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Personalized cooling as an energy efficiency technology for city energy footprint reduction

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ABSTRACT

This study analyses the influence of Personalized Conditioning (PC) systems for potential savings of energy, cost, and CO_2 emissions from commercial buildings in different U.S. cities. This analysis characterizes potential benefits from the deployment of PC systems during peak cooling hours for peak load shifting. PC systems deployed in coordination with the central building air conditioning systems could have a large-scale influence on a city's energy footprint. Specifically, portable PC systems that use Phase Change Materials (PCMs) for heat rejection, allow for heat absorption during the working hours and heat rejection during non-working hours typically coinciding with the off-peak (base) utility rates when the commercial building tend to be unoccupied. However, there are limiting factors for the potential energy and cost savings with the use of PC systems. Therefore, this study assesses the use of PC systems in addition to the existing building air conditioning system during cooling seasons. The assessment entails potential energy end-use savings for 7 major cities located in different geographical/climatic regions of the U.S. Furthermore, the study calculates potential cost savings based on the variations in the peak and off-peak (base) electricity rates for different local Time of Use (TOU) programs. This simulated evaluation of local building systems and utility programs allows for regional various on the city's energy footprint reduction to emerge. The analysis shows that midrise apartments are a better building type than office buildings for the deployment of PC systems during a cooling season. The cash savings per person for the deployment of PC systems for midrise apartments are \$62/year, \$40/year, and \$37/year for Honolulu, NY City, and Phoenix, respectively. The simulations also showed that using extended setpoint temperatures could reduce the CO_2 emissions up to 21.4% per year.

1. Introduction

Improvement of energy efficiency in the building sector is the most effective strategy to mitigate the impact of people on the built environment and to match the energy and power production with the demand. Residential and commercial buildings account for 41% of source energy in the U.S. (Commercial Building Energy Consumption Survey (CBECS), 2012). Commercial and residential buildings account for 9.9% and 5.4% global Greenhouse Gas Emission (GHG) emissions, respectively (Shen, 2017). The U.S. is responsible for 21% of the world's CO_2 emissions, and 98% of the U.S. emissions are from the energy consumption (Attari et al., 2010). Recent studies elaborated the serious side effects of CO_2 emissions on national economies due to global warming and climate change (Chang, 2015). It is expected that if the warming trend continues for the next 50 years it could increase the mean air temperature up to 1.3 °C (Davis et al., 2010). This increase and other effects of global warming do not vary equally throughout the planet in time nor space, suggesting regional extreme temperature conditions could follow different patterns than the global warming (Shepherd, 2015). For example, a study has shown that the China's CO_2 peak emission could occur prior to 2030 with careful considerations of GHG emission mitigation strategies based on limits to Gross Domestic Product (GDP) and energy/CO_2 intensity (Mi et al., 2017). Importantly, the GHG emission rates could be resolved to different spatial scales varying from the city to the globe (Meng et al., Liu). Consequently, the influence of the energy systems on climate change requires regional strategies. Retrofitting existing buildings to use significantly less energy is an essential part of any climate change mitigation and energy security strategy. Implementation of energy efficiency measures in existing buildings or design of energy efficient buildings are common approaches to reduce energy

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Acronyms

AHS	American Housing Survey
BAS	Building Automation System
CAV	Constant Air Volume
CBECS	Commercial Building Energy Consumption Survey
CDD	Cooling Degree Days
DOE	The U.S. Department of Energy
FTE	Full Time Employee
GHG	Greenhouse Gas Emission
HVAC	Heating, Ventilation, and Air Conditioning
LMP	Locational Marginal Pricing
PC	Personalized Conditioning
PCM	Phase Change Material
RECS	Residential Energy Consumption Survey
TOU	Time of Use
VAV	Variable Air Volume

consumption in the buildings or curb GHG emissions from the buildings (Dahlhausen et al., 2015). Although these approaches could support energy efficiency improvements, there is a need to move the boundaries beyond the current design and retrofit practices.

One practical approach would be to benefit from the advances in the other disciplines and develop new technologies, especially for the space heating and cooling, to improve their energy efficiency (Raman et al., 2014). However, any disruptive technology requires original evaluation for economic survival strategy. This study considers advances in the design of energy efficient Personalized Conditioning (PC) systems to reduce the impacts of buildings on GHG emissions. Among the energy end-uses, space cooling and heating take up to 31% and 43% of the total building primary energy consumption (Huang and Gurney, 2016). Therefore, an effective deployment of PC systems considers the reduction of space conditioning in the building sector. These systems offer several benefits, including electricity peak load shifting, thermal comfort, and space air conditioning.

Depending on the purpose of the PC systems, there are various PC heating and cooling systems available, including cooling and heated chairs (Brager et al., 2015), hand/foot warmers (Zhang et al., 2015), and portable Phase Change Material (PCM) supported systems (Dhumane et al., 2016a). Hand warmers, hand ventilation, foot warmers, head ventilation, and portable fans are among the most recent PC systems (Brager et al., 2015). The primary focus of PC systems is not on the reduction of energy consumption. Thermal comfort and increases in productivity are typically the primary factors in the deployment of these PC systems (Zhu et al., 2017). Consequently, thermal comfort satisfaction is not necessarily correlated with the associated energy consumption. Providing thermal comfort satisfaction of all occupants is not possible due to the individual differences, including age, gender, clothing, activity, and body mass (Van Hoof, 2008). It is even more difficult to satisfy all occupants using the centralized systems. Consequently, one practical approach is to create a local thermal comfort zone for the building's occupants and address individual complaints using PC heating and cooling systems.

Among the energy consumption commodities in buildings, space cooling is a significant portion of building energy consumption patterns. According to Commercial Building Energy Consumption Survey (CBECS) 2012, space cooling in the U.S. requires 19% of the total electricity consumption (Commercial Building Energy Consumption Survey (CBECS), 2012). In addition, among the commercial building types, offices account for 17% and 19% of the commercial building floor area and primary energy consumption, respectively (2010 Buildings Energy Data Book, 2011). Therefore, among commercial buildings, office buildings are a good starting point for energy saving technologies (Heidarinejad et al., 2014). For residential buildings, Residential Energy Consumption Survey (RECS) and the American Housing Survey (AHS) are sources of data with the focus on data from 1970 to 2011 (Moura et al., 2015; Belzer, 2014). The total floor area for residential buildings increased from 87 million square feet to 211 million square feet from 1970 to 2011 (Belzer, 2014). Therefore, one promising strategy to reduce the energy consumption in buildings is to consider reduction in space cooling through no-cost/low-cost building operation energy efficiency measures to deployment of novel technologies. Increasing the cooling setpoint, decreasing the heating setpoint, and decreasing the ventilation rate of the building's primary Heating, Ventilation, and Air Conditioning (HVAC) systems are among the main assumptions to save energy consumption (Heidarinejad, 2014). The suggested change for the setpoint is to decrease the heating setpoint or increase the cooling setpoint of the primary HVAC system to 4–5 K (Hoyt et al., 2015). The current state-of-the-art showed up to 60% energy savings (Veselý and Zeiler, 2014). These assessments are mainly based on the use of building energy modeling that is a powerful tool to assess potential energy and cost savings as well as GHG emission mitigation associated with implementing different saving strategies. Consequently, this study benefits from building energy modeling to evaluate potential energy and cost savings as well as GHG emission reduction at a large-scale. The validation and verification of the building energy models requires relying on a systematic calibration of the building energy models. The authors have demonstrated using building energy modeling for understanding office building occupancy patterns (Kim et al., 2017), building energy retrofits of office buildings (Dahlhausen et al., 2015), and quantification of the urban microclimate on a multi-family residential building (Liu et al., 2015).

Significant impacts on the energy efficiency of buildings require a large-scale analysis at the neighborhood, city, or nation scale. Cities are living laboratories since they are located in different geographic locations and have different policies. However, the deployment of PC systems at the city scale is expensive and mostly impractical with the current resources. This study suggests a much less expensive approach to perform the initial analysis computationally with validated numerical models and provide suggestions for the large-scale deployment of these PC systems in various cities in the U.S. City scale modeling requires consideration of energy market constrains, e.g. demand response programs, Locational Marginal Pricing (LMP), and Time of Use (TOU). The aim of these programs for the utility providers is to provide (1) electricity load shifting from the peak hours to off-peak hours (Qiu et al., 2016) and (2) opportunities for the customers to reduce their electricity bill cost (Kirkeide, 2012). These PC systems could offer additional features, e.g. heatwave conditions when the peak load on the power grid increases drastically (Hannah, 2015). Consequently, this study considers seven different cities that have different local climates and energy markets so there are opportunities to test the implementation of different mitigation technologies with the support of PC systems.

The current study considers energy and cost saving features, including laying out assumptions based on the current-state-of-the-art for PCM supported portable PC systems that could offer several benefits from potential energy and cost savings to thermal comfort. Overall, the aim of this study is to:

1. Quantify the potential energy end-use and cost savings for office and midrise apartment buildings located in different climate