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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