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Urban cooling primary energy reduction potential: System losses caused by microclimates

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ABSTRACT

Temperatures in cities are amplified through the urban heat island effect by anthropogenic heat emissions into microclimates. The trapping of solar energy in urban canyons plays the most significant role. Our analysis, however, considers how urban air conditioning systems influence their local microclimate. Using models and simple observations we demonstrate how the heat rejected from these machines creates a direct feedback on the machine performance. Thermodynamically, the temperature of the environment directly controls the efficiency of the common refrigeration cycle found in air conditioning systems via the second law. A city, with its complex topography of urban canyons and skyscrapers, produces small microclimates with varying temperatures. This project investigates three urban settings that create microclimates that are detrimental for the efficiency of cooling in New York. First, the overall urban heat island effect, second the effect of roof temperature on rooftop package air conditioning units, and third the impact of local heat emission from agglomerations of window air conditioners. The efficiency loss is investigated by considering the range of temperature changes that can be observed in the surrounding environment of air conditioning systems, and determining the subsequent impact on the Coefficient of Performance (COP). Our COP analyses indicate a range of potential energy increases of around 7%–47% due to increases in environmental temperature around air conditioners. An analysis of the building stock of New York City showed that the annual electrical energy demand is potentially increased by these effects by nearly 10 PJ (3000 GWh) combined, which is more than 10% of the total cooling demand for the city.

1. Introduction

This paper investigates the impact of high-density urban situations on the energy efficiency of air conditioning units whose performance is sensitive to the surrounding environmental temperatures. The focus lies on three factors that change the environment in which the heat exchanger of the air conditioner is working. The first is the Urban Heat Island (UHI) effect, which is the overall increase in temperature due urban form, material, and emissions that raises the local temperature for all units. The second is the surface material in the immediate surrounding of the units raising the temperature locally. The last factor is the geometrical distribution of units where the dissipated heat raises the temperature for units in the vicinity or themselves as in the densely arranged and vertically oriented units shown in the photos in Fig. 1. Even though these three factors are complementary this paper investigates the impact of them individually. We present the background on these factors on which we build our assumptions and models, then we describe the methods we used to estimate the impact on thermodynamic performance, we present the results for each scenario, and then we discuss the results including their implications and uncertainties.

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Fig. 1. Image illustrating the stacking of heat exchange units in the urban canyons of New York City (left), and attached to buildings in Singapore (right).

2. Background

2.1. Urban heat island (UHI)

The urban heat island effect has been identified as, "high surface and thermal structure heterogeneity, complex localized flow patterns inside street canyons radiative trapping, artificial materials, anthropogenic heat releases, as well as finite domains for heat conduction, instead of the semi-infinite sub-surface domain that can be assumed over natural terrain" (Wang, Bou-Zeid, & Smith, 2010). Causes that have been identified include excessive anthropogenic heat, storage of solar radiation in large thermal masses with insufficient circulation, reducing the ability for infrared radiation to escape the atmosphere, causing nighttime temperatures in urban areas to rise significantly above surrounding conditions (Oke, 1981). The absorbed radiation is stored in the attached materials and dissipated through radiation (Takebayashi & Moriyama, 2007). Depending on the thermal storage capability of the surrounding materials, the dissipation of the absorbed energy is delayed for a few hours and leads to the known fact of increased temperature in cities overnight (Oke, 1981). Since the UHI effect produces a temperature differential during the night hours, an impact on air conditioning performance relative to nominal conditions would happen at night and would therefore affect roughly 1/3 of the time in summer.

The adverse impact of urban heat islands has been extensively studied and identified to increase energy consumption and peak electricity demand during cooling seasons as well as decreasing the Coefficient of Performance (COP) by as much as 25% (Santamouris et al., 2001), eventually deteriorating the outdoor thermal comfort (Meehl et al., 2000). Strategies for maintaining the urban thermal balance have been developed including increasing the albedo of the urban environment, expanding the urban green spaces and utilizing natural heat sinks within or near the vicinity of the urban area. Such mitigation techniques have been demonstrated to be effective and beneficial for large-scale applications (Santamouris, Synnefa, & Karlessi, 2011).

Of the aforementioned mitigation techniques, some are not as usable as the others: The available free ground in cities, for example, isn't always as abundant as the designers would like to believe, and could render the implementation of large-scale mitigation methods ineffective. The mitigation methods that are based on roofs, on the other hand, are highly preferable due to their flexibility and ease of implementation due to the costs, thereby cultivating strategies that aimed at increasing the albedo effect of cool/reflective roofs (Zinzi, 2010).

Previous studies have also considered the impact of environmental temperatures on air conditioner performance (Allegrini, Dorer, & Carmeliet, 2012; Gracik, Heidarinejad, Liu, & Srebric, 2015). Allegrini et al. looked at the impact of urban form and UHI on building performance using simulation and analysis of convective and radiant heat exchanges caused by urban conditions, but it did not consider specifically the direct impacts and feedback between temperature and system performance as these aspects were built into the simulation tool (Allegrini et al., 2012). Likewise, F. Salamanca et al. created an extensive atmospheric model showing that air conditioning systems cause 1 °C increase in the urban heat island in Phoenix, but did not analyze the feedback on the performance of the air conditioning systems (Salamanca, Georgescu, Mahalov, Moustaoui, & Wang, 2014). Gracik et al. used computational fluid dynamics to simulate temperatures and did study the influence on the performance of air conditioners, but the analysis was limited to simulation of simplified large scale building forms to facilitate the complex fluid dynamics analysis (Gracik et al., 2015). We are interested in three specific aspects of the microclimate in the context of a case study of New York City.

2.2. Surface materials

The local temperature is impacted by the material relationship to its immediate surroundings, in particular the material absorption and storage capacity. It affects local temperatures and impacts equipment such as rooftop package air conditioners. Prado explains how the radiative exchange of the solar radiation depends strongly on the material and can range from 10% to 73% (Prado & Ferreira, 2005). The orientation also plays a critical role in the radiant heat transfer and the retransmission into the local microclimate by convection and emission. Even for high albedo surfaces, the more times short wave radiation bounces, the more likely it is to be absorbed instead of reflected. The orientation of surfaces toward the sun and the geometry that generates these reflections are critical in understanding the heat stored and exchanged within local microclimate (Oke, 1981).