Measured Energy Use and Indoor Environment Quality in Green Office Buildings in China

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**Abstract**

Recently green buildings are booming rapidly in China. In order to improve the performance of green buildings, energy consumption in 31 and indoor environment quality(IEQ) in 10 green office buildings are compared with common ones through energy data collection, physical parameters measurement and satisfaction survey. The results indicate that for building type A (mix-mode), it is only in Hot-Summer Cold-Winter zone that green buildings’ energy consumption is statistically significantly less than common buildings. For type B (mechanically conditioned), no statistically significantly difference between green and common has been observed in all climate zones. It is also found that in Hot-Summer Cold-Winter zone the average energy consumption of type A and B are 15% and 23% lower than the upper limit values required by the Chinese standard [27]. However in other climate zones, they are above the upper limit. In terms of the IEQ and building service performance, the satisfaction of users in green is marked higher than that in common in the field of thermal comfort, indoor air quality(IAQ), facilities, operating & maintenance. In addition, factors affecting buildings’ energy consumption are analyzed in order to provide guidance for further enhancing the performance of green buildings in design and operation stages.

**Keywords**

Green Building, Energy Consumption; Indoor Environment Quality (IEQ); Field measurement; Occupant satisfaction survey

1. **Introduction**

The first Chinese comprehensive green building evaluation standard was developed by the Chinese Academy of Building Research [1] in 2006. After that, green buildings experienced a booming development. Certificated green buildings in China are expected to be awarded a one to three stars green building label. Recently energy conservation and emission reduction was increasingly valued by Chinese government as well as Chinese society. The government has raised its support for green buildings and the laws and regulations have been developed to create a good environment to promote the rapid development of green buildings. Gradually, the building energy efficiency standards and green building-related technical codes have covered all climate zones, different building types and the whole process of planning, design, construction and operation. Till May, 2015, there were about 2800 green building projects in China (approximately 300 million m2) [2].

There is a need to assess if green buildings are able to create better Indoor Environmental Quality (IEQ) with less energy consumption. Newsham G et al (2009) conducted a re-analysis of data from Cathy T’s (2008) study and reported that LEED buildings, on average, consumed 18-39% less energy per floor area, but 28%-35% of LEED buildings’ energy consumption are higher than their conventional counterparts. Further, there was independent relationship between the measured energy performance and certification level or the number of energy credits achieved by the LEED buildings at design time [3]. Scofield’s (2009) research showed that LEED-certified buildings are not lowering source energy consumption or reducing greenhouse gas emission [4]. Scofield’s (2013) another research examined large New York City office buildings’ energy consumption and greenhouse gas emission in the year of 2011, and concluded that the LEED-certified buildings showed no savings as compared with non-LEED buildings [5]. The energy situations in other geographical areas have also been analyzed by various researchers in order to assess the implementation of green building technologies and renewable energy strategies [6-14]. Badea A. and Baracu T. (2014) performed a life-cycle cost analysis of a passive house in Romania to present energy efficient buildings in a more balanced evaluation [15]. Newsham et al (2013) reported that green buildings exhibited superior performance, including environmental satisfaction, satisfaction with thermal conditions, the view to the outside, aesthetic appearance, workplace image, etc.[16]. JG Allen et al (2015) found that the initial scientific evidence indicates better indoor environmental quality in green buildings versus non-green buildings [17]. Baird’s (2010) review concluded that, in general, image for visitors, furniture, cleanliness, availability of meeting room, meeting job demand, overall light and demand (overall) of green buildings were most satisfactory [18]. However, Gou’s comparative study of two LEED offices and a sample of conventional offices in the same city suggested no difference in overall satisfaction with IEQ (2011) [19]. Altomonte S and Schiavon S (2013) conducted a study by evaluating occupant satisfaction with IEQ of 144 buildings (65 LEED certified), and concluded that there is not a significant influence of LEED certification on occupant satisfaction with indoor environmental quality, except air quality and amount of light [20]. Schiavon S and Altomonte S (2014) in another paper investigated the influence of factors unrelated to environmental quality on occupant satisfaction in LEED and non-LEED certified buildings, and the results showed that such factors statistically significantly influence the difference in occupant satisfaction in LEED and non-LEED certified buildings, but the effect size of such variations is practically negligible for most [21].

The actual operating performance of green buildings has been studied by many researchers in other countries  [22-26]. By contrast, although green buildings have been developing rapidly in China, these buildings were assessed as “green” at the time of their design in most cases, and there was little follow-up attention to identify if post-occupancy performance meets expectations. This paper focused on the performance of actual energy consumption and IEQ, the gap between the design goal and the actual performance, and occupant satisfaction to have a better understanding of current state of the green office buildings in China and provide guidance for the design and operation of green buildings, which are able to create better indoor environment with less energy consumption and carbon emissions.

1. **Methods**

*2.1 Case buildings and determination of building type: A versus B*

In China, buildings which have three-star green building label certification would be affirmed as green buildings. Chinese green buildings contribute to reduce consumption of resources, including energy, land, water and materials, protect the natural environment, minimize pollution, and provide healthy and comfort space. It should be noted that in this paper, green buildings specifically refer to Chinese green buildings rather than a general classification or concept. In this paper, 31 green office buildings located in Beijing, Tianjin, Tanggu, Jinan, Langfang, Shanghai, Nanjing, Suzhou, Chongqing, Shenzhen, and Guangzhou are selected to compare their actual energy consumption with the energy consumption requirement in the *Chinese Standard for Energy Consumption of Buildings* (SECB), LEED-certified buildings in the United States and common office buildings in China. In addition, the main factors affecting HVAC energy consumption are analyzed through detailed research of HVAC system in some green buildings, as well as lighting electricity consumption.

Climate zones in China are usually divided into severe cold zone, cold zone, hot-summer & cold winter zone, hot-summer & warm winter zone and mild zone, which are divided by different HDD or CDD. The buildings investigated in this research are located in cold zone(C), hot-summer & cold winter zone(HSCW), and hot-summer & warm winter zone(HSWW), as shown in Table 1.

Table 1 Climate zones of each city

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| --- | --- | --- | --- | --- |
| Location | HDD/CDD | Climate zone | Mean temperature of zones | |
| Summer | Winter |
| Beijing, Tianjin, Tanggu, Jinan, Langfang | 2000≤HDD18<3800, CDD26>90 | C | 25.6°C | -1.1°C |
| Shanghai, Nanjing, Suzhou | 1200≤HDD18<2000 | HSCW | 25.7°C | 6.4°C |
| Chongqing | 700≤HDD18<1200 |
| Shenzhen, Guangzhou | HDD18<500 | HSWW | 28.0°C | 15.3°C |

A.C. Boerstra et al (2015) developed a new, updated version of ISSO 74 (ATG) guideline, in which spaces or buildings were distinguished as Type α or Type β. α refers to free-running situations in summer with operable windows and other adaptive opportunities for the occupants (particularly, a non-strict clothing policy), whereas β refers to summer situations that primarily rely on centrally controlled cooling [27]. Similarly, in the Chinese Standard for Energy Consumption of Buildings (SECB) [28], buildings are divided into type A and type B.

*2.2* *Physical parameters measurement and questionnaire survey*

To evaluate green buildings, IEQ is as important as energy consumption. In order to analyze the IEQ and occupant satisfaction of green buildings in China, the research group has taken a dozen systematic investigations of green office buildings in recent years.10 of the 31 green office buildings are selected to analyze IEQ through field investigation and long-term measurement of indoor environment parameters by self-recording instruments, combined with user subjective questionnaire survey. The dataset for the analysis of IEQ and occupant satisfaction presented in this paper is based on the same field investigation described in a previous study by the authors [29]. The methods for the physical parameters measurement and questionnaire survey of the buildings to be included in the green and common groups are described in detail in the previous published paper [29]. The selected green and common buildings for detailed IEQ satisfaction analysis were as similar as possible, like the same size and age, the same occupancy hours, in the same climate zone, with the same kind of occupants doing similar work. The basic information of the case study office buildings could be seen in Table 2. It should be noted that in China, the overall office building stock were built before energy efficiency of buildings were regulated via *Design Standard for Energy Efficiency of Public Buildings (GB 50189-2005)*. Anonymous questionnaires are distributed by hand to staff in each case study building to collect occupant subjective evaluations. In order to reflect the objective situation, firstly the questionnaire survey is based on a selection of at least 20% of users in the entire building; meanwhile, we guarantee that the number of questionnaires collected in each building is more than 20. Occupant satisfaction is scored on a scale from -1(very dissatisfied) to +1(very satisfied), shown as Fig.1.

Table 2 Case study buildings

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| --- | --- | --- | --- | --- | --- | --- |
| Building type | Data type | Sample size | Climate zone | Occupancy | Construction time | Main characteristics |
| Green office building | Energy consumption | 31 | Cold, HSCW, HSWW | 9am-6pm on weekdays | 2009-2012 | Many green building techniques, such as high-performance envelope, renewable energy systems, ventilation/heat recovery, etc. |
| IEQ questionnaire | 10 (360) | Cold, HSCW |
| Common office building | Energy consumption | 481 | Cold, HSCW, HSWW | 9am-6pm on weekdays | 1990-2010 | No green building technology |
| IEQ questionnaire | 8 (244) | Cold, HSCW | 2005-2010 |

Note) Sample size refers to the number of case study buildings, and the number of valid questionnaires in parenthesis

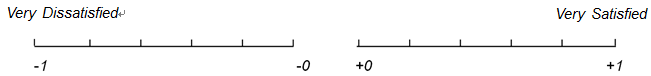


Fig.1 Scale Model of Satisfaction

In this paper, satisfaction with IEQ and building service performance (BSP) are analyzed through SPSS statistical software, including thermal environment, IAQ, lighting environment, acoustic environment and overall environment, comfort of facilities, decoration, work/storage space, visual privacy, communication convenience, cleanliness, operating & maintenance(O&M). The two-sample mean-comparison test we use rejects the null hypothesis on 5% level that the occupant satisfactions for the two types of buildings (green and common) come from different distributions. In all boxplots, the bottom and the top of the boxes represent 25th and 75th percentiles and the triangle near the middle of the boxes is the median. The ends of the whiskers indicate the minimum and maximum.

1. **Results**

*3.1 Analysis of total energy consumption of green office buildings*

Fig.2 shows the actual total site energy consumptions of 31 office buildings located in cold climate zone, hot-summer & cold-winter zone, and hot-summer & warm-winter zone by two different building types. These results are based on the annual monthly electricity consumption from energy metering systems installed in each building. 7 office buildings of the 15 cases in cold zone, shown with orange bars, use electric heat pump for heating in winter, and the rest 8 buildings use district heating, whose heat consumption are converted into electricity consumption, in accordance with the electricity equivalent conversion method[30], shown with red bars in Fig.2.

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| Fig.2 Total energy consumption of green buildings in China (kWh/m2a） |

Note) a. A/B-C/CW/WW refers to the building type A/B in cold/ hot summer& cold winter/ hot summer& warm winter zone

b. Blue frame refers to cold climate zone, green frame refers to hot-summer & cold-winter zone, and red frame refers to hot-summer & warm-winter zone

Table 3 Comparison of energy consumption of green office buildings to SECB

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | Type A | | | | Type B | | | |
| Climate zone | Upper limit (kWh/m2·a) | Recommended value (kWh/m2·a) | Green office median (min, max) | Difference | Upper limit (kWh/m2·a) | Recommended value (kWh/m2·a) | Green office median (min, max) | Difference |
| Cold | 60 | 45 | 79.8 (40.1, 143) | 33% (77%) | 80 | 60 | 90 (45.4, 144.7) | 13% (50%) |
| hot-summer cold-winter | 75 | 60 | 63.7 (52, 83.2) | -15% (6%) | 110 | 80 | 85 (53, 110) | -23% (6%) |
| hot-summer warm-winter | 70 | 55 | 75.0 (50, 83.5) | 7% (36%) | 100 | 75 | 120 | 20% (60%) |

Note) Difference refers to the percentage difference between the measured median and the upper limit, and the recommended value in parenthesis. A positive difference indicates higher energy consumption in green office buildings

The energy consumption requirements for building type A and building type B in the *Chinese Standard for Energy Consumption of Buildings* (SECB) are shown in Table 3, as well as the median, min and max value of measured energy consumption. Statistics indicate that in hot-summer & cold-winter zone, the average total energy consumptions for both two building types are close to the recommended value of 60 and 80 kWh/(m2a), which means the energy performance of green office buildings in this climate zone is aligned with the standard. However, in cold and hot-summer& warm-winter zones, the energy consumption of both type A and type B are higher than upper limit, although the value of type B in hot-summer & warm-winter zone may be not representative because of the sample size. It should be noted that the upper limit and recommended value for cold zone in the SECB do not include the district heating energy consumption, and that in Fig 2, 7 of the 15 cases in cold zone shown with orange bars use air-conditioning system for heating and the rest 8 cases use district heating in winter, and red bars show the heat consumption converted into electricity consumption. The analysis of existing data indicates that the heat consumption for district heating of green buildings is about 12-24 kWh/(m2a), significantly lower than 32-38 kWh/(m2a) of common buildings [31]. Ionescu C. and Baracu T. (2015) reviewed the historical evolution of the energy efficient buildings [32]. According to the current state of the energy efficient buildings definitions, most Chinese green office buildings could be characterized as low energy buildings, a few of which are close to ultra-low energy buildings.

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| Fig.3 Energy consumption of green office buildings, China versus US  Note) D refers to design. O refers to operation |

The Fig.3 compared energy consumption level of green office buildings in China and LEED-certified buildings in the United States. No significant correlation was observed between measured energy performance of green office buildings with certification level of the building in China, which is similar to the case of LEED buildings in US by Newsham G et al (2009)[3]. In general, the total energy consumption of Chinese green office buildings is approximately 1/3 of LEED-certified buildings in the United States. Fig.3 just presented general energy consumption levels of green buildings in China and US for a preliminary understanding. Overall comparisons that take into account quality and services of buildings should be considered for further exploration.

Table 4 Electricity consumption intensity comparison in three different climate zones

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | Cold zone | | Hot summer-cold winter | | Hot summer-warm winter | | Overall | |
| Green | Common | Green | Common | Green | Common | Green | Common |
| N | 22 | 121 | 18 | 302 | 8 | 58 | 48 | 481 |
| First quartile | 57.7 | 60.1 | 52.8 | 88.1 | 52.6 | 65.7 | 55.1 | 75.8 |
| Median (kWh/m2) | 80.0 | 82.0 | 77.6 | 110.6 | 71.5 | 88.5 | 77.1 | 97.8 |
| Third quartile | 100.4 | 111.0 | 110.2 | 136.0 | 80.3 | 123.7 | 101.5 | 128.2 |
| SD | 30.6 | 44.1 | 37.9 | 37.3 | 28.0 | 56.7 | 32.9 | 42.9 |
| Skewness | 0.6 | 1.3 | 0.1 | 0.9 | 0.2 | 1.6 | 0.3 | 1.0 |

Table 4 presented the comparison of green and common office buildings in three different climate zones, including 48 green office buildings, of which the additional 17 cases were from the survey of Chinese Society for Urban Studies, and 481 common office buildings from survey of Xiao H (2011) [33]. As shown in Table 3, the median of green office buildings is 30%, 19% lower than the figure for common office buildings in the hot summer & cold winter zone and the hot summer & warm winter zone respectively. However, in the cold zone, the electricity consumption of green office buildings is similar to that of non-green buildings, only 2% difference. For overall buildings, the median of green is 21% lower than the figure of common buildings.

Building type is a key factor affecting a building’s actual energy consumption. Fig.4 and Table 5 present difference and statistical significance of the median difference between green and common office buildings of type A and type B buildings in three different climate zones. These results indicate that type A buildings have different energy consumption features compared to type B buildings in term of comparison between green and common office buildings. By comparing the median of energy consumptions in the corresponding climate zones, for building type A, it is only in hot-summer & cold-winter zone that the green value is statistically significantly less than common value. On the contrary, for building type B, there is no statistically significantly difference in the medians of electricity consumption between green and common office buildings whatever climate zone. It is also worth noting that due to improvements in building technology, operation and management of green office buildings, the maximum energy consumption can be reduced effectively compared to common buildings whatever the building type A or B.

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| Fig. 4 Difference in actual electricity consumption of green and common office buildings in three different climate zones |

Note) There are only 2 green cases of building type B in hot summer & warm winter zone, so the maximum and minimum are same with the 25th and 75th percentiles respectively, and the median refers to the mean.

Table 5 Statistical significance of the difference in median of EUI (ΔEUI, green minus common)

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | Type A | | | Type B | | |
| Climate zone | Cold | Hot-summer & cold-winter | Hot-summer & warm-winter | Cold | Hot-summer & cold-winter | Hot-summer & warm-winter |
| ΔEUI (green-common)  kWh/(m2•a) | 13.7n.s. | -38.5\*\*\* | 10.3n.s. | -7.5n.s. | -1.3n.s. | -6.9n.s. |

Note) \*\*\*p < 0.001; \*\*p < 0.01; \*p < 0.05; n.s.-not significant.

*3.2 Analysis of HVAC electricity consumption of green office buildings*

The statistical results of HVAC energy consumption are shown in Fig. 5 and Table 6, by splitting the energy consumption of the green cases in this study. It could be found that HVAC consumption of type A buildings is significantly lower than that of type B on average for hot-summer & cold-winter and hot-summer & warm-winter zone. Comparison of HVAC energy consumption and corresponding total energy consumption shows that the HVAC energy consumption of a high total energy consumption building is not necessarily high, such as case BJ-6 and Su-3. While, for some green office buildings, high HVAC energy consumption is indeed one of the causes of high total energy consumption, such as case TJ-3 and TJ-4. In sum, HVAC consumptions affect different cases differently, as shown with percentage in Fig.5.

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| Fig.5 Analysis of HVAC electricity consumption  Note) Percentage refers to the proportion of HVAC electricity consumption in total energy consumption |

Table 6 Distribution of HVAC electricity consumption

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| --- | --- | --- | --- | --- | --- | --- |
|  | Type A Green | | | Type B Green | | |
| Cold | Hot summer-cold winter | Hot summer-warm winter | Cold | Hot summer-cold winter | Hot summer-warm winter |
| Mean | 43.4 | 32.7 | 23.2 | 39.5 | 42.7 | 62.0 |
| Median | 40.0 | 35.0 | 19.6 | 35.0 | 46.0 | 62.0 |
| Min | 16.5 | 21.8 | 12.4 | 28.0 | 35.0 | 62.0 |
| Max | 73.3 | 41.0 | 33.2 | 53.9 | 47.0 | 62.0 |
| SD | 19.6 | 6.4 | 9.0 | 11.7 | 6.7 | N/A |
| Skewness | 0.4 | -0.6 | 0.2 | 0.5 | -1.7 | N/A |

Through detailed research of HVAC system in some green buildings, the following four factors significantly affect HVAC energy consumption

1) Indoor temperature

2) Energy efficiency of air-conditioning equipment or system

3) Energy consumptions of distribution system and fresh air system

4) HVAC system partition and optimal control strategy.

*3.2.1 Indoor temperature*

In the survey of green building cases it can be found that in winter the indoor temperature of some buildings is relatively high, which indicates a further energy-saving potential. Take case TJ-2 for example to estimate the influence of indoor temperature on the HVAC energy consumption. Estimated influence of indoor temperature on energy consumption is about（∆tactual-∆tdesign）/∆tactual=3% with the outdoor design temperature in winter of -10 oC, the indoor design temperature of 20oC, the actual mean indoor temperature of open-plan office of 21 oC and ignoring the humidity load. And the electricity consumption of HVAC in winter could be reduced to 14.7 kWh/(m2a) from 15.2 kWh/(m2a) through the indoor temperature control optimization. In sum, indoor temperature affects energy consumption of HVAC, but its impact is not significant.

*3.2.2 The energy efficiency of AC equipment or system*

The COP of HVAC system is a ratio of cooling provided by the entire system (including cold and heat sources, distribution system and air-conditioning terminals, etc.) to electrical energy consumed, which reflects the level of efficiency of AC system. Fig.6 shows the relationship between COP of system and electricity consumption of cooling in 8 cases, all of which use THICS (temperature and humidity independent control air conditioning system). Comparing the case BJ-2, BJ-3, BJ-5 and TJ-1 in cold zone, it could be found that the energy consumption of air-conditioning increases with the decrease of the system’s COP, which means the energy efficiency of system can affect energy consumption of air-conditioning. However, when comparing the case SZ-1, SZ-2 and SZ-3 in hot-summer & warm-winter zone, results show that the system’s COP of SZ-3 is highest, and the energy consumption of air-conditioning is not the lowest, but the highest. Conversely, the air-conditioning energy consumption of SZ-1 is the lowest with the minimum system’s COP, which indicates that energy efficiency of system is not the only most important factor.

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| Fig.6 The influence of system’s COP on HVAC energy consumption |

*3.2.3 Energy consumptions of distribution system and fresh air system*

Comparison between green case BJ-2 and BJ-5 can illustrate the huge impact of high energy consumption of fresh air on HVAC energy consumption. Both BJ-2 and BJ-5 use THICS, and the actual operating mode of BJ-2 is small load condition, i.e. a chiller combined with a plate heat exchanger, and the actual operating mode of BJ-5 is two chillers for making low and high temperature chilled water respectively. Fig.7-8 and Table 7 show the comparisons of energy consumption, efficiency indicator and cooling allocation between the two cases (case A is BJ-2 and case B is BJ-5)[34].

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| Fig.7 Comparison of EUI among Case A, B and index value | Fig.8 Comparison of HVAC EUI among Case A, B and index value |

Table 7 Comparisons of Energy Consumption, Efficiency Indicator and Cooling Allocation between BJ-2 and BJ-5

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| --- | --- | --- | --- | --- |
|  | BJ-2  Cooling season | BJ-5  Cooling season | Mean Value in Study | Limit Value  (Annual Accumulated) |
| Accumulated Cooling Loads (kWh/m2a) | 42.80 | 50.29 |  | 40-90 |
| Power Consumption for Cooling (kWh/m2a) | 22.24 | 20.44 |  |  |
| EER0 of HVAC System | 2.01 | 2.53 | 2.3 |  |
| EER’(SCOP) of Cooling Station | 3.28 | 3.02 | 2.8 | ≥4 |
| EER’’ of Cold Source | 4.2 | 3.54 | 3.6 |  |
| EERⅠ(COP) of Chiller | 5.97 | 4.22 | 4.6 | ≥4.5 |
| EERⅡ of Chilled Water System | 14.97 | 20.47 | 20.2 | ≥30 |
| EERⅢ of Cooling Water System | 20.20 | 43.34 | 25.5 | ≥25 |
| EERⅣ of Terminal System | 5.17 | 15.47 | 18.7 | All Air≥6；  Primary Air +FCU：≥9；  FCU：≥24 |
| EERⅤ of Cooling Tower | 90.90 | 103.03 | 104.5 |  |

The HVAC energy consumptions of the two cases are similar, but the accumulated cooling loads are respectively 43 kWh/(m2a) and 50 kWh/(m2a). For case BJ-2, the COP of chiller is higher and the energy consumption of chiller is lower than that of BJ-5. The actual number of users is much less than the design one, but the fresh air handling unit is still fixed-frequency running with design fresh air volume, which results in huge fresh air volume, high cooling load of fresh air (cooling for fresh air handling unit accounting for 76% and cooling for terminals accounting for 24%). The whole system is actually like an all air system and the EERⅣ of air-conditioning terminals is low. However, for cooling allocation of BJ-5, fresh air handling units and metal radiant panels account for 42% and 58% respectively, and the whole system is similar to primary air fan-coil system. So the EERⅣ of air-conditioning terminals is significantly higher than that of BJ-2.

*3.2.4 HVAC system partition and optimal control strategy*

Through field investigation, it could be found that HVAC system partition and optimal control strategy have a significant effect on energy consumption of HVAC system. Take TJ-2 for example, a combination of radiant floor and ceiling fans in summer and optimization of AC system control strategy achieve the effect of increasing indoor temperature and reducing uptime of heat pump under the premise of ensuring occupants’ thermal comfort, so that the energy consumption of air-conditioning in summer is reduced to 10.48 kWh/(m2a). For the characteristics of large difference in thermal sensations between men and women in radiant floor cooling system (women are heat-resistant inherently and usually wear skirts, shorts and sandals in summer, so they often complain of the cold when men are satisfied with the indoor temperature), the mixing ventilation combined with ceiling fans can increase indoor temperature in summer. Under the premise of meeting the requirement of women’s apparent temperature, turning on the ceiling fans above men’s heads makes it possible to be satisfied with indoor thermal environment for both women and men with the mean indoor temperature of 26-27 oC [35].

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| Fig.9 Combination of AC and ceiling fans in Case TJ-2 |

SH-2 is the other typical outstanding case with a combination of natural ventilation, ceiling fans and air-conditioning. This building, located in Shanghai, is designed in the north-south exposure, with a semi-open rest garden on each floor of south, whose layout facilitates natural ventilation. Indoors, ceiling fans are installed according to the layout of each office, and play a role in strengthening the ventilation in summer and transition seasons. So that under the premise of ensuring indoor thermal comfort, the energy consumption of air-conditioning is only 20 kWh/(m2a) with a reduction of 20% in air-conditioning system uptime [36,37].

According to the characteristics of load in different functional zones, building SZ-2, located in Shenzhen, adopts different HVAC systems, combined with zone control. For example, offices are designed with primary air fan-coil system and other non-office spaces are designed with separate AC system, such as the separate chiller and fresh air handler in the lecture hall, the VAV system in underground laboratory and some functional areas, and split air conditioners in experts’ apartments etc. Meanwhile, it adopts a combination of air-conditioning and natural ventilation to make use of natural ventilation actively, which shortens the running time of air-conditioning equipment by more than 40% compared with similar buildings in Shenzhen. The opening direction of this building’s is the prevailing wind direction in summer, which facilities ventilation. Breaking through the traditional mode of ventilation, the bold attempts of multi open-surfaces design, movable external walls and grille envelopes achieve great natural ventilation, such as the openable external walls of the lecture hall, the grille envelopes of firefighting staircase and the outdoor terraces etc. Thanks to the reasonable zone design of HVAC system and the mixed operation mode of natural ventilation and air-conditioning, the annual electricity consumption of air-conditioning is only 15.2 kWh/(m2a) [38].

*3.3* *Analysis of lighting electricity consumption of green office buildings*

Although most of green buildings surveyed in this research are installed sub-metering system, reliable itemized metering data are still difficult to acquire because lighting power consumptions are often mixed with equipment power consumptions, which makes it difficult to split. For six buildings it was possible to disaggregate the lighting energy consumption. (see Fig.10). Results show that the median energy use is 13.8 kWh/(m2a), which is 37% less than the reference standard of 22 kWh/(m2a) [31]. Furthermore, the causes of low lighting power consumption vary from case to case. For example, in case TJ-2, the large window-wall ratio of south and north walls, the sunspace on the third and fourth floors and the reflectors in the south are conducive to natural lighting. Thanks to the plentiful light tubes of peripheral offices and the side windows of the exhibition hall, Building TJ-5 achieves great lighting effect without too much artificial lighting.

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| Fig.10 Analysis of lighting electricity consumption |

*3.4 Comparison of occupant satisfaction with IEQ between green and common office buildings*

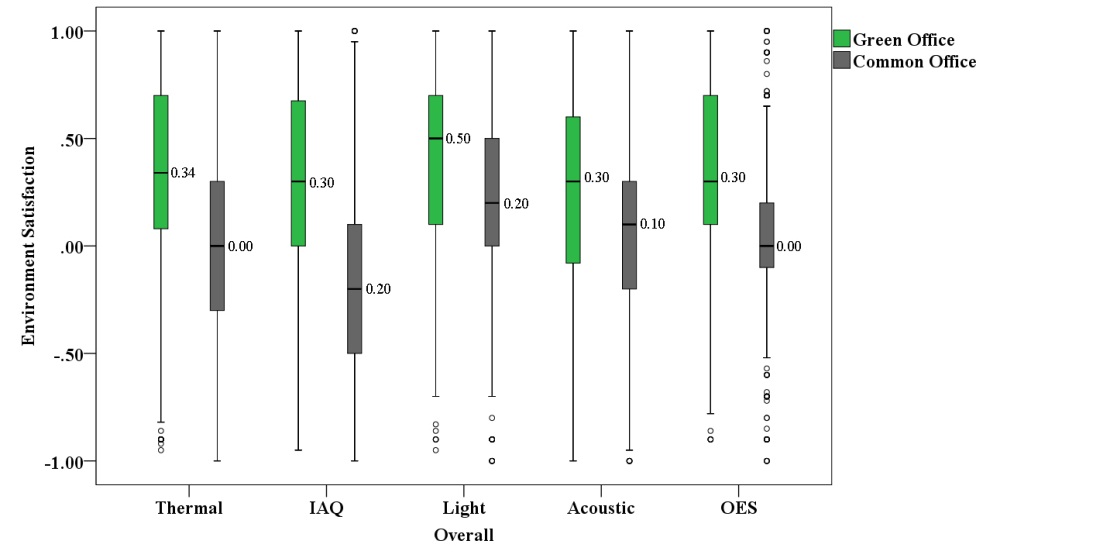


Fig.11 Satisfaction with IEQ

Note) OES refers to overall environment satisfaction

Table 8 Statistical significance of the difference in satisfaction with IEQ

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| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| IEQ | Green | | Common | | p | ΔS (green-common) | ΔS% | % of dissatisfied | |
| SG | Variance | SC | Variance | green | common |
| Thermal | 0.34 | 0.20 | 0 | 0.20 | 0.0000 | 0.34 | 17% | 20% | 41% |
| IAQ | 0.3 | 0.18 | -0.2 | 0.20 | 0.0000 | 0.5 | 25% | 23% | 64% |
| Light | 0.5 | 0.17 | 0.2 | 0.14 | 0.0000 | 0.3 | 15% | 15% | 19% |
| Acoustic | 0.3 | 0.20 | 0.1 | 0.16 | 0.0000 | 0.2 | 10% | 26% | 39% |
| OES | 0.3 | 0.15 | 0 | 0.13 | 0.0000 | 0.3 | 15% | 15% | 39% |

Fig.11 and Table 8 present difference and statistical significance of the difference in median of satisfaction with IEQ between respondents in the green and common buildings acquired by this study. It could be found that median values of all IEQ items in green buildings are statistically significantly higher than those in common buildings. Satisfaction with IAQ is below neutral for common building, but above neutral for green buildings. There is little effect of building type on satisfaction with acoustic environment (SC=0.1, SG =0.3), and this might be a logical consequence of space out design, which considered more on daylighting penetration than on noise control. In sum, green building users are more satisfied with IEQ than common building users, with significantly difference for thermal environment and IAQ. For the same type of buildings, satisfaction with light is the highest.

*3.5 Comparison of satisfaction with building service performance (BSP) between green and common building*

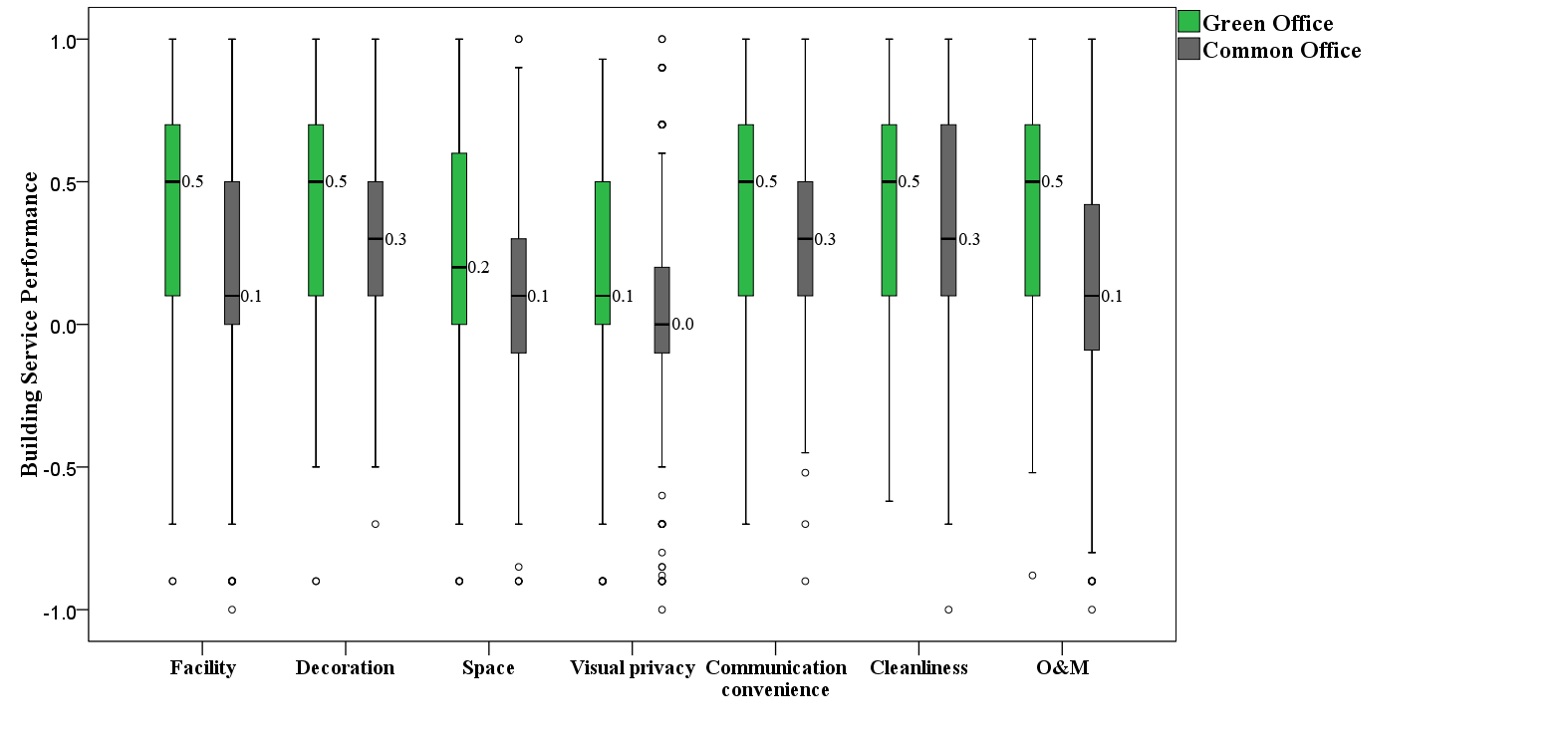


Fig.12 Satisfaction with building service performance

Table 9 Statistical significance of the difference in satisfaction with BSP

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| BSP | Green | | Common | | p | ΔS (green-common) | ΔS% | % of dissatisfied | |
| SG | Variance | SC | Variance | green | common |
| Facility | 0.5 | 0.14 | 0.1 | 0.19 | 0.0000 | 0.4 | 0.2 | 9% | 23% |
| Decoration | 0.5 | 0.12 | 0.3 | 0.12 | 0.0000 | 0.2 | 0.1 | 5% | 8% |
| Space | 0.2 | 0.18 | 0.1 | 0.16 | 0.0002 | 0.1 | 0.05 | 20% | 27% |
| Visual privacy | 0.1 | 0.19 | 0.0 | 0.16 | 0.0000 | 0.1 | 0.05 | 25% | 38% |
| Communication convenience | 0.5 | 0.12 | 0.3 | 0.12 | 0.0000 | 0.2 | 0.1 | 6% | 11% |
| Cleanliness | 0.5 | 0.13 | 0.3 | 0.12 | 0.0023 | 0.2 | 0.1 | 7% | 7% |
| O&M | 0.5 | 0.12 | 0.1 | 0.18 | 0.0000 | 0.4 | 0.2 | 5% | 25% |

Similarly, difference and statistical significance of the difference in satisfaction with building service performance are shown in Fig.12 and Table 9. It could be found that there is a high level of statistical significance for difference in all BSP items between green and common. The difference of satisfaction with comfort of facilities and O&M between building types is significant (ΔS=0.4). Little difference in work/storage space or visual privacy is found (ΔS=0.1).

It is beyond the topic of this article to analyze the factors affecting satisfaction with IEQ. We limit ourselves here by just describing the difference in satisfaction between green and common office buildings in China. However, there are many previous researches concerning on factors affecting satisfaction with IEQ. Deuble and de Dear (2012) concluded that occupants in green buildings were more forgiving of their less-than-ideal conditions, which might result from higher levels of environmental concern [39]. Apart from environmental attitudes, personal control over the indoor environment and thermal experience of occupants and many other factors are also related to satisfaction [40.41].

1. **Conclusions**

The green buildings are developed rapidly in China recently. To evaluate the total performance of green buildings, the operational energy consumption in 31 green buildings and IEQ in 10 green buildings are compared with those of common office buildings in three different climate zones of China. Energy consumption data, physical parameters and occupant satisfaction survey were collected and analyzed.

The study indicates that in hot-summer & cold-winter zone, the average total energy consumptions for type A and type B green building are close to the recommended value of 60 and 80 kWh/(m2a) in the Standard for Energy Consumption of Buildings. However, in cold and hot-summer& warm-winter zones, the energy consumption of green buildings for both type A and type B are higher than upper limit. For building type A, it is only in hot-summer & cold-winter zone that the green’s energy consumption is statistically significantly less than common value. For building type B, there is no statistically significantly difference between green and common office buildings in all climate zones.

Regarding to occupant satisfaction about IEQ and building service performance, a higher occupant satisfactory level was observed in green building than in common building, especially in the field of thermal environment, IAQ, facilities and operating & maintenance. And the satisfaction level with the lighting environment is the highest for both types of buildings.

In addition, factors affecting the level of green office buildings’ energy consumption are analyzed. It was found that firstly indoor temperature affects energy consumption of HVAC slightly. In addition the energy efficiency of air-conditioning equipment or system affects energy consumption but is not the only most important factor. Furthermore, high energy consumptions of fresh air system have a huge impact on energy consumption of HVAC system. Lastly HVAC system partition and optimal control strategy can reduce HVAC system energy consumption effectively. In terms of IEQ, the proper passive designs, such as natural ventilation and natural lighting, and the introduction of effective control equipment of IEQ for occupants can not only improve the user satisfaction but also reduce energy consumption effectively.

Due to the various types of green buildings and many factors affecting energy consumption and IEQ, a further study to increase the sample size, take continuous long-term test of indoor environment parameters and analyze energy consumption is needed. Besides, other factors affecting energy consumption and IEQ should be considered for further exploration, such as occupant behavior, working schedule, occupant density and so on. Through this we could further understand the performance characteristics of green buildings and provide guidance for the design and operation of green buildings, which are able to create better indoor environment with less energy consumption and carbon emissions.

**Symbols and notations**

|  |  |
| --- | --- |
| IEQ | indoor environmental quality |
| IAQ | indoor air quality |
| SECB | Chinese standard for energy consumption of buildings |
| LEED | leadership in energy and environmental design |
| HVAC | heating, ventilation, and air conditioning |
| HDD | twelve month heating degree-days with a base temperature of 18 °C |
| CDD | twelve month cooling degree-days with a base temperature of 26 °C |
| C | cold zone |
| HSCW | hot summer & cold winter zone |
| HSWW | hot summer & warm winter zone |
| BSP | building service performance |
| O&M | operating & maintenance |
| A/B-C/CW/WW | building type A/B in C/ HSCW/ HSWW zone |
| THICS | temperature and humidity independent control air conditioning system |
| OES | overall environment satisfaction |
| Difference | the percentage difference between the measured median and the upper limit, and the recommended value in parenthesis. A positive difference indicates higher energy consumption in green office buildings |
| D | design |
| O | operation |
| Percentage | the proportion of HVAC electricity consumption in total energy consumption |

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