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Clustering and statistical analyses of air-conditioning intensity and use patterns in residential buildings

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ABSTRACT

Energy conservation in residential buildings has gained increased attention due to its large portion of global energy use and potential of energy savings. Occupant behavior has been recognized as a key factor influencing the energy use and load diversity in buildings, therefore more realistic and accurate air-conditioning (AC) operating schedules are imperative for load estimation in equipment design and operation optimization. With the development of sensor technology, it became easier to access an increasing amount of heating/cooling data from thermal energy metering systems in residential buildings, which provides another possible way to understand building energy usage and occupant behaviors. However, except for cooling energy consumption benchmarking, there currently lacks effective and easy approaches to analyze AC usage and provide actionable insights for occupants. To fill this gap, this study proposes clustering analysis to identify AC use patterns of residential buildings, and develops new key performance indicators (KPIs) and data analytics to explore the AC operation characteristics using the long-term metered cooling energy use data, which is of great importance for inhabitants to understand their thermal energy use and save energy cost through adjustment of their AC use behavior. We demonstrate the proposed approaches in a residential district comprising 300 apartments, located in Zhengzhou, China. Main outcomes include: Representative AC use patterns are developed for three room types of residential buildings in the cold climate zone of China, which can be used as more realistic AC schedules to improve accuracy of energy simulation; Distributions of KPIs on household cooling energy usage are established, which can be used for household AC use intensity benchmarking and performance diagnoses.

1. Introduction

Energy consumption in residential buildings accounts for a large portion of global energy use, which drives many researchers and policy makers towards energy conservation of residential buildings. In 2012, the U.S. residential sector accounted for 22.2% of the total primary energy consumption [1]. In the northern part of the European Union, residential buildings account for 30% of the total energy consumption [2]. In 2015, the total building energy consumption in China was 864 million tce (Mtce), accounting for approximately 20% of the total energy use, while the urban residential buildings (excluding northern urban heating) consumed 199 Mtce (including 430 TWh of electricity), accounting for 23% of the total building energy use. The total energy use of the subsector of urban residential buildings has tripled from 2001 to 2015. Domestic water heating, space cooling, and space heating, are smaller end-uses, but they have increased considerably and at a high rate from 14% to 31% in the last 15 years [3,4].

There is a wide variation in household cooling energy use. Li et al. [5] carried out a survey of the air-conditioning (AC) energy consumption in 25 residential apartments in Beijing in 2006, and found that the electricity consumption for cooling systems varied from 0 to 15 kWh/m^2 among households in the same building. An et al. [6] studied the household cooling usage distribution in a community with approximately 400 households, and found that the highest consumed 8,000 kWh of cooling energy in two months, which is three times higher than the average cooling energy use. Brounen et al. [7] investigated 305,001 Dutch homes in 2008–2009 and also found a wide variation in household consumption. Parker et al. [8] verified the home energy saver suite for online simulation, by conducting a detailed year-long study. The homes studied exhibited a three-fold variation in measured energy use.

Yoshino et al. [9] summarized the outcomes from IEA EBC Annex 53. They reported six key factors influencing real energy use in buildings: building envelope, building equipment (energy systems), building operation and maintenance, weather, indoor com-

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fort criteria, and occupant behavior, and the latter three factors related to occupants have greater influence than the former three. The behavior of occupants is a key factor influencing the building life cycle and determining energy use in buildings [10,11]. Yun and Steemers [12] analyzed the relationship between the cooling energy and influencing factors, such as the climate, occupant behavior, and house type, in residential buildings in the USA, thus revealing that the occupant's behavior was the most significant issue in determining how often, and where AC was used. Ren et al. [13] concluded that the AC usage in the summer is not only related to the weather and the characteristics of AC systems, but is also strongly influenced by the residents' behavioral patterns. Zhou et al. [14] discussed the influence of AC use modes on the energy consumption in residential communities using simulations, and revealed that AC use modes can lead to more than ten times of variation in electricity use among households. Eguaras–Martinez et al. [15] showed that the inclusion or exclusion of occupant behavior in building simulations, could result in up to a 30% difference in predicted energy use. IEA EBC Annex 66 introduced new methods and tools to standardize the representation and simulation of occupant behavior [16]. Better consideration of occupant's interaction with building equipment and system, including the adjustment of thermostats for comfort, switching lights, opening/closing windows, pulling up/down window blinds, and moving between spaces, can improve the prediction of thermal loads and energy use in buildings [17,18].

Duo to the privacy concerns of residents, many researchers have analyzed occupants' behavioral patterns in residential buildings based on questionnaire surveys and case studies [13,14,19,20]. However, these methods have some limitations: Questionnaire survey is more suitable for large-scale data collection, but the reliability of results highly depends on the questionnaire design, sampling method and qualify of response; Case study is a more specific but time-consuming method, which is often applied to detailed investigation and modeling of typical households instead of to obtain the behavior distribution of a large group of occupants. With the development of sensor technology, it became easier to access an increasing amount of data. Accompanied by various data analysis methods, large-scale metered data contributes to have a comprehensive understanding of building energy usage and occupant behaviors [21–26]. Pan et al. [24] extracted occupant-behavior related electricity load patterns using the K-means clustering approach from smart-metering data in two communities in China. Zhao et al. [27] proposed a data mining approach to understand the occupant behaviors and power consumption in an office building in the USA. Luo et al. [22] developed load shape parameters, and representative load shapes, based on electric load meter data for small- and medium-sized commercial buildings in California, USA, and applied these data to energy benchmarking and retrofit analyses.

There are growing applications of district heating/cooling systems, and corresponding thermal energy metering systems in many countries. The thermal energy consumption systems can be used to record the cooling/heating consumption of each household, based on their real thermal energy usage, thereby providing incentives to inhabitants to save energy. In China, there is an increasing trend whereby thermal energy metering systems are installed in newly built residential districts with centralized heating, ventilation, and air-conditioning (HVAC) systems [28,29]. Therefore, many researchers utilized the metered data for better understanding of building energy use. For instance, Kiluk [30] took advantage of the large datasets obtained from district heating billing systems to detect system faults by applying the data mining method. Gadd and Werner [31] identified four typical load patterns based on yearly heating loads of the smart heat grids in two districts, which could be applied to define the customer categories. Shahrokni et al. [32] analyzed the energy consumption of different building vintages in Stockholm and estimated one-third of energy could be saved if the building stock is retrofitted to meet the current building energy codes. However, except for the thermal energy consumption benchmarking, current studies lack effective and easy approaches to analyze AC usage and provide actionable insights for inhabitants, which is of great importance for inhabitants to understand their thermal energy use and save energy cost through adjustment of their AC use behavior, as well as for engineers to obtain realistic AC use patterns for HVAC system design and performance simulation. Therefore, this information from thermal metering systems is of great importance, especially to developing countries, such as China, where residential occupant behavior is diverse and has significant influence on residential energy use.

This study proposes a data-driven approach to analyze the AC use patterns of residential buildings, and develops new key performance indicators (KPIs) beyond the traditional total thermal energy to gain a deep understanding of the AC usage, based on the long-term metered data of cooling loads. These KPIs could be used to benchmark inhabitants' AC cooling usage and to guide energy conservation effort. We use several KPIs to analyze the household cooling energy consumption in a residential district comprising approximately 300 households in Zhengzhou, China. The district installed a central cooling plant as well as a smart metering system to collect the long-term cooling loads of each air-conditioning equipment. The K-means clustering approach is applied to characterize the typical air-conditioning use patterns of various room types (i.e., bedroom, living room, dining room), which can be used in building performance simulation to improve the accuracy of simulated cooling energy use.

The remaining parts of this article is organized as follows: Section 2 introduces the technical approach as well as the data, methods, and indicators; Section 3 shows the analysis results for a residential district including the cooling usage analyses and representative AC use patterns; Section 4 discusses the potential applications of the research outcomes; Section 5 presents the policy implications and limitations of this study; And finally, conclusions are summarized in Section 6.

2. Data and methods

2.1. Data source

The residential district in this study was built in 2011 by one developer, and is located in the city of Zhengzhou in China. The district is in China's cold climate zone with the average temperature of the coldest month from −10 to 0^0C, and the warmest month from 18 to 28^0C. The district has eight buildings, including three high-rise buildings (two are 16 floors and one is 18 floors) with pre-installed fan-coil units (FCUs) for cooling and heating in each room except from bathrooms and corridors. The FCUs are served by a centralized ground-source heat pump system. Therefore, these three buildings constitute the research objects of this study. The sketch map of the case district is shown in Fig. 1. In Fig. 1, the numbering refers to the building number, and the arrow lines refer to the flow direction of chilled water. Each room, except the bathrooms and corridors, has one FCU with individual control panel, which can be operated individually by the users (e.g., turn on/off, increase/decrease the speed of supply fan). The three buildings have 324 households with 1402 FCUs, and seven apartment types with different floor area (90–160 m^2), and number of air-conditioned rooms with FCUs (3, 4, or 5 rooms). Fig. 2 shows the sketch floor plan of one typical apartment unit.

A thermal energy metering system is used to collect the cooling/heating data of each FCU for utility bills. The collected energy data is the accumulated cooling energy consumption from the time