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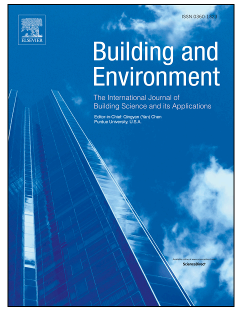

Developing a landscape of urban building energy use with improved spatiotemporal representations in a cool-humid climate

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Developing a landscape of urban building energy use with improved spatiotemporal representations in a cool-humid climate

Wenliang Li[1], Yuyu Zhou*[1], Kristen S. Cetin[2], Sha Yu[3], Yu Wang[4], Bingqing Liang[5]

[1] Departments of Geological and Atmospheric Sciences, Iowa State University, Ames, IA, 50011, USA

[2] Department of Civil, Construction and Environmental Engineering, Iowa State University, Ames, IA, 50011, USA

[3] Joint Global Change Research Institute, Pacific Northwest National Laboratory, College Park, MD 20740, USA

[4] Department of Political Science, Iowa State University, Ames, IA, 50011, USA

[5] Department of Geography, University of Northern Iowa, Cedar Falls, IA 50614, USA

***Corresponding author:**
Department of Geological and Atmospheric Sciences
Iowa State University
Ames, Iowa, 50011, USA
Phone: (515) 294-2842
Fax: (515) 294-6049
yuyuzhou@iastate.edu

Abstract

Urban buildings account for up to 75% of total energy use in the United States (U.S.). Understanding urban building energy use is important for developing feasible options to mitigate energy use and greenhouse gas emissions. In this study, an improved bottom-up building energy use model, named City Building Energy Use Model (CityBEUM), was developed to estimate building energy use for all buildings in Polk County, Iowa. First, 28 commercial and 6 residential building prototypes were designed by combing Assessor's parcel data and building footprint data. Then, the EnergyPlus in the CityBEUM was calibrated for all building prototypes using the U.S. Energy Information Administration's survey data, monthly utility meter data, and actual weather data. Finally, spatial and temporal variations of building energy use in the study area were estimated using the CityBEUM. Results indicate that the spatial variation of building energy use in the study area can be captured using the CityBEUM. With the monthly-calibrated model, the temporal pattern of urban building energy use can be well represented. The comparison of building energy use using the Typical Meteorological Year and actual weather data demonstrates the importance of using actual weather data in building energy modeling for an improved temporal representation.

Keywords: CityBEUM, Urban building energy use; high spatiotemporal resolution; calibration

1. Introduction

In the past several decades, the world has experienced rapid urbanization [1]. While this urbanization brings many benefits [2-4], it creates various challenges including increased energy consumption and greenhouse gas emissions [5-7]. In response, many countries have developed plans for reducing energy use and greenhouse gas emissions. For instance, compared to 2015, China expects to reduce 15% of energy use and 18% of carbon emissions per Gross Domestic Product (GDP) by 2020 [8]. The United States (U.S.) takes the emissions in 2005 as the baseline and plans to reduce 17% and 26-28% of greenhouse gas emissions by 2020 and 2025, respectively [9]. The European Union takes the emissions in 1990 as baseline and has begun to implement plans to reduce 20%, 40%, and 80-95% of greenhouse gases by the end of 2020, 2030 and 2050, respectively [10]. While reduction plans are proposed at the national level, actions must be taken at the state and ultimately the city level. For example, the states in the U.S. adopt energy codes, such as the International Energy Conservation Code (IECC), that new buildings must comply with. However, it is often the city that drives the enforcement of these energy efficiency practices. In the U.S., the building sector is the largest energy use sector; buildings in cities contribute significantly to this total energy use. As there are large variations in the number, types, and sizes of buildings among different cities, the portion of energy consumed by buildings varies. However, studies have found that urban buildings can account for up to 75% of total energy use in some regions [11-13]. Therefore, an improved understanding of building energy consumption is important for developing feasible options to improve building energy efficiency to reduce total energy consumption and greenhouse gas emissions [14-16].

City-scale building energy models are useful tools to simulate building energy consumption and explore potential actionable options for energy and emissions mitigation. Numerous attempts have been made for simulating building energy consumption at a neighborhood or city scale [17-20]. These efforts can be classified into top-down and bottom-up approaches [21-24]. The top-down approaches treat buildings as a single energy body, and energy models are usually developed using long-term economic data [25-30]. Although the top-down approaches can provide long-term energy use forecasting with limited input information, they are unable to account for non-linear technological improvements. The bottom-up approaches, conversely, encompass individual end-uses with consideration of internal load and occupant use variations to predict building-level performance [20, 31-35]. At the building level, the bottom-up approaches use statistical and/or physics-based methods combined with historical data to predict individual end-uses and/or whole-building energy use [36, 37]. Statistics-based methods are developed using significant historical data, and physics-based models are developed with detailed information on building geometries, building envelope material properties, and heating, ventilation, and air conditioning (HVAC) system characteristics. Integrated with the building level information, the modeling result at the building level is then scaled to represent a larger number of buildings at the neighborhood or city levels.

Bottom-up physics-based models have been developed in several studies to investigate urban building energy use. Heiple and Sailor [38] developed a model for estimating building energy use for the city of Houston, TX through integrating building energy simulation software with building prototype models. Zhou and Gurney [39] estimated building energy use and onsite CO_2 emissions for Indianapolis/Marion County, IN through combining building floor areas, number of floors, and building prototypes from GIS dataset, and building energy use intensity (EUI) simulated by eQUEST with typical meteorological year (TMY) weather data. Massachusetts Institute of Technology (MIT) proposed an Urban Modeling Interface (UMI) [40] model to simulate operational energy use, neighborhood walkability, and daylighting at the regional and community level based on the Rhino design environment. Cerezo et al. [36] developed an urban building energy model (UBEM) to simulate energy consumption for the city of Boston. The Ecole Polytechnique Fédérale de Lausanne University developed a new tool, CitySim [41] for quantifying building energy use at the urban district scale based on a simplified thermal model. Quan et al [42] introduced an Urban-EPC engine based energy use simulation tool for urban building energy use modeling. Recently, Lawrence Berkeley National Laboratory developed a web-based platform, City Building Energy Saver (CityBES) [43], for modeling building energy use in the U.S. cities, which allows a quick urban building energy use modeling and supports building retrofit energy efficiency analysis.

Although these approaches have proven valuable for simulating building energy consumption at the city scale, several challenging problems remain. One of these issues is the source of weather data that serves as the key for a realistic building energy modeling. It is commonly agreed that actual weather data need to be used for calibrating and simulating energy use at the building level. However, as the wide availability and free access to TMY datasets, the TMY data have been widely used in urban building energy modeling work worldwide, such as studies in Houston [38], Boston [36], Indianapolis [39], Kuwait [44], and Hong Kong [45]. TMY weather data are derived from a long period of historical weather records and represent weather conditions in a "typical" year for many locations worldwide. However, they are not actual weather data and do not reflect climate extremes that commonly occur in a particular year and location. Therefore, TMY data are not representative of realistic weather conditions in a particular year, but rather an average over a period of many years. When it is applied to the building energy consumption modeling at the scale of urban district, it cannot precisely reflect the actual energy consumption, especially its temporal pattern, in a specific year. When calibrating urban energy models using the real energy use data, the real weather data must be used [46].

In addition to the issue of weather data, another challenging problem is the model calibration. So far, most proposed urban building energy models are calibrated on an annual or otherwise low-frequency basis. Calibration at this level limits the ability of the model to predict energy consumption at higher frequencies [47, 48]. This limitation is often due to the frequency of energy use data available for use in the development of such models. The higher the frequency of the model, the more information and details can be estimated, including those for evaluating impacts of energy-efficient technologies. The models calibrated using higher frequency data show better performances in estimating energy usage pattern changes, calculating detailed energy costs, and identifying existing equipment problems at the building [49, 50] and urban scales. In most studies, the Residential Energy Consumption Survey (RECS) and Commercial Building Energy Consumption Survey (CBECS) data from the U.S. Energy Information Administration (EIA) have been generally used for calibrating models and estimating building energy use. However, these datasets consist of a statically representative survey data collected from buildings in each regions of the U.S., and only a limited number of buildings from a particular study area are included. Therefore, these datasets can only provide limited information for regional building energy use, additional local building energy use information is needed for model calibration and application. Moreover, the RECS and CBECS data are all reported with a relatively low temporal frequency, usually at the annual level.

To address aforementioned challenging problems, we proposed an improved bottom-up building energy use model, named City Building Energy Use Model (CityBEUM), for simulating building energy use in a case study area of Polk County, IA. This proposed CityBEUM was calibrated using actual weather data, as well as metered monthly building utility data collected from Polk County buildings, and energy use reference data from both the RECS and CBECS for the West North Central Census division. Moreover, we optimized the model calibration procedures from both spatial and temporal aspects to improve the modeling performance. Calibrated using the actual weather data and higher temporal frequency building energy use data, this CityBEUM can provide an improved urban energy modeling performance. The remainder of this paper is structured as follows. Section 2 introduces the study area and major data sources. Section 3 describes the framework for urban building energy modeling, including the identification of building prototypes, the building EUI modeling, and the final building energy use calculation. The urban energy modeling results and discussions are reported in Section 4, and the conclusions are included in Section 5.

2. Study area and data

Polk County, located in the central part of the State of Iowa in the U.S., was selected as the study area (Fig. 1). The county seat is the city of Des Moines, which is the largest city and also the capital city of Iowa. Polk County is also included in the Des Moines-West Des Moines Metropolitan area. Located in ASHRAE Climate Zone 5A [51], the Polk County has a total area of 1,533 km^2, including 97% land and 3% water. It is the most populous county in Iowa with a total population of 459,862 in 2014. With rapid urbanization, the residential and commercial areas in Polk County are expanding significantly, which raises several challenging problems associated with high energy consumption and greenhouse gas emissions in this county. The city of Des Moines is also in the City Energy Project with an ambitious goal of reducing its energy consumption 50% by 2030 [52], which makes this study area as an ideal testbed to develop and test the proposed urban building energy model.

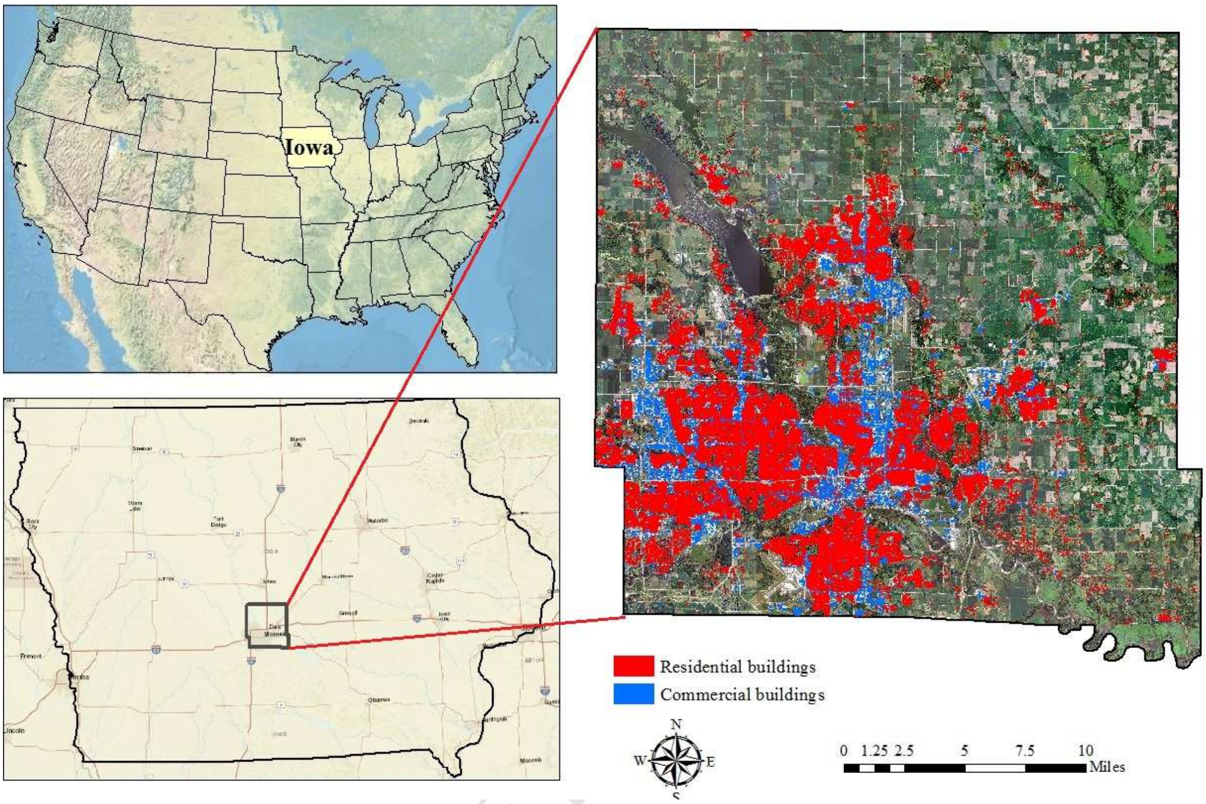

Fig. 1. Study area of Polk County, Iowa, U.S.

In this study, the key data include building information, building height, weather data, and reference data of building energy use. The city-wide building information was first obtained from the government website of the city of Des Moines [53]. Residential and commercial parcel data were collected from the Polk County Assessor Database [54]. The parcel data include information about building types, building locations, year of construction, and building HVAC system. Digital elevation model (DEM) and LiDAR data were also collected and processed to derive building height information using the software ERDAS IMAGINE [55]. For model calibration, the RECS dataset from 2009 and the CBECS from 2012 for the West North Central

Census Division were used [56, 57]. Monthly electricity and natural gas usage in 2010 for all building prototypes were also collected from a local utility company. Actual weather data (e.g., temperature, solar radiation, wind speed, and precipitation) from 2009, 2010, and 2012 were used for calibrating the residential and commercial building energy use models. As potential impacts of climate changes on weather data, it is essential to apply actual weather data in calibrating and estimating building energy use at the city level.

3. Methodology

The CityBEUM was developed by combining building prototypes from the Assessor's parcel data, building conditioned floor area from GIS footprint data, the number of building floors from DEM data and LiDAR-derived digital surface model (DSM) data, and the EUI of building prototypes from the calibrated EnergyPlus simulation (Fig. 2).

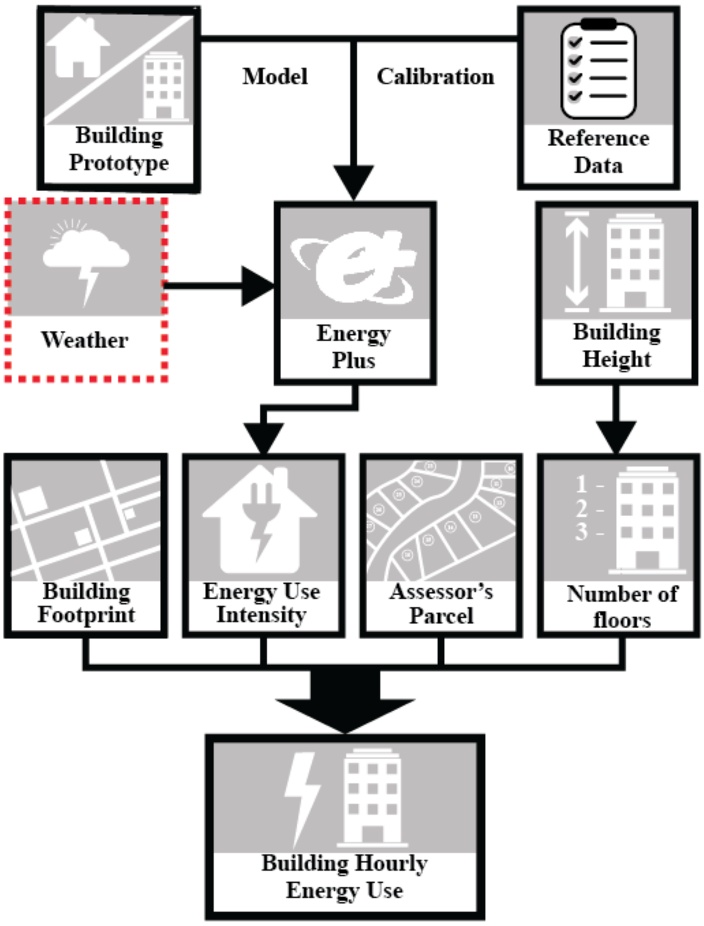

Fig. 2. The framework of the proposed CityBEUM.

3.1 Building prototypes

In this study, building typologies were designed to represent residential and commercial buildings in Polk County. Through careful examination of city's real buildings, there are 124 building types according to the parcel data. To represent all real buildings in the study area, a lookup table was built between the building prototypes and all buildings types. This table was used to group all real buildings into 28 commercial and 6 residential building prototypes based on the type of buildings, type of energy use, size, and age. For instance, the building prototype of large office pre1980 (offices with the total floor areas over 5,110 m^2 and built before the year of

1980) was grouped from building types in the original parcel data including company office, government office, retail office, general office, organization office. For commercial buildings, they were first classified as office, hotel, retail store, shopping mall, warehouse, primary school, secondary school, supermarket, quick service restaurant, full-service restaurant, and hospital. Based on past studies, all commercial building prototypes were further divided into pre-1980 and post-1980 categories due to the differences in typical characteristics and energy use for buildings constructed before and after 1980 [38, 39, 58]. Building year information was extracted from the building parcel data. In addition, office buildings were further divided into three types, large- (>5,110 m^2), medium- (511 m^2- 5,110 m^2), and small-offices (<511 m^2). Hotel buildings were further separated into large (>5110 m^2) and small hotels (<5110 m^2) [58]. For residential buildings, they were grouped into single-family and multi-family homes, followed by further subdivision of four types according to the heating method, single-family electrical heating (SF-electricity), single-family gas heating (SF-gas), multi-family electrical heating (MF-electricity), and multi-family gas heating (MF-gas). As for midrise apartments (Midrise MF), they were treated as residential buildings and subcategorized only based on the building year (i.e., before or after 1980).

3.2 Building energy use intensity modeling

EnergyPlus 8.5 was used to model hourly EUI (i.e., energy consumption per unit area) for the 34 defined building prototypes. EnergyPlus is an open source whole building energy use simulation program which integrates the capabilities and features from the Building Loads Analysis and System Thermodynamics (BLAST) and DOE-2 models [59]. EnergyPlus can incorporate many advanced features such as complex and customized HVAC systems and multi-zones airflows. It is a highly vetted and tested physics-based modeling software and has been widely used for modeling energy and water consumption in buildings.

For the creation of the energy models in EnergyPlus, information including elevation, latitude, longitude and local weather data were first compiled for the study area. Additional parameters including building geometry (e.g., building shape, surface areas, and glazing) and non-geometry parameters (e.g., building construction, HVAC systems, and occupancy schedules) were taken from the models developed by the U.S. Department of Energy for all 28 commercial building prototypes and the midrise apartment building prototype [58]. For the residential buildings, four buildings prototypes were used. These parameters were developed by age or code compliance level and obtained from the models developed by the Pacific Northwest National Laboratory (PNNL) for the state of Iowa [60].

The energy models in EnergyPlus were then calibrated for Polk County. The calibration is a key step for a realistic estimation of city-scale building energy consumption because significant differences may exist between the initial energy models developed and actual conditions. Without calibration, the simulation model may not be able to reflect the actual energy consumption of buildings. In this study, the model calibration has been conducted through adjusting major parameters such as internal lighting and equipment power intensity, cooling and heating setpoints within rational ranges using a two-step method. First, we calibrated the model at an annual level to minimize the discrepancy of the simulated annual EUI of all designed building prototypes within 10% of the collected reference data from the 2009 RECS and the 2012 CBECS data for the West North Central Census Division from the U.S. EIA [39]. Second, the monthly building EUI patterns of all building prototypes, including electricity and gas, were calibrated using the collected monthly utility data in 2010.

3.3 Building energy use calculation

The EUI of all building prototypes in Polk County were estimated using the calibrated energy models, with a reduced discrepancy between the simulated and observed EUI. These EUIs were then used to calculate the final energy consumption of each building in the city through combining the simulated EUIs, building floor areas, and number of building floors as follows:

$$E_{i,j} = EUI_{i,j} \times A_j \times N_j \tag{1}$$

where $E_{i,j}$ is the final energy consumption for energy use type *i* (electricity and gas) and building *j*, $EUI_{i,j}$ is the EUI for energy use type *i* and building *j*, A_j is the building floor area of building *j*, and N_j is the number of floors for building *j*. N_j is calculated as follows:

$$N_j = \frac{DSM_j - DEM_j}{H_m} \tag{2}$$

where DSM_j represents the elevation of building *j* derived from the LIDAR data, DEM_j is the elevation of the terrain's surface, and H_m is the floor to floor height for building prototype *m*.

4. Results

4.1 Model calibration

In this study, the EnergyPlus models in the CityBEUM were improved for each building prototype through calibration at both the annual and monthly level using actual weather and building energy use data. The simulated annual EUIs of all building prototypes were compared with the annual energy use data from the US EIA RECS data and CBECS data for the West North Central Census Division [56, 57]. Discrepancy between the simulated and reference RECS and CBECS survey annual EUIs for all building prototypes is from -9.66% to 9.88% (Fig. 3). The mean electricity and gas annual EUI of residential buildings is 81.73 and 102.19 kWh/m^2, respectively. The mean electricity and gas annual EUI of commercial buildings is 240.81 and

170.80 kWh/m^2, respectively. Single-family houses with gas heating show the smallest annual electricity and gas EUIs. For commercial buildings, quick service restaurants show the largest annual electricity and gas EUIs, while warehouses show the smallest annual electricity and gas EUIs.

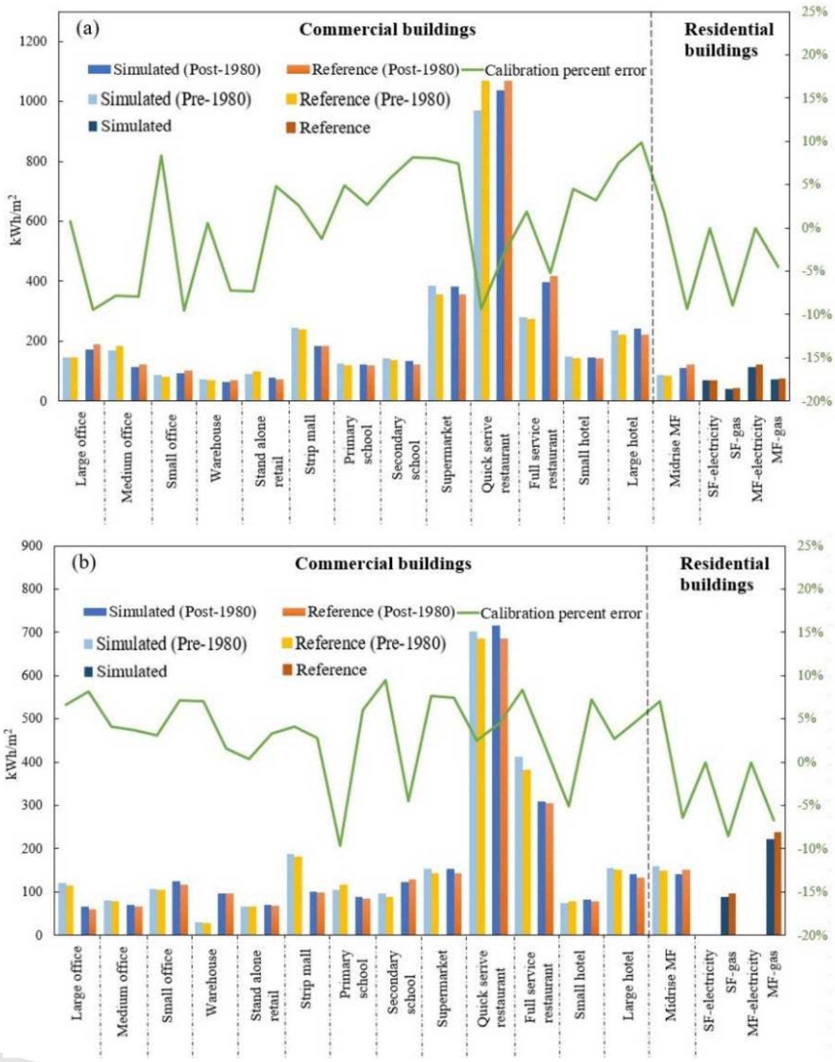

Fig. 3. Comparison of calibrated and reference annual electricity (a) and gas (b) use intensity.

After the initial calibration at the annual level, the further calibration using the monthly utility data improves the performance of the EnergyPlus models in the CityBEUM for capturing the monthly EUIs (Fig. 4). For instance, post-1980 large offices were originally developed as only using gas heating. However, the monthly utility data indicate that the heating is provided by both electricity and gas, depending on the building prototypes in the study area. In order to calibrate the model to represent all pre-1980 large offices in the study area, we considered two fuel types for heating (i.e., electricity and gas). The simulated EUIs for schools, such as pre-1980 primary schools, show high electricity use in the summer while the utility data shows low electricity use during the summer break when the school is closed. Therefore, the cooling setpoint and the electricity-using internal loads for these schools during the summer break were adjusted in the calibration.

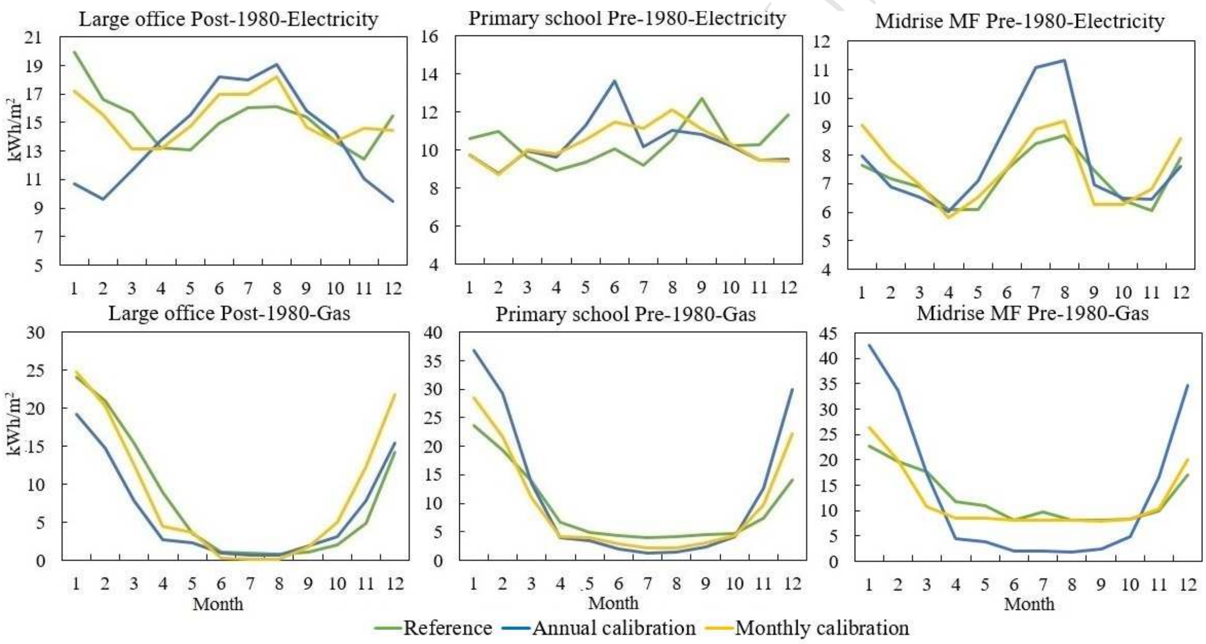

Fig. 4. Comparison of annual calibrated, monthly calibrated, and reference monthly EUIs for selected building prototypes.

4.2 Spatial patterns of building energy use

Spatial patterns of electricity and gas use corresponds well with the known information about the study area (Fig. 5). The highest electricity and gas consumption was located in the center of Polk

County with the largest building density and tallest buildings. In contrast, building energy use in residential areas, mostly in the outskirts of the county, is relatively low and homogeneous. In summary, the total annual energy use of buildings in Polk County progressively decreases from the urban core – mostly consisting of commercial buildings such as offices, hotels, and retail stores – to the suburban areas, where are mostly composed of single-family and multi-family houses.

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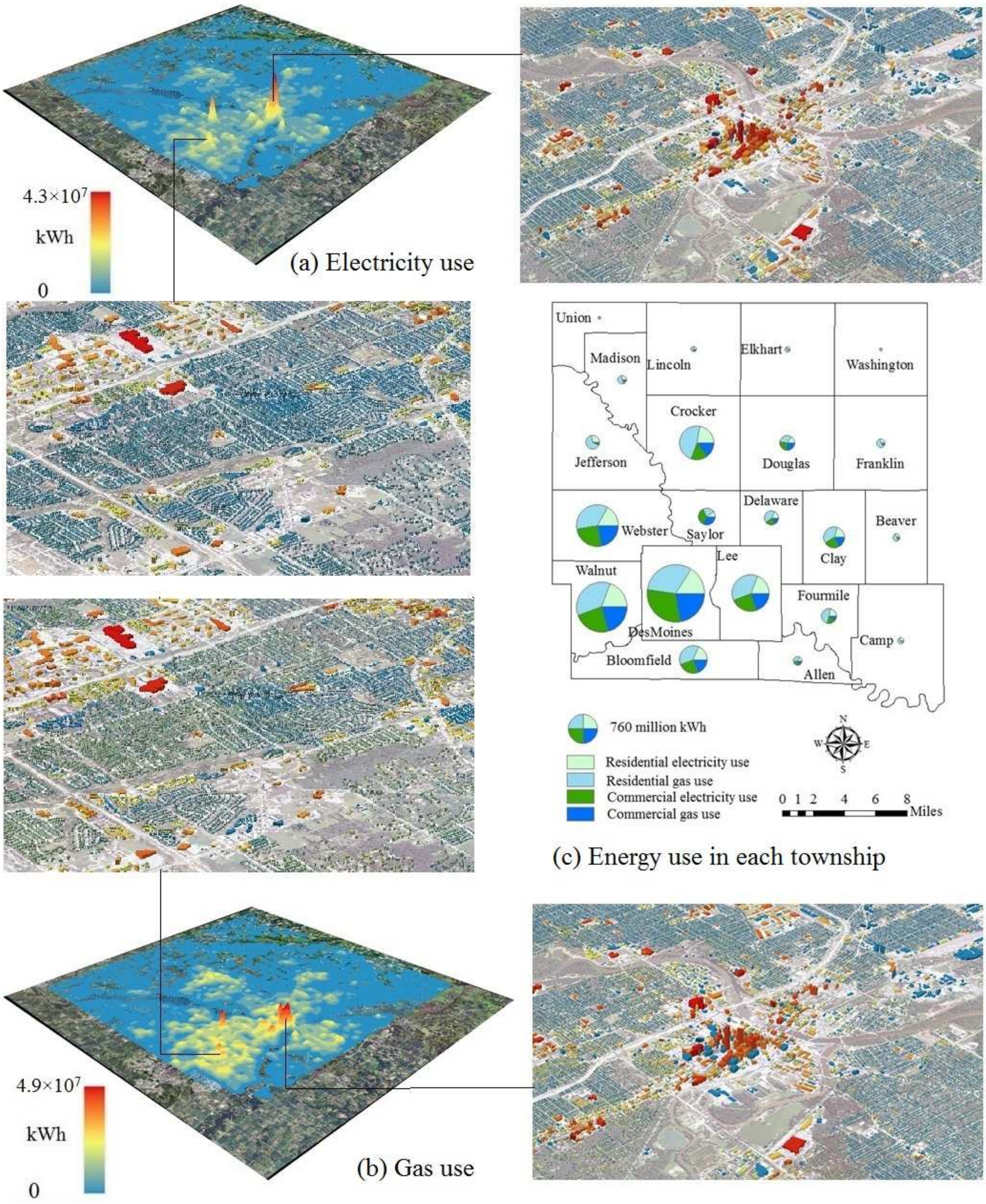

270 **Fig. 5.** Spatial patterns of estimated annual building electricity (a) and gas (b) use, and total
271 energy use in each township (c) in Polk County in 2010.

The total electricity and gas use of both residential and commercial buildings within the 21 townships in Polk County are illustrated in Fig. 5(c). Among all commercial buildings, the city of Des Moines shows the largest total annual electricity (900 million kWh) and gas consumption (679 million kWh), whereas the total energy use of buildings in the Union Township is the smallest. Large numbers of commercial buildings with more floor numbers and large conditioned spaces are concentrated in the city of Des Moines, resulting in its high electricity and gas use. The total annual electricity and gas consumption of residential buildings in the Des Moines Townships is also largest, followed by the Walnut Township. The Union Township shows the smallest total annual electricity and gas use of residential buildings. High residential energy use in the city of Des Moines is mainly attributed to a large number of houses in this area.

4.3 Temporal patterns of building energy use

4.3.1 Seasonal and monthly patterns

The electricity and gas use show different seasonal patterns in Polk County (Fig. 6). The electricity use is high in both summer and winter, which can be mostly attributed to cooling and heating demands. The gas consumption is highest in the winter for heating purposes. In cold climates, natural gas is commonly used in the U.S. for heating as electric-based HVAC systems do not generally work well in very cold conditions. The gas use is lowest in the summer because gas is generally only used for cooking and water heating at that time. The electricity and gas consumption of both residential and commercial buildings also show strong seasonality at the monthly level (Fig. 7). In particular, residential buildings show two electricity consumption peaks and one gas consumption peak in the year of 2010. The first electricity use peak occurs in the summer (around July and August) owing to a high electricity demand for cooling, and the later peak in the winter (around January) is mostly due to heating demand. This is expected given the typical patterns of demand on the electric grid [61]. The gas use of residential buildings from April to October is stable because the gas is mainly used for water heating and daily cooking (Fig. 7). In Polk County, most residential buildings appear to use gas for heating, therefore, a significant peak of gas use occurs in January because of high heating demand. This is consistent with the U.S. EIA that approximately 67% of homes in this region use natural gas for heating purposes [61]. Within commercial buildings, the electricity use peaks in the summer (July and August) when demand for space cooling is high. Similar to residential buildings, approximately 66% commercial buildings use gas for heating in this region [62], therefore the gas use peaks in the winter around January, the coldest time of the year.

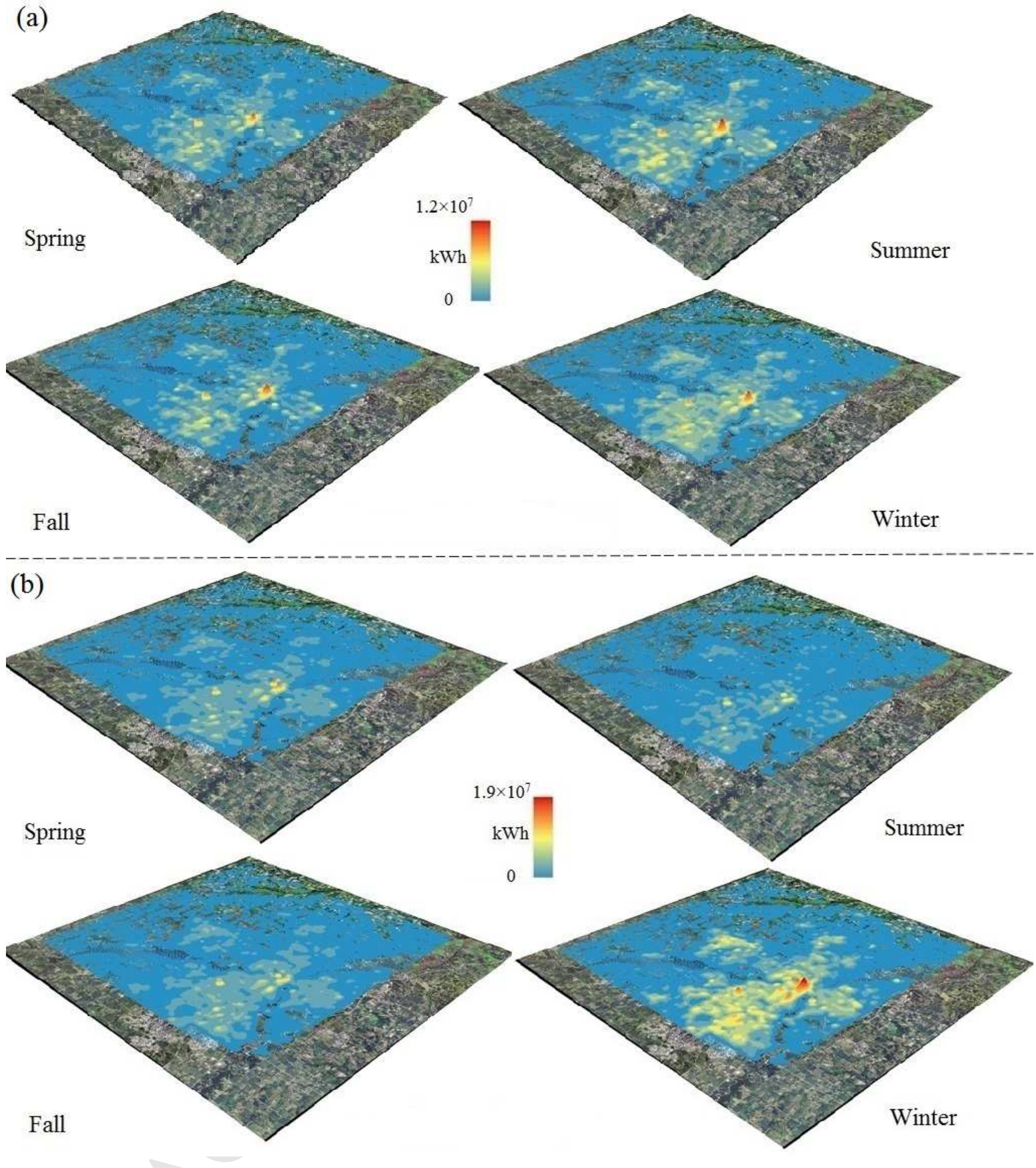

Fig. 6. Spatial patterns of seasonal electricity (a) and gas (b) use in Polk County in 2010.

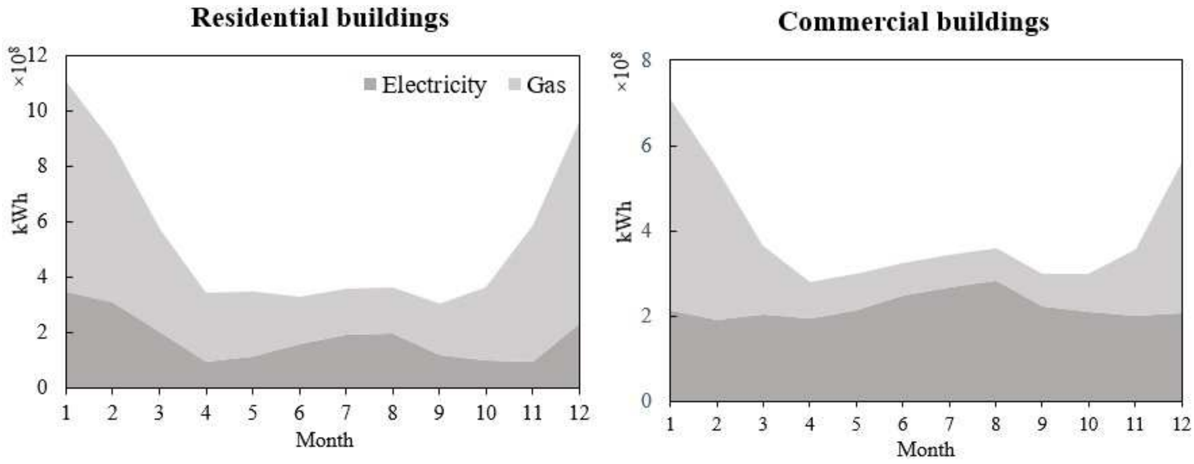

Fig. 7. Monthly building energy use in Polk County in 2010.

4.3.2 Hourly patterns

Hourly building energy use of residential and commercial buildings in the coldest day (January 2) and hottest day (July 14) in 2010 in Polk County is shown in Fig. 8. The hourly electricity use for residential buildings is fairly constant over the entire day on January 2, 2010 (Fig. 8a). The hourly gas consumption on the same day shows two peaks with one at around 8 am and the other at around 7 pm (Fig. 8a). On July 14, 2010, two electricity use peaks occur in the residential buildings (Fig. 8b). The first corresponds to cooling demand in the mid-day, and the later peak occurs around 8 pm as most people return back home, which leads to increased demands for cooling and other internal electricity loads. The hourly gas consumption of residential buildings on July 14, 2010 shows relatively stable patterns during the daytime with one peak around 7 pm (Fig. 8b). Significantly different hourly electricity and gas use patterns occur for commercial buildings (Fig. 8c and d). For example, one electricity use peak and one gas use peak occur on January 2 (Fig. 8c) and July 14 (Fig. 8d), respectively.

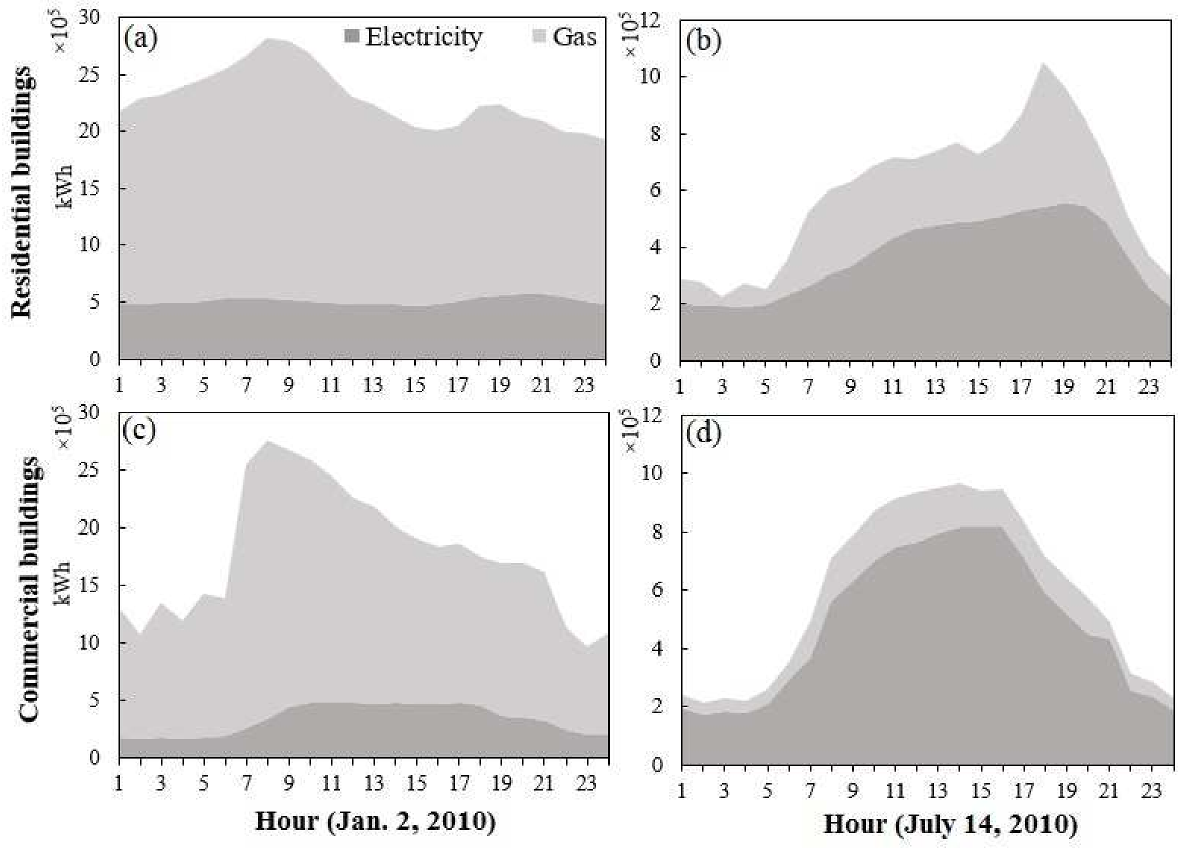

Fig. 8. Simulated hourly building energy use for residential on January 2, 2010 (a) and July 14, 2010 (b) and commercial on January 2, 2010 (c) and July 14, 2010 (d) in Polk County.

4.4 Comparison of building energy use using TMY and actual 2010 weather data

There are significant discrepancies in the estimated building energy use using TMY and actual weather data because the temperature in 2010 is lower in the winter and higher in the spring and summer compared to the TMY (Fig. 9). Specifically, residential buildings show higher electricity use for cooling in the summer and higher gas use for heating in the winter in 2010 compared to the TMY. The electricity use of residential buildings in the summer is significantly underestimated (over 25% in August) using the TMY weather data. The gas consumption is underestimated in the winter (13.1% in December) and is significantly overestimated in the spring (26.2% in March and 30.0% in April) using the TMY weather data. For commercial buildings, the electricity use is underestimated over 10% in the summer, and the gas use is underestimated in the winter (24.3% in December) and is overestimated in the spring (over 17% in April).

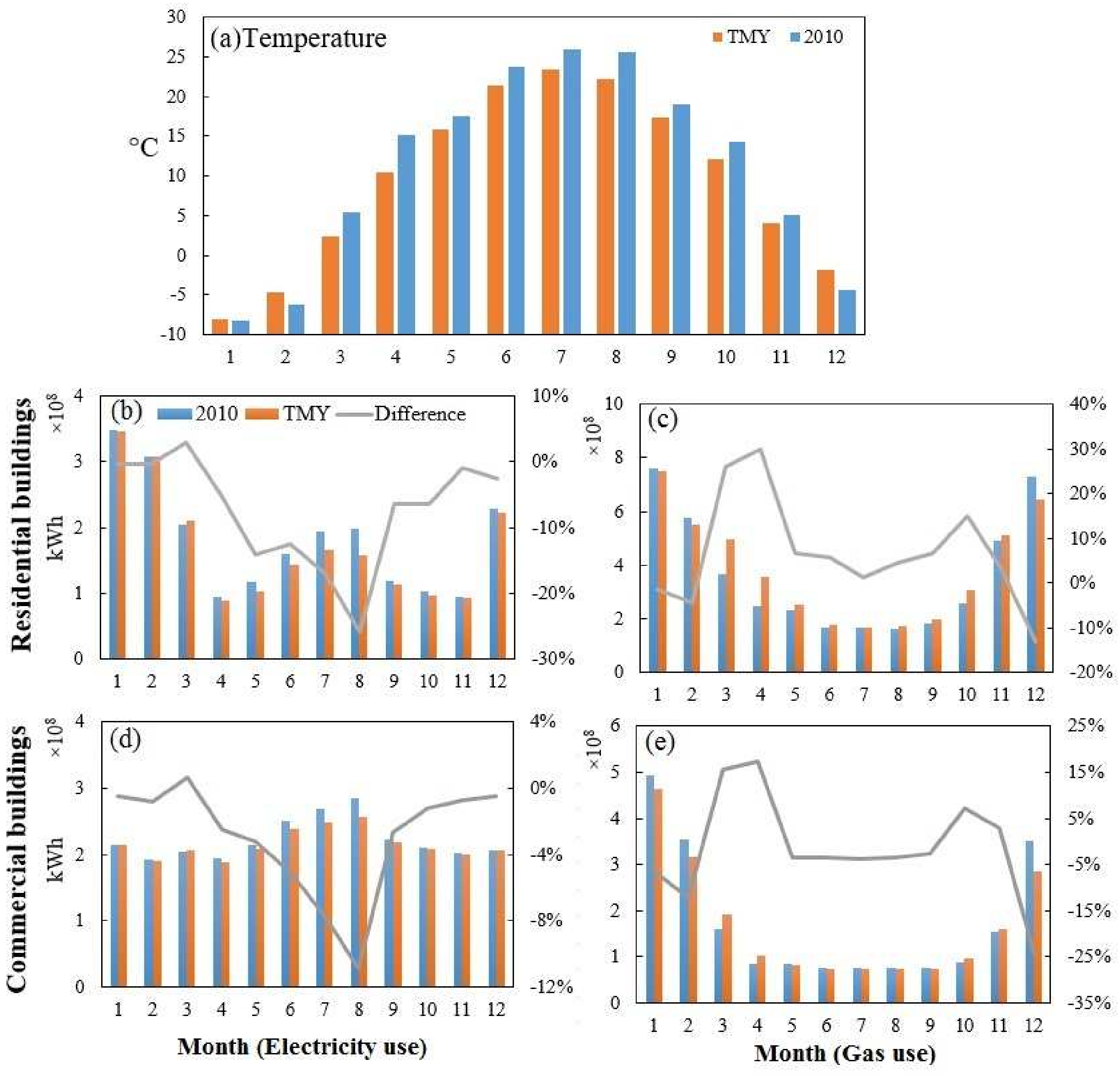

Fig. 9. Monthly temperature in TMY and 2010 weather data (a), simulated residential building electricity (b) and gas (c) use, and simulated commercial buildings electricity (d) and gas (e) use using TMY and 2010 weather data. The grey line is the difference of modeled building energy

use using TMY and 2010 weather data. It was calculated by subtracting modeled building energy use using 2010 weather data from modeled building energy use using TMY weather data.

Significant differences in the modeled hourly energy use using TMY and 2010 actual weather data on January 2nd and July 14th can be found as the temperature in 2010 is much lower on January 2nd and higher on July 14th compared to TMY weather data (Fig.10). In particular, the gas use for heating on January 2nd of 2010 is much higher and the electricity use for cooling on July 14th of 2010 is higher compared to building energy use simulated using TMY weather data. Using TMY weather data, the building gas use on January 2nd was significantly underestimated throughout the entire day, and the building electricity use on July 14th was slightly underestimated, particularly during the hottest time of the day (around 12 pm) and the evening time (around 6pm-9 pm). Overall, due to the extreme temperature in 2010 (lower on January 2nd and higher on July 14th), the underestimation of the combined building energy use is more significant in 2010 if TMY weather data were used in the estimation of building energy use as in previous studies.

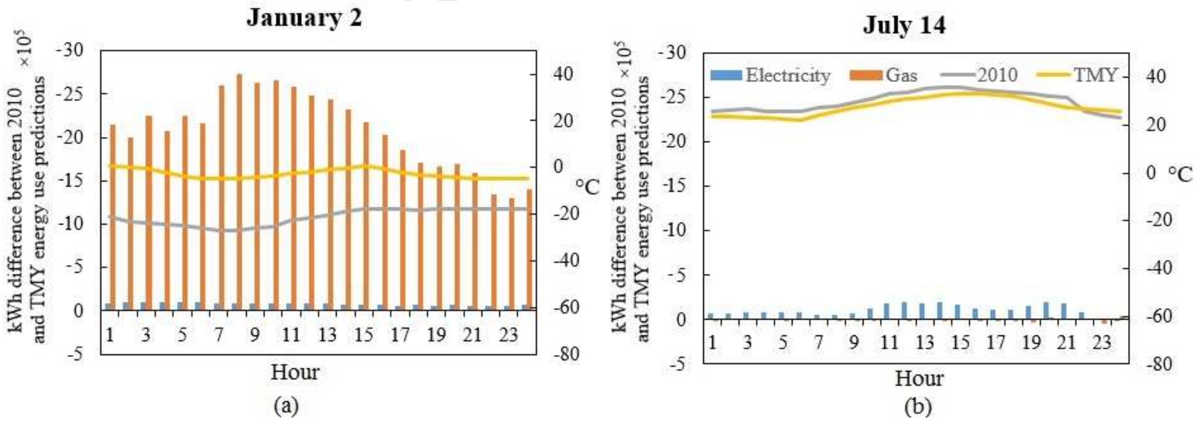

Fig.10. Hourly temperature and differences of modeled building energy use using TMY and 2010 weather data on January 2nd (a) and July 14th (b). The difference was calculated by

subtracting modeled building energy use using 2010 weather data from modeled building energy use using TMY weather data, and the negative energy use difference represents higher building energy use modeled using 2010 weather data.

Overall, the building energy use is sensitive to the surrounding weather conditions such as temperature, wind speed, and humidity. Although the TMY weather data are publicly available for many places, it is not the actual weather data. It is worth to note that the TMY data is not the actual year-to-year weather data and cannot capture extreme weather conditions. Therefore, the urban building energy use using the TMY weather data could be significantly underestimated or overestimated compared to the actual energy use.

5. Discussion

By using all available information for each building at the city level, the CityUBEM can provide an improved spatial representation of building energy use estimation. These information, such as the building type from Assessor's parcel data, the building area from GIS footprint data, and the building height data from the DEM and DSM, is unique for each single building at the city level and ensures to capture electricity and gas use in each building.

5.1 Weather data in urban building energy modeling

Weather data are important in urban building energy modeling for both calibration and simulation. It is clear that the actual weather data should be used in calibrating building energy model and further simulation, and it is common knowledge discussed in building energy model guidelines and currently used in industry. However, the TMY data have been generally used in the city-scale building energy modeling worldwide [36, 38, 39, 44, 45]. The TMY data are generated from the historical weather data over a period of multiple decades and represent average weather conditions rather than the extreme weather condition that might be experienced on a year-to-year basis. As building energy use and its temporal patterns are sensitive to surrounding weather conditions, actual weather data are highly recommended for model calibration and simulation in urban building energy models for a real representation of spatial and temporal patterns of building energy use at the city scale. In the CityUBEM, we embedded the capability of calibrating EnergyPlus using the collected actual weather data at the city scale to ensure that the model is calibrated appropriately using weather data and building energy use data from the same year, while only mismatched TMY weather data were used in previous studies on the city-scale building energy use modeling [36, 38, 39, 44, 45]. Our results also demonstrate a significant difference in building energy use modeled using the TMY and actual weather data and highlight the improvement in the CityUBEM with the consideration of applying actual weather data for model calibration and prediction in studies at the city scale.

5.2 Calibration of urban building energy model

The model calibration in urban building energy models is the key for a successful simulation. However, due to the lack of high-frequency reference data, an improved calibration remains challenging. While the RECS and CBECS data are widely available and used in the urban building energy use modeling work, they can only provide data at the regional scale (usually the total energy use of several states) and annual level. It is hard to get access to metered monthly utility data at high spatial scales (e.g., city, district, or individual building). In fact, due to spatial variations of environmental and socioeconomic conditions (e.g., climate, population density, and economic development), building energy consumption could be different spatially, and the national or regional scale reference data from the RECS and CBECS may not be enough to capture the actual building energy use pattern for a specific location. This may in turn make the calibrated model become unreliable and the final energy use modeling become biased. The challenging issues have been addressed using both regional and local scale reference data from the annual to monthly levels in the CityUBEM modeling framework. The model calibration was initially conducted at the regional level using the RECS and CBECS data. Later, the model was further calibrated using monthly metered electricity and gas use data from the local utility company. Therefore, the proposed CityUBEM shows an improved performance of the city-wide building energy use modeling for the temporal representation with calibrations at the both annual and monthly level as compared to previous studies on the city-level building energy modeling [36, 38, 39, 41].

6. Conclusions

In this study, an improved bottom-up urban building energy use model (CityBEUM) was developed to estimate the annual, monthly, and hourly building energy consumption (including both electricity and gas) of residential and commercial buildings for Polk County. The CityBEUM combines data on building floor areas from GIS footprint data, building prototypes from Assessor's parcel data, number of floors from the LIDAR image-extracted building height data, and EUIs of building prototypes from EnergyPlus. This is the first time that the actual weather data were used for building energy use modeling at the city level although it is a general practice in studies at the single building level. The proposed CityBEUM shows improved performance in calibrating building energy use modeling at the city level with the capability of incorporating actual weather data and both regional and local energy use reference data as compared to previous studies on the city-level building energy modeling [36, 38, 39, 41]. This improvement can reduce the under- and over-estimation of building energy use at the city level if the TMY weather data are used in the model calibration for each building prototype in previous studies. Improved calibrations and the information for all single buildings at the city level provide the possibility for an improved building energy use estimation and prediction at the city scale. Finally, the building electricity and gas consumption in Polk County in 2010 were estimated using the calibrated CityBEUM and actual weather data in 2010.

Several conclusions can be drawn from this study. First, the spatial variation of both electricity and gas consumption is primarily driven by three factors, building type, building height, and building density. The largest electricity and gas consumption locates in the center of the county covered by offices, hotels, and retail stores with the largest building density and height. The building energy use progressively decreases from the urban center to suburban areas, which are composed mostly of residential buildings. Second, the temporal pattern of building energy use was significantly improved with the proposed two-step calibration using the monthly utility data. Finally, comparative analysis indicates that the building energy use could be significantly overestimated or underestimated using the TMY weather data due to its non-trivial difference compared to the actual weather data.

While the modeling performance of urban building energy consumption has been improved in this study through integrating the monthly utility data and actual weather data for model calibration and final simulation, there are still some challenging problems that would benefit from further consideration. First, it is worth to note that there are uncertainties from both the regional and local reference energy use data. For instance, in natural gas distribution networks, very old diaphragm gas meters are widely installed in many countries. While the average percentage errors and the weighted mean error of meters have been found to be acceptable, a large number of meters have failed in subsequent verification and showed limited stability, and may further result in the uncertainties of the collected metered data [63]. When more accurate data (e.g., smart metered energy usage) become available, the CityUBEM can be improved further for better calibration and estimation of building energy use at the city scale. Second, this study only calibrated the building energy use model at the annual and monthly levels. While the hourly building energy use was also estimated and reported, it has not been validated yet. Therefore, to improve the model performance for hourly patterns, hourly metered utility data are needed for calibration in future studies. Third, in this study, only weather data at a single location (airport) were used in estimating building energy consumption for the whole county. However, the building energy use may be sensitive to various surrounding weather conditions such as temperature, which can be influenced by local microclimates such as urban heat island. Previous studies found that the urban heat island effect could increase a city's temperature several degrees as compared to nearby rural areas, especially at night [64]. Therefore, another future research avenue could be to develop spatial varied hourly weather data with the consideration of local microclimates (e.g., urban heat island) and apply our developed urban building energy modeling framework to examine the impact of urban heat island effect on energy consumption. Finally, most previous studies focused on the present or past energy use modeling. An improved understanding of future energy consumption could be equally or even more important as it can offer support for government policy making and city sustainable development planning. Another possible future research avenue could be to investigate future urban building energy consumption under different climate scenarios [65].

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Highlights:

1. An improved urban building energy use model (CityBEUM) was developed
2. The CityBEUM can be calibrated better using monthly reference data
3. Temporal patterns of estimated building energy use were improved using actual weather data
4. Spatial patterns of estimated building energy use were well represented at the county level