig. 5 Brager diagram of the two studied buildings in natural ventilation during four periods (current, 2030, 2050 and 2080)

Table 2 Building characteristics

Component	One World Trade Centre	Shanghai tower
Developer	Port Authority of New York and New Jersey	Shanghai Tower Construction
Construction	2006–2013	2008–2014
Use	Office, Observation, Communication	Hotel, Office
Total cost	$ 3.9 billion	–
Style	Modern contemporary	Post-modern architecture
Building material	Structure: Reinforced-concrete (conductivity:2.5 W/m–K; specific heat:1000 J/kg-K; Density:2400 kg/m^3) Steel (conductivity:45 W/m–K; specific heat:480 J/kg-K; Density: 7800 kg/m^3) Facade: Armored glass Aluminum(conductivity:160 W/m–K; specific heat:880 J/kg-K; Density: 2800 kg/m3)	Reinforced concrete (conductivity:1.4 W/m–K; specific-heat:840 J/kg-K; Density:2100 kg/m^3) Double-layer façade in glass (conductivity:1.2 W/m–K; specificheat:750 J/kg-K; Density:2000 kg/m3) Aluminum (conductivity:230 W/m–K; specific heat:880 J/kg-K; Density:2700 kg/m^3)
Height	541.3 m	632.0 m
Floor area	325,279 m^2	380,000 m^2
Floors	104	128

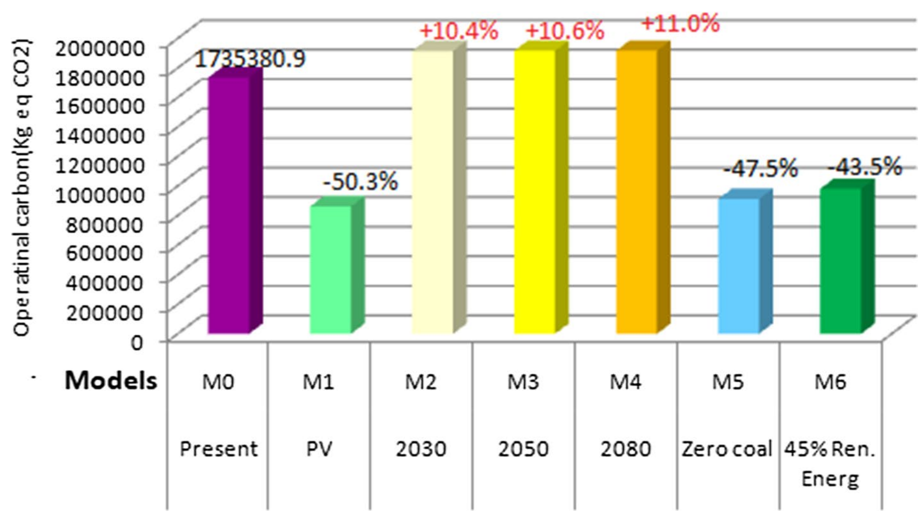

Fig. 6 Carbon rate emission during the operational phase of 1WTC

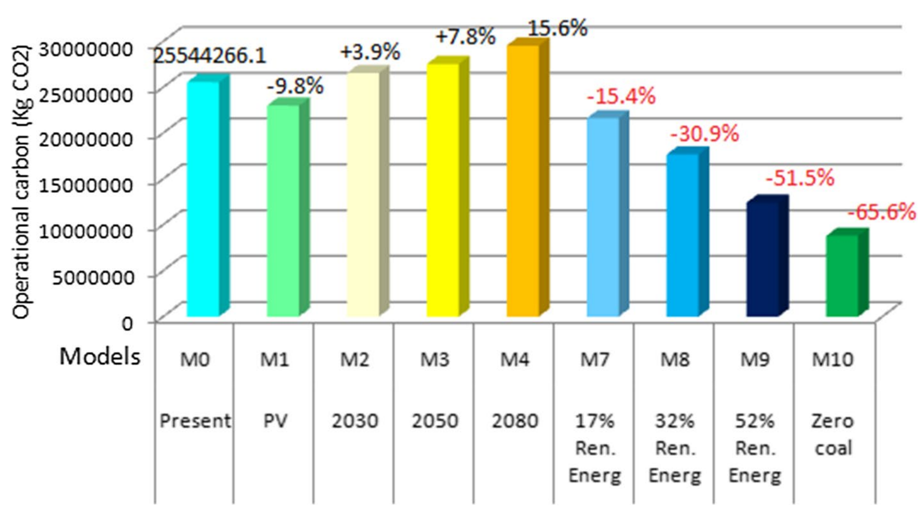

Fig. 7 Carbon rate emission during the operational phase of ST

Table 3 Ten models

Model	Main feature	USA-1WTC	China-ST
M_O	Control model	Climate: current + Energy mix: current (8% of nuclear; 12% of renewable energy; 13% of coal; 31% of gas; and 36% of Oil) + Building material: existing (shell in concrete + steel and aluminum facades + armored glass)	Climate: current + Energy mix (10% of nuclear; 1.7% of renewable energy; 63.7% of coal; 19% of oil; and 5.6% of gas)
M_1	Application of renewable energy: PV	Green energy injected into the network:298,147 kwh	Green energy injected into the network:293,533 kwh
M_2	Climate change: year	2030	2030
M_3	Climate change: year	2050	2050
M_4	Climate change: year	2080	2080
M_5	Energy mix: variation	8% of nuclear (+0%) + 25% of renewable energy(+13%) + 0% of coal(−13%) + 31% of gas(+0%) + 36% of Oil(+0%)	–
M_6	Energy mix: variation	8% of nuclear (+0%) + 45% of renewable energy(+33%) + 2% of coal(−11%) + 40% of gas(+9%) + 5% of Oil(−31%)	–
M_7	Energy mix: variation	–	10% of nuclear(+0%) + 16.7% of renewable energy(+15%) + 48.7% of coal(−15%) + 19% of oil(+0%) + 5.6% of gas(+0%)
M_8	Energy mix: variation	–	10% of nuclear(+0%) + 31.7% of renewable energy(+30%) + 33.7% of coal(−30%) + 19% of oil(+0%) + 5.6% of gas(+0%)
M_9	Energy mix: variation	–	10% of nuclear(+0%) + 51.7% of renewable energy(+50%) + 13.7% of coal(−50%) + 19% of oil(+0%) + 5.6% of gas(+0%)
M_{10}	Energy mix: variation	–	10% of nuclear (+0%) + 65.4% of renewable energy(+63.7%) + 0% of coal(−63.7%) + 19% of oil(+0%) + 5.6% of gas(+0%)

1WTC and 9.8% in the case of the ST. This variation is normal, because the energy produced by a green source (solar), comes to compensate for energy that should have been produced by a more polluting source of energy. It is found that the impact of the solar panel is more significant in the 1WTC (USA) than in ST (China). This result shows that, despite the amount of renewable energy produced on the Shanghai Tower, this building remains strongly dominated by the fossil energy supply (the coal rate is very high in electricity production in China).

By analyzing the results given by models M2, M3 and M4 (Figs. 5 and 6), associated with future evolution, it was noticed that the average carbon rate will increase by 10.4% for 1WTC and 3.9% for ST in 2030; by 10.6% for 1WTC and 7.8% for ST in 2050; and to 11% for 1WTC and 15.6% for ST in 2080, compared to the rate of CO_2 recently emitted. Globally, in 2030, the CO_2 emitted by the building is expected to be 92.7% higher in ST than 1WTC buildings. While in 2050, ST is expected to emit 93.1% higher than 1WTC. So, we conclude that the shape and orientation of the building can have a significant effect on the emission impacts of a building. This conclusion confirms some findings found in other studies (Dakwale et al. 2012).

All these hypotheses are described in Table 3.

As shown in Fig. 8, the CO_2 concentration emission due to the operational phase is 155 times higher than the CO_2produced by the renovation phase in the ST. The carbon emitted during the operational phase is estimated to be 90 times higher than the carbon emitted during the renovation phase at the 1WTC. It is important to notice that the majority of carbon dioxide is released during the use of the two buildings.

The renovation trend shows as a curve may be, because in future, the 1WTC will not be continuously renovated across the whole use phase.

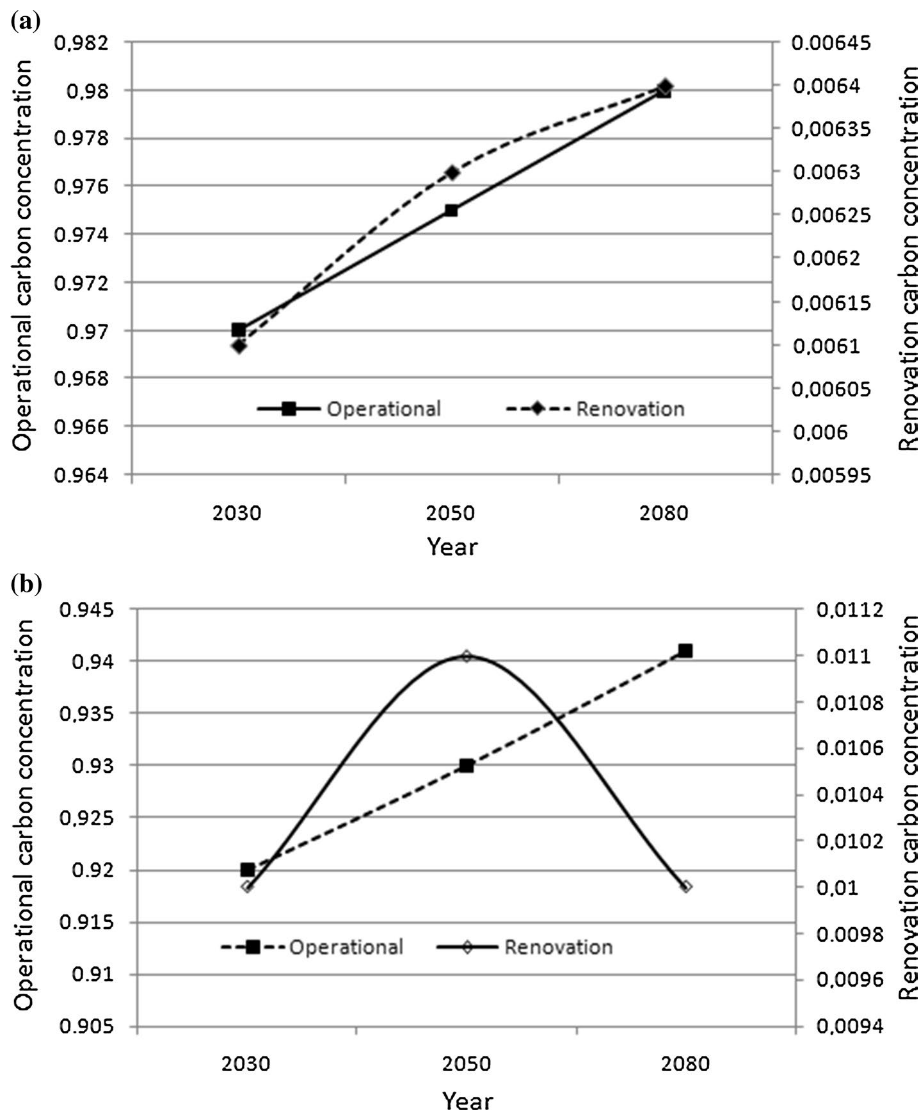

Fig. 8 Operational and Renovation carbon concentrations at ST (**a**), and 1WTC (**b**), for three periods (2030, 2050 and 2080)

In model M5: We assume that in 2050, the USA won't consume more coal; that is to say that the percentage of coal in its electricity mix will be set to zero (0%). To achieve this goal, the authors added more renewable energies in the electricity mix, thus increasing the renewable energy rate from 12 to 25%, in favor of coal which is decreased from 13 to 0%. Simulations respecting this new hypothesis produced a reduction of 47.5% of total carbon emitted by the One World Trade Center compared to model M0.

In model M6: We assume that the USA is determined to fight against climatic change, for that, it decides to produce even more green energy in 2050. We increased the renewable energy rate up to 45%, whereas coal and oil have been reduced to 11% and to 31%, respectively, in the energy mix of the USA. When we carried out some simulations respecting this new hypothesis, we noticed a decrease of 43.5%of the total CO_2 emitted by the 1WTC compared to the recent quantity.

In model M7, setting 17% of renewable energy in the energy mix of China in future, the simulations respecting this new hypothesis produced a decrease of 15.5%(3,946,373 kgCO_2) of the total CO_2 emitted by the ST compared to the recent quantity.

In model M8, setting 32% of renewable energy in the energy mix of China in future, simulations respecting this new hypothesis generated a decrease of 30.9%(7,892,745.9 kgCO_2) of the total CO_2 emitted by the ST compared to the recent quantity. In addition, in model M9, setting 52% of renewable energy in the energy mix of China in future, simulations respecting this new hypothesis generated a decrease of 51.5% of the total CO_2 emitted by the ST compared to the recent quantity. Finally, in model M10, the authors assumed that in 2050, China will no longer consume coal, which means that the percentage of coal in its energy mix will be set to zero (0%). To achieve this goal, more renewable energies are added, thus increasing the rate of renewable energy from 1.7% to 65.4%, whereas coal is decreased from 63.4 to 0%. Simulations respecting this new hypothesis produced a reduction of 65.6% (16,758,930.5 kgCO_2) of total carbon emitted by the Shanghai Tower by 2050, compared to the recent quantity.

The analysis of all these results shows that carbon concentration is the most significant in Shanghai Tower. Regarding these results, it is important to note that the best solutions are M5 (1WTC) and M10 (ST) scenarios that require both countries (USA and China) to opt for zero percent (0%) energy production from coal by 2050. Note also that the model M1, adding photovoltaic panels, is significant for 1WTC but that the improvement of the Chinese electricity mix is much more important for ST. However, the impacts of model M1 vary depending on the type of photovoltaic panels installed. How to request the governments of these two countries to adopt zero coal at the horizon of 2050 for the protection of our planet? It is difficult to force these two powerful countries. Imperative change may be required only by their citizens. Seen the current human mentality, it will be difficult to opt for a scenario where 100% of world energy is produced under the base of renewable energy sources producing zero carbon. But this scenario could be considered in the case of some sustainable countries in future.

These examples justify the intensity of the current CO_2 level rejected by the USA and China. It is a huge contribution to the destruction of the environment. In the year 2050, a total of 3,282,715 kgCO_2 can be avoided in the USA for each high-rise building similar to 1WTC, provided to reduce to 0% the coal rate in the USA energy mix. It is very important to notice that electricity based on fossil fuel production has a great impact on CO_2 concentration. Besides, a previous reference explained that energy produced by fossil fuels emits CO_2 corresponding to around 80 g/MJ (Nielsen 2008).

Carbon emission per area

In this study, it was noticed that the CO_2 concentration emission varied according to studied zone and living area. Figure 9 shows the quantity of carbon produced per area in each studied building. Initially, during the building operation, the average amount of greenhouse gas produced was around 23.2 kgCO_2/m^{2}from One World Trade Center and around 61.2 kgCO_2/m^2 from Shanghai Tower. However, after applying solar panels on these two buildings, a second evaluation of GHG gave around 20.4 kgCO_2/m^2 due to 1WTC and 55.1 kgCO_2/m^2 due to ST. These results show that the operational carbon emission rate per square meter is 2.6 times higher in Shanghai Tower than in 1WTC.

Suppose a significant increase in the use of renewable energy, whereas, we reduce coal in the country energy mix, to reach two tall buildings totally independent of coal (coal consumption: set to 0%): the average amount of GHG should be around 21.5kgCO_2 (1WTC), and 20.9kgCO_2 (ST). In this specific case, carbon rate emission per area unit is higher in 1WTC than ST.

To validate our conclusions, we will check the order of magnitude of our results. For this, we compare these ones with the results present in the scientific literature. In 2015, Lotteau et al. (2015) carried out a critical review of the state of the art regarding the emission of different environmental impacts at the neighborhood scale. They found after analyzing various studies that the emission rate in the conventional buildings ranged from 11 to 124 kgCO_2/m^2. The average released in this study is 23.2 kg CO_2/m^2 for 1WTC and 61.6 kg CO_2/m^2 for ST. These results may be acceptable. Then, these results may be compared with values given by Ali Sayigh (2017) for the environmental tower designed by Norman Foster in 1999 and located at 30 St Mary, Axe Tower 26, London, UK. This high-rise building

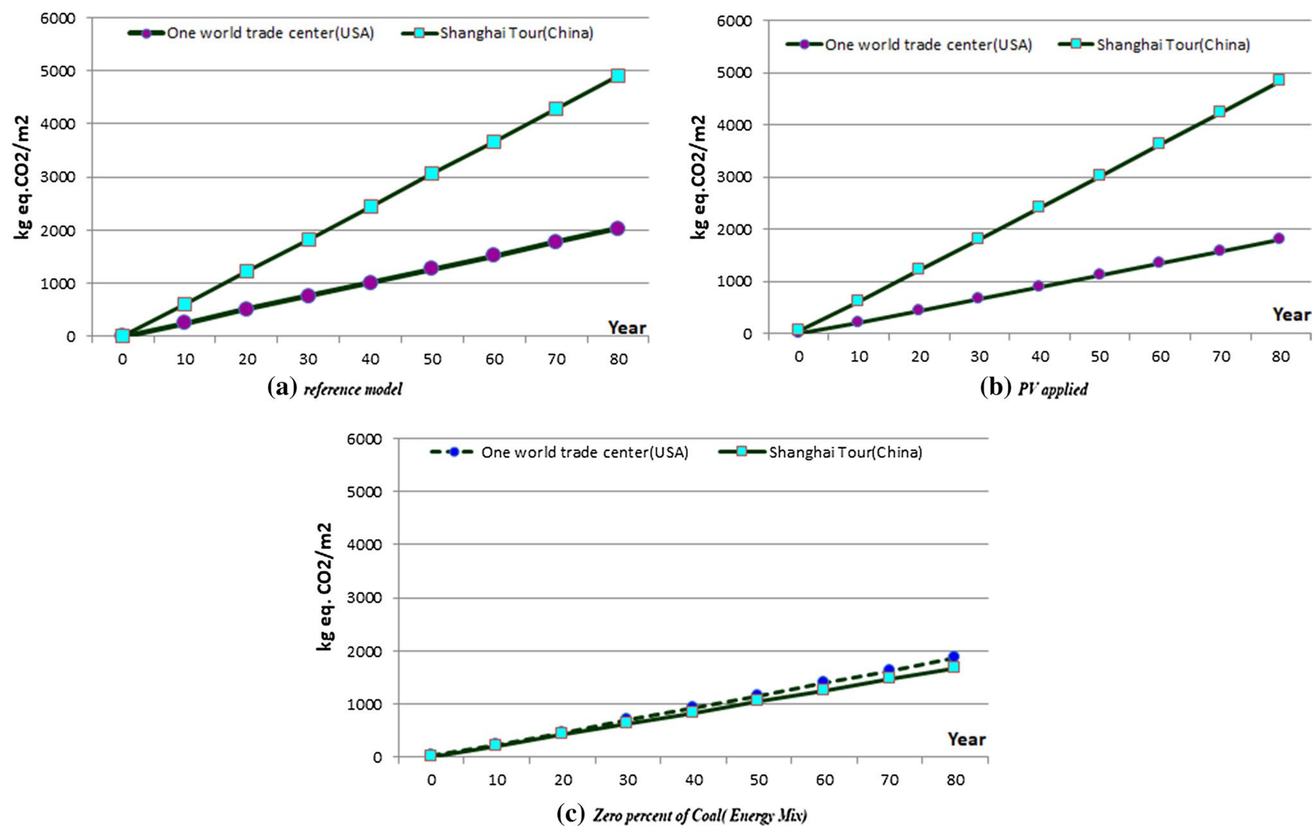

Fig. 9 CO_2 concentration emission per square meter of floor area during the operational stage of building in three cases: reference model (**a**); introduction of PV (**b**); Zero percent of Coal (**c**)

is a 179.8 m tall tower, including 64,470 m^2 of floor area, with a double skin façade allowing natural ventilation of the building. He gives an operating CO_2 concentration emission of the building reaching 76.31 $kgCO_2/m^2$.year. This previous study allows us to consider that the operating carbon values calculated in this article are validated.

The different causes of CO_2 production in tall buildings is mainly due to construction materials and electricity production during the operational stage. These findings confirm the results found by Kaspersen et al. (2016) who found that plumbing, HVAC and elevators produce a small amount of carbon per square meter from 12 floors in the skyscrapers.

Looking at Fig. 9, we see that the difference in carbon emitted between the two tall buildings is very high, this is explained by the fact that the simulation is carried out over several cycles (10 years, 20 years, 30 years, 40 years, etc.), and to each building life cycle, we apply the energy mix and the change in the outside climate, which considerably increases the rate of carbon emitted.

Embodied carbon and construction cost

In this study, it was found that the building material is one of the most important sources of embodied carbon. In the literature, some researchers (Gan et al. 2019; Zhao et al. 2015) showed that some materials such as concrete, steel etc. produce a greater quantity of CO_2 than wooden, earth brick etc. The rate of CO_2 emission depending on the local conditions at the production site as energy resources, climate and transportation distances (Björklund and Jönsson 1996; IStruct 1999). The carbon emission rate and the price of each construction material are all incorporated into the Design Builder simulation software used in this research. These different values come from several internationally recognized databases, such as: ICE, Ecoinvent, EN ISO standards etc. The Ecoinvent database is a global leader to provide the environmental impacts of each construction material and their standard price.

The concept of the embodied carbon of a building defines means all the CO2 emitted in producing materials. It's estimated from the energy used to extract and transport raw materials as well as emissions from manufacturing processes.

The embodied carbon produced by the Shanghai Tower is around 15,911.8t CO_2. This is due to the greenhouse gas emissions arising from the manufacturing, transportation, installation, maintenance, and disposal of building materials. It corresponds only to less than a year of operational carbon emissions of the same building. The total embodied carbon produced by 1WTC is around 6940.8t CO_2, namely a total amount of embodied CO_2 emissions 2.23 times lower than that emitted by the ST. Here are three factors that influence these numbers: the ST includes a built surface which is 1.29 times higher than the number of m^2 of 1WTC; 1WTC has a single-layer façade, and all the building's materials of 1WTC contain 25 percent recycled-content materials.

Table 4 gives embodied carbon of some materials in the literature. It is seen that some materials, the most commonly used ones, have a very high rate of embodied carbon. The statistical analysis of these building materials showed that concrete produced the most important quantity of embodied CO_2 emissions in the two studied buildings, because of the large quantities of concrete used in both high-rise buildings.

The analysis of this table shows that the embodied carbon of some materials as the insulation lambda 0.025 is null. This kind of material should be used for reducing CO_2concentration. Stone(basalt) and wood are two materials showing a low rate of embodied CO_2 in the two countries. Indeed, wood demonstrated an important effect in combating climate change. It was seen that the use of wood reduces greenhouse gas emissions by substituting for fossil fuel intensive products. Frühwald (2002) explained that if only 10% of all residences in Europe were designed with wood as a material, carbon emissions will be reduced up to 1.8 million tons. However, one of the drawbacks of wood is that it is difficult, and even impossible to build multi-floor buildings with this type of material, because of the high stress and the instability of the pressure at a certain height.

In both cases, steel emits around 1.77kgCO_2 per kg, while 1 kg of iron/cast emits 1.91 kgCO_2. Furthermore, all materials directly and indirectly acting on the environment must be referenced and used according to the standards recommended by the architects. Important results are found in this study as well as in research conducted by Lai et al. (2012), Lai (2015), Lai and Lu (2019), Mengxue (2020) analyzing carbon emissions of commercial buildings. These results may be beneficial for new researchers who wish to orient themselves in this field.

Table 5 gives an estimation of the construction cost of one World Trade Center (1WTC) and Shanghai Tower (ST) (in $). For this estimation, we suppose there's no PV applied to these two buildings. Increasing the energy efficiency requires most often a surplus of the cost of the initial construction of the building. Despite this, in the long run, the energy savings achieved completely offset these higher initial costs. Estimation of construction costs of the two studied buildings has been done to analyze the distribution of their construction costs.

As shown in this table, 46% of building construction cost is related to the structure and super structure. The total gross

Table 4 Embodied carbon of some materials

Material	Embodied carbon (kgCO_2 m^{-2})	Embodied carbon (kgCO_2 kg^{-1})	Thickness (m)
Expanded Polystyrene	0.740	2.500	0.02
insulation lambda 0.025	0.000	0.000	0.02
Timber Flooring	8.970	0.460	0.02
Plasterboard	13.830	0.380	0.02
Glass Wool	1.840	1.530	0.02
Cast Concrete	16.00	0.080	0.02
Asphalt 1	1.050	0.050	0.02
Extruded Polystyrene	3.024	2.880	0.02
Brick	43.000	0.220	0.02
Marble	6.160	0.110	0.02
Aluminum	49.365	8.550	0.02
Steel	276.1000	1.770	0.02
Rubber	105.290	3.500	0.02
Mortar	10.630	0.180	0.02
Zinc	47.662	3.310	0.02
Bronze	71.330	4.100	0.02
Granite	2.030	0.380	0.02
Stone(basalt)	0.057	0.010	0.02
Wood	0.490	0.450	0.02
Glass mosaic	3.390	0.850	0.002
Ceramic/Porcelain	29.890	0.650	0.02
Iron/cast	286.480	1.910	0.02

Table 5 Estimation of the construction cost of One World Trade Center and Shanghai Tower (in $)

Building	Structure	HVAC	Lighting	Sub-structure	Super structure	Glazing	Total construction
1WTC(M$)	353.1	252.2	100.8	184.9	353.2	168.2	1412.5
ST(M$)	357.5	255.4	102.1	187.3	272.5	289.5	1464.3

1WTC financing cost published by the US government was $ 3.9 billion. In this study, construction cost is found at $ 1,412,561,620. But if we add to this cost: the cost of buying land, the cost of designing the 1WTC, the cost of equipment, transport, wages of workers etc. it is likely that the total amount of funding could be close to $3.9 billion as claimed by the USA government. This proves that our results can be validated.

There are many kinds of materials that can be chosen during building design. That choice can have an important role in CO_2 emissions. In this research, it is recommended a more important utilization of low carbon materials such as shown by Gustavsson et al. (2006), Ardente et al. (2008), Upton et al. (2008), Reddy (2009), Salazar and Meil (2009), Norman et al. (2006), Boardman (2007). In addition, better design [45–46], and encourage use of local materials (2006) should be required, even for skyscrapers. The extension and design of positive energy buildings with low carbon emissions can facilitate the reduction of CO_2 levels in the atmosphere. But unfortunately, their implementation requires an additional initial investment cost compared to more conventional buildings.

Overall, the improved lifestyle of the occupants and the implementation of the new advanced technologies have facilitated the increase in anthropogenic carbon emissions. Thus, to slow down anthropogenic emissions, it is recommended that the population take ecological measures to reduce buildings energy consumption. The introduction of good emission abatement policies by each country will save a lot of carbon emissions. This policy may allow countries such as China and the United States to strongly reduce their emission rate over the next 20 years. Table 6 shows some countries with zero coal used for the production of their electricity and other countries with a high level of renewable energy in their energy mix. The concentration of CO_2 produced during the operational stage of tall buildings is strongly dependent on the energy mix of the country. It is advisable to design furthermore the tall buildings in most of the countries presented in Table 6 to limit CO_2 emission.

China and the United States, which are two of the most polluting countries in the world, should follow this example. This will curb global warming.

Overall, as seen in Table 1, the Shanghai Tower has a hotel inside, this significantly affects the energy demand and CO2 concentration. This can be one of the causes of the high carbon emission in the ST compared to that of the WT. We can significantly reduce carbon emissions by choosing the least polluting materials during the construction stage of the building (example: Straw Bales, Recycled Plastic, Wood Rammed Earth, Timbercrete, etc.), and by reducing the concentration of fossil energy in the energy mix. The number of skyscrapers under construction in China and the USA in future is given in this reference (LFTB 2020). It is shown that by 2050, more than 40 tall buildings are under construction in China, and only six in the United States.

Limit of study

In this study, not all of the building life cycle assessment stages are included. Only the use and demolition stages are detailed.

Conclusion

This study assesses, analyses and compares the CO_2 emission rate of the two tallest buildings located in the two most polluting countries in the world (China and the United States). The concentration of carbon released by the two buildings is very significant. The amount of CO_2 emitted by the Shanghai Tower during the operational phase, per square meter, is almost 2.6 times higher than that resulting from the 1WTC. One source of carbon emissions that can be reduced in buildings is the embodied carbon related to building materials. A best practice example for high-rise buildings is given by 1WTC: all its building's materials contain 25 percent recycled-content materials. But the main source of

Table 6 Some countries with zero coal and high renewable energy production in their electricity mix (EIA 2016)

Some countries with 0% coal in electricity mix	Cuba; Ecuador, Nicaragua, Algeria, Angola, Equatorial Guinea, Palestine, Swiss
Some countries with more than 30% renewable energy in electricity mix	Slovenia, Switzerland, Cameroon, Mozambique, Georgia, Democratic Republic of the Congo, New Zealand, UK
Some countries with more than 40% renewable energy in electricity mix	Denmark, Netherlands, Iceland, Sweden, Costa Rica, Paraguay, Uruguay, Burundi, Swaziland, Zambia, Bhutan, Tajikistan

carbon emissions, even for the two studied super tall buildings, remains the operational carbon emissions due to energy consumption during the use phase. The strong dependence of both countries on fossil energy sources considerably increases buildings CO_2 emissions. Among several strategies to promote a reduction of CO_2 emissions, improving the energy efficiency of a building and the environmental qualities of its electricity mix are the best options. Finally, in order to reduce construction costs of high-rise buildings, their structure and super structure should be optimized, because the 46% of building construction cost of the two studied skyscrapers is related to their structure and super structure. The next research will analyze and compare some scenarios allowing to reduce the building energy consumption rate in the tallest 10 buildings located in the top 10 countries having the highest CO_2 emission in the world.

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Declarations

Conflict of interest All authors declare that they have no conflict of interest.

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