Energy and Buildings 80 (2014) 57–71

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Measured temperature reductions and energy savings from a cool tile roof on a central California home

Pablo J. Rosado, David Faulkner, Douglas P. Sullivan, Ronnen Levinson*

Lawrence Berkeley National Laboratory, Berkeley, CA, United States

ARTICLE INFO

Article history:
Received 19 November 2013
Received in revised form 8 January 2014
Accepted 7 April 2014
Available online 24 April 2014

Keywords:
Cool roof
Energy savings
Solar reflectance
Thermal mass
Above-sheathing ventilation
Residential building
Temperature reduction
Ceiling heat flow
Asphalt shingle
Concrete tile

ABSTRACT

To assess cool-roof benefits, the temperatures, heat flows, and energy uses in two similar single-family, single-story homes built side by side in Fresno, California were measured for a year. The “cool” house had a reflective cool concrete tile roof (initial albedo 0.51) with above-sheathing ventilation, and nearly twice the thermal capacitance of the standard dark asphalt shingle roof (initial albedo 0.07) on the “standard” house.

Cool-roof energy savings in the cooling and heating seasons were computed two ways. Method A divides by HVAC efficiency the difference (standard − cool) in ceiling + duct heat gain. Method B measures the difference in HVAC energy use, corrected for differences in plug and window heat gains.

Based on the more conservative Method B, annual cooling (compressor + fan), heating fuel, and heating fan site energy savings per unit ceiling area were 2.82 kWh/m^2 (26%), 1.13 kWh/m^2 (4%), and 0.0294 kWh/m^2 (3%), respectively. Annual space conditioning (heating + cooling) source energy savings were 10.7 kWh/m^2 (15%); annual energy cost savings were \$0.886/m^2 (20%). Annual conditioning CO_2, NO_x, and SO_2 emission reductions were 1.63 kg/m^2 (15%), 0.621 g/m^2 (10%), and 0.0462 g/m^2 (22%). Peak-hour cooling power demand reduction was 0.88 W/m^2 (37%).

1. Introduction

The number and size of air-conditioned homes in hot climates has risen significantly over the past 20 years, increasing U.S. residential cooled floor area by 71% [1]. Boosting the albedo (solar reflectance) of a building’s roof can save cooling energy in summer by reducing solar heat gain, lowering roof temperature, and decreasing heat conduction into the conditioned space and the attic ducts. It may also increase the use of heating energy in winter. Prior research has indicated that net annual energy cost savings are greatest for buildings located in climates with long cooling seasons and short heating seasons, especially those buildings that have distribution ducts in the attic [2–7].

Solar-reflective “cool” roofs decrease summer afternoon peak demand for electricity [3,8,9], reducing strain on the electrical grid and thereby lessening the likelihood of brownouts and blackouts. Reducing peak cooling load can also allow the installation of a smaller, less expensive air conditioner. This is referred to as a “cooling equipment” saving [9]. Smaller air conditioners are also typically less expensive to run, because air conditioners are more efficient near full load than at partial load.

Roofs can cover a substantial fraction of the urban surface. For example, when viewed from above the tree canopy, roofs comprise about 19–25% of each of four U.S. metropolitan areas—Chicago, IL; Houston, TX; Sacramento, CA; and Salt Lake City, UT [10]. Citywide installation of cool roofs can lower the average surface temperature, which in turn cools the outside air. A meta-analysis of meteorological simulations performed in many U.S. cities found that each 0.1 rise in urban albedo (mean solar reflectance of the entire city) decreases average outside air temperature by about 0.3 K, and lowers peak outside air temperature by 0.6–2.3 K [11]. Cool roofs thereby help mitigate the “daytime urban heat island” by making cities cooler in summer. This makes the city more habitable, and saves energy by decreasing the need for air conditioning in buildings. Cooler outside air can also improve air quality by slowing the temperature-dependent formation of smog [12,13].

Replacing a hot roof with a cool roof immediately reduces the flow of thermal radiation into the troposphere (“negative radiative forcing”), offsetting the global warming induced by emission of greenhouse gases [14–16]. Most recently, Akbari et al. [17] estimated that increasing by 0.01 the albedo of 1 m^2 of urban surface provides a one-time (not annual) offset of 4.9–12 kg CO_2. Substituting 100 m^2 of cool white roofing (albedo 0.6) for standard

---

* Corresponding author. Tel.: +1 510 486 7494.
E-mail address: RML27@cornell.edu (R. Levinson).

http://dx.doi.org/10.1016/j.enbuild.2014.04.024
0378-7788/

gray roofing (albedo 0.2) would provide a one-time offset of about 20–48 t CO_2.

The direct cooling benefits of increasing the albedo of a residential roof have been simulated or measured by several workers. For example, Akbari et al. [3] simulated with the DOE-2 building energy model the annual cooling and heating energy uses of a variety of building prototypes in 11 U.S. cities. They found that raising the albedo of an RSI-3.3 asphalt-shingle roof by 0.30 reduced the annual cooling energy use of a single-story home by 6–15%, and increased annual heating energy use by 0–5%.

Parker and Barkaszi [18] measured daily cooling energy uses in summer before and after applying white roof coatings to nine single-story Florida homes. Savings ranged from 2 to 40% and averaged 19%. In a home with RSI-3.3 ceiling insulation, increasing the albedo of an asphalt shingle roof by 0.44 (to 0.59 from 0.15) reduced daily cooling energy use by 10%, and lowered peak cooling power demand by 16%.

Miller et al. [19] measured cooling energy uses in three pairs of Northern California homes. Each pair of homes had color-matched standard (lower albedo) and cool (higher albedo) roofs. The first pair had brown concrete tile roofs with albedos of 0.10 (standard) and 0.40 (cool); the second, brown metal roofs with albedos of 0.08 (standard) and 0.31 (cool); and the third, gray-brown shingle roofs with albedos of 0.09 (standard) and 0.26 (cool). After adjusting for widely disparate occupancy patterns, summer daily cooling energy savings were estimated to be about 9% in the homes with the cool tile and cool metal roofs; savings for the cool shingle roof were unclear.

High thermal capacitance and/or subsurface natural convection (“above-sheathing ventilation”) in the roof system can further cool the building [20–23]. For example, Miller and Kosny [24] measured the summer daily heat flows through an SR 0.13 flat tile roof on double battens and through an SR 0.09 shingle roof, each installed over a modestly insulated (RSI-0.9) ceiling in a test assembly. The heat flow through the tile roof was only half that through the shingle roof, even though the solar absorptance (1 – solar reflectance) of the tile was only 4% lower than that of the shingle. Note that above-sheathing ventilation (air flow in the space between sheathing, or roof deck, and the roofing product) is usually driven by buoyancy, rather than wind, because building codes typically require the air space at the eave (bottom edge) of the roof to be closed for fire protection [25].

Two of the most popular roofing product categories in the western U.S. residential roofing market are fiberglass asphalt shingles (hereafter, “shingles”) and clay or concrete tiles (hereafter, “tiles”). Surveys by *Western Roofing Insulation & Siding* found that shingles and tiles comprised 50% and 27% of 2007 sales, respectively, and 63% and 14% of projected 2013 sales [26,27]. Substituting a light-colored tile for a dark asphalt shingle reduces the roof’s solar heat gain, roughly doubles its thermal capacitance [28], and provides above-sheathing ventilation. In a mild-winter climate where heating is needed primarily in the morning, this substitution may even decrease heating energy use in winter. This is possible because increasing the roof’s thermal capacitance keeps the attic warmer overnight, while high roof albedo has little consequence after sunset.

The present study compares two side-by-side, single-story, single-family houses in Fresno, California. Fresno is located in the state’s Central Valley, a hot climate in which homes use air conditioning from approximately May to October. The first house has a standard dark asphalt shingle roof, and the second a cool concrete tile roof; they are otherwise quite similar in construction and use. The homes serve as show models and are open to the public every day from 09:00 to 17:00 local time (LT). By monitoring temperatures, heat flows, and energy consumption in these air-conditioned houses, we investigate the extents to which over the course of a year the cool roof reduces (a) roof and attic temperatures; (b) conduction of heat into the conditioned space and into HVAC ducts in the attic; (c) cooling and heating energy uses; and (d) peak-hour power demand. We also compare measured cooling energy savings to cooling energy savings calculated from heat flow and temperature measurements, in order to evaluate whether a simplified experimental configuration without power meters can be used in future cool roof experiments.

2. Theory

While the tested homes share similar floor and elevation plans, differences other than roof construction, such as those in plug load (appliances and lights), fenestration (window area, orientation, construction, and coverings), and occupancy, can influence building conditioning energy use. Here, we derive two ways to isolate the energy savings attributable to the cool roof.

2.1. Heat balance

The conditioned space (hereafter, “room”) can gain or lose heat through its envelope (ceiling, walls, floor, and windows), and gain heat from internal sources, including plug loads (appliances and lighting) and people. Conditioned air can also gain or lose heat as it flows through the attic ductwork from the air conditioner or furnace to the room. Denoting the rates of heat gain (power) in the room and ductwork as q_{room} and q_{duct}, the building’s combined heat load is

$$q_{\text{load}} \equiv q_{\text{room}} + q_{\text{duct}}. \tag{1}$$

The rate q_{HVAC} at which the furnace or air conditioner must remove heat to regulate room air temperature (positive in the cooling season, negative in the heating season) is

$$q_{\text{HVAC}} = q_{\text{load}}. \tag{2}$$

We disaggregate q_{room} into gains from the ceiling, plug load, windows, and other sources (e.g., walls, floor, infiltration and occupants), such that

$$q_{\text{room}} = q_{\text{ceiling}} + q_{\text{plug}} + q_{\text{window}} + q_{\text{other}}. \tag{3}$$

The rate of heat gain through the ceiling, q_{ceiling}, is the product of ceiling area and ceiling heat flux (power/area). The rate of plug load heat gain, q_{plug}, equals the plug load electric power demand. The rate of heat gain through the windows, q_{window}, can be estimated from solar irradiance and the area, construction, orientation, and coverings of windows.

The rate of heat gain through attic ductwork is

$$q_{\text{duct}} = \dot{m} c_{\text{p}} [\delta T_{\text{supply}} + \delta T_{\text{return}}] \tag{4}$$

where $\dot{m}$ and c_{p} are the mass flow rate and specific heat capacity of the duct air, δT_{supply} is the temperate rise (outlet – inlet) along the supply duct, and δT_{return} is the temperature rise along the return duct. Note that neglecting minor thermal storage in the duct work, duct heat gain vanishes when the HVAC system is off ($\dot{m} = 0$). If duct air temperature rises have not been measured, q_{duct} can be estimated as

$$q_{\text{duct}} = \bar{U} A_{\text{duct}} \frac{\theta_{\text{out}} - \theta_{\text{in}}}{\ln(\theta_{\text{out}}/\theta_{\text{in}})} \tag{5}$$

where $\bar{U}$ is the thermal transmittance of the duct wall, A_{duct} is duct surface area, inlet temperature depression $\theta_{\text{in}} = T_{\text{attic air}} - T_{\text{inlet}}$, and outlet temperature depression $\theta_{\text{out}} = T_{\text{attic air}} - T_{\text{outlet}}$ [29]. In the supply duct, T_{inlet} can be estimated from room air temperature and HVAC equipment specifications of temperature drop across the evaporator (often approximately 10 °C) and temperature rise across