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Energy and behavioral impacts of integrative retrofits for residential buildings: What is at stake for building energy policy reforms in northern China?

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HIGHLIGHTS

- ► Integrative retrofits significantly reduce residential heating energy in north China.
- ► Energy effects of retrofits, incentive, billing and behavioral changes were studied.
- ► Monetary incentive, control or metering technologies did not lead to behavior change.
- ► Potential energy savings due to occupants' behavioral changes are sizable.
- ► Thermal integrity needs to be enhanced in future building standards and policies.

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ABSTRACT

Based upon the results from extensive building monitoring and surveys on occupant's behaviors in a representative nine-story apartment building in northern China, building energy simulations were performed to evaluate the impacts of integrative retrofits implemented. Integrative retrofits required by the newer building energy standard produced significant heating-energy savings (i.e., 53%) when compared with baseline buildings commonly built in early 1980s. Taking into account district-heating-system upgrades as part of integrative retrofit measures, a representative apartment building was 66% more efficient than the baseline building. Contrary to expectation, little behavioral change was found in response to the provisions of monetary incentive, billing-method reform, or metering of heating energy use in individual apartment units. Yet this paper identified sizable energy savings potential if occupants' behavioral changes were to actually happen. This indicates that provisions of financial incentives or individual metering were insufficient for triggering substantial behavioral changes leading toward more energy savings in the current buildings. It is recommended that innovative energy policies, technology upgrades, and education would be needed to promote behavioral changes toward additional energy savings. Finally, measures and strategies to further enhance thermal integrity criteria (e.g., insulations of roof and balcony) are recommended in China's future building energy policy reforms.

1. Introduction

With unprecedented economic and infrastructure development in China, buildings' total floor spaces in urban areas have experienced significant increase in recent decades, from three billion square meters in 1996 to approximately nine billion square meters in 2008 in northern China. Annual heating energy use in buildings located in cities and urban areas in northern China accounted for approximately 40% of total energy use in the buildings, equivalent to about one quarter of total building energy consumption in China annually (Building Energy Research Center (BERC) (2010)).

In northern China, average heating energy intensity, defined as annual heating energy consumption per building floor area, was higher than that of developed countries in the same latitude by a factor of up to two (Lu and Wu, 2007). Zhong et al. (2009) reported that Chinese governments carried out several steps to improve building energy efficiency of heating zones in Northern China, including reforming the urban heating supply system, establishing new heating price mechanism, and retrofitting

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existing buildings. In 2007, China's Finance Ministry issued financial incentives for retrofitting existing residential buildings in Northern China. Lu et al. (2009) analyzed energy efficiency retrofit demonstrations in Harbin, Tianjin, Tangshan, and Baotou and found building energy efficiency in Northern China was low and poor insulation of building envelopes was identified as the major cause. Wang et al. (2007) developed a performance indicator for evaluating the cost effectiveness of wall insulations based upon building life-cycle analysis. Yang et al. (2008) analyzed energy performance of building envelopes in different climate zones in China based on empirical study. As part of district heating system's efficiency improvement, Li et al. (2011) proposed a novel heating system to recover the low-grade energy using hot water absorption heat pump in the substation of district heating system. Compared to conventional district heating system, the new heating system can save energy by 23% to 46%. Zhao et al. (2009a) investigated a technology line suitable for heating metering and energy efficiency retrofit of existing residential buildings. In addition, they (Zhao et al., 2009b) built a mathematical model to evaluate heat metering and energy efficiency of existing residential buildings in northern heating areas of China. Xu et al. (2009) surveyed the effects of consumer behaviors on water flow performance by probability analysis, and found that implementing new energy billing systems through metering heating energy use could lead to about 10% reduction in heating energy use when compared with traditional billing systems. Li et al. (2009) investigated the optimal choice of building energy efficiency standard in the context of centralized urban district heating system in northern China by employing a techno-economic analysis approach. Their analyses indicated that the current building energy efficiency standard implemented in China is sub-optimal and should be tightened immediately in order to achieve a better energy and environmental performance while reducing the associated life-cycle social costs.

Xu and Huang (2009) reported several retrofit measures adopted in new residential buildings in a heat reform and building energy efficiency project supported by the World Bank, as a key part of its international assistance program to assist China to implement heating reform policies and promote more energy-efficient design and construction of residential buildings. Based upon the monitoring results from that study, in this paper, we further analyze energy and behavioral impacts from integrative retrofits adopted for residential space heating in the selected building. The term "integrative retrofits" in this paper means simultaneous implementation of efficiency measures, and monetary and non-monetary strategies to improve overall energy performance of buildings in northern China. For example, increasing insulation and airtightness of building envelope, implementing demand-responsive heating supply systems through installing variable water flow controllers, installing metering device for heating energy use, and creating consumption-based billing system. Prior to this, there was limited data available from field monitoring and evaluation of heating system's energy performance in district heating systems where integrative retrofits were implemented.

In order to promote on energy efficiency improvements in residential buildings in northern China and to understand effectiveness of building energy policies and technologies, it is necessary to advance the understanding of energy and behavior impacts of integrative retrofits in residential buildings in northern China. Such new knowledge will also help to further stimulate and support relevant enabling policies targeted at improving energy efficiency of residential buildings effectively.

The goal of this paper is to advance the understanding of energy and behavioral impacts of integrative retrofits in residential buildings in northern China. The new knowledge can be used to promote energy efficiency improvements in residential buildings, and to strengthen energy policy reforms aiming to enable best practices applicable to the regions with significant heating energy consumption. The specific objectives were to:

a) Quantify the magnitudes of energy-saving effects of the integrated retrofit measures,
b) Assess energy performance of recently constructed buildings in comparison with that of baseline buildings per local building energy standards; and
c) Identify the areas in design and construction of building systems, monetary and non-monetary strategies, and behavioral changes that could potentially lead to improved energy efficiency, and develop recommendations for augmenting future policy reforms.

2. Methods

Based upon the results from field monitoring of building systems and surveys on occupants carried out in a representative apartment building recently constructed per the newer building standard, building energy simulations using DOE-2 were performed to quantify magnitudes of energy savings from implementing energy efficiency measures that were integrated in typical northern China' residential buildings.

Specifically, detailed plan reviews and energy audits were conducted for a pool of representative apartments and buildings in Tianjin, China. Tianjin located in Northern China, cold climate zone, with heating degree days (HDD) of 2699 using 18 °C as the base. The current buildings were built to comply with the latest energy efficient design standards for residential buildings in Tianjin (Tianjin Construction Management Committee (TCMC) (2004)). This is the same requirement for the "cold climate" zone in China's national standards. Based upon the reviews of design drawings and results from field monitoring and on-site occupant surveys, energy simulation model using DOE-2 were built and calibrated for energy impact analyses.DOE-2 is one of most widely used and tested building energy simulation tools developed by U.S. Department of Energy. Additional analyses and discussion were carried out to corroborate energy performance of the buildings, occupant behaviors, and integrative retrofit measures.

A nine-story apartment building in Tianjin, China, built in 2006, was selected for monitoring because it was among the first residential development designed and constructed according to the local energy efficient design standards (Tianjin Construction Management Committee (TCMC) (2004)). The standard-conforming buildings designed and constructed after 2004 were expected to save 65% heating energy when compared to baseline residential buildings constructed in the same region in early 1980s. The selected apartment building was among many other buildings served by a large hot water district heating system, which was supplied by a combined heat and power plant. The centralized district heating system does not provide domestic hot water service. As part of integrative retrofits, the district heating supply system was equipped with variable speed circulation pumps for supplying hot water, individual meters of heating energy use per household or unit, and thermostatic temperature control valves. Each apartment unit is heated by radiators with thermostatic radiator valves. Each unit had an ultrasonic meter for recording heating energy use cumulatively during the heating season. This cumulative heating energy consumption was used to calculate the monthly heating energy bills. In this building, three apartment units located on the top, middle, and bottom floors were selected for detailed measurements and monitoring in the heating season between November 15, 2007 and March 15, 2008. The monitoring included ambient air temperatures and relevant weather data throughout the heating season; and indoor air temperatures in each individual room within the three units. In addition, 25 families were recruited to participate in the occupant surveys. The following activities were carried out to characterize the building and occupants:

- Collection of design and construction information, including construction drawings and physical properties of materials and components used,
- Sample survey of households regarding household size (e.g., number of people), home appliances and rated capacities (e.g., kW), occupancies and schedules,
- Sample survey of household incomes, satisfaction of metering equipment for heating energy use, overall satisfaction of heating system, behavioral changes in response to energy billing and metering,
- Sample survey of similar households' characteristics in the region.

Based upon the information collected and compiled from the reviews and field measurements, a building energy model was built and calibrated to simulate the heat loads and to quantify energy consumption of each apartment unit as well as the whole building, as compared with the baseline case stipulated in the local building energy standard. Results from on-site surveys on occupants were then analyzed. Energy and behavioral impacts of the integrative retrofits for the residential buildings were quantified, and discussion and recommendations were made for augmenting future policy reforms in China.

3. Results

3.1. Input of simulation model

3.1.1. Geometry and thermal zones

The nine-story apartment building has a total of 72 apartment units, with each floor having eight units. Each unit has three bedrooms, one master bedroom in south and two guest rooms facing south and north each. Each unit also has one living room, one dinning space, and one kitchen. The area of a typical apartment unit is 150 m^2.The south facing windows are relatively large, compared with northern facing windows. On the east side, there are only two small window strips extended from the large south and north facing windows. The architecture drawings show the balcony facing south as an unconditioned space. However, in the real usage, the balcony was commonly enclosed with single-pane glasses, and the occupants seldom closed the door between the balcony and the living room. The balcony door was made of wood with no insulation. Therefore, in the model, we treated the balcony space as a conditioned space and it was part of the living room thermal zone. The balcony to floor area is 4% in each unit. Each unit was modeled as a multi-zone unit with multiple radiators and thermostats.

Fig. 1 shows the room layout of one unit for the existing apartment building selected in this study. The layout of simulation model is the same as the architecture drawings.

We simulated one half of the building, because the other half of the building is geometrically identical to the half and the effect of switching the east facing window with the west is insignificant because of their small size. The window to wall ratio of west and east façade is approximately 8%. Since three representative apartment units were monitored separately, we built the model for each floor level and calibrated the model with the measured results for each unit separately. Table 1 shows representative input parameters of the model for half of the current building.

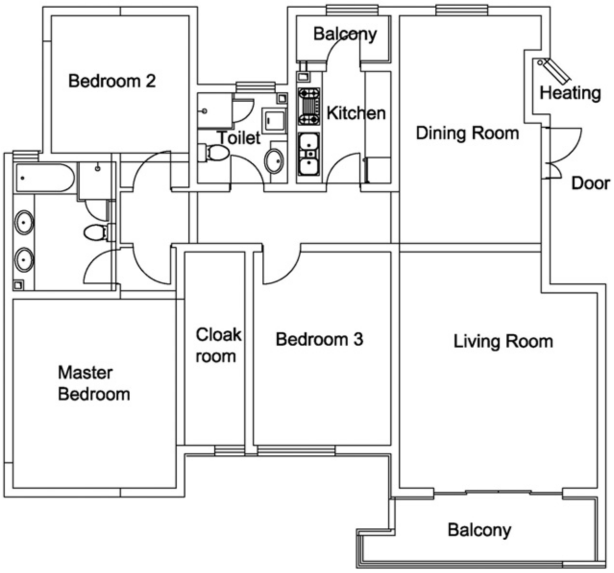

Fig. 1. Floor layout of the typical apartment of the building.

3.1.2. Measured internal loads and schedules

We used the measured electricity consumption in each selected unit to emulate the internal loads during the heating season. The variations in internal load are also indicated variations of occupancies and activities within the households. Fig. 2 shows the hourly electricity usage measured for one unit on a typical weekday. The data shown in Fig. 3 is the seasonal average value. On a typical day, the occupants got up and started the light and home appliance around 7:00 AM. After the breakfast, around 8:15 AM, the occupants left the room. The morning load in average was slightly higher than that of afternoon, which indicates elevated use of appliances in the morning. Occupants came back and the dinner started around 7 PM and the internal load reached its peak from then till 11 PM.

Temperature measurement showed that the indoor air temperature was seldom below 18 °C. The heating system seemed to be on 24 h a day and the temperatures swung between 18 and 21 °C. To emulate the measured temperatures, 18.5 °C was used as set point in the simulation model, with a three-degree dead band.

Based upon the hourly internal loads measured in the field, load schedules exhibited in Table 2 were developed for model input.

3.2. Model calibrations using field measurements

The heating season started on November 15, 2007 and ended on March 15, 2008. The simulation model was calibrated using the measured heating data. These data included the hourly monitoring of heating energy use for the selected units for the period between December 20, 2007 and January 4, 2008; daily measurements of heating energy use for two months; and the total seasonable heating energy use for each of the three units. Because of the delay in starting the project and an unexpected data loss, the data on daily heating energy use were actually available for dates from December 23, 2007 to January 23, 2008. Instead of using typical year weather files, e.g., TMY2, hourly weather data from the nearby airport were used for the 2007–2008 heating season in running the simulations.

Table 1
Input parameters of simulation model.

Building envelope	Material	K-value (W/m^2 K)	Size (m^2)
Roof	120 mm concrete 110 mm thermal foam expanded poly-styrene (EPS)	0.45	655
Exterior wall	200 mm thick concrete 80 mm thermal foam EPS	0.53	4155
Window	Double-pane clear glazing	2.7	291
Floor	bottom floor (concrete slab) Other floors (concrete slab)	11.2 11.2	619 612

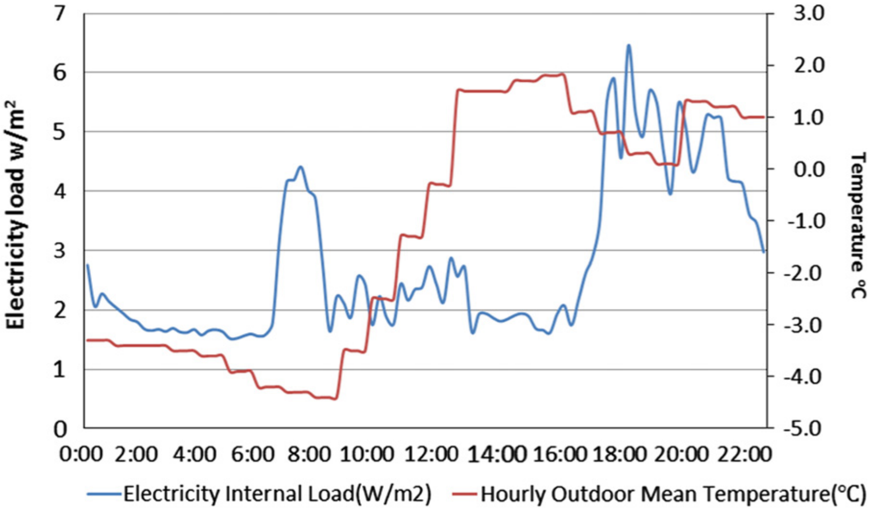

Fig. 2. Measured hourly electricity internal load and hourly outdoor air temperatures.

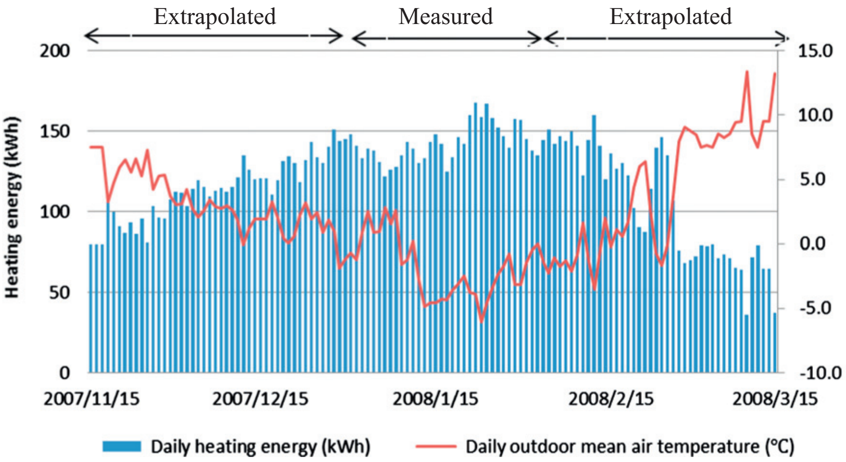

Fig. 3. Daily heating energy use of the middle-floor unit (measured and extrapolated combined).

Table 2
Electrical internal loads and intensity schedules.

Time period Hour: Minute	Lighting (kW)	Equipment (kW)	Total (kW)	Lighting (W/m^2)	Equipment (W/m^2)	Total (W/m^2)
0:00–7:00	0	0.23	0.23	0	1.73	1.73
7:00–8:15	0.16	0.38	0.54	1.21	3.03	4.25
8:15–18:15	0	0.28	0.28	0	2.17	2.17
18:15–24:00	0.20	0.42	0.62	1.56	3.38	4.94

3.2.1. *Measured data and extrapolation*

In order to better understand the daily heating energy use for those day on which the measured data were missing (i.e., periods between 11/15/07 and 12/22/07; and between 1/24/08 and 3/15/08), a simplified regression model was developed to extrapolate the daily heating energy use, based upon the hourly weather data from the following equation that uses 18.5 °C as a hypothetic base for heating degree–hour estimation):

$$E_i,j = C(18.5 - T_{i,j}) \qquad (1)$$

where

$E_{i,j}$ is hourly heating energy use for the hour j of day i, kWh,
C is a constant, kWh/°C,
$T_{i,j}$ is outdoor air temperature for hour j of day i, °C.

$$E_j = \sum_{i=1}^{24} E_i,j = \sum_{i=1}^{24} C(18.5 - T_{i,j}) \qquad (2)$$

where E_j is daily heating energy use on day j.

The data of measured and extrapolated daily heating energy use was then summed for all days in the heating season as the estimated whole-season heating energy use. As a result, Table 3 shows the estimated whole-season heating energy use and measured whole-season heating energy consumption for each of the three units and for a representative building section (i.e., one building section that included one bottom-floor unit, seven middle-floor units, and one top-floor unit). We have found that the simplified regression method based upon the hourly heating degrees works fairly well for extrapolation, exhibited by the close estimation of whole building heating energy use, which deviated little from the measured data for the whole heating season.

Fig. 3 shows the measured and extrapolated daily heating energy use for the entire 2007–2008 heating season of the middle-floor unit (402), and the corresponding daily outdoor air temperatures. The daily heating energy use peaked at around the end of the January, the coldest period in the heating season. The data of measured and extrapolated daily heating energy use was then used to calibrate the simulation model.

3.2.2. Model calibrations

We used the current building model that we developed in Section 3.1.1 to perform energy simulations. Because these buildings are fairly tight, initial infiltration rate was set at 0.1 air change per hour. The infiltrate rate was set as 0.15 air change per hour after the model calibration. The simulation model was calibrated so that annual heating energy use of the building section matched well while some difference is expected between simulated daily heating energy use and the measured daily heating energy use (including the days when extrapolated values were used). Building shell, internal load, and the indoor air temperature set points were all fixed. Figs. 4–6 show the simulation results in daily heating energy for the selected unit on the top floor, the middle floor, and the bottom floor, respectively.

To further verify the accuracy of the current building model, we compared the simulated whole-season heating energy use with the measured data. The measured data for whole-season heating energy use was actual energy consumption with no extrapolation. Fig. 7 shows the resulting values of whole-season heating energy use for each of the three units, and for one representative building section (i.e., measured and simulated values). The differences between measured and simulated data on the whole-season basis were within 3% range.

Corresponding to actual heating energy consumption in the whole season, heating energy intensity of individual apartment units ranged from 92 kWh/m^2 of middle floor to 173 kWh/m^2 of top floor. The top-floor unit exhibited much higher daily energy use, most likely due to the system the design, sizing and operation, in addition to roof effects. In fact, sizes of radiators in the top-floor units are much larger than the ones in the lower-floor units. Because the occupant did not modulate the control valves provided, the top-floor units used much more heating energy.

Table 3
Daily heating energy use extrapolation results.

Heating energy consumption (all in GJ)	Period	Bottom-floor unit	Middle-floor unit	Top-floor unit	One building section*
Sum of daily data (measured)	From 12/23/2007 to 01/23/2008	16.1	15.7	28.9	154.9
Sum of daily data (extrapolated)	From 11/15/07 to 12/22/07; and from 1/24/08 to 3/15/08	44.8	38.1	51.8	363.6
Whole-season heating energy (estimated, i.e., sum of daily data for the 2007–2008 season)	From 11/15/2007 to 03/15/2008	60.9	53.8	80.7	518.5
Whole-season heating energy (measured)		56.9	49.5	93.3	496.7

* *Note*: One building section = one bottom-floor unit + seven middle-floor units + one top-floor unit.

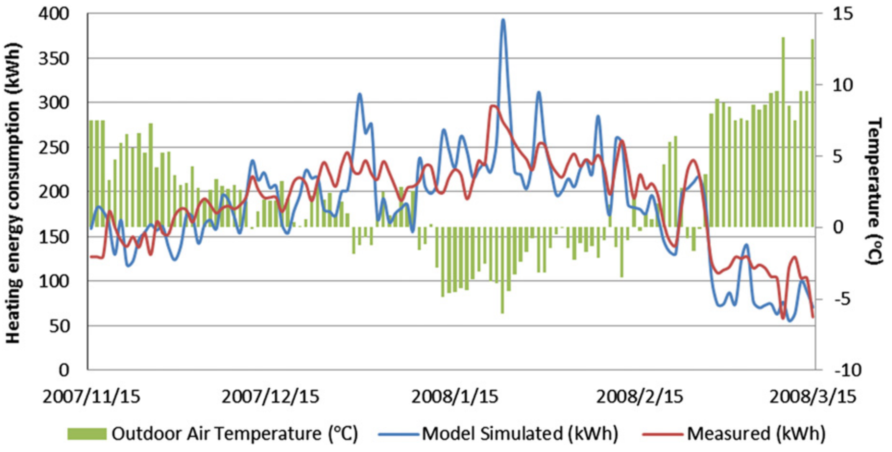

Fig. 4. Model calibration of daily heating energy use (top-floor unit, #902).

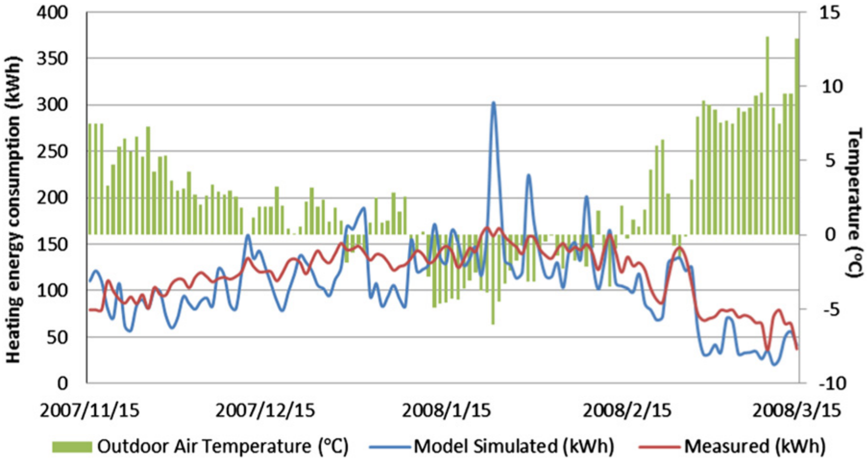

Fig. 5. Model calibration of daily heating energy use (middle-floor unit, #402).

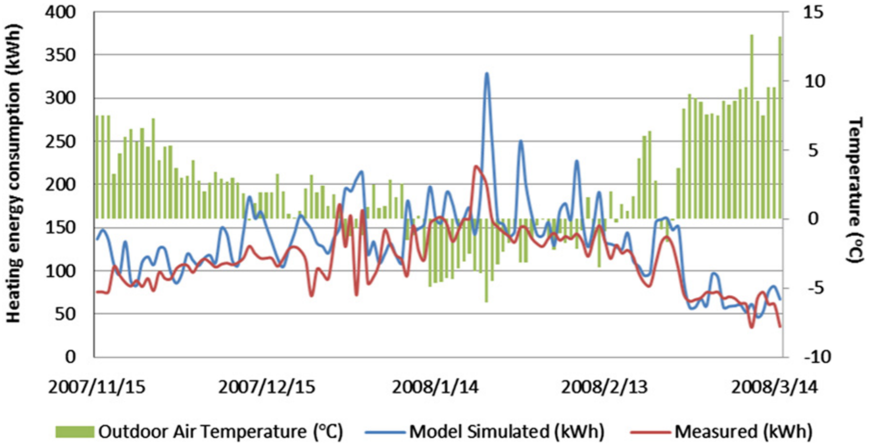

Fig. 6. Model calibration of daily heating energy use (bottom-floor unit, #102).

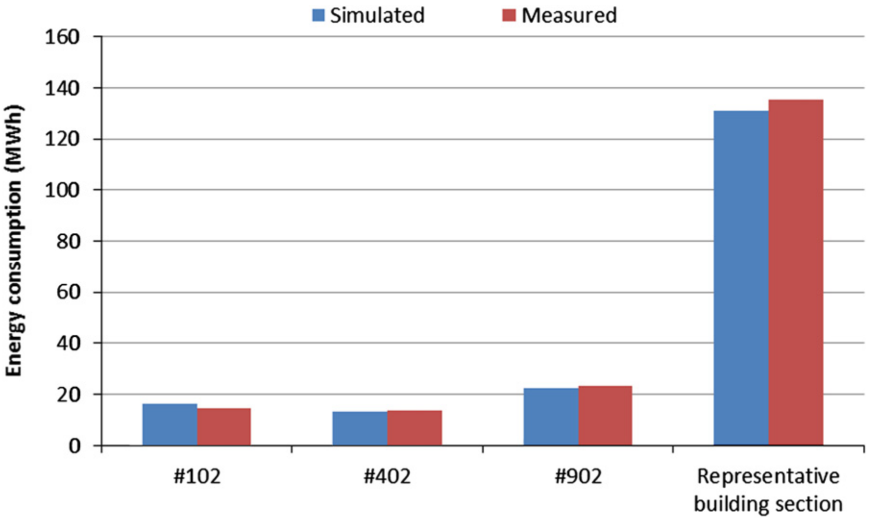

Fig. 7. Model calibration of seasonal heating consumption.

3.3. *Occupant behaviors associated with integrative retrofit technologies and energy incentive policy*

3.3.1. *Occupant behaviors associated with technologies*

Analyzing the subjective survey data and the trends of indoor air temperatures can help to understand occupants' interactions with the building systems (e.g., the option of temperature control in rooms).

Fig. 8 shows the trend of hourly indoor air temperatures within various rooms of the middle-floor unit during a 24-h period for a typical week day. The air temperature of each room was different from each other. The inner zones, such as the master

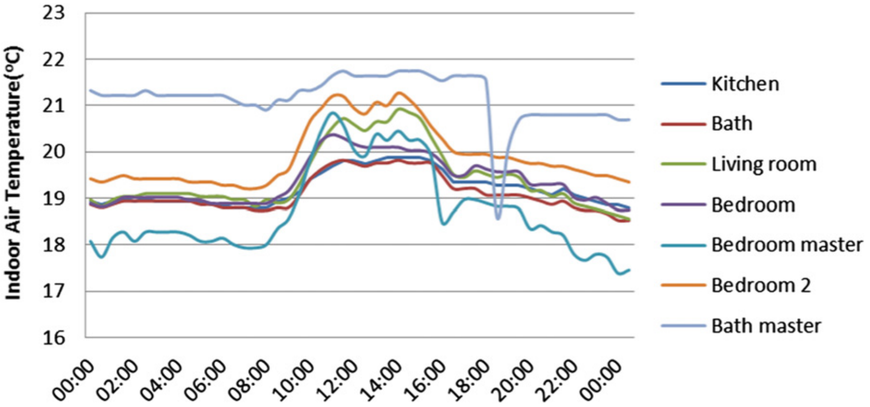

Fig. 8. Typical days indoor air temperature (middle-floor unit, #402).

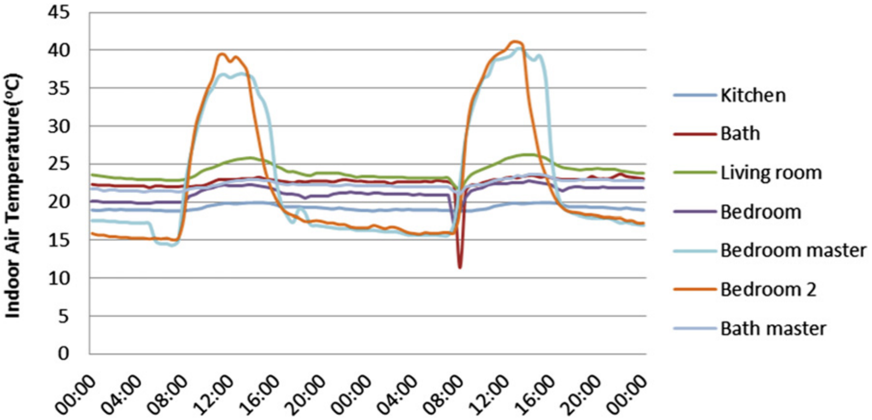

Fig. 9. Indoor air temperatures in typical days (top-floor unit, #902).

bath room, were warmer than outer zones. The master bedroom and living room temperatures were generally lower partly due to larger glazing areas and exterior wall (thus more heat losses to outdoor air), while kitchen and bedroom two exhibited slightly higher temperatures. In general, air temperatures in the majority of rooms were higher than 18 °C most of the time. During noon hours, the air temperatures in the majority of the rooms were close to or higher than 20 °C. From the temperature trends, it is clear that the heating was supplied continuously including the daytime hours even when there was nobody within the unit. For example, during the daytime while there was no occupant present, indoor air temperatures in all rooms became much higher than those in the early morning and in the evening, due to continuous heating supply, elevated outdoor temperature, and added solar gains. This indicates that temperature setback by occupants did not seem to have been in effect, if happened at all, for the non-occupancy hours. A further review of the onsite survey on occupant behaviors has confirmed this, i.e., the occupants in this unit did not exercise temperature setback although they were given the option.

Fig. 9 shows the trend of hourly indoor air temperatures within various rooms of a top-floor unit during a 48-h period for typical week days. In this unit, the heating system was changed from radiator to floor heating by the owner, resulting in substantial increase in heat exchange area while the supply hot water temperature remained the same. Such a remodel had led to over sizing of the heating system for the unit, e.g., sizes of radiators in master bedroom and living room are much bigger than those of other rooms. The master bedroom and bedroom 2 experienced the higher room air temperatures. From the temperature trends, we have found that room air temperatures were higher during daytime, with some rooms overheated to over or 30 °C or even 40 °C for a prolonged period of time. From field monitoring in all three units on the top floor (including the others with radiator systems), higher temperatures were recorded than those on middle-floor units. In practice, it is common to design and install larger heating systems in top-floor units than those in the middle-floor units in the region, with the intent to compensate heat losses due to insufficiency in roof insulations. The monitoring results have confirmed the over sizing of heating systems on the top-floor unit. Room air temperatures became unnecessarily higher while heating energy waste was increased, whereas the field survey found that virtually no action was taken by the occupants to reduce the temperature set points during the hours of either occupancy or non-occupancy, even though controllers were provided. In fact, from the onsite survey of occupants in 25 apartment units, no obvious behavioral changes were observed. For example, out of the 25 families surveyed, only one reported that routine temperature setback was performed to maintain the desired temperatures; 23 occupants reported that they maintained daily habits of opening windows for ventilation in early mornings.

We have also found that it was not a straightforward task for the occupants to perform temperature setback at different time of a day, given that there were five radiators and five different thermostat valves in one typical unit. In fact, the only reset that some occupants did was to adjust the set point for the entire heating season, or to turn off the system when they left the apartments for vacation time. Routine reset on the daily basis was essentially not observed in our study. In this regard, there is room for technology upgrades that would allow user-friendly interventions, e.g., reliable and programmable thermostats.

3.3.2. Occupant behaviors associated with energy incentive policy

Common practice in billing of heating energy use in the region has been to charge the occupant based upon floor area of her apartment unit. For this apartment building, the billing method was reformed as part of the enabling policy reform aiming to improve building energy efficiency. By adoption of the new billing method, total heating energy billing included a portion based upon floor areas, and another portion based upon actual heating energy use. The intent of the billing reform was to increase users' awareness of financial impact of their heating energy usage, in the hope of encouraging occupants' actions (e.g., behavioral changes) to use their heating system more efficiently. Prior to the study, the utility company and local government agencies carried out outreach activities aiming to educate the local residents about how to save energy for the heating season. The residents were informed of actions that could be taken by occupants (owners or renters) at home to improve energy efficiency, e.g., avoiding unnecessarily high temperatures in rooms, minimizing window-opening to reduce already high air temperature in rooms, and setting back the temperatures for night and unoccupied hours. Based upon the survey of occupants in 25 apartment units, no obvious behavioral changes in response to the incentive or technology provisions were observed, e.g., 23 occupants reported that they maintained daily habits of opening windows for ventilation in early mornings.

In the old billing method, heating charge was around 20 RMB/m^2 for one heating season, or 3000 RMB for a 150 m^2 unit. The new billing method required a basic charge of 10 RMB/m^2, plus usage charge. Occupants were typically required to pre-pay 3000 RMB before the heating season starts and the district heating company will refund the user based upon the usage, with the financial savings of no more than 1500 RMB (or, about US$ 210 in 2008) for the whole season. Given that is the selected building was a relative high-end apartment development, with average selling price around 15,000 RMB/m^2, or 2.2 million RMB (over US$300,000) for a typical 150-m^2 unit, seasonal monetary savings of up to 1500 RMB did not appear to be effective as an incentive for the occupants to reduce energy use. It is apparent that the provision of monetary incentives was insufficient for triggering substantial behavioral changes leading toward more energy savings in the current buildings, because the scale of financial savings due to energy savings and actual heating energy price was too small compared to other consumption (e.g., real estate value). In fact, actual energy prices for heating in northern China have been lowered due to subsidies. As a result, the provision of added incentive for energy saving has unfortunately diminished its intended impact on occupant behavioral change toward saving more energy. In addition, from the survey results, no correlation was found between the reported behaviors and family incomes or sizes.

In summary, little behavioral change by building occupants has been found, in response to energy incentives, billing method reform, or available options of individual temperature controls.

3.4. Impacts on energy savings

After calibrating the baseline model of the current completed construction, we performed parallel simulation runs for the following scenarios to estimate the energy savings of the building to further understand the energy and behavioral impacts of integrative retrofits. Table 4 summarizes results from the simulation runs for the enlisted scenarios.

Based upon the surveys on building occupants in this study, we made several assumptions as part of input parameter for the current case in which integrative retrofits were already implemented per the latest building standard. Specifically, in the current case construction model, each apartment unit has 1-m^2 window opening for one hour from 7:00 AM to 8:00 AM on the daily basis. The infiltration rate was calculated using wind-driven ventilation model. We used average wind speed of 2 m/s from Tianjin's meteorology data. No temperature setback by occupants was included for active temperature control.

For the current case in which integrative retrofits were implemented, the annual heating energy use of the one representative building section was 144,036 kWh (107 kWh/m^2). The energy intensity of top unit heating usage was 150 kWh/m^2, approximately 50% higher than that of a middle- and bottom-floor unit (100–113 kWh/m^2).

3.4.1. Baseline case—No insulation

A building without the integrated insulation included in the current building, termed as "no insulation" here, was the baseline building referred in Tianjin's latest energy efficient design standards for residential buildings (Tianjin Construction Management Committee (TCMC) (2004)). The baseline building typically built in early 1980s was a traditional brick building with no insulation in walls or roofs. Table 4 indicated that for the baseline case, the annual heating energy use of the whole building in Tianjin was 309,707 kWh, corresponding to annual energy intensity of 229 kWh/m^2. A top-floor unit in the baseline building typically used approximately 473 kWh/m^2, more than twice of the heating

Table 4
Annual building heating energy consumption.

		Bottom unit	**Middle unit**	**Top unit**	**One building section**
Case 0: Current - integrative retrofits implemented	kWh	16,919	14,956	22,425	144,036
Case 1: Base case— No insulation	kWh	31,541	29,611	70,889	309,707
	1-Case0/Case1, in %	46%	49%	68%	53%
Case 2: Behavioral change—no morning natural ventilation	kWh	16,521	14,375	21,496	138,642
	1-Case2/Case0, in %	3%	4%	4%	4%
Case 3: Behavioral change—temperature setback	kWh	14,425	12,723	19,036	122,522
	1-Case3/Case0, in %	15%	15%	15%	15%
Case 4: Behavioral change—no morning ventilation and temperature setback	kWh	13,885	12,235	18,478	118,008
	1-Case4/Case0, in %	18%	18%	18%	18%
	1-Case4/Case1, in %	56%	59%	74%	62%

- Case 0: Current construction (building with integrative retrofits implemented, after 2005).
- Case 1: No insulation (built in 1980s).
- Case 2: Current design + No morning natural ventilation.
- Case 3: Current design + temperature setback at nights and unoccupied hours.
- Case 4: Current design + no morning natural ventilation + temperature setback at nights and unoccupied hours.

energy use by a unit on either middle- or bottom-floor (197–210 kWh/m^2).

In this study, integrative retrofits were built in the selected apartment building, which exhibited significant thermal improvement over the traditional baseline building, saving approximately 53% heating energy compared to the traditional baseline building. The energy savings from a top-floor unit were 68% compared with its baseline counterparts, which were larger than did the units on other floors (e.g., 49% for middle floors), partly due to thermal improvements on a larger scale on the top floor, i.e., increased insulation in roofs in the current building.

In addition, the district heating company reported that the distribution system was 5% more efficient than the old system and the boiler was 8% more efficient. When being compared the source energy consumption in the heating season, the selected apartment building would be approximately 66% more efficient than the baseline building specified in the latest standard (Tianjin Construction Management Committee (TCMC) (2004)). According to the latest local standard, the new buildings built after 2006 are expected to save 65% heating energy when being compared to the baseline building. It is clear that integrative retrofits were effective in improving building energy efficiency due to the success in implementation of new building standard; in addition, the success of the standard enforcement also changed the ways of how buildings were designed and constructed.

3.4.2. *Elimination of morning natural ventilation*

The intent of installing heating energy meter in each apartment unit was to provide real-time information for users and a tool to affect occupants' responses to the built environment and financial choices. Such interactions were intended to promote occupant behaviors that minimize the waste of heating energy. For example, if occupants were convinced to stop or minimize opening windows in early mornings, the annual heating energy savings were estimated to be 138,642 kWh (or 103 kWh/m^2), around 4% of total heating energy use in the current building.

3.4.3. *Temperature setback at nights and unoccupied hours*

An extended purpose of installing the heating energy meters would allow occupants to make informed and proactive decisions, e.g., perform setback of the temperature set points during night and unoccupied hours. Our simulation estimated that when such actions were taken, the annual heating energy savings were estimated to be 122,522 kWh (or 91 kWh/m^2), around 15% of total heating energy use in the selected apartment building.

3.4.4. *Elimination of morning natural ventilation and temperature setback*

We also investigated the energy impacts from combining the elimination of morning natural ventilation and performing temperature setback, if the occupants can make informed decisions to achieve energy savings. Based upon the simulation, we estimated that 18% of annual heating energy can be saved as a result from elimination of morning natural ventilation and temperature setback.

When comparing the energy use in current building, in which integrative retrofits were implemented and occupant behaviors were changed (i.e., eliminate morning window opening and perform temperature setback), to that of the baseline building constructed in early 1980s, the magnitudes of energy savings are even more striking. The annual heating energy use of the whole building was 118,008 kWh (or 87 kWh/m^2.), equating to 18% savings over the current building, or 62% savings over the baseline building. The top unit heating energy intensity was 123 kWh/m^2, about 50% higher than the middle and bottom unit (82–93 kWh/m^2).

4. Conclusions and recommendations

Based upon the results from on-site monitoring and surveys on residential occupants' behaviors, building energy simulations were performed to evaluate the energy and behavioral impacts of integrative retrofits implemented in the newer generation of multi-story apartment buildings in northern China. We also investigated and discussed the effectiveness of several measures and enabling policies (monetary and non-monetary) in influencing behaviors (designer and occupants). The following summarizes our conclusions and recommendations.

- Implementing current building energy standard by including integrative retrofit measures in current building design and construction has clearly produced significant energy savings in newly constructed multi-story apartment buildings in north China. Compared with baseline buildings with no insulation installed, the nine-floor apartment building selected in this study exhibited a 53% reduction in annual heating consumption in the 2007–2008 heating season. Taking into account district-heating-system upgrades as part of integrative retrofit measures, a representative apartment building was approximately 66% more efficient than the baseline building specified in the latest building standard (Tianjin Construction Management Committee (TCMC) (2004)). It is clear that integrative retrofits were effective in improving building energy efficiency due to the success in implementation of new building standard; in addition, the success of the standard enhancement and enforcement also changed the ways of how buildings were designed and constructed.
- Contrary to our expectation, little behavioral change by the building occupants was found in response to the monetary and non-monetary provisions of energy incentive, billing-method reform, or metering of heating energy use in individual apartment units. Yet our analysis identified sizable energy savings potential if occupants' behavioral changes were to actually happen. This indicates that the provisions of financial incentives or individual metering technology were insufficient for triggering substantial behavioral changes leading toward more energy savings in the current buildings. There was room for technology improvement to stimulate occupant behavioral changes in operation.
- For baseline and current buildings, heating energy use by the top-floor units was found to be much higher than that of lower-floor units. Balconies, typically poorly insulated, were commonly converted to enclosed space and used in tandem with conditioned space. We recommend that further tightening of criteria for thermal integrity and heating system design be pursued in future building standard updates (e.g., roof and balcony).
- This paper recommends that innovative policies, technology upgrades, and education would be needed to promote behavioral changes toward additional energy savings. Finally, effective measures and strategies to further augment the thermal integrity criteria are critical for China's future building energy policy advancement and reforms.

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