



# Modeling impacts of roof reflectivity, integrated photovoltaic panels and green roof systems on sensible heat flux into the urban environment

Adam Scherba, David J. Sailor\*, Todd N. Rosenstiel, Carl C. Wamser

Portland State University, PO Box 751-ME, Portland, OR 97207, USA

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## ABSTRACT

This study presents results of a modeling effort to explore the role that sustainable roofing technologies play in impacting the rooftop energy balance, and the resultant net sensible heat flux into the urban atmosphere with a focus on the summertime urban heat island. The model has been validated using data from a field experiment conducted in Portland Oregon. Roofing technologies explored include control dark membrane roof, a highly reflective (cool) roof, a vegetated green roof, and photovoltaic (PV) panels elevated above various base roofs. Energy balance models were developed, validated with experimental measurements, and then used to estimate sensible fluxes in cities located in six climate zones across the US.

On average the black roof and black roof with PV have the highest peak daily sensible flux to the environment, ranging from 331 to 405 W/m<sup>2</sup>. The addition of PV panels to a black roof had a negligible effect on the peak flux, but decreased the total flux by an average of 11%. Replacing a black roof with a white or green roof resulted in a substantial decrease in the total sensible flux. Results indicate that if a black membrane roof is replaced by a PV-covered white or a PV-covered green roof the corresponding reduction in total sensible flux is on the order of 50%. The methodology developed for this analysis provides a foundation for evaluating the relative impacts of roof design choices on the urban climate and should prove useful in guiding urban heat island mitigation efforts.

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## 1. Background

Rooftops are playing an increasingly important role in urban sustainability efforts. Various roofing technologies have been promoted for reducing stormwater runoff, generating electricity, reducing building energy consumption, or mitigating the urban heat island (UHI). While some prior research has explored the efficacy of such technologies, these studies are typically limited to a single technology or a specific location (climate). They also tend to lack a quantitative connection between the rooftop surface energy balance and the urban climate system.

### 1.1. Context and previous work

For several decades now research has been conducted into the use of cool roof (high solar reflective or high “albedo”) technologies both for building energy savings and urban heat island mitigation [1–5]. Cool roofs provide an alternative to dark asphalt, black membrane, or rock ballasted roofs. Due to their high albedo, cool

roofs absorb less incoming solar radiation than comparable roofs with greater solar absorptivities. As a result, cool roofs maintain a lower surface temperature which can reduce heat transfer into the building, as well as into the urban environment. In some climates there may be a slight winter penalty associated with cool roofs, but this is typically outweighed by the summer benefit, and can also be negated if the roof is covered with snow in the winter [6]. After initial installation of a green roof, the accumulation of dirt can affect the albedo of a roof. The roof pitch, location and climate all influence the degree to which albedo is impacted by weatherization. It has been shown that most of the weathering occurs during the first year after roof installation, with albedo decreases averaging 0.15. If the roof is washed, the albedo can be restored to within 90% of its original value [6]. The typical albedo of an unweathered membrane roof ranges from 0.06 (dark black) to 0.83 (high albedo white) [7].

Measurements in various climates have shown that white roofs can reduce rooftop temperatures 20–42 °C as compared to dark roofs [8–10]. In one of the early studies of cool roofing, researchers used building energy simulation of prototypical buildings across 11 US metropolitan areas to evaluate the potential energy savings of highly reflective roofing [11]. In extrapolating their results to the

\* Corresponding author. Tel.: +1 503 725 4265; fax: +1 503 725 8255.  
E-mail address: [sailor@cecs.pdx.edu](mailto:sailor@cecs.pdx.edu) (D.J. Sailor).

entire US, Akbari estimated that replacing dark roofs with white roofs has the potential to save up to 10 TWh ( $10^{13}$  Wh) per year (circa 1999). According to the US Energy Information Administration, electricity sales in 1999 were  $1.14 \times 10^{15}$  Wh and  $1.00 \times 10^{15}$  Wh in the residential and commercial buildings sectors, respectively [12]. So, the savings potential reported by Akbari amounts to about 0.5% of all building electricity use. Another building energy simulation study [13] found that a white roof with a summertime mid-day surface temperature reduction of 8 °C produced an annual energy savings of approximately 3%.

The few studies that have explored urban climate impacts of roof albedo have generally done so using coarse resolution meso-scale models that do not represent the morphology of the city or the thermal characteristics of insulated roofing (e.g., [14–16]). Despite their limitations such modeling efforts do provide a quantitative assessment of potential for reducing urban air temperatures. For example, Ref. [14] found that increasing the average albedo of Los Angeles, California by 0.14 would reduce summertime peak daytime air temperatures by as much as 1.5 °C.

In recent years there has been an increased interest in use of vegetated green roofs (also referred to as ecoroofs) to provide a variety of ecosystem services (e.g., [17–22]). Research suggests that green roofs can aid in stormwater retention, reduce building energy loads, mitigate the urban heat island effect and increase the lifespan of a roof [23]. In response to the reported benefits of green roofs, cities such as Portland Oregon and Toronto Canada are beginning to offer incentives, or even mandates, for green roof installation [24,25]. Many studies have investigated the impact of green roofs on building surface temperatures, heat fluxes into the building, and building energy use [26–28]. Few studies, however, have tried to quantify the urban climate impacts of green roofs. One such study, Ref. [29], used a microscale model to estimate the temperature reduction potential of green walls and roofs in nine cities around the world. While this study was physically-based, representing the key physical properties and processes, it had several limitations. The model framework and canyon geometries investigated were two-dimensional, buoyancy effects were not considered, and the buildings were modeled as solid blocks of concrete with no windows, and more importantly, no insulation – thus overestimating thermal storage in the building envelope. The study also lacked comparison and validation with observations.

Another trend in sustainable building technologies is the use of rooftops for the generation of energy. While this sometimes involves wind power, most applications involve the collection of solar energy. In recent years, installation of building integrated photovoltaic (PV) solar panels has increased dramatically [30]. Between 2007 and 2008 the installed PV capacity in the United States increased by 63%, with projections for even greater future growth. Rooftop mounted systems accounted for 74% of the installed PV generation capacity in the US during 2008. This increased adoption of PV technology can be attributed to the decreasing cost of PV modules, increasing module efficiency, and incentives provided by utilities, states and federal government. Additionally, there is growing interest in moving towards renewable energy sources to garner credits from building rating systems such as the US Green Building Council's LEED program.

These sustainable roofing trends are leading to changes in urban rooftop environments that may impact the urban climate. As more research on the benefits of these systems is conducted, cities may become motivated to increase incentives or establish mandates for such technology. This change has the potential to result in widespread alteration of urban surfaces. Such changes to the built environment should, therefore, be looked at from the perspective of implications for the urban atmospheric environment. Furthermore, it is important to explore comparative advantages of one

technology over another and the potential for technologies to be combined in a synergistic way.

## 1.2. Rooftop surface energy balance

The energy balances of traditional and photovoltaic roofs are shown in Fig. 1. The goal of the present study is to evaluate the sensible flux terms for each roof type in order to provide a measure of the contribution of each roof type to the urban heat island. The remaining energy balance terms influence the roof surface temperature, thereby influencing the magnitude of the sensible flux term. In the case of the PV roof, it is important to consider the fact that a PV panel has two surfaces exposed to ambient air, which increases the heat transfer surface area.

When analyzing the Urban Heat Island impact of different roof treatments for a given day of the year, it is meaningful to consider the peak sensible flux ( $\text{W}/\text{m}^2$ ), as well as the total daily flux ( $\text{W h}/\text{m}^2$ ). The peak flux will impact daytime maximum temperature, which in turn impacts air conditioning energy demand, heat related mortality, urban air quality, and peak electric loads. On the other hand, total daily flux will influence nighttime cooling of a city, which also plays a role in energy use, heat related mortality and perpetuation of a UHI cycle. In fact, the UHI intensity generally reaches a peak in early morning hours [31]. If only the roof's peak surface temperature or peak flux were considered, the impact on a nighttime heat island is not accounted for.

## 1.3. Overview of this study

The goal of this study was to compare the heat island impact of various commercial building roof treatments. Black and white membrane roofs, as well as vegetated green roofs are compared in

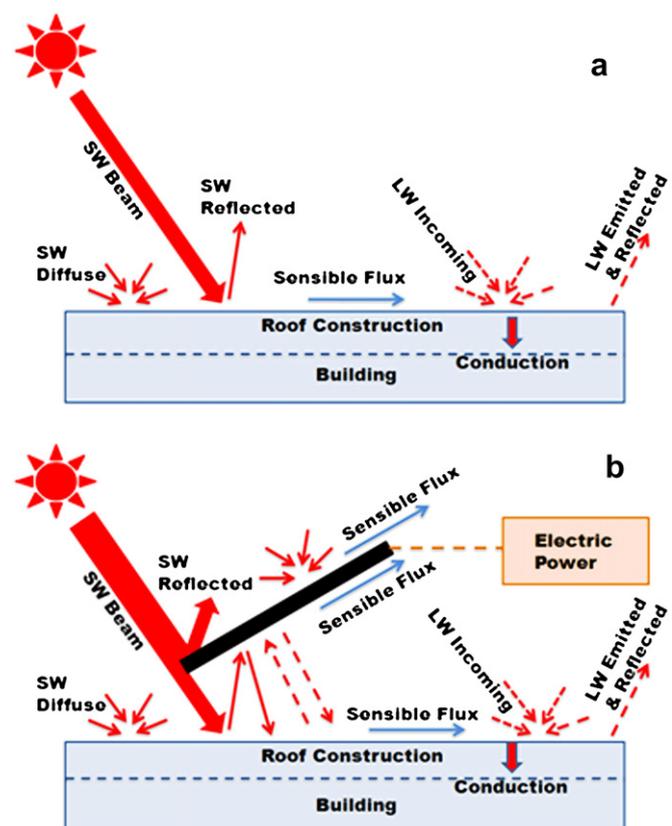


Fig. 1. Surface energy balance for (a) unshaded and (b) shaded PV roofs.

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