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# Comparison of building energy codes in Australia, United States and China for Australian commercial building energy conservation

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## ABSTRACT

Building energy codes have been widely implemented in the world to regulate energy consumption and CO<sub>2</sub> emissions from the building sector. In order to assess the impacts of building energy codes on Australian building performance, this paper has compared the energy efficiency requirements of the Building Code of Australia (BCA) with the USA ASHRAE Standard 90.1 and Chinese GB50189, in terms of the building envelope, HVAC chiller efficiency, internal load density, and HVAC temperature set-points. Then, the whole building energy performance simulation has been conducted using EnergyPlus for a typical large office building in Brisbane to contrast differences in efficiency requirements of building energy codes within three countries. The results have shown that the GB50189-2015 and ASHRAE 90.1-2016 demonstrated 25.0% and 20.8% annual energy savings respectively compared to the BCA 2016, together with 312,429kg and 259,955kg annual CO<sub>2</sub> emissions reduction respectively. In light of this, recommendations for further revision of the Australian building energy code have been provided.

## 1. INTRODUCTION

Buildings currently consume around 40% of the world's total electricity energy and are responsible for more than 30% greenhouse gas (GHG) emissions globally<sup>[1]</sup>. It is expected that, with the rapid expansion of the urban population and economic growth, the total building energy consumption and GHG emissions would continue to grow over the next several decades. According to the International Energy Agency (IEA), the global energy demand in buildings will increase by 60% between 2007 and 2050 and the CO<sub>2</sub> emissions from the building sector will nearly double from 8.1 Gt to 15.2 Gt<sup>[2]</sup>.

In Australia, the building sector contributes about 40% of the nation's electricity energy consumption as well as 27% GHG emissions. Commercial buildings, in particular, account for approximately 61% of the total national building energy consumption and 10% total building carbon emissions in Australia<sup>[3]</sup>. An Australian government report at the beginning of the millennium predicted that the energy usage in buildings would rise faster than in any other sector and the GHG emissions from the built environment would more than double by 2050 if no appropriate actions to be taken<sup>[4]</sup>.

As a signatory to the Paris Climate Change Agreement, Australia has committed to reducing GHG emissions to 26–28% below 2005 levels by 2030, and achieving net zero carbon emissions from buildings by around 2050<sup>[5]</sup>. Therefore, improving energy efficiency in buildings is significantly important for Australia to achieve building energy consumption and GHG emissions reductions.

Considered to be the most effective approach to achieving building energy conservation, the incorporation of energy efficiency requirements into building regulations has been implemented in many countries around the world over the past several decades<sup>[6]</sup>.

A number of researchers around the world have also been examining building energy codes, using simulation tools to evaluate their effectiveness. For example, Chua and Chou<sup>[7–9]</sup> investigated and employed the Envelope Thermal Transfer Value (ETTV) approach to improve energy performance for residential and commercial buildings in Singapore, using eQuest and DOE-2.1E computer simulation.

They found that the ETTV displayed a strong linear relationship with the annual building cooling energy consumption. Chen and Lee<sup>[10]</sup> conducted a comparative study between the Hong Kong Building Environment Assessment Method (HK-BEAM) and the Chinese residential building energy efficiency standards for a representative residential building under main Chinese climates. By assessing the yearly building energy use and the Overall Thermal Transfer Value (OTTV), they found that the OTTV in China's codes was lower by 32%, but the annual energy use and cooling load were higher by 13.4% and 37.4% than those in the HK-BEAM.

Zhao et al.<sup>[11]</sup> and Feng et al.<sup>[12]</sup> conducted a comparative study of the Chinese GB50189-2014 Design Standard for Energy Efficiency in Public Buildings with the previous 2005 version. They also evaluated the energy savings performance of the GB50189-2014 compared with the ASHRAE Standard 90.1-2013 for a commercial building in different cities in China. They demonstrated that the new 2014 standard could yield an average of 24% site energy savings over the previous version, with payback periods from 2.9 years to 4.1 years for different climates.

However, the GB50189-2014 energy savings performance was 20% less than the ASHRAE Standard 90.1-2013. Gilbraith et al.<sup>[13]</sup> compared the energy performance and cost benefits of ASHRAE 90.1-2010 to its predecessor ASHRAE 90.1-2007 through the analysis of state-level climatic, environmental, and social benefits for American commercial buildings.

By using EnergyPlus simulation, they pointed out that by adopting the updated energy code, reductions in site energy use intensity ranged from 93 MJ/m<sup>2</sup> (California) to 270 MJ/m<sup>2</sup> (North Dakota). The total social benefits from the upgraded code were estimated to be \$506 million for all states annually.

There are also several review papers about the building energy codes and energy rating for buildings in Australia, in terms of the development, application, and improvement<sup>[14–19]</sup>. However, there is little published academic research using building energy simulation to assess the energy savings potential for the BCA.

Therefore, this paper will investigate the impacts of the BCA's energy efficiency regulations on Australian commercial building energy performance by comparing its stringency with the codes in China (GB50189) and USA (ASHRAE Standard 90.1), in term of building envelope, HVAC system, installed appliances, and lighting system et al.

The objective is to evaluate the most effective building energy policies (from the selected codes) and help Australia to achieve greater savings by learning from others. It will also provide recommendations for further revision of Australian building energy codes and evidence to support arguments for an increase in code stringency.

## 2. METHODOLOGY

The building energy performance for the comparison of different building energy codes will be conducted by computer simulation using building energy modelling software. EnergyPlus has been selected for the modelling, as it has been tested satisfactorily against the BESTEST<sup>[20]</sup> for building energy modelling, and its capabilities meet the requirements of the Australian Building Codes Board (ABCB) for building energy analysis<sup>[21]</sup>.

Chinese and USA building energy codes were selected for this comparison because both China and the USA have multi-climatic zones with different code requirements, similar to Australia. In addition, the Chinese and USA building energy codes have been shown to be effective in achieving building energy reductions, with 50% energy savings achieved for the ASHRAE Standard 90.1-2013 compared to ASHRAE Standard 90.1-2004 in America<sup>[22]</sup> and 25% for GB50189-2014 compared to GB50189-2005 in China<sup>[12]</sup>.

### 2.1 Building model description

The building model for simulation is a 10-storey, 5-zone per floor square office building with a basement carpark, which is recommended as Building Type A by the ABCB to represent a large office building in Australia<sup>[23]</sup>. The building geometry and EnergyPlus building model is shown in Figure 1.

The building footprint dimensions are 31.6m × 31.6m floor area, 2.7m floor-to-ceiling height and 0.9m plenum height. The total building height is 36m and the total air conditioned area is 9985.6m<sup>2</sup>. The total conditioned window-to-wall ratio (WWR) is 0.5 with the window dimension of 31.6m × 1.35m for each facade.

Each floor has one core zone and four perimeter zones with 3.6m depth. The climatic location for the building energy modelling is Brisbane.

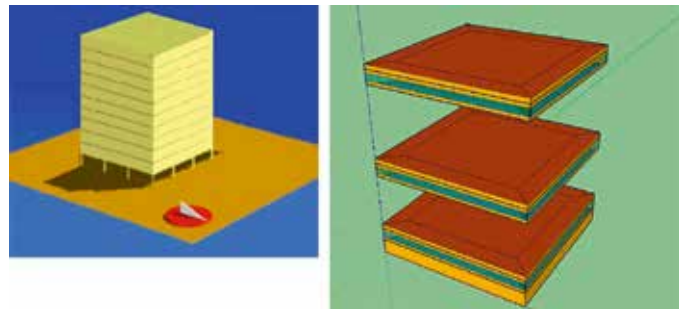


Figure 1: Building Type A and EnergyPlus model.

## 2.2 Description of the Building Code of Australia, GB50189, and ASHRAE Standard 90.1

### 2.2.1 The Building Code of Australia

In Australia, the National Construction Code (NCC) regulates the minimum performance requirements for building and plumbing construction. It is a national uniform set of technical provisions for Australia to build and construct buildings and other structures, as well as plumbing and drainage systems.

The energy efficiency requirements for commercial buildings are described in Section J Energy Efficiency of the NCC Building Code of Australia (BCA) Volume One, which specifies the provisions for building envelope, HVAC system, lighting and power, hot water supply and swimming pool, and energy monitoring.

The BCA is a performance-based building code which includes a performance hierarchy that encompasses Objectives, Functional Statements, Performance Requirements and Deemed-to-Satisfy (DtS) Provisions<sup>[24]</sup>. Compliance with the Performance Requirements could be achieved by either a DtS Solution or a Performance Solution or a combination of both. The energy efficiency requirements in the BCA allow for variations based on different climatic zones, and it is up to each state to determine if, and to what extent, they adopt the model codes presented in the NCC<sup>[25]</sup>. The most recent version is the NCC BCA 2016 and the ABCB is currently considering revisions to the energy efficiency provisions for commercial buildings in NCC BCA 2019.

### 2.2.2 GB50189 Design Standard for Energy Efficiency in Public Buildings

In China, the energy efficiency requirements for commercial buildings are prescribed in GB50189, which is derived from a hotel standard prescribed in the 1980s. The first version of GB50189 came into effect in 2005 with the goal of reducing energy consumption by 50% compared to the baseline buildings constructed in 1980s. It specified the energy efficiency requirements of the building envelope and HVAC system for public buildings covering all climatic zones in China except the Temperate Zone, where there is little heating and cooling demand.

The GB50189 was then further revised recently in 2015, which added efficiency requirements for the water supply and drainage system, electrical system, and renewable energy application, targeting an energy reduction of 30% from the 2005 version<sup>[26]</sup>. It should be noted that the lighting requirements are prescribed in a separate code called the 'Standard for Lighting Design of Buildings' (GB50034), which can be cross-referenced to GB50189-2015<sup>[27]</sup> for the energy-related provisions.

$$EUI = \frac{E_{total}}{A} = \frac{E_{fan} + E_{pump} + E_{cooling} + E_{heating} + E_{rej} + E_l + E_{equip}}{A} \quad (1)$$

The Chinese building energy code is mandatory at the national level but it also allows for modifications or improvements at the provincial-level to meet local requirements.

### 2.2.3 ASHRAE Standard 90.1 Energy Standard for Buildings Except Low-Rise Residential Buildings

The ASHRAE Standard 90.1 is a building energy standard developed by ASHRAE to indicate the cost-effective construction of buildings to save energy. It is applicable to all buildings except residential buildings of three storeys or less, with particular applications for large and complex commercial blocks. It contains energy efficiency requirements for the building envelope, HVAC, service water heating, lighting, power, other equipment and renewable energy systems for both newly-constructed and existing buildings. It is a very comprehensive and complicated building energy efficiency standard that prescribes values for different parts of the building and its energy systems at a very detailed level according to different climatic zones<sup>[6]</sup>.

Compliance with ASHRAE Standard 90.1 can be achieved by different ways including the Prescriptive Approach, Energy Cost Budget Method, Design Energy Cost Method, and Performance Rating Method (which permits trade-offs among the building physical elements and system components). It is upgraded every three years and the latest version is ASHRAE Standard 90.1-2016<sup>[28]</sup>.

## 2.3 Climatic zone comparison

In order to compare the building energy codes in Australia, China and US, the first and foremost task is to understand how the climatic zones are classified in these three countries and find out the climatic zones from China and US that are comparative to Brisbane's climatic condition. This is used to determine which code requirements should be used from GB50189-2015 and ASHRAE Standard 90.1-2016 for the building envelope as they set different requirements for the building envelope thermal insulation based on different climatic conditions.

The most commonly used method for climatic zone classification is based on heating and cooling degree-days (HDD and CDD). The IEA<sup>[6]</sup> simplifies the world's diverse climates into six zones based on HDD18 and CDD18 (Table 1).

	Heating	Cooling
Cold climate	2000 ≤ HDD18	CDD 18 < 500
Heating based	2000 ≤ HDD18	500 ≤ CDD18 < 1000
Combined climate	2000 ≤ HDD18	1000 ≤ CDD18
Moderate climate	HDD18 < 2000	CDD18 < 1000
Cooling based	1000 ≤ HDD18 < 2000	1000 ≤ CDD18
Hot climate	HDD18 < 1000	1000 ≤ CDD18

Table 1: Simplified climate zones, heating and cooling degree-days<sup>[6]</sup>.

Location	HDD18	CDD18	Outdoor Design Conditions		
			Summer		Winter
			DB (°C)	WB (°C)	DB (°C)
Brisbane	332	1022	29.9	22.8	5.8
Guangzhou	374	2090	34.5	26.1	5.8
Houston	693	1731	34.7	25.7	0.0

Table 2: Climatic data in Brisbane, Guangzhou and Houston<sup>[29]</sup>.

According to 2013 ASHRAE Handbook – Fundamentals<sup>[29]</sup>, Guangzhou, China and Houston, US have similar climatic conditions to Brisbane with the same HDD18 and CDD18 ranges specified in Table 1. Therefore, Guangzhou and Houston will be considered as the equivalent climatic zones with Brisbane. The climatic data for Brisbane, Guangzhou and Houston is summarised in Table 2 below from 2013 ASHRAE Handbook – Fundamentals<sup>[29]</sup>.

The outdoor design conditions are based on design days developed using 99.6% heating design temperatures and 1% dry-bulb (DB) and 1% wet-bulb (WB) cooling design temperatures as defined in ASHRAE Standard 90.1-2016 Normative Appendix G<sup>[28]</sup>.

## 2.4 Performance indicators

The following performance indicators will be selected for the comparison of the performance of different building energy codes on Australian commercial buildings.

- Annual building energy consumption intensity in MJ/m<sup>2</sup>.
- Annual building CO<sub>2</sub> emissions in kg/m<sup>2</sup>.

The annual building energy consumption intensity is defined as the ratio of total building energy consumption to the total conditioned building area using equation (1):

where  $E$  is the energy consumption of each electricity-consumed component in MJ and  $A$  is the total conditioned building area in m<sup>2</sup>.

The annual building CO<sub>2</sub> emissions per square meter is expressed by equation (2):

$$M_{CO_2} = CO_2 \text{ factor} \times EUI \times 0.278 \quad (2)$$

Where  $M_{CO_2}$  is the annual building CO<sub>2</sub> emission intensity in kg/m<sup>2</sup>,  $CO_2 \text{ factor}$  is the emission factor for electricity consumption in kg CO<sub>2</sub>-e/kWh, and the value is 1.00<sup>[30]</sup> for Brisbane.

# 3. RESULTS

## 3.1 Code requirements comparison results

This section compares the different energy efficiency requirements for commercial buildings as included in the three codes (BCA 2016, GB50189-2015 and ASHRAE Standard 90.1-2016), in terms of building envelope, HVAC system, and

internal load density such as lighting, plug load equipment, occupancy density and outdoor air rate requirements. The input parameters related to the whole building energy performance simulation is also based on the data discussed in this comparison.

### 3.1.1 Building envelope

The energy efficiency regulation for the building envelope is prescribed by setting minimum U-values (China and USA) or R-values (Australia) for walls, roofs, floors and fenestrations based on different climate zones. Brisbane is classified as Climate Zone 2 Hot Humid Summer Mild Winter zone in the BCA. Guangzhou is identified as Hot Summer Warm Winter zone in China.

Houston is identified as Climate Zone 2A Hot Humid climate in ASHRAE. This paper only compares the building envelope requirements for Brisbane equivalent climates. The corresponding building envelope requirements within three countries are compared in the following tables. The R-values described in BCA have been converted to U-values for uniformity purpose.

From Table 3 it can be seen that different countries set the roofs, walls and floors thermal performance requirements according

to different criteria. In ASHRAE Standard 90.1-2016, the thermal performances of roofs, walls, and floors are set based on different construction materials. While in GB50189-2016, they are prescribed according to the thermal inertia value D for roofs and walls, which is expressed as the sum of the material thermal resistance multiplied by its heat accumulation coefficient in the building envelope construction.

However, in BCA 2016, the roofs thermal transmittance is set based on the roof upper surface solar absorptance value  $p$ , and the floors thermal performances are set based on floor types. Generally, for roofs, ASHRAE 90.1-2016 sets the most stringent requirements with the U-value ranges from 0.153 W/m<sup>2</sup>·K to 0.233 W/m<sup>2</sup>·K, followed by BCA 2016 of 0.238 W/m<sup>2</sup>·K to 0.313 W/m<sup>2</sup>·K and GB50189-2016 of 0.5 W/m<sup>2</sup>·K to 0.8 W/m<sup>2</sup>·K. For walls, BCA 2016 has the lowest thermal transmittance requirement of only 0.303 W/m<sup>2</sup>·K, followed by ASHRAE 90.1-2016 ranging from 0.504 W/m<sup>2</sup>·K to 0.857 W/m<sup>2</sup>·K and GB50189-2015 of 0.8 W/m<sup>2</sup>·K to 1.5 W/m<sup>2</sup>·K. For floors, ASHRAE Standard 90.1-2016 sets the best thermal performance of 0.188 W/m<sup>2</sup>·K to 0.606 W/m<sup>2</sup>·K, followed by BCA 2016 of 0.5 W/m<sup>2</sup>·K to 1.0 W/m<sup>2</sup>·K and GB50189-2015 of 1.5 W/m<sup>2</sup>·K.

U-value (W/m <sup>2</sup> ·K)	BCA 2016		GB50189-2015		ASHRAE 90.1-2016	
			D ≤ 2.5	D > 2.5		
Roofs	$p \leq 0.4$	0.313	0.50	0.80	Insulation entirely above deck	0.220
	$0.4 < p \leq 0.6$	0.270			Metal building	0.233
	$0.6 < p$	0.238			Attic and other	0.153
Exterior walls	0.303		0.80	1.50	Mass	0.857
					Metal building	0.533
					Steel-framed	0.479
					Wood-framed and other	0.504
Floors	A slab on ground floor	0.80	1.50		Mass	0.606
	A suspended floor (1) without an in-slab conditioning system (2) with an in-slab conditioning system	1.00			Steel-joist	0.214
		0.80				
	Other floors	0.50			Wood-framed and other	0.188

Table 3: Building envelope requirements comparison for roofs, walls, and floors.

GB50189-2015			ASHRAE 90.1-2016		
Single-orientation exterior window	U-value (W/m <sup>2</sup> ·K)	SHGC (E,S,W/N)	Vertical Fenestration, 0 ≤ WWR ≤ 0.4	U-value (W/m <sup>2</sup> ·K)	SHGC
WWR ≤ 0.20	5.2	0.52/-	Non-metal framing, all	2.10	0.25
0.20 < WWR ≤ 0.30	4.0	0.44/0.52			
0.30 < WWR ≤ 0.40	3.0	0.35/0.44	Metal framing, fixed	3.07	
0.40 < WWR ≤ 0.50	2.7	0.35/0.40			
0.50 < WWR ≤ 0.60	2.5	0.26/0.35	Metal framing, operable	3.69	
0.60 < WWR ≤ 0.70	2.5	0.24/0.30			
0.70 < WWR ≤ 0.80	2.5	0.22/0.26	Metal framing, entrance door	4.71	
WWR > 0.80	2.0	0.18/0.26			

Table 4: Building envelope performance comparison for glazing.

$$E_{Glazing} = \sum_i^n A_i [SHGC_i (C_A \times S_{Hi} + C_B \times S_{Ci}) + C_C \times U_i] \tag{3}$$

For the fenestration performance requirements comparison, Table 4 demonstrates that China defines the U-value and SHGC (solar heat gain coefficient) of the glazing system based on different WWR values, while the USA standard specifies the glazing performance by windows framing types for the WWR under 40%. However, if the WWR is over 40%, ASHRAE 90.1-2016 prescribes the exterior glazing properties using trade-off methods<sup>[12]</sup>.

It should be noted that the BCA 2016 does not specify the requirements for the U-value or SHGC for glazing but uses the aggregate air conditioning energy value. It prescribes that the aggregate air conditioning energy value caused by the glazing must not exceed the allowance obtained by multiplying the facade area exposed to the conditioned space for the orientation by the energy index<sup>[25]</sup>. The aggregate air-conditioning energy value is given by equation (3):

where  $A_i$  is the area of each glazing element in  $m^2$ ;  $SHGC_i$  is the total system SHGC of each glazing element;  $C_{A,B,C}$  are the energy constants A, B and C for the specific orientation;  $S_{Hi}$  is the heating shading multiplier for each glazing element;  $S_{Ci}$  is the cooling shading multiplier for each glazing element; and  $U_i$  is the total system U-value of each glazing element in  $W/m^2 \cdot K$ . The values of the energy index,  $C_{A,B,C}$ ,  $S_{Hi}$ , and  $S_{Ci}$  are prescribed in BCA volume one Section J2.4 based on climatic zones and orientations.

### 3.1.2 HVAC system

In this section, the comparison of the chiller performance requirements and cooling and heating set-points in BCA 2016, ASHRAE 90.1-2016 and GB50189-2015 are presented.

Table 5 illustrates that for the chiller performance requirements, both ASHRAE 90.1-2016 and GB50189-2015 set the COP and IPLV values based on chiller types and cooling capacities, with ASHRAE 90.1-2016 being more stringent than GB50189-2015. However, the BCA 2016 only specifies the minimum COP and IPLV requirements for chillers with a capacity not more than 350kW, and the gaps are quite significant compared to the Chinese and USA codes.

Table 6 below demonstrates that the GB50189-2015 sets the highest cooling set-point and the lowest heating set-point temperatures compared with ASHRAE 90.1-2016 and the BCA 2016, while the HVAC set-points in the BCA 2016 are quite similar to ASHRAE 90.1-2016. It should be noted that the BCA 2016 JV3 specifies that the conditioned space should remain 18°C to 26°C for 98% of the plant operation time, while the 24°C cooling set-point and 21°C heating set-point is specified in AIRAH DA09 Air Conditioning Load Estimation<sup>[31]</sup>.

	GB50189-2015		ASHRAE 90.1-2016		BCA 2016	
	Operation	Setback	Operation	Setback	Operation	Setback
Cooling Set-point (°C)	26	37	23.9	26.7	24	—
Heating Set-point (°C)	20	5	21.1	15.6	21	—

Table 6: Cooling and heating set-point comparison.

Chiller Type		GB50189-2015			ASHRAE 90.1-2016			BCA 2016		
		CC <sup>1</sup>	COP	IPLV	CC	COP	IPLV	CC	COP	IPLV
Air-cooled or evaporative cooler	Reciprocating/ scroll	CC≤50	2.80	3.20	CC<528	2.99	4.05	CC≤350	2.5	3.4
		CC>50	2.90	3.45	CC≥528	2.99	4.14			
	Screw	CC≤50	2.90	3.10	CC<528	2.99	4.05			
		CC>50	3.00	3.20	CC≥528	2.99	4.14			
Water-cooled	Reciprocating/ Scroll	CC≤528	4.40	5.25	CC<264	4.89	6.29	CC≤350	4.2	5.2
					264≤CC<528	5.33	6.52			
	Screw	CC≤528	4.90	5.65	528≤CC<1055	5.77	6.77			
		528<CC≤1163	5.30	6.00	1055≤CC<2110	6.29	7.04			
		CC>1163	5.60	6.30	CC≥2110	5.77	6.40			
	Centrifugal	CC≤1163	5.40	5.55	CC<528	5.77	6.40			
					528≤CC<1055	6.29	6.77			
		1163<CC≤2110	5.70	5.85	1055≤CC<1407	6.29	7.04			
		CC>2110	5.90	6.20	1407≤CC<2110	6.29	7.04			
			CC≥2110	4.89	6.29					

<sup>1</sup>CC: Cooling Capacity in kW

Table 5: Chiller performance comparison.

In addition, both of the Chinese code and the US code set setback temperatures for the HVAC system. However, this requirement is not included in the Australian code.

### 3.1.3 Internal load requirements

The comparison of internal load density requirements, including lighting, plug load equipment, occupancy, outdoor air requirement as well as their total accumulated operation profiles in hours per week, is shown in Table 7. It indicates that BCA 2016 and GB50189-2015 have the same performance requirements for lighting, plug load and occupancy density, but that these requirements differ from ASHRAE requirements. The BCA specifies the highest outside air requirement followed by ASHRAE 90.1 and GB50189. In addition, the accumulated weekly lighting operation profile is much higher in BCA than in the other two codes, reaching 65.8 hours per week.

It is obvious that for lighting operation profile, equipment utilisation rate and occupancy rate, the GB50189 is the lowest. However, ASHRAE 90.1 requires the highest weekly HVAC operation time and equipment utilisation rate among three codes. This is because ASHRAE 90.1 specifies 30% to 50% continuous plug load equipment operation in Saturday and 30% continuous plug load equipment operation in Sunday.

It also requires 12 hours HVAC operation in Saturday and 5 hours more HVAC operation per day on weekdays compared to the BCA and GB50189.

## 3.2 Whole building energy performance simulation results

### 3.2.1 Annual building energy consumption

The main input parameters for the whole building energy performance modelling are illustrated in Table 8, based on the above discussion. Since the BCA does not prescribe the specific U-value and SHGC for glazing, the U-value and SHGC are selected as 2.44 W/m<sup>2</sup>·K and 0.24 respectively for simulation, referencing from the National Fenestration Rating Council (NFRS ID: P-CUW-22314) [32].

The simulated annual building energy performance is shown in Figure 2. Overall for the typical large office building in hot humid climates like Brisbane, the GB50189-2015 code resulted in the lowest annual onsite electricity consumption (337.8 MJ/m<sup>2</sup>) followed by ASHRAE 90.1-2016 (356.7 MJ/m<sup>2</sup>) and BCA 2016 (450.3 MJ/m<sup>2</sup>). Interior plug load equipment, interior lighting, and space cooling are the main contributors to the performance gap between the BCA and the other two codes.

	GB50189-2015	ASHRAE 90.1-2016	BCA 2016
Lighting (W/m <sup>2</sup> )	9	8.5	9
Equipment (W/m <sup>2</sup> )	15	8.07	15
Occupancy (m <sup>2</sup> /person)	10	18.58	10
Outdoor air requirement (L/s/person)	8.33	9.44	10
Lighting operation profile (h/week)	47.25	55.3	65.8
Equipment utilisation rate (h/week)	44.25	86.15	60.3
Occupancy rate (h/week)	47.25	48.6	47.5
HVAC operation schedule (h/week)	55	92	55

Table 7: Comparison of internal load intensity requirements.

	GB50189-2015	ASHRAE 90.1-2016	BCA 2016
Lighting power density (W/m <sup>2</sup> )	9	8.5	9
Equipment power density (W/m <sup>2</sup> )	15	8.07	15
Occupancy (m <sup>2</sup> /person)	10	18.58	10
Outdoor air requirement (L/s/person)	8.33	9.44	10
HVAC system type	VAV with Reheat		
Chiller COP	5.30	5.77	4.2
Roof U-value (W/m <sup>2</sup> ·K)	0.80	0.233	0.313
Exterior wall U-value (W/m <sup>2</sup> ·K)	1.50	0.857	0.303
Floor U-value (W/m <sup>2</sup> ·K)	1.50	0.606	0.80
Glazing U-value (W/m <sup>2</sup> ·K)	2.7	2.1	2.44

Table 8: Main modelling input parameters.

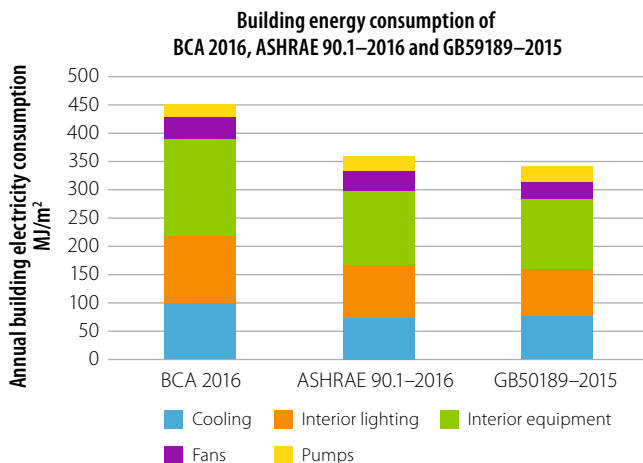


Figure 2: Office building annual energy performance comparison.

### 3.2.2 Annual CO<sub>2</sub> emissions

The annual CO<sub>2</sub> emission result is demonstrated in Figure 3. It shows that for the Building Type A, the annual building CO<sub>2</sub> emission is about 125.2 kg/m<sup>2</sup> by adopting the BCA 2016 but these emissions could be reduced to 99.15 kg/m<sup>2</sup> and 93.9 kg/m<sup>2</sup> if using ASHRAE 90.1-2016 and GB50189-2015 respectively.

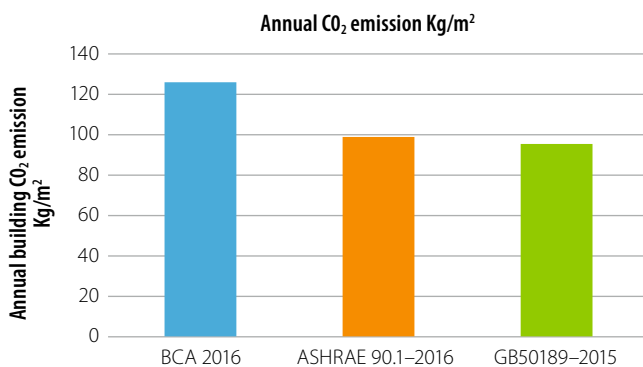


Figure 3: Office building annual CO<sub>2</sub> emissions comparison.

## 4. DISCUSSIONS

Many factors influence building energy performance, such as the building envelope thermal performance, HVAC system equipment efficiency, lighting power density, plug load equipment power density, and HVAC set-points. According to the previous comparison, for a hot and humid climatic zone, ASHRAE 90.1 sets the most stringent requirements for the building envelope overall.

Based on different construction materials, the envelope thermal performance requirements range from 0.153 to 0.233W/m<sup>2</sup>·K for roofs, 0.533 to 0.857W/m<sup>2</sup>·K for exterior walls, and 0.188 to 0.606W/m<sup>2</sup>·K for floors. The BCA energy efficiency stringency for the building envelope is moderate, ranging from 0.238 to 0.313W/m<sup>2</sup>·K for roofs, 0.303W/m<sup>2</sup>·K for exterior walls and 0.5 to 1.0W/m<sup>2</sup>·K for floors. The Chinese GB50189 sets the loosest requirements for building envelope.

For the glazing system, both GB50189 and ASHRAE 90.1 set the minimum U-value and SHGC based on either WWR or construction materials, while the BCA specifies the glazing system performance using aggregate air-conditioning energy value equation and related orientation coefficients.

From the building envelope comparison, it can be predicted that for the same building and climate zone, the building envelope construction of the ASHRAE 90.1-2016 would result in the lowest building load followed by the BCA 2016 and GB50189-2015.

The annual building energy performance simulation results indicated that the ASHRAE 90.1-2016 and GB50189-2015 could achieve the annual total building energy savings of about 20.8% and 25.0% respectively compared to the BCA 2016. The most significant savings lie in the plug load equipment, cooling, lighting, and fans consumptions.

For cooling, ASHRAE 90.1-2016 consumed the least energy of only 77.84 MJ/m<sup>2</sup>, followed by GB50189-2015 of 81 MJ/m<sup>2</sup> and BCA 2016 of 107.88 MJ/m<sup>2</sup>. This is due to the highest chiller performance requirement and better building envelope performance in ASHRAE 90.1, despite the longer HVAC operation hours. Meanwhile, for the plug load equipment, lighting, and fans energy consumptions, the BCA 2016 performed the worst, followed by ASHRAE 90.1-2016 and GB50189-2015. The ASHRAE 90.1-2016 could save 23.07%, 18.93%, and 11.72% annual electricity consumption for equipment, lighting, and fans compared to the BCA 2016, with the total annual building CO<sub>2</sub> emissions reduction of 259,955.13kg. If adopting the Chinese code, the equipment, lighting, and fans energy consumptions could achieve 26.67%, 28.25% and 26.15% reductions for Australian large office buildings in Brisbane. In addition, the total saved building CO<sub>2</sub> emissions could be 312,429.45kg annually.

## 5. CONCLUSIONS

This paper conducted a quantitative comparison study of the impacts of building energy codes on Australian office building performance. EnergyPlus simulation was conducted to predict the annual building energy consumption and CO<sub>2</sub> emissions for a typical large office building in Brisbane. Detailed comparison and analysis of the code requirements for the BCA 2016, ASHRAE 90.1-2016 (USA), and GB50189-2015 (China), in terms of building envelope, HVAC chiller efficiency, internal load density and HVAC set-points, have also been investigated. The following conclusions can be drawn based on the following analysis:

- For the hot and humid climatic zone, overall ASHRAE 90.1-2016 has the most stringent requirements for the building envelope, followed by the BCA 2016 and GB50189-2015.
- ASHRAE 90.1-2016 has the most rigid requirements for chiller efficiency, lighting power density, equipment power density and occupancy density.
- GB50189-2015 sets the same HVAC operation schedule and internal load densities with the BCA 2016, but more moderate cooling and heating temperature set-points.
- The annual total building energy conservation could be 25.0% and 20.8% respectively if using GB50189-2015 and ASHRAE 90.1-2016 compared to BCA 2016, and the corresponding annual CO<sub>2</sub> emissions reduction could be 312,429kg and 259,955kg.

Based on this analysis it is recommended that the BCA be revised to improve the stringency of its energy efficiency requirements, specifically through:



- Improving plug load equipment and lighting efficiency.
- Further improving building envelope thermal performance to reduce building load.
- Explicitly specifying glazing performance requirements.
- Improving chiller efficiency requirements, especially for chillers with capacities greater than 350kW.
- Optimising HVAC cooling and heating set-points and including setback temperature control.

Although a detailed comparison and analysis of the Australian, Chinese, and USA building energy codes on building energy performance has been investigated in this paper, there are still certain limitations to be addressed for future work:

- More building models need to be considered such as Building Type B, C, and E.
- More Australian climatic zones need to be included, such as all the capital cities.
- More comprehensive results analysis should be conducted such as peak demand analysis, cost-benefit analysis, and life cycle assessment. ■

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