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Assessment of operational carbon emission reduction potential of green building technologies

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ABSTRACT

The concept of green building plays an important role in carbon emission reduction. This paper focuses on the energy conservation in the building operational phase to assess the carbon emission reduction potential of several major green building technologies. Energy use intensity is simulated using EnergyPlus with prototypical models of various green building scenarios for office buildings and hotels in Shanghai and Harbin. The carbon emission factor is calculated according to the energy structure in the building sector in China. Results shows that passive technologies such as daylighting and natural ventilation can bring significant reductions in carbon emissions followed by retrofitting of building envelopes and energy efficiency improvement of HVAC equipment. Covering all green building technologies considered, the total operational carbon emission reduction rate can reach nearly 19% for office buildings and 25% for hotels.

Keywords: green building, carbon emission, energy conservation, building simulation

NONMENCLATURE

Abbreviations	
CEF	Carbon Emission Factor
CEI	Carbon Emission Intensity
EUI	Energy Use Intensity
HVAC	Heating, Ventilation and Air Conditioning
GMST	Global Mean Surface Temperature
Symbols	
f_i	CEF of primary energy resource i
Sb_i	share of resource i in building energy use

1. INTRODUCTION

The global mean surface temperature (GMST) in 2020 was 1.2 ± 0.1 °C warmer than the pre-industrial baseline, making 2020 one of the three warmest years on record[1]. Global warming has had serious impacts on the ecosystem and human society[2-4]. The Paris Agreement proposes that the rise of GMST in this century should be limited to 2 °C above the pre-industrial baseline and that more efforts should be made to limit the rise in temperature to 1.5 °C[5]. One of the largest causes of global climate change is greenhouse gas emissions[6]. From 23.3 billion tons in 2000 to 34.0 billion tons in 2018, the global carbon emission is still increasing[7]. Prediction[8] shows that from 2007 to 2035, global oil consumption will increase by 30%, and natural gas and coal consumption will increase by 50%, resulting in annual carbon emission increase of more than 2%. Therefore, to mitigate the risks of global warming, reducing carbon emissions is essential.

The building sector plays an important role in tackling global warming[9]. Energy consumption in buildings accounts for 36% of the total global final energy consumption, and the resulting carbon emissions account for almost 40% of the total[10]. Building operational energy, materials embodied energy and mobility energy are all contribute to the total carbon emissions. Fenner et al.[11] find that building operational phase accounts for 70% of the total carbon emissions, followed by mobility (24%) and embodied carbon (6%). Building operational energy conservation has become an important part of building carbon emission reduction.

The concept of green buildings is introduced as an approach to achieve sustainability in the building sector.

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Green buildings refer to the environmentally friendly buildings planned, designed, constructed and operated with efficient energy and water consumption and low environmental impacts[12]. Evaluation standards for green buildings consist primarily of Leadership in Energy and Environmental Design (LEED) from the United States, Building Research Establishment Environmental Assessment Method (BREEAM) from Britain, Comprehensive Assessment System for Building Environmental Efficiency (CASBEE) from Japan[13]. China, as the world's largest energy consumer and carbon emitter, has enacted a range of standards to adopt green building technologies[14]. Design Standard for Energy Efficiency of Public Buildings (GB 50189) was revised in 2015 and applied in energy-saving building design. Moreover, Assessment Standard for Green Building (GB/T 50378) was revised in 2019, which has launched many demonstration projects covering green building technologies, such as solar thermophotovoltaic system, green lighting system, HVAC system, green roof and other energy-efficient technologies.

Existing studies mainly focus on the adoption process[12-14] and innovation[15] of green building technologies and lack the perspective of carbon emission in green buildings. This paper assesses the potential of energy conservation and relative operational carbon emission reduction of several major green building technologies. The main approach is building energy simulation with physics-based method. Establishment of prototypical building models and carbon emission calculation method are introduced in Section 2. Section 3 introduces the scenarios of simulation for different green building technologies. Section 4 shows the assessment results and Section 5 gives suggestions on the application of green building technologies in carbon emission reduction.

2. METHODS

2.1 Building operational carbon emission

As shown in Fig 1, the calculation model from IPCC[16] combining activity level and emission factors to estimate building carbon emissions can be described as Eq.1,

$$CE = BFS \times CEI \quad \text{(Eq.1)}$$

where CE is the carbon emission ($kgCO_2$), BFS is the building floor space (m^2), and CEI is the carbon emission intensity ($kgCO_2/m^2$).

This paper focuses on the carbon emission in the building operational phase which is the primary emission source of the whole building life cycle[11]. Building operational carbon emission is related to energy consumption and can be calculated with Eq.2,

$$CEI = EUI \times CEF \quad \text{(Eq.2)}$$

where EUI is the energy use intensity (kWh/m^2), and CEF is the carbon emission factor ($kgCO_2/kWh$).

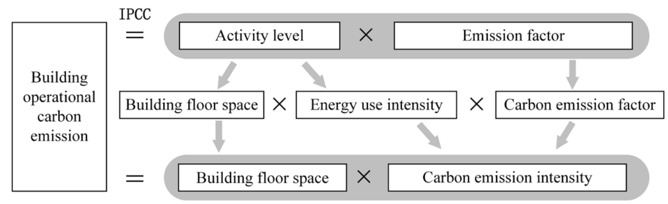


Fig 1 Building carbon emission calculation model.

2.2 Building energy use intensity

Building energy use intensity is simulated with building physics-based method. Building physics-based method[17] is to establish building physics model and complete numerical analysis using building simulation programs. The objects studied in this paper is office buildings and hotels, which are significantly different in operation schedules. Considering the differences of weather data, hot-summer and cold-winter zone, taking Shanghai as the example, and severe cold zone, taking Harbin as the example, are selected as representatives of climate zones in China.

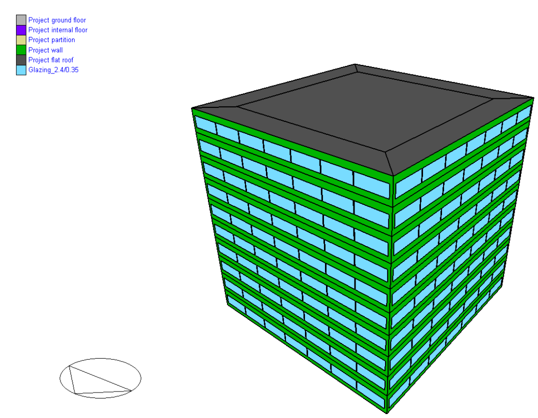


Fig 2 Prototypical building model.

Table 1 Building geometric parameters.

Geometric parameters	Unit	Value
Building length	m	40
Building width	m	40
Storey height	m	4
Storey quantity		10
Building shape factor	m^{-1}	0.15
Depth of external zones	m	5
Building orientation		North

Prototypical building models are established using DesignBuilder as shown in Fig 2. The geometric parameters of the model are shown in the Table 1. The operation schedules including occupancy, lighting and internal equipment are different for office buildings and hotels, which have great impacts on building energy consumption. Schedules for simulation are set referring to the Design Standard for Energy Efficiency of Public Buildings (GB 50189-2015) as shown in Fig 3 (Office building) and Fig 4 (Hotel). Based on the prototypical building models, building energy use intensities of different scenarios for green building technologies are simulated using EnergyPlus and calibrated with the limit values in China Standard for Energy Consumption of Building (GB/T 51161-2016).

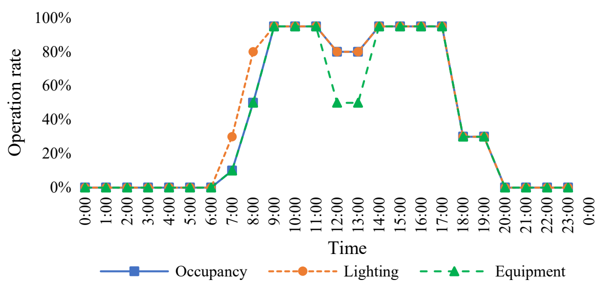


Fig 3 Schedules for office buildings.

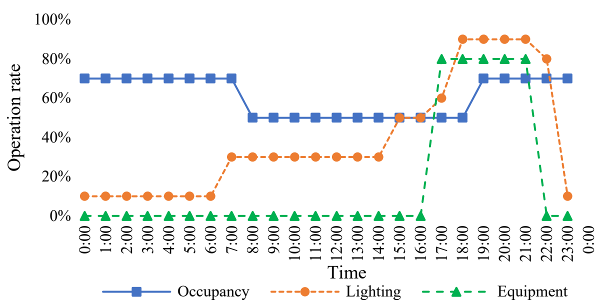


Fig 4 Schedules for hotels.

2.3 Building carbon emission factor

Besides energy use intensity, building carbon emission factor is necessary to estimate building operational carbon emission. Building carbon emission factor is related to the energy structure in the building sector and can be calculated with Eq.3,

$$CEF=FDBH\times\sum_{i}(f_i\times Sb_i) \qquad \text{(Eq.3)}$$

where FDBH is the coal equivalent consumption factor for power generation, set as 0.307 kgce/kWh for China in this paper, i represents the types of primary energy resource, including coil, oil, natural gas and non-fossil fuel, f_i is the carbon emission factor of primary energy resource i in coal equivalents, and Sb_i , reflecting the energy structure in the building sector, is the share of primary energy resource i in the total building energy consumption converted to coal equivalents.

Referring to the China Energy Statistical Yearbook 2020[18], the Table 2 shows the energy structure in the building sector of Shanghai and Harbin. Calculated with Eq.3, building carbon emission factor of Shanghai is 0.62 $kgCO_2$/kWh, and the value of Harbin is 0.72 $kgCO_2$/kWh.

3. CALCULATION

China Assessment Standard for Green Building (GB/T 50378-2019) make a series of criterions for the application of green building technologies, including building envelope retrofitting, HVAC equipment energy efficiency improvement, daylighting, natural ventilation and so on. This paper simulates building energy consumption for several scenarios of major technologies to assess their energy conservation and emission reduction potentials compared with the baseline scenario described in the Design Standard for Energy Efficiency of Public Buildings (GB 50189-2015).

3.1 Baseline scenario

At the present stage, GB 50189-2015 has been widely applied in energy-saving building design in China[14]. The building energy consumption level described in GB 50189-2015 is taken as the baseline scenario for the assessment of operational carbon emission reduction potential of green building technologies. Model parameters of office buildings and hotels in Shanghai and Harbin in the baseline scenario are shown in Table 3. Building energy use intensity in the baseline scenario can be simulated with EnergyPlus according to the parameter settings.

Table 2 Carbon emission factor calculation.

City	Energy structure in the building sector Sb_i				CEF in coal equivalents	CEF
	Coil	Oil	Natural gas	Non-fossil	$kgCO_2$/kgce	$kgCO_2$/kWh
Shanghai	32.4%	53.7%	12.9%	1.0%	2.02	0.62
Harbin	75.1%	15.9%	4.1%	4.8%	2.35	0.72
f_i ($kgCO_2$/kgce)	2.66	1.636	2.15	0		

Table 3 Model parameters in Shanghai of baseline scenario.

Parameters	Unit	Shanghai	Harbin
Winter design temperature	°C	22	22
Summer design temperature	°C	26	26
Roof U value	$W/(m^2 \cdot K)$	0.40	0.28
External wall U value	$W/(m^2 \cdot K)$	0.60	0.38
Floorslab U value	$W/(m^2 \cdot K)$	0.70	0.38
Window-wall ratio		0.5	0.5
Window U value	$W/(m^2 \cdot K)$	2.4	1.9
Solar heat gain coefficient		0.35	0.5
Air infiltration rate	h^{-1}	0.2	0.2
Occupancy density	p/m^2	0.1 (Office) 0.04 (Hotel)	0.1 (Office) 0.04 (Hotel)
Equipment power density	W/m^2	15	15
Lighting power density	W/m^2	9 (Office) 7 (Hotel)	9 (Office) 7 (Hotel)
Cooling system		Chiller + FCU + DOAS	
Heating system		Gas-fired hot water boil	District heating
Chiller COP		5.6	5.6
Gas boiler efficiency		0.9	0.9
Fan efficiency		0.7	0.7

Notations: U value means the heat transfer coefficient, COP means Coefficient Of Performance, FCU means Fan Coil Unit, and DOAS means Dedicated Outdoor Air System.

3.2 Green building compulsory level

GB/T 50378-2019 classifies green buildings into compulsory, one-star, two-star and three-star levels. Buildings that meet all the compulsory criterions are classified as the green building compulsory level. As the baseline model is divided into internal and external zones, the green building compulsory level scenario can be set with indoor temperature setpoints and lighting operation schedules controlled in zoning, timing and occupancy-responding ways required by compulsory criterions in GB/T 50378-2019.

3.3 Retrofitting of building envelopes

Considering the energy-saving design of building envelopes, GB/T 50378-2019 stipulates that the thermal performance of three-star green building envelopes should be at least 20% higher than that in GB50189-2015. The building envelopes retrofitting scenario can be set through decreasing the heat transfer coefficient of building envelopes by 20% than baseline scenario.

3.4 Energy efficiency improvement of HVAC equipment

GB/T 50378-2019 stipulates that energy efficiencies of cooling and heating source, terminal and distribution equipment of green building HVAC system are better than the criterions of GB 50189-2015. Compared with baseline scenario, COP of chiller is increased by 12%, the energy efficiency of gas boiler is increased by 4%, and the efficiency of fan is increased by 20% in HVAC equipment energy efficiency improvement scenario.

3.5 Daylighting

To create a comfortable indoor visual environment, GB/T 50378-2019 requires that green buildings should make full use of daylight, while reducing the lighting power density of main zones. The daylighting scenario is set by adding the daylighting module in EnergyPlus and reducing lighting power densities to 8 W/m^2 (office) and 6 W/m^2 (hotel) according to target values in Standard for Lighting Design of Buildings (GB 50034-2013).

3.6 Natural ventilation

In order to create a healthy and comfortable indoor thermal environment, GB/T 50378-2019 requires that the green buildings should optimize the building space and layout to improve the effect of natural ventilation. The natural ventilation module in EnergyPlus is added to the baseline scenario. The natural ventilation rate is set as 2 h^{-1} and adjusted with outdoor air temperature. Meanwhile, the mechanical supply air ratio of fresh air is reduced in a corresponding proportion.

3.7 Shading

The role of the shading is to avoid direct solar radiation into rooms resulting in the excessive heat gain and glare. GB/T 50378-2019 requires that green buildings should be equipped with adjustable shading facilities to improve indoor thermal and visual comfort. Based on this criterion, outer shading blinds, adjusted with the change of solar radiation, are added to the baseline model in shading scenario.

3.8 Renewable energy sources utilization

GB/T 50378-2019 stipulates that the green buildings should make rational use of renewable energy sources, considering local climate and natural resources. The utilizations of renewable energy in buildings mainly focus on solar energy, geothermal energy and wind energy. In the scenario of renewable energy utilization, the HVAC cooling and heating source system is replaced by ground source heat pump. In addition, solar photovoltaic power generation is added with the proportion of 4% in building total electricity consumption.

3.9 Green building three-star level scenario

In order to reflect the comprehensive performance of green building technologies, the three-star level scenario of green building is a combination of the above 7 scenarios in Section 3.2 to 3.8, covering various green building technologies.

4. RESULTS AND DISCUSSION

4.1 Results

Based on the description of the above 9 scenarios, the building energy use intensities (EUIs) is simulated as the results shown in Table 4. Results of carbon emission intensities and carbon emission reduction rates of each green building technology scenario compared with the baseline scenario are shown in Fig 5 and Fig 6 for office buildings and hotels in Shanghai and Harbin.

4.2 Discussion

For different building types, the carbon reduction potential of green building technologies ranks similarly. Passive technologies such as daylighting and natural ventilation bring significant reductions in carbon emissions, of which daylighting can reduce emissions by about 13% for office buildings and 20% for hotels, and natural ventilation can reduce emissions by about 8% for office buildings and 12% for hotels. The applicability of shading technology is related to climate zones. The carbon emission reduction potential of building shading in hot-summer and cold-winter zone is about 12%, which is 2 times of that in severe cold zone. The retrofitting of building envelopes and improvement of the energy efficiency of HVAC equipment bring modest effects on emission reduction by about 3% to 4% for office buildings and 6% to 8% for hotels.

Covering all green building technologies considered, the operational carbon emission reduction rate of the three-star level scenario can reach nearly 19% for office buildings and 25% for hotels.

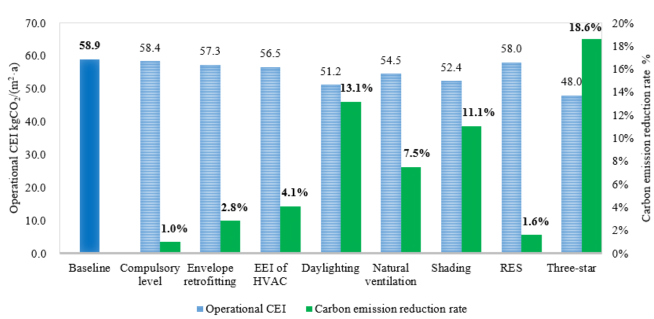
4.3 Limitations

The results are based on the assumptions according to criterions in China Assessment Standard for Green Building (GB/T 50378-2019), and limited to the carbon emissions in building operational phase. Further studies may cover mobility and embodied carbon emissions.

Table 4 Building energy use intensity simulation results.

Building type	Location	Building energy use intensity of scenarios (kWh/m^2)								
		Baseline	Compulsory level	Envelope retrofitting	EEI of HVAC	Daylighting	Natural ventilation	Shading	RES	Three-star
Office building	Shanghai	95.2	94.2	92.5	91.3	82.7	88.0	84.6	93.7	77.5
	Harbin	125.0	123.8	120.7	120.3	109.2	114.4	117.7	124.6	101.3
Hotel	Shanghai	109.3	104.9	100.5	101.1	86.8	96.8	95.4	101.6	81.6
	Harbin	155.6	151.8	146.5	146.8	126.6	135.4	145.0	155.3	116.4

Notations: EEI value means the energy efficiency improvement, and RES means renewable energy sources.



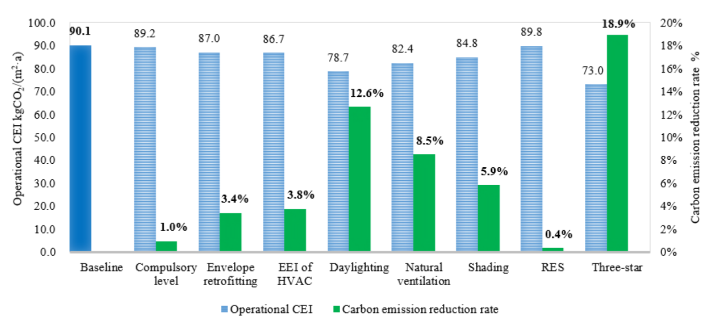
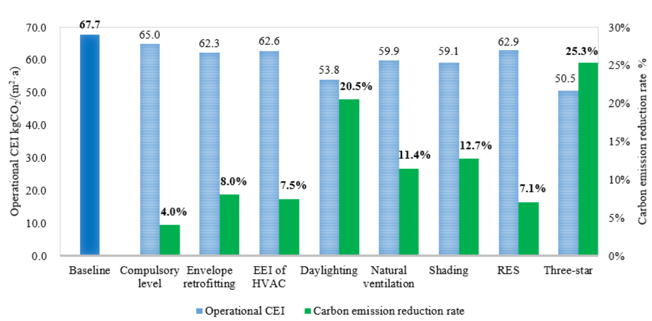


Fig 5 Operational carbon emission reduction potential of office buildings in Shanghai (left) and Harbin (right).



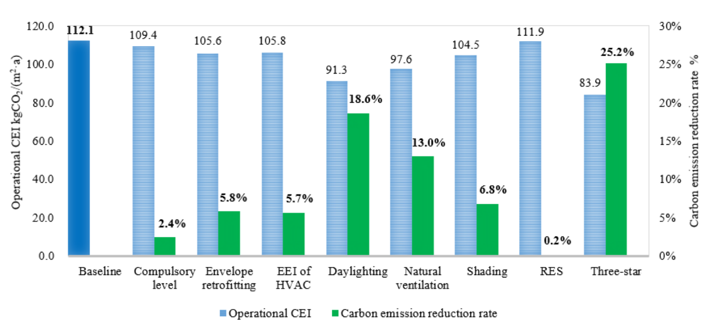


Fig 6 Operational carbon emission reduction potential of hotels in Shanghai (left) and Harbin (right).

5. CONCLUSIONS

(1) The building carbon emission intensity in central heating areas in China is higher than that in non-central heating areas. It is suggested that clean heating approaches such as cogeneration, heat pump technology, waste heat and biomass energy should be promoted to improve the energy efficiency of central heating. Meanwhile, strengthening the insulation and air tightness of building envelopes can further reduce heating energy consumption.

(2) Passive technologies such as daylighting and natural ventilation can bring significant emission reduction potentials. In the design phase of buildings, it is suggested to reserve sufficient daylighting areas and natural ventilation openings. The building design in hot-summer and cold-winter zone shall fully consider the exterior shading coupled to the envelopes.

(3) It is suggested to promote the utilization of solar thermal, photovoltaic and related energy storage technologies in combination with building design. Moreover, promoting the utilization of ground source and water source heat pump systems in public buildings can also make full use of the advantages of clean, efficient, energy saving and emission reduction of renewable energy sources.

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