Evaluating Energy Savings Retrofits for Residential Buildings in China

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Abstract

Building retrofit plays an important role in reducing energy consumption and carbon dioxide emissions whilst increasing occupant thermal comfort. This study used DesignBuilder to predict the energy saved by retrofitting a typical flat in Chongqing, a city in the hot summer, cold winter region of China. To increase the reliability of predictions, the model was verified by measured indoor air temperature for a one-week period in April. Five retrofit measures were evaluated, external wall insulation, new windows, increased air tightness, external shading, and higher efficiency of air conditioning. Three types of households with different AC operating schedule were assumed, high, medium and low. The variance in the model predictions due to the uncertainty in the model input parameters was calculated. The results showed that the energy saved depended on the use that was made of the AC system. For high energy users, 40 to 68% of the annual space-conditioning energy could be saved depending on the retrofit, whereas for low energy users the savings were 30 to 58%. Thermal comfort has improved in winter for low and medium energy users, but no improvement in summer.

Introduction

The hot summer, cold winter (HSCW) region of China accounts for 40% of China's population, and buildings in HSCW zone account for 45% of the country's energy consumption (L. Xu et al., 2013). The climate in this zone has a large variation. In winter, the average temperature can drop to 0-10°C. In summer, the average temperature can reach up to 25-30°C (Li et al., 2011). According to China's design regulation for the HSCW zone, central space heating is not required (MOHURD, 1993), because central space heating is provided according to geographic location defined by the central government, where HSCW zone lies below the heating line (Guo et al., 2015).

The newly enforced construction codes and regulations aim to reduce the building energy consumption in HSCW zone by providing guidelines on the required building fabric and passive design (MOHURD, 2001). However, many urban dwellings (residential buildings) were constructed prior to the implementation of building regulations, and thus often lack adequate building fabric (L. Xu et al., 2013).

In winter, indoor air temperatures of urban dwellings in HSCW zone can drop to 5-15°C, which is much lower than urban dwellings in north China (20-25°C) with space heating, where the outdoor temperature can drop to -10 to 0°C (Li et al., 2014). In the summer buildings in the HSCW zone can be overheated, with indoor air temperature rising to 25-35°C.

As living standards increase, the number of urban dwellings with installed air conditioning systems (AC) in HSCW zone is also increasing. This leads to a sharp increase in energy consumption and greenhouse gas emissions (McNeil et al., 2016).

The aim of this study is to evaluate the effect of applying retrofit measures to urban dwellings in order to reduce energy consumption and greenhouse gas emissions. Many studies have investigated building fabric retrofit in the HSCW zone (Ouyang et al., 2009; Yu et al., 2008; Zhao et al., 2015). Results showed that retrofitting (e.g. external wall insulation, new windows) has the potential to reduce energy consumption. However, these studies fail to consider the uncertainty of input parameters, which can cause large variations of the output parameters (Hopfe and Hensen, 2011).

Occupant behaviour, particularly in relation to energy consumption, is a significant factor in the overall building energy performance, yet most previous studies had only evaluated one type of energy user (L. Xu et al., 2013; Yu et al., 2008). Literature showed that different households have radically different AC operating hours (Chen et al., 2015), which cause large variation of AC electricity consumption.

Model verification prior to dynamic thermal simulation can improve reliability of predictions when evaluating energy savings of retrofit (IPMVP, 2002). Only a limited number of studies have considered verifying the indoor temperature prediction in DTM, which may lead to model prediction discrepancies with measured data (P. Xu et al., 2013) and thus, less reliable predictions of energy savings retrofits.

Many studies evaluate retrofits that are not realistic in practice and lead to over-prediction of energy savings. For example, one study of urban dwelling in the HSCW zone suggested reducing the air infiltration rate to 0 ach^{-1} (Zhao et al., 2015). However, health problems occur when air infiltration rates are below 0.5 ach^{-1}, and mechanical ventilation would be required (Fu et al., 2017).

This study sets out to address all the above limitations by evaluating realistic retrofit measures using a verified dynamic thermal model, accounting for different AC operating schedules and the uncertainty of input parameters.

The aim of this study will be achieved through the following objectives;

- Identify a representative urban dwelling in the context of HSCW zone;
- Verify a dynamic thermal model for the case study dwelling using measured data;
- Evaluate the energy saved by applying individual and combined retrofit measures for households with different AC operating schedules;
- Evaluate the effect of uncertainty in the input parameters on the predicted energy savings.

Methodology

Case study building

A case study building located in the city of Chongqing (a major city in HSCW zone) was selected for the research reported here. This building was built with typical construction materials in HSCW zone which requires retrofit and is used as University accommodation (Figure 1). It is a nine-storey building and was constructed in 1996. The ground and the first floor are for commercial use. A flat (apartment) located on the second floor, with the main facade facing 30° east of north was chosen as the case study. It consists of a living room, bedroom, kitchen and toilet.

The external wall of the case study building is 200 mm thick consisting of two 20 mm cement layers on both sides of a 160 mm brick wall (Table 1). The window is made of 3 mm single clear glazing with aluminium frame. No overhang or other shading devices are present. Heating and cooling is provided by an intermittent split single-zone heat pump, with an estimated COP of 1.9 for heating and 2.3 for cooling. Other modelling assumptions are listed in Table 2.

Table 1: Construction properties of external wall

Construction	Conductivity (W/mK)	Specific heat (J/kgK)	Density (kg/m^3)
Cement	0.72	840	1860
Brick	0.72	840	1920
Cement	0.72	840	1860

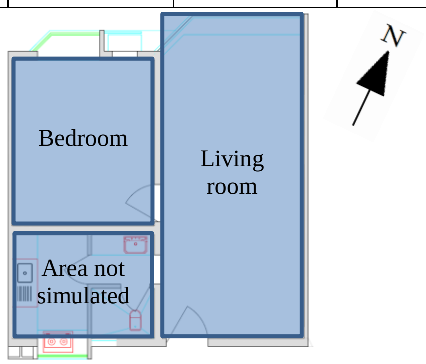

Figure 1: Floor plan of the case study flat (source: Yao 2017)

Table 2: Summary of modelling assumptions

Parameter	Value
U-value of external wall	2.33 W/m^2K
U-value of window	5.89 W/m^2K
SHGC value of window	0.86
U-value of interior wall	1.86 W/m^2K
U-value of party wall	0 W/m^2K
U-value of party ceiling	0 W/m^2K
U-value of party floor	0 W/m^2K
Infiltration rate	1.4 ach^{-1}
Number of occupants	2 occupants
Lighting density	0.59 W/m^2 (Yu et al., 2008)
Internal heat gain	4.3 W/m^2 (MOHURD, 2010a)

Measured data

Measurements of indoor air temperature were undertaken between 7th April 2017 (15:00) and 13th April 2017 (16:00) in the living room when the flat was unoccupied, and the windows were closed. The temperature was measured at 5 minutes interval, using a HOBO UX100-003 Temp/RH logger with precision ±0.21°C. Four temperature sensors (H1, H2, H3 and H4) were clipped on the chairs (Figure 2), and one sensor (HC) was placed on the table (Figures 2 and 3). Outdoor dry-bulb temperature, relative humidity and horizontal solar radiation were recorded at one-minute intervals at the nearby weather station (~1 km distance) at Chongqing University.

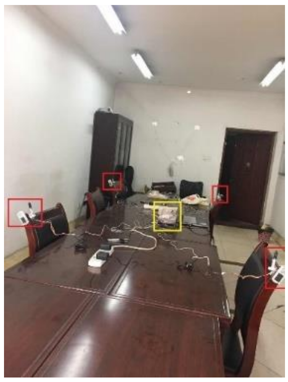

Figure 2: View of living room and location of sensors (source: Yao, 2017)

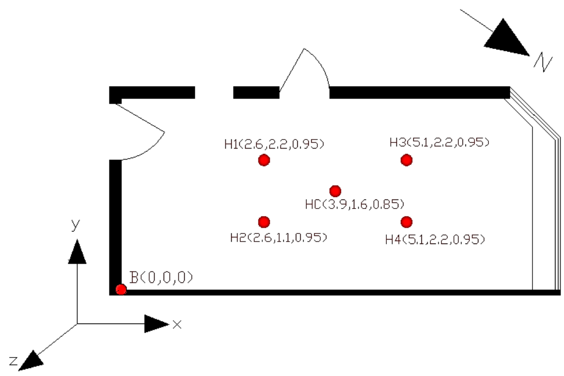

Figure 3: Plan view of the sensor's location in the living room, in coordinates for x,y,z in meters from internal corner B (original source: Yao 2017)

There was a small difference between the temperature readings throughout the measurement period (Figure 4). Sensors H3, H4 read higher temperature due to their proximity to the windows and potentially had higher exposure to solar radiation. Measured indoor temperature was taken as the average of all sensors (Figure 4).

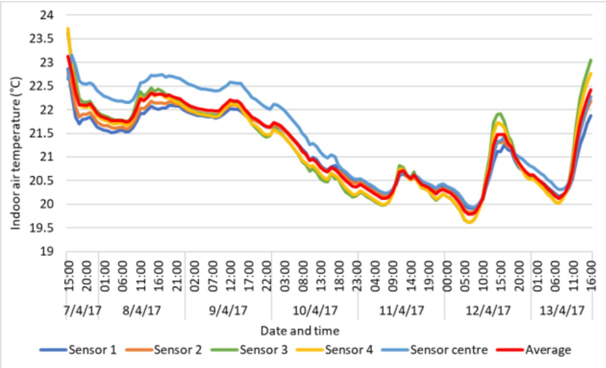

Figure 4: Measured indoor air temperature for different sensors (original source: Yao 2017)

Dynamic thermal model

DesignBuilder based on EnergyPlus for dynamic thermal model (DTM) was used to model the case study flat. Two zones (bedroom and living room) were simulated (Figure 1). The other flats in the building were excluded and modelled as adiabatic blocks, to simulate the effect of shading (Figure 5).

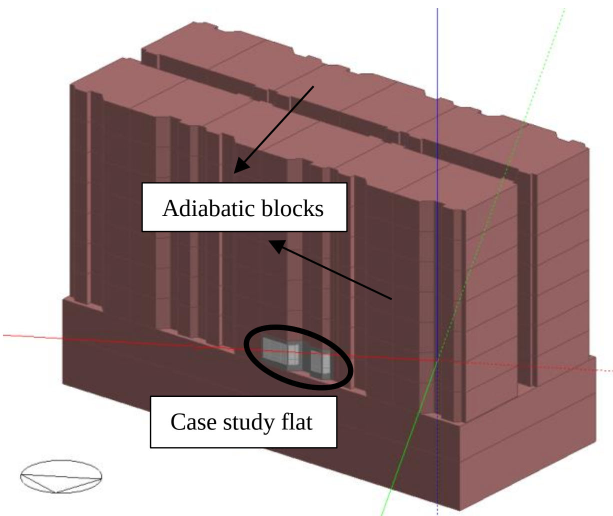

Figure 5: Dynamic thermal model of the building showing circled the base case flat

Model verification

The DTM was verified by comparing the simulated indoor air temperature to the measured indoor air temperature in the case study flat. Four construction properties (U-value of wall, U-value of window, SHGC and air infiltration rate) were adjusted with referenced to uncertainty bands developed, to provide best match between the simulated and measured indoor air temperature.

The measured outdoor dry-bulb temperature, relative humidity and horizontal solar radiation were used to create a customised weather file for running the DTM. As only global horizontal radiation was collected, the direct and diffuse radiations were predicted from the global horizontal radiation using equations listed in Duffie et al., (2013) (Figure 6).

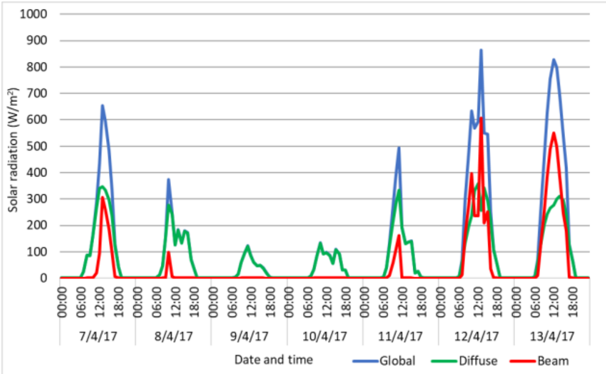

Figure 6: Prediction of diffuse and beam radiation from global horizontal solar radiation

The predicted indoor air temperature was compared with the measured data, and the performance of the model was evaluated using the Mean Bias Error (MBE) (equation 1), and the coefficient of variation of the Root Mean Square Error (CvRMSE) (equation 2).

$$MBE(\%) = \frac{\sum_{i=1}^{N_p}(m_i - s_i)}{\sum_{i=1}^{N_p}(m_i)} \qquad (1)$$

$$CvRMSE(\%) = \frac{\sqrt{\left(\sum_{i=1}^{N_p}(m_i - s_i)^2/N_p\right)}}{\overline{m}} \qquad (2)$$

where m_i and s_i are the measured and simulated data points for each model instance 'i', and N_p is the number of data points at interval 'p' and $\overline{m}$ is the average of the measured data points.

Patterns of energy use

Three types of energy users were created to represent the large variation of AC operation in flats found in literature.

AC heating and cooling operating hours and daily occupancy were defined according to literature (Chen et al., 2013, 2015; Yoshino et al., 2006) (Figure 7). The heating set-point of the living spaces was assumed to be 20°C, and the cooling set-point to be 26°C (Chen et al., 2015).

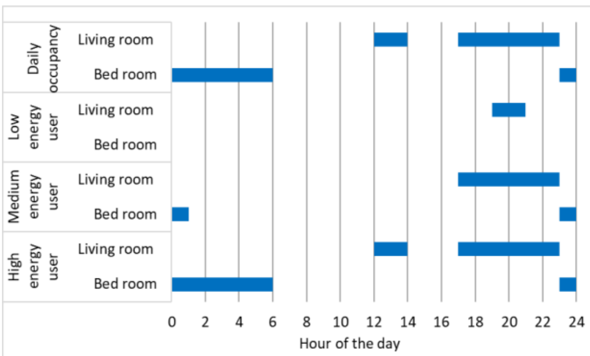

Figure 7: AC heating and cooling operating hours and daily occupancy, for living room and bed room

Setting up realistic retrofit measures

Realistic retrofit measures were developed according to literature and are shown in Table 3. For external wall insulation, 20mm Expanded Polystyrene (EPS) insulation was selected because the Chinese standard (MOHURD, 2010a) suggests a U-value for walls of 1.0 W/m^2K for new urban dwellings. New windows with double glazing and solar control were selected according to the Chinese standard (MOHURD, 2010a), which suggest a window U-value of 2.8 W/m^2K and SHGC of 0.47 for new urban dwellings. An air infiltration rate of 0.5 ach^{-1} was selected, because health problems occurs when indoor air exchange rate is lower than 0.5 ach^{-1} (Fu et al., 2017), and mechanical ventilation is required below 0.5 ach^{-1}, resulting in electricity use for mechanical ventilation which is larger than the AC electricity reduction by increase air tightness (Fu et al., 2017). An overhang length of 0.5 m was proposed (Yao et al., 2018). The air conditioning COP was selected from Chinese standard (MOHURD, 2010b).

Table 3: Selection of realistic retrofit measures

Retrofit measure	Changes
External wall insulation (20mm EPS insulation)	U-value of wall = 1.06 W/m^2K
New windows (double-glazed with solar control)	U-value of window = 2.8 W/m^2K, SHGC = 0.47
Increased air tightness	Air infiltration rate = 0.5 ach^{-1}
New overhang	Overhang length = 0.5m
Higher efficiency of AC	Heating COP = 3.2, cooling COP = 3.2

Setting up uncertainty bands

Urban dwellings constructed in the 1990s have different building properties, which cause uncertainty of input parameters. Thus, two categories (low band and high band) were defined for the purpose of this work (Table 4).

- U-value of wall: Some urban dwellings with lower U-value have thicker (~240mm) external wall, and buildings with higher U-value have thinner (~160mm) external wall (Wang et al., 2015; L. Xu et al., 2013; Yu et al., 2009);
- U-value of window and SHGC: Single glazing is commonly use in urban dwellings (Yu et al., 2009), U-value of window range from 4.7-6.554 W/m^2K and SHGC range from 0.7-0.95;
- Air infiltration: Urban dwellings have either very poor air infiltration performance with 2 ach^{-1} (McNeil et al., 2016), or poor air infiltration performance with 1 ach^{-1} (Yu et al., 2013, 2008);
- Overhang: Some household in HSCW zone have an overhang installed, the length was assumed to be 0.3m;
- Heating and cooling COP: Values were chosen from literature, range of heating COP is 1.9-2.5 and cooling COP is 1.9-2.8 (MOHURD, 2010a; Yu et al., 2008).

Table 4: Uncertainty band for input parameters

Input parameter	Base case	High band	Low band
U-value of wall (W/m^2K)	2.23	1.79	2.36
U-value of window (W/m^2K)	5.89	4.7	6.55
SHGC (-)	0.86	0.7	0.95
Air infiltration (ach^{-1})	1.4	1	2
Overhang length (m)	0	0.3	0
Heating COP (-)	1.9	2.5	1.9
Cooling COP (-)	2.3	2.8	1.9

Parametric tool

A parametric study was carried out to investigate the effect of uncertainty on the energy savings retrofits for individual and combined retrofit measures. Input parameters for the base case for the parametric study are shown in Table 3, with medium energy users (Figure 7). For the evaluation of the individual retrofit measures, one input parameter was varied at a time from the base case to the high band and then the low band (Table 3). For the evaluation of combined retrofit measures, all input parameters were varied from the base case values to the high band and to the low band (Table 3). The parametric study was repeated with different AC operating schedule (low and high). Heating and cooling AC electricity consumption was predicted for each case, with a total of 54 simulations.

Evaluation metrics

The percentage change of AC electricity consumption due to uncertainty (P_l and P_h) respective to base case, and percentage of AC electricity reduction after retrofit were calculated by:

$$P_l = (E_b - E_l)/E_b \times 100\% \qquad (3)$$

$$P_h = (E_b - E_h)/E_b \times 100\% \qquad (4)$$

$$P_r = (E_b - E_r)/E_b \times 100\% \qquad (5)$$

where P_l, P_h are the percentage of AC electricity reduction caused by uncertainty of low band and high band of input parameters (Table 3), P_r is the percentage of AC electricity reduction after retrofit. E_l, E_b, E_h and E_r are the AC electricity consumption for case of lower band, base case, high band and retrofit respectively.

Sensitivity index (SC) was defined to evaluate the sensitivity of the uncertainty on retrofit savings. When SC is large, the uncertainty has a large effect on retrofit savings, when SC is small, the uncertainty has a small effect on retrofit savings. The equation is:

$$SC = (P_l + P_h)/P_r \qquad (6)$$

where SC is the sensitivity index.

Percentage of AC electricity reduction after retrofit for low (S_l) and high (S_h) band parameters are calculated by:

$$S_l = (E_l - E_r)/E_l \times 100\% \qquad (7)$$

$$P_r = S_b = (E_b - E_r)/E_b \times 100\% \qquad (8)$$

$$S_h = (E_h - E_r)/E_h \times 100\% \qquad (9)$$

where S_l, S_b, S_h are the percentage of AC electricity reduction for urban dwelling after retrofit for low band, base case and high band respectively.

Thermal comfort for pre-retrofit (base case) and post-retrofit conditions were evaluated by comparing the average indoor air temperature during occupied hours in living room and bed room. Thermal comfort in winter (December to February) and summer condition (June to August) were considered. Adaptive thermal comfort model was used, range of comfortable temperature was 17.5 to 27.6°C (Li et al., 2011).

Results and discussion

Verification of indoor temperature

When the simulation ran from 7/4 to 13/4, the DTM over-predicted the indoor temperatures (MBE = 5.24%, CvRMSE = 5.83%). This is due to a large difference between the thermal condition (wall, floor, ceiling and indoor air temperature) of the flat for the simulation and measurement at the start of the period (Figure 8). Consequently, a pre-validation period was introduced, which the simulation ran from 24/3 to 13/4, by repeating the one-week weather data for the pre-validation period (2 weeks) to match the thermal condition of the flat before 7/4. Results showed that DTM matches more closely to measurements (MBE = -0.21%, CvRMSE = 2.36%) after adjusting the weather data (Figure 8).

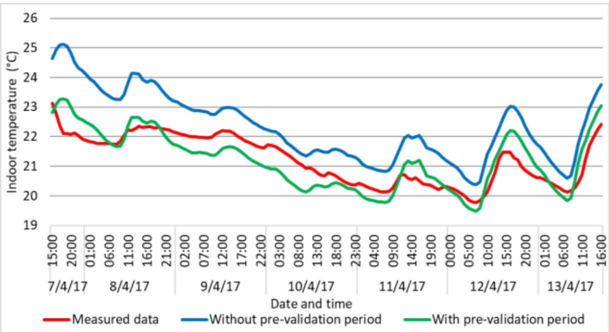

Figure 8: Model verification - comparison between measured and simulated room temperatures

The four construction properties were varied using assumptions developed in Table 3. The variation of indoor air temperature was insignificant for different U-value of wall (Figure 9), U-value of window and SHGC (Figure 10). In contrast, the variation of indoor temperature was significant for air infiltration. An air infiltration rate of 1 ach^{-1} provides the best match between the simulated and measured indoor air temperature (MBE = 0.39%, CvRMSE = 2.1%) (Figure 11).

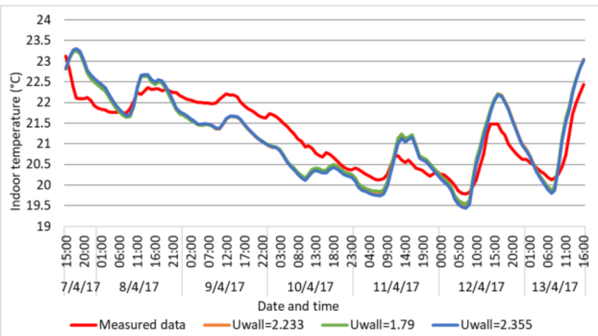

Figure 9: Variation of indoor temperature for different U-value of the external wall

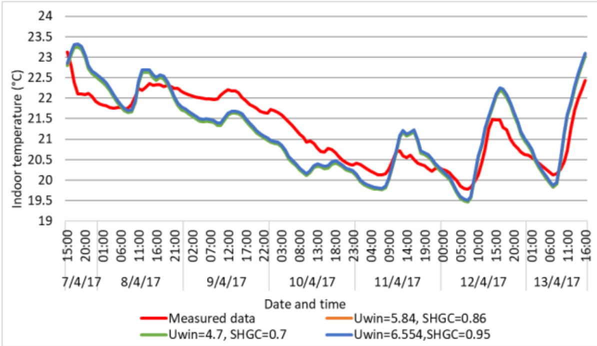

Figure 10: Variation of indoor temperature for different U-values of window and SHGC

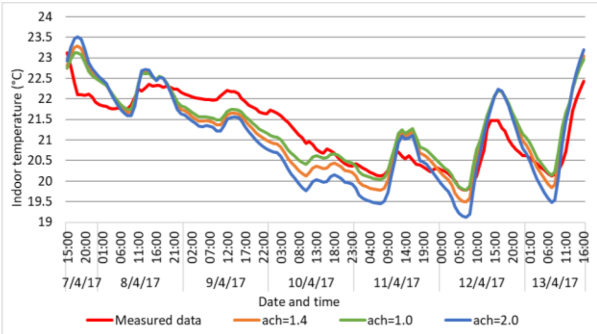

Figure 11: Variation of indoor temperature for different air infiltration rates

Energy savings of retrofit for case study flat

For the case study flat before retrofits (base case), the AC electricity consumption for different types of energy user varies significantly (Table 5). The low energy user consumes less than 30% of the AC electricity used by the high energy user. The proportion of AC electricity for heating and for cooling is about 50/50 for all three types of energy users. A monitoring study by Ouyang et. al, (2009) of heating and cooling electricity consumption in a typical urban dwelling in HSCW zone for one year, provided heating and cooling AC electricity consumption values of 5.51 and 6.77 kWh/m^2, respectively, which is in line with the results of the research reported here.

Table 5: Base case AC electricity consumption

	Heating (kWh/m^2)	Cooling (kWh/m^2)	Total (kWh/m^2)
Low energy users	3.19	3.94	7.13
Medium energy users	8.79	9.6	18.39
High energy users	12.75	13.35	26.1

The energy saving retrofits performed differently when considering heating, cooling and total AC electricity (Figure 12), calculated by equation 5. Higher efficiency AC resulted in the highest heating (41%), cooling (28%) and total (34%) AC electricity savings. External wall insulation provided the second highest savings in heating (20%), while new windows provided the second highest savings in cooling (17%). But when combing heating and cooling, increasing the building's air tightness ranks the second (11%).

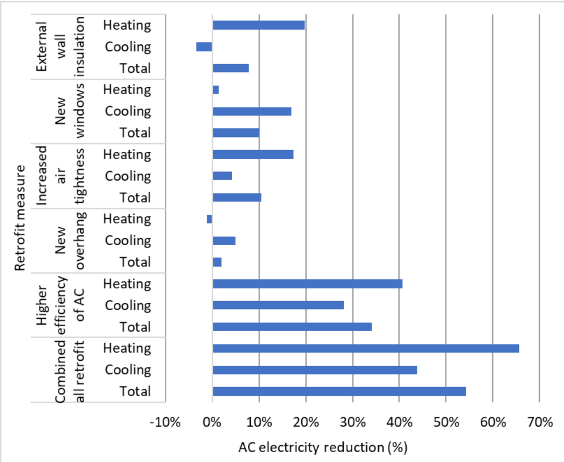

Figure 12: Percentage of AC heating, cooling and total electricity reduction after retrofit with medium energy users

The percentage saved in the total electricity use after retrofit is larger for high energy users (57%) and smaller for low energy users (47%) (Figure 13). The percentage of electricity saved for new windows, improve air conditioner and installed overhang are similar (1% difference) for different energy users. External wall insulation saves less (4%) electricity for low energy users and more (2%) for high energy users. Improve air infiltration saves less (5%) electricity for low energy users and more (1%) for high energy users.

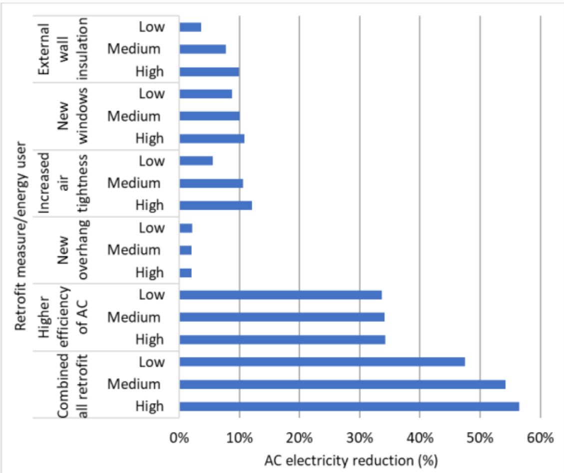

Figure 13: Percentage of AC electricity reduction after retrofit with low, medium and high energy users

The absolute values of AC electricity saved show large variations when different energy users are considered (Figure 14). For combined retrofit measure, energy savings are 3.39 kWh/m^2, 9.97 kWh/m^2 and 14.77 kWh/m^2 for low, medium and high energy users respectively, the difference between a low and high energy user is four folded. (Figure 14).

Effect of uncertainty in the input parameters on energy savings

The effect of uncertainty in the input parameters on the percentage of AC electricity saved is significant (shown in red and blue bar in Figure 15 for medium energy users, calculated by equation 3 for low band and equation 4 for high band), compared to the percentage of AC electricity saved after retrofit (blue plus green bar, calculated by equation 5). Retrofit savings can reach 54% (blue and green bar) if all retrofit measures are implemented. However, the uncertainty reaches 60% (red and blue bar), which is higher than the percentage of retrofit savings.

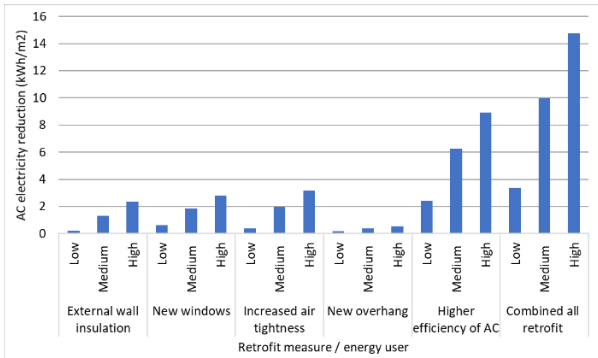

Figure 14: Absolute value of AC electricity reduction after retrofit for case study flat with low, medium and high energy users

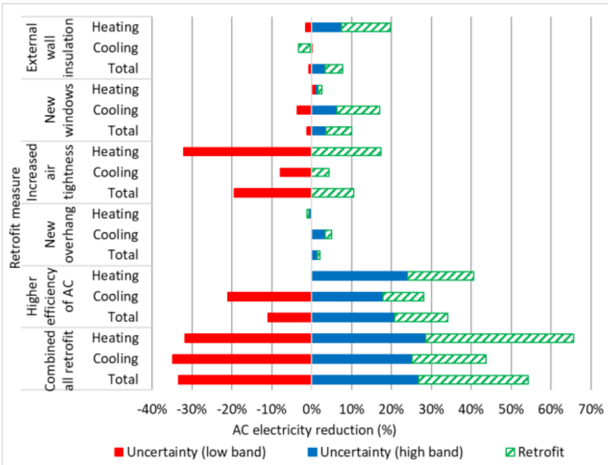

Figure 15: Uncertainty of AC heating, cooling and total electricity reduction for case study building with medium energy users

The effect of uncertainty varies for different input parameters. Uncertainty of increased air tightness has a high impact on AC heating electricity, the uncertainty reaches 32% but the energy saving from retrofit is 17.4%. Uncertainty of new windows has a low impact on AC cooling electricity, the uncertainty is 10% but the energy saving from retrofit reaches 17%. The effect of uncertainty on individual and combined retrofits are further demonstrated in Table 6.

The sensitivity of increased air tightness is the largest (SC=1.83). Possible reasons are the difference between air infiltration rate for low band (2 ach^{-1}) and high band (1 ach^{-1}) is large. The uncertainty of new windows is the smallest (SC=0.46) (Table 6). For low energy users, the total uncertainty reduces (51.1%) but retrofit savings also reduces (47.5%). For high energy users, the total uncertainty increases (63.1%) but retrofit savings also increases (56.6%). However, the sensitivity index for low, medium and high energy users are similar.

Table 6: Effect of uncertainty of input parameters on retrofit savings

Retrofit measure	Energy user	P_l+P_h	P_r	SC
External wall insulation	Medium	4.1%	7.8%	0.52
New windows		4.6%	10.1%	0.46
Increased air tightness		19.4%	10.6%	1.83
New overhang		1.4%	2.0%	0.69
Higher efficiency of AC		31.8%	34.1%	0.93
Combined all retrofit		60.2%	54.2%	1.11
Combined all retrofit	Low	51.1%	47.5%	1.08
Combined all retrofit	High	63.1%	56.6%	1.11

For medium energy users, the percentage of AC electricity saved is the largest for input parameter with low band (66%) and smallest for input parameter with high band (38%) (Figure 16). When different energy users are considered, low energy users have lower percentage of AC electricity saved (30-58%) and high energy users have higher percentage of AC electricity saved (40-68%) (Figure 15). AC electricity saving varied from 30-68%.

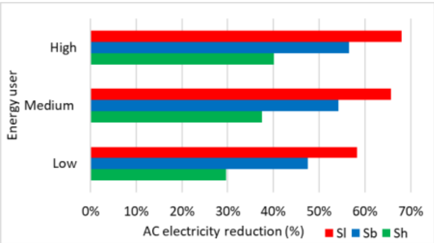

Figure 16: Percentage of AC electricity reduction after retrofit for upper band, base case and lower band for combined retrofit measures

The uncertainty of the input parameters caused a large variation of absolute energy saved when different energy users are considered (Figure 17). The variation of the AC electricity saved for the low energy users (0.93 to 3.23 kWh/m^2) is much smaller than that of the high energy users (3.49 to 8.26 kWh/m^2) for higher efficiency of AC. Considering all retrofit measures, the uncertainty of AC electricity saved for the low energy users (1.58 to 5.19 kWh/m^2) is much small than that of the high energy users (7.59 to 24.06 kWh/m^2).

The results showed that higher efficiency of AC achieves highest energy savings (34%). However, different AC operating schedules and the uncertainty of input parameters has a large effect on predicting energy savings of retrofit. Thus, it is important to identify these parameters accurately before DTM when predicting energy savings for retrofit.

Thermal comfort conditions

For low and medium energy users, the predicted average indoor air temperature post-retrofit increased by 0.4-1.6°C during winter but remain the same in summer. This is because the chosen combination of retrofit measures is more effective at reducing heat loss in winter, but less effective at reducing heat gain in summer. For high energy users, the temperature is the same post-retrofit, as the AC is operated throughout the occupied hours.

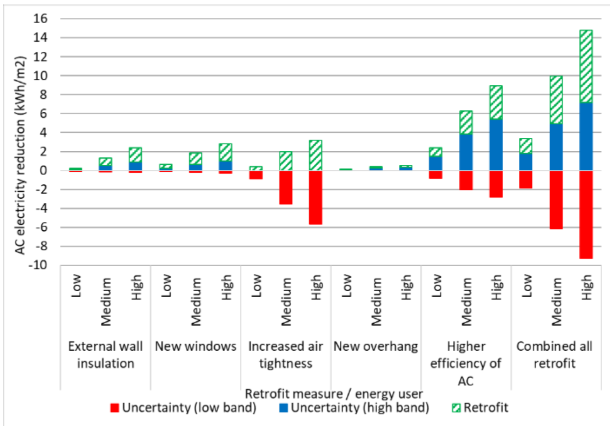

Figure 17: Absolute value of AC total electricity consumption for different energy users and retrofit measure

In winter, for medium energy users, the living room is within the comfort range pre-retrofit, with 0.4°C increase post-retrofit (Figure 18). However, the bedroom is outside comfort range pre-retrofit and post-retrofit. For low energy users, both the living room and bedroom are outside comfort range post-retrofit.

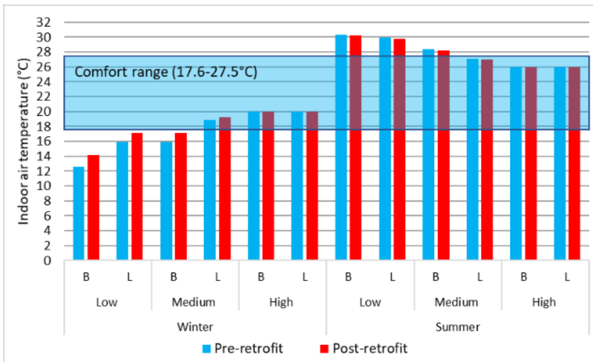

Figure 18: Average indoor air temperature for pre-retrofit and post-retrofit conditions for winter and summer (B: Bedroom, L: Living room)

Conclusion

The study evaluated realistic retrofit measures using a verified dynamic thermal model, accounting for different AC operating schedules and the uncertainty of input parameters, to predict the energy savings from retrofit measures. The following conclusions can be drawn from this study:

- The ranking of recommend retrofit measures are different when considering heating (higher efficiency of AC and external wall insulation produce the greatest savings), cooling (higher efficiency of AC and new windows) and total AC electricity (higher efficiency of AC and increased air tightness);
- For combined retrofit measures, the percentage savings varies by 47 to 57% for different energy users. However, the absolute value of savings shows a large variation from 3.39 to 14.77 kWh/m^2, for different energy users, which indicates that that AC operating schedules should be identified accurately before evaluating energy savings for retrofits;
- The uncertainty of input parameters leads to variation in the percentage of savings for different energy users.

The range of energy savings for low (30 to 58%), medium (38 to 66%) and high (40 to 68%) energy users shows that percentage of energy saved depends on the use made of the AC system;

- The range of energy savings for low (1.58 to 5.19 kWh/m^2), medium (5 to 16.1 kWh/m^2) and high (7.59 to 24.06 kWh/m^2) energy users, due to uncertainty in input parameters is large. The energy saving for low energy users (5.19 kWh/m^2) can be higher than for medium energy users (5 kWh/m^2). This shows the importance to identifying the input parameters accurately before evaluating energy savings from retrofits.
- For low and medium energy users, the average indoor air temperature post-retrofit has increased by 0.4-1.6°C during winter and has been predicted to be remain the same in summer. For high energy users, temperature is the same post-retrofit.

Future work will include evaluation of energy retrofits in further flats (apartments) in the building, identification of archetypal building designs and evaluation of energy savings due to retrofits in a city scale DTM model.

Acknowledgement

This research was supported by the UK Engineering and Physical sciences Research Council (EPSRC EP/N009797/1) for the collaborative China-UK project Low carbon climate responsive Heating and Cooling of cities (LoHCool). The authors would like to thank Prof. Runming Yao and Ms. Xinyi Li for taking measurements.

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