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Cool roofs in China: Policy review, building simulations, and proof-of-concept experiments

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ABSTRACT

While the concept of reflective roofing is not new to China, most Chinese cool roof research has taken place within the past decade. Some national and local Chinese building energy efficiency standards credit or recommend, but do not require, cool roofs or walls. EnergyPlus simulations of standard-compliant Chinese office and residential building prototypes in seven Chinese cities (Harbin, Changchun, Beijing, Chongqing, Shanghai, Wuhan, and Guangzhou) showed that substituting an aged white roof (albedo 0.6) for an aged gray roof (albedo 0.2) yields positive annual load, energy, energy cost, CO_2, NO_x, and SO_2 savings in all hot-summer cities (Chongqing, Shanghai, Wuhan, and Guangzhou).

Measurements in an office building in Chongqing in August 2012 found that a white coating lowered roof surface temperature by about 20 °C, and reduced daily air conditioning energy use by about 9%. Measurements in a naturally ventilated factory in Guangdong Province in August 2011 showed that a white coating decreased roof surface temperature by about 17 °C, lowered room air temperature by 1–3 °C, and reduced daily roof heat flux by 66%.

Simulation and experimental results suggest that cool roofs should be credited or prescribed in building energy efficiency standards for both hot summer/warm winter and hot summer/cold winter climates in China.

1. Introduction

China surpassed the United States in 2010 to become the world's largest energy consumer, and accounted for 71% of global energy consumption growth in 2011 (BP, 2012). China's energy mix is carbon intensive, using coal to supply 71% of the 85 quadrillion BTU (90 EJ) it consumed in 2008. The U.S. Energy Information Administration predicts that China's electricity generation will increase to 10.5 trillion kW h by 2035, over triple the production in 2009 (U.S. EIA, 2012).

Facing challenges of energy security, global climate change, and environmental pollution, China has prioritized renewable energy and energy efficiency. In The Twelfth Five-Year Plan for National Economic and Social Development of the People's Republic of China released in July 2012, the government set year-2015 targets of reducing energy consumption per unit per-capita GDP by 16%, CO_2 emission per unit per-capita GDP by 17%, national emission of SO_2 by 8%, and national emission of NO_x by 10%, all relative to year-2010 levels (CG, 2011).

Improving building energy efficiency is an important element of the government's strategy for saving energy (CG, 2011). In 2008, Chinese buildings consumed 655 Mtce (million tonnes coal equivalent) (20 EJ), accounting for about 23% of national energy use (TUBEEC, 2011). Air conditioning was responsible for 11% of annual energy use in residential buildings in 2008 (TUBEEC, 2011), and 19% of annual energy use in public buildings in 2005 (TUBEEC, 2010).

One way to raise building energy efficiency is to select a ‘cool’ roof with high solar reflectance (ability to reflect sunlight, spectrum 0.3–2.5 μm) and high thermal emittance (ability to emit thermal radiation, spectrum 4–80 μm). By minimizing solar absorption and maximizing net thermal emission, such a roof stays cooler under the sun, reducing heat flow into the building (Levinson et al., 2005). A cool roof on an air-conditioned building can save energy and reduce power-plant emissions of CO_2, SO_2, and NO_x (Akbari et al., 1999; Levinson and Akbari, 2010), while a cool roof on an unconditioned building can lower indoor air temperature and improve indoor comfort (Synnefa et al., 2007).

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Cool surfaces, including roofs, walls, and pavements, can also lower outdoor air temperature, further reducing the need for air conditioning and slowing the temperature-dependent formation of smog (Rosenfeld et al., 1998). Finally, negative radiative forcing by cool roofs can cool the atmosphere, mitigating warming induced by greenhouse gases (Akbari et al., 2012).

Choosing a cool roof instead of a standard roof can slightly increase the need for heating energy in cold weather (e.g., winter). However, winter penalties are often much smaller than summer savings (Levinson and Akbari, 2010) because solar availability in cold latitudes is limited in winter. For example, the northern mainland U.S. (latitude ≥ 40°N) receives about 3 to 5 times as much daily sunlight in summer as in winter (Levinson, 2009).

Building construction in China's urban areas has surged over the past decade, increasing building stock floor area to 20.4 billion m^2 by 2008 (TUBEEC, 2010). This presents many opportunities to specify and apply the climate-appropriate use of energy-saving cool roofing products when roof waterproofing is first installed, and when it is replaced at the end of its 10–20 year service life.

In 2010, the United States Department of Energy (DOE) and China's Ministry of Housing and Urban-Rural Development (MOHURD) formed the U.S.-China Cool Roof Working Group to evaluate the potential benefits of cool roofs in China. In 2011, Lawrence Berkeley National Laboratory (Berkeley, California, USA) partnered with Chongqing University (Chongqing) and the Guangdong Provincial Academy of Building Research (Guangzhou) to further investigate cool roof science and policies within the U.S.-China Clean Energy Research Center Building Energy Efficiency (CERC-BEE) Consortium (CERC-BEE, 2014).

2. Methods

Decades of progress in cool roof science, technology, and policy have been summarized in articles reviewing cool roof materials (Santamouris et al., 2011), energy savings (Levinson et al., 2005; Akbari and Konopacki, 2005), urban heat island mitigation (Santamouris, 2012; Navigant, 2009), global cooling (Akbari et al., 2012), standards (Akbari and Levinson, 2008), and weathering (Berdahl et al., 2008; Sleiman et al., 2011, 2014).

The current study focuses on the annual conditioning (heating and cooling) energy savings attainable by reducing roof solar heat gain. First, it reviews roof reflectance requirements in current Chinese building energy efficiency standards. Next, it simulates the energy savings, energy cost savings, and emission reductions attainable in various Chinese climates by increasing the solar reflectance of roofs on code-compliant prototypes of office and residential buildings. Finally, as proofs of concept for cool roofs in China, it measures summer-day cooling energy savings after a white roof coating was applied over part of a Chongqing office building, and summer-day roof heat flux and room air temperature reductions after a white roof coating was applied over part of a naturally ventilated factory building in Foshan (near Guangzhou).

2.1. *Review of roof and wall requirements in Chinese building energy efficiency standards*

China has national, provincial, and—in some cities—municipal building energy efficiency standards. These standards usually have different provisions for residential and public (nonresidential) buildings. To better understand how cool roofs (and walls) are treated, we reviewed national, provincial, and municipal standards, seeking language prescribing, crediting, or recommending the use of reflective or light-colored building envelope surfaces.

2.2. *Cool roof simulations*

2.2.1. *Past research*

Cool roof savings and penalties have been simulated for many locations outside China. For example, annual cooling savings and heating penalties have been computed for building prototypes in hundreds of U.S. cities (Akbari et al., 1999; Akbari and Konopacki, 2005; Levinson and Akbari, 2010; Parker et al., 1998a); five Indian climate zones (Bhatia et al., 2011); eight provinces in Andalucía and 49 cities in Spain (Boixo et al., 2012); and 27 world cities (Synnefa et al., 2007). Most studies also calculate energy cost savings based on local energy prices, and some report emission reductions based on local emission factors. For example, Levinson and Akbari (2010) found that the average annual cooling site energy savings per unit conditioned roof area for the U.S. commercial building stock was 5.0 kW h/m^2, with annual heating site energy penalty 1.9 kW h/m^2 (0.065 therm/m^2), annual energy cost savings \$0.36/m^2, and annual emission reductions of 3.0 kg CO_2/m^2, 4.8 g NO_x/m^2, 12 g SO_2/m^2, and 61 μg Hg/m^2.

No comparable analyses of cool roof savings and penalties across China were found in the literature. To fill this gap, the current study simulates energy savings, energy cost savings, and emission reductions attainable in various Chinese climates by increasing the albedo (solar reflectance) of roofs on code-compliant prototypes of office and residential buildings.

2.2.2. *Overview of simulations in current study*

The annual heating and cooling loads of a prototype office building and a prototype residential building were simulated with three different levels of roof albedo in five representative Chinese climates. Heating load savings (negative) and cooling load savings (positive) were calculated by subtracting heating and cooling loads with high roof albedo from those with low roof albedo. Load savings were then used to estimate site energy savings, source energy savings, energy cost savings, and emission reductions. Results for seven selected Chinese cities in the five Chinese climates zones were then compared to those in U.S. cities with similar climates.

2.2.3. *Prototype design*

Prototypes of the top floor of an office building (Fig. A1) and the top floor of a residential apartment building (Fig. A2) were assigned envelope characteristics, ventilation and infiltration rates, internal loads, operating schedules, and cooling and heating setpoints compliant with prescriptive requirements or recommended design values in current Chinese building energy efficiency standards. Table 1 details each prototype, hereafter denoted as "office" and "residence" for brevity.

Note that while these prototypes should be typical of current Chinese construction, no single prototype can represent all buildings in its class. Hence, savings for a specific building may differ from those computed here.

2.2.4. *Modeling heating and cooling loads*

The annual heating and cooling energy loads (heat energy per unit roof area to be supplied or removed) of each prototype were simulated with version 3.0.0.105 of DesignBuilder, a front end to the EnergyPlus building energy model (EnergyPlusDLL-32 7.0.0.036). For simplicity, loads were calculated by conditioning each building with ideal sources and sinks of heat (district heating and cooling).