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Correlating cooling energy use with urban microclimate data for projecting future peak cooling energy demands: Residential neighbourhoods in Seoul

Choo Yoon Yi, Chengzhi Peng*

School of Architecture, University of Sheffield, Arts Tower, Western Bank, Sheffield S10 2TN, UK

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ABSTRACT

The paper presents a relational study of correlating cooling energy use with local weather station and apartment price data in Seoul. The overall analysis at a macro-level shows monthly variations in the correlation coefficients of cooling energy use and local weather station data during summer months. A further analysis at a micro-level shows temporal and spatial variations in the correlation. As the August correlation appears the strongest across all city districts, up to $r = 0.972$, a simple bivariate regression (SBR) model is derived to predict peak cooling energy use for each district. Given the latest climate change projections for Seoul, we use the SBR models to estimate increases of cooling energy use for each city district in August 2050s. The largest predicted increase rate (IR) is 96.1% in one city district (from 124.5% in 2012–220.6% in 2047). The smallest IR is 6.0% in another city district (from 51.5% to 57.5%). In 2047, the city district with the highest predicted IR is up to 292.8%, while the lowest is up to 57.5%. We discuss the implications of the projected future peak cooling energy demands for sustainable resilience as well as citizen's health and wellbeing.

1. Introduction

Better understanding energy use in residential buildings for cooling is becoming increasingly important from the perspective of climate change even in heating-dominant countries. Intuitively, residential cooling energy use is largely related to weather conditions as buildings interact with their immediate surroundings. However, looking beneath the overall city level, the scene is much more complex. Not all cooling energy use can be neatly characterised into some uniformity. How does cooling energy use in urban residential buildings correlate with urban weather? Can any such correlation be reliably drawn through collecting and examining field measurements? To what extent, is the correlation spatial-temporal specific? A better understating of these questions will improve our ability to project cooling energy demands in future climate scenarios to inform longer-term energy policy making. Furthermore, a robust projection capability is more likely to be applied to planning and design of urban neighbourhoods and buildings, either retrofitting or constructing new ones.

We have identified that Seoul is the only city in the world where the datasets from field measurements required to address our research questions have been made publicly available. Our research aims to develop a methodological framework for analysing open heterogeneous datasets and deriving correlational models that could project future cooling energy demands of urban residential neighbourhoods at a micro-climatic scale (up to 1 km). Using Seoul's city districts as case studies, we expect that the proposed methodological framework can be applicable to other cities for site-specific analyse and modelling as long as these cities start similar data collections and make them accessible to researchers.

2. Theory and open data

2.1. Factors affecting cooling energy use in residential buildings

Yu et al. (2011) identified several factors as major determinants affecting energy use in residential buildings which can be categorised into three groups: (a) climate, e.g. external temperatures; (b) building physical environment, e.g. building envelop and service systems; and (c) user related aspects such as occupants' behaviours, activities and socio-economic statuses. As informed by more recent studies, we consider climate change an important additional factor that takes into account the likely effects of rising outdoor ambient temperature and increased frequencies of heatwave on cooling energy demand.

Firstly, climate is one of the most significant factors affecting building thermal and energy performance. Of the wide range of climate variables, air temperature, humidity, wind pattern (speed and direction) and solar radiation are considered the most significant parameters (de La Flor & Domınguez, 2004). Especially, dry-bulb temperature is

* Corresponding author.
E-mail address: c.peng@sheffield.ac.uk (C. Peng).

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one of the most influential climatic variables in measuring heating and cooling degree days (HDDs and CDDs) (Lee & Levermore, 2010), which affects building energy use. de La Flor and Domınguez (2004) investigated the impacts of microclimate on building energy use through modification of weather variables based on an integrated computational model. Allegrini et al. (2012) studied influence of microclimate, effect of neighbouring buildings in street canyon, on building heating and cooling demand using building energy simulation. Moonen et al. (2012) reviewed and highlighted the importance of investigation of urban microclimate to assess building energy demand, and several other authors suggested outdoor and indoor integrated or coupling assessment methods based on computational model as a solution to improve building energy use and the accuracy of the assessment (Bouyer, Inard, & Musy, 2011; He, Hoyano, & Asawa, 2009; Yang, Zhao, Bruse, & Meng, 2012). Despite of the importance of microclimate for assessing building energy use, very few studies have been carried out to investigate interrelations between microclimate and building energy use (Asimakopoulos et al., 2001), especially involving actual field measurements in residential buildings. Santamouris et al. (2001) investigated urban climate impacts on building energy use based on climatic measurements from almost 30 urban and suburban stations, which was conducted with one representative office building for all locations. Other related studies for residential buildings have been carried out, using alternative inputs rather than location-specific weather data, e.g. city-wide HDDs and CDDs for the energy modelling study (Aydinalp, Ugursal, & Fung, 2002) and weather normalization process based on equation of line-of-best fit between HDDs (and CDDs) and energy use dataset for energy correlation study (Touchie, Binkley, & Pressnail, 2013).

The importance of microclimatic consideration on building energy use is owing to diversity of urban weather conditions such as Urban Heat Island (UHI). UHI is often considered as the most typical example of anthropogenic climate modifications, resulting from the energy (heat) interactions between urban surfaces and the ambient atmospheric layers (Arnfield, 2003;Rizwan, Dennis, & Chunho, 2008). For the period 1999–2002 in Seoul, Lee and Baik (2010) found that the maximum daily UHII during non-precipitation days (and precipitation days) was observed to 4.5 °C (2.6 °C) in spring, 3.5 °C (2.4 °C) in summer, 4.8 °C (3.2 °C) in autumn and 4.5 °C (3.2 °C) in winter. At the building level, the effect of UHI creates site-specific microclimate conditions and they in turn have significant impacts on building energy use, especially on summer cooling. Santamouris et al. (2001) and Kolokotroni et al. (2006) studied the effect of urban heat island on cooling energy use in office buildings in Athens and London respectively: in Athens, where the mean UHII exceeded 10 °C, the urban cooling load was double of rural buildings; in London, the cooling energy demand of rural reference building was 84% of urban and there was no cooling demand investigated in the optimised rural building, maintaining indoor temperature below 24 °C. To improve building energy assessment, Chan (2011a) highlighted using the site-specific modified typical meteorological year (TMY) weather file as a weather input in building simulation to reflect diversity of urban weather, such as the UHI; applying the modified weather input in the Hong Kong case study, there was about 10% increase in air-conditioning demand compared to the existing TMY in both office building and residential flat. More closely related to our current study, Salvati et al. (2017) reported the UHI impacts on residential cooling energy use in Barcelona: the maximum UHI intensity at street level was 4.3 °C, and its impact on sensible cooling load was estimated to increase of 18%-28%.

Secondly, energy use in the residential building sector is also affected by user-related factors, such as residents' behaviour (Yun & Steemers, 2011), occupant age (Chen, Wang, & Steemers, 2013) and socio-economic circumstances (Schuler, Weber, & Fahl, 2000). However, the strength of these factors varies by location and the type of energy use (e.g. heating or cooling). Resident behaviour was influential for cooling in the US (Yun & Steemers, 2011), and occupant age was found more significant than income for both heating and cooling in Hangzhou, China (Chen et al., 2013). Socio-economic characteristics were found significant but less influential than building physical characteristics for heating in western Germany (Schuler et al., 2000). In the Netherlands, occupant characteristics and behaviour explained only 4.2% variation for heating while building characteristics explained 42% (Santin, Itard, & Visscher, 2009). As the literature reviewed have shown that user related aspects could play a role but such influence might be inconclusive depending on location and energy use type, our study therefore included the property price data of apartment buildings in Seoul as a socio-economic indicator reflecting to some extent the residents' cooling energy use decisions.

Thirdly, the impact of climate change on building energy use has been investigated by many researchers world-wide, some of which focussed on residential buildings. De Wilde and Coley (2012) reviewed the known impacts on residential buildings in the UK (Collins, Natarajan, & Levermore, 2010; Gaterell & McEvoy, 2005; Hacker, De Saulles, Minson, & Holmes, 2008), in Switzerland (Frank, 2005), in Australia (Wang, Chen, & Ren, 2010), and in Hong Kong (Chan, 2011b). Li et al. (2012) reviewed the impacts in different climate zones and highlighted the most significant impacts would be seen where hot summer and warm winter climates occur. Quantitatively, Crawley (2008) estimated that the overall energy use would increase by more than 20% from the current level in 'tropical' climates; and in middle latitude climates, it would reduce by 25% for heating and increase by 15% for cooling. In South Korea, Chung et al. (2004) found that the increase of annual mean temperature during 1974–2002 was 1.5 °C in Seoul, while the increase in the rural area was 0.6 °C. Also, there was 259 mm increase of precipitation during the last century. Wang et al. (2007) analysed 227 years daily precipitation records in Seoul and found that there was increase of mean summer precipitation between the Cheugugi period (1778–1907) and the modern period (since 1908): the former was 861.8 mm whereas the latter was 946.5 mm. Moreover, during the past 20 years, the torrential rain frequency data showed that the torrential rain was increased to 25% and heavy rain warning was increased to 60% (Seo & Lee, 2011). According to the Fifth-Generation Penn State/NCAR Mesoscale Model (MM5, Grell, Dudhia, & Stauffer, 1994) climate change projection downscaling for South Korea, the temperature during the summer period of 2071–2100 was predicted to increase 5.5 °C with reference to 1991–2000 (Boo, Kwon, & Baek, 2006).

2.2. Seoul's open data

The City of Seoul consists in 25 "*gu*" (districts), and each city district contains a number of "*dong*" (administrative neighbourhoods). We first analyse Seoul's open data to search for potential correlations between (a) the actual residential cooling energy use extracted from the energy bill data from the apartment neighbourhoods, and (b) the actual location-specific microclimate urban weather data as measured from the city district (CD) automatic weather stations (AWS).

2.2.1. Urban microclimate data

The urban microclimate data collected at the AWS of each city district in Seoul are publicly available (KMA, 2017; MDOP, 2016). However, the scope of AWS data is limited to temperature (dry-bulb), wind direction/speed and precipitation (above 0.5 mm). As dry-bulb temperature is the most influential weather variable affecting building thermal conditions and energy use, it was chosen to represent the urban weather data in this study. Fig. 1 shows the locations and boundaries of the 19 city districts identified, considering the sample size for statistical analyses (see 2.2.2). The boundary of 1 km radius within the AWS location is set according to the spatial scale of urban microclimate (Oke, 2006). Thus, a total of 98 apartment neighbourhoods (*Danji*) are identified across the 19 district sites. Table 1 shows the locations of the 19 AWS, including height (above sea level), estimated street and