Comparative Analysis of Urban Heat Island Effects on Building Energy Consumption in the U.S. Midwest

A combined workflow using Urban Weather Generator and Future Typical Meteorological Year Climate Scenarios

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ABSTRACT: Urban areas often experience higher air temperatures than their surrounding rural counterparts, a phenomenon known as the urban heat island (UHI) effect. This significant human-induced alteration of urban microclimates has notable consequences, especially on urban energy consumption and resulting economic implications. This study presents an in-depth analysis of the UHI effect on urban building energy consumption in a US Midwest neighbourhood. Utilizing a three-phase methodology, the research first simulated UHI intensities with current and future Typical Meteorological Year (TMY) data, integrated with the Local Climate Zone (LCZ) classification system and the Urban Weather Generator (UWG) model. The second phase employed the urban modelling interface (umi) for building energy simulation, capturing the UHI impact on both residential and commercial buildings. The third phase demonstrates that UHI effects lead to reduced heating demand but increased cooling requirements in the future, with residential areas being more affected. The study's findings reveal critical challenges for urban planners and policymakers, emphasizing the need for sustainable designs to address fluctuating heating and cooling demands in changing climates.
KEYWORDS: Urban Heat Island, Local Climate Zones, Urban Weather Generator, Urban Modelling Interface, Building Energy Consumption

1. INTRODUCTION

One of the most documented phenomena of urban climate change caused by urbanization is known as the “urban heat island” (UHI), which conventionally refers to the difference between the urban temperature and corresponding rural or suburban areas [1]. Today, UHI effects are a global concern and have been observed in cities regardless of their locations and size; Chicago, IL [2], Phoenix, AZ [3], Houston, TX [4] in the U.S., Beijing [5] and Xian [6] in China, Sydney [7] and Melbourne [8] in Australia, Stuttgart [9] Germany, and Dublin [10] Ireland to name a few. A number of factors contribute to the formation of the UHI; however, it is largely caused by low evapotranspiration, high solar radiation absorption, air flow blockage, and high anthropogenic heat release in cities [11]. The UHI effects threaten the health and productivity of urban populations and cause general discomfort, respiratory difficulties, and heat-related mortality in climatically diverse cities [12-15]. In addition, the rise in urban temperatures has a significant effect on building energy usage, leading to an increase in cooling energy needs by 10% to 120%, and a reduction in heating energy demands by 3% to 45% depending on location [16].

To measure the UHI intensity in different urban contexts, the conventional approach is to compare air temperature data gathered at one to two meters above ground for “urban” and “rural” conditions at two or more fixed sites and/or from mobile temperature surveys [1]. Utilizing this methodology, [17] examined a decade of air temperature data from five Berlin sites, finding pronounced night-time warmth in the city during summer and slight warmth throughout winter days compared to a reference site scattered with trees. Using urban and suburban weather data collected, [18] reported that UHI effects can double cooling loads and triple peak electricity loads for cooling in urban buildings in Athens, Greece. [19] studied the effect of the London Heat Island on heating and cooling energy in an office building across 24 locations, finding a 25% increase in cooling and a 22% decrease in heating needs in urban versus rural areas. [20] discovered that relocating buildings from suburban to urban areas in Manchester, UK, with average summer UHI, raised chiller energy demands by 9.4% to 12.2%, influenced by building design and glazing ratio. The study used data from iButton temperature sensors.

A major challenge caused by the conventional approach of comparing air temperatures in urban and rural areas to analyse the UHI effects is the substantial variation in urban areas in terms of building density, surface types, and green spaces. To address this, the Local Climate Zones (LCZ) classification system [21] offers a standardized method to categorize urban areas based on their physical and climatic attributes. The LCZ classification scheme recognizes 17 standard classes, 10 built types ranging from LCZ 1 to LCZ 10 and 7 land cover types ranging from LCZ A to LCZ G. Each LCZ type is associated with a typical range of parameter values that describe surface cover, building heights and street aspect ratio, etc.

Another challenge in studying urban heat islands is the need for extensive measuring equipment and effort. To overcome this, modelling tools have been developed, such as the Urban Weather Generator (UWG) [22]. Utilizing the EnergyPlus building energy simulation engine [23] and incorporating the principles of the Town Energy Balance (TEB) model [24], the UWG considers urban characteristics, building properties, and anthropogenic heat for detailed urban temperature simulations. The model calculates hourly air temperature and humidity in urban canyons from measured weather data outside of urban areas. However, determining the ideal model size for accurate urban area simulations and the need for specific data inputs, especially when field data are unavailable, limits the use of the model. This can be particularly challenging for architects and building engineers in the early design phases, where time and resources are limited. To bridge these gaps, a novel methodology was proposed by [25], that couples the LCZ classification with the UWG. This approach generates modified weather data reflecting the unique thermal and morphological characteristics of each LCZ. Using the aforementioned methodology, this study aids in estimating UHI intensity at a neighbourhood scale, thereby enhancing the comprehension of UHI effects on building energy use. The modified weather data, suitable for use in standard energy simulation tools, were generated over a year of simulation at the LCZ scale with UWG providing urban-specific weather data. The data was then combined with Future Typical Meteorological weather data developed by [26]. Subsequently, this UHI-induced weather data, were incorporated into the Urban Modelling Interface (*umi*) developed by [27] to conduct an in-depth energy simulation of urban buildings.

2. METHODOLOGY AND CASE STUDY

Elevated temperatures in urban locales affect building energy performance through significantly increase in cooling loads and to some extent decrease building heating loads. In this context, understanding the intricate relationship between UHI and urban energy consumption is of paramount importance. This study provides a comprehensive understanding of UHI effects on urban building energy consumption, in a scale of urban neighbourhood focusing on the Capitol East, a low-income neighbourhood in the US Midwest city of Des Moines, IA. This neighbourhood was chosen as the pilot study area because of its unique socio-economic characteristics that potentially limit residents' adaptive capacity to regulate indoor temperatures, making it a representative case for many urban areas with similar challenges. The study utilizes both existing Typical Meteorological Year 3 (TMY3) [28] and future projected TMY climate data at the canopy level of the neighbourhood. Fig. 1 depicts the proposed workflow employed in this study, encompassing three fundamental stages:

2.1 Step 1: Weather Data Simulation

The initial phase was centred around hourly simulations of UHI intensities using both current TMY3 and future weather data. This was achieved by coupling the LCZ classification system with the UWG tool. According to the description provided by the LCZ classification dataset, the Capitol East neighbourhood is categorized as Open Low-Rise, LCZ 6 (Fig. 2) in which buildings are small, detached to attached in row, with 1 to 3 stories. Also, scattered trees and abundant plant coverage exist in LCZ 6. After extracting the urban characteristics data such as anthropogenic heat flux, surface albedo, and terrain roughness class from the LCZ dataset sheet, the neighbourhood 3D model [29, 30] was incorporated into the UWG. The UWG was initially developed in MATLAB, with later versions created in Python.

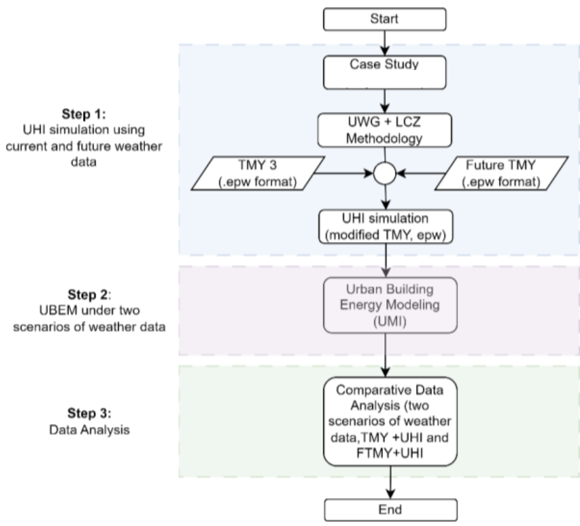

Figure 1. Workflow to study UHI impacts on building energy consumption utilizing both TMY3 and projected Future TMY.

Additionally, the Ladybug tools [31] introduced a user-friendly version of the UWG through Dragonfly, a Grasshopper 3D plugin, enabling urban designers to conduct climate and UHI modelling within the Rhino 3D interface. To ensure a holistic representation of both buildings and trees, spatially explicit data from a complete inventory of 340 existing buildings and

1142 trees (both yard and street trees) and buildings were added into the model.

Figure 2. Images, 3-D illustration, and properties of LCZ6 - Open low-rise, for the Capitol East neighborhood, Des Moines, IA.

Fig. 3 illustrates levels of data that the neighbourhood 3-D model includes. According to the assessor's data collected for 340 buildings in the neighbourhood, 259 buildings had active air conditioning systems and 81 were naturally ventilated. In the UWG model, construction information detailing the material properties and performance of the entire structure was incorporated to represent conditioned buildings and their associated waste heat. Buildings without active air conditioning were treated as shading devices.

Figure 3. Layers added into the neighborhood 3-D model.

Consequently, 21 building templates, 13 for buildings with active AC and 8 for non-AC buildings, were generated in the UWG model to represent both commercial and residential buildings in the neighbourhood. After integrating required data, the UHI simulation were run for two scenarios of weather data; existing TMY 3 data recorded at the Des Moines airport and future TMY created by combining existing TMY data with model-projected changes in climate.

The calendar-year-long simulation showed that the average annual UHI intensity was at 0.54° with the current weather data and 0.56°C for the future weather scenario. Moreover, the maximum UHI peaked at 12.4°C for the current scenario and 13.6°C for the future scenario, both occurring on February 1st in the afternoon post-sunset. This pattern indicates a potential rise in urban heat effects in future conditions due to the changing climate. The generated weather data in this step, tagged as TMY3+UHI and FTMY+UHI formatted in EnergyPlus Weather (EPW), serve as the major input for the subsequent phase of this study.

2.2 Step 2: Urban Building Energy Modelling (UBEM)

To conduct the building energy simulation at the neighbourhood scale, the urban modelling interface (*umi*), a Rhinoceros-based urban modelling design tool, was employed. *umi* utilizes EnergyPlus as a simulation engine for buildings thermal simulation. *umi* is based on the Shoeboxer algorithm, a fully automated, reliable, abstracted, and rapid multizone urban simulation workflow to decrease the geometric complexity of thermal models and facilitate large-scale urban simulations [32, 33]. Several recent studies [34-36] have employed *umi* to simulate energy usage within urban environments including the Grove Park neighbourhood of Atlanta, two neighbourhoods in Boston, MA, USA, and an area in Dublin city centre.

Four main scenarios were designed for this study using four weather files: the current TMY3, TMY3+UHI, align with future projections FTMY and FTMY+UHI. The building construction materials and trees geometry were added in *umi* model based on the data gathered from the Assessor's office of the County.

The city of Des Moines, IA falls under climate zone 5A based on the International Energy Conservation Code (IECC), classifying it as a cold climate. The neighbourhood is characterized predominantly by single-family housing [37], has emerged as a focal point for revitalization efforts, led collaboratively by residents and city planners. Covering an area of 282,778 square meters, the area's housing stock, dating back to the early 1900s, underscores an urgent need for enhancements [38-39].

2.3. Step 3: Comparative Data Analysis

In order to examine the UHI impacts on the energy needs for heating, cooling, and their cumulative demand, an energy simulation framework was developed. This framework utilized four distinct weather data files: the current TMY3 and TMY3+UHI, in conjunction with future projections FTMY and

FTMY+UHI. These were instrumental in performing energy simulations using the *umi* software and the findings from this step are detailed in the following sections.

Fig. 4 demonstrates that the UHI effects resulted in an increase of consumption for cooling by 7.31% in the current weather scenario and 2.77% for future projections for all buildings in the neighbourhood. The most significant rise in cooling energy requirements for all buildings occurred in April and May, a pattern consistent in both the current and future scenarios. In contrast, the heating demand exhibits a decline of 3.17% in the current scenario and 3.23% in the future scenario. This decrease was most pronounced in September and October for both the current and future scenarios. When the impacts of UHI are taken into account, the overall energy consumption (cooling + heating) shows a decrease of 2.23% and 2.29% in the current and future scenarios, respectively. This translates to a fall from 4881 MWh to 4772 MWh in the current, and from 4405 MWh to 4304 MWh in future scenario. The UHI effect consistently caused a decrease in heating requirements while simultaneously increasing the demand for cooling in both scenarios. Additionally, the overall energy consumption, when considering the UHI, is on a downward trend, with the decrease being nearly identical for both the current and future scenarios.

Moreover, a sector-specific analysis of the UHI effect indicates subtle differences in energy consumption for both scenarios. In the residential sector, there was a decline in energy usage for combined heating and cooling purposes from 4094 MWh to 3993 MWh, marking a 2.46% reduction for the current scenario, and from 3649 MWh to 3551 MWh, showing a 2.71% decrease for the future scenario. Conversely, the commercial sector exhibited a modest downturn from 787 MWh to 778 MWh, amounting to a 1.11% decrease in the current scenario, and a marginal decline from 755 MWh to 754 MWh, or 0.18%, in the future scenario.

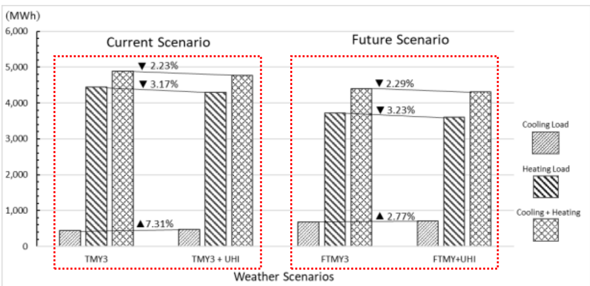

Figure 4. Actual and percentage change in cooling, heating, and combined energy consumption under four weather scenarios

Delving into a comparative analysis between current and future energy scenarios, Fig. 5 depicts patterns of energy consumption for cooling, heating, and their cumulative effect across the four noted scenarios. These scenarios are arranged from the highest to the lowest total energy consumption, considering both the presence and absence of UHI effects.

The initial scenario, using current TMY3 weather data without the UHI effect, shows the highest energy consumption. Simulations suggest a notable reduction of 9.75% in annual energy use when transitioning to the future scenario, with figures dropping from 4881 MWh to 4405 MWh. This change is marked by a 56% increase in cooling load and a 16.27% decrease in heating load for neighbourhood buildings.

Incorporating the UHI effect into both the current TMY3 and future TMY scenarios leads to a decline in total energy consumption, primarily due to a reduction in heating load, which is more significant than the increase in cooling load. By comparing current TMY3 with UHI effects to future TMY with UHI, an estimated 9.81% decrease in overall energy use, a 16.32% reduction in heating loads, and a 49.79% increase in cooling loads are observed. Among these scenarios, the future weather data with the added UHI effect shows the lowest energy use for combined heating and cooling.

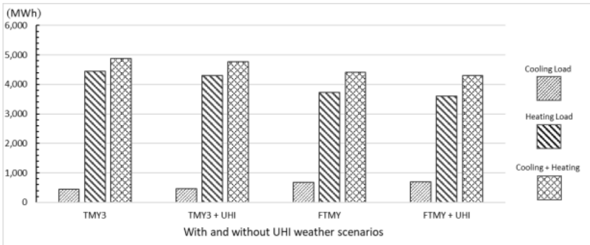

Figure 5. Energy consumption comparison for cooling, heating, and combined energy under current and future weather scenarios with and without the UHI effect.

The analysis between residential and commercial buildings indicates different impacts of projected changes. Under the future TMY scenario, residential buildings' cooling load is anticipated to rise by 75% compared to the current TMY3 scenario. However, this increase is reduced to 62% when the UHI effect is taken into account, comparing the current TMY3 with UHI against the FTMY with UHI. This reduction can be attributed to the fact that the difference between the future TMY and the current TMY3 already accounts for a significant temperature increase, which is further amplified in the scenarios with UHI. Commercial buildings, in contrast, exhibit a 36.4% increase in cooling load when comparing current and future data, with a slight increase to 36.6% when including the UHI effect. For heating, residential buildings are anticipated to have a 15.80% increase in demand from the current TMY3 to the future TMY, and a similar increase from the UHI-influenced current TMY3 to the future TMY.

3. DISCUSSION AND CONCLUSION

This paper offers significant insights into UHI effects and their implications on building energy consumption at an urban scale. It described a three-step methodology that involves simulating UHI intensity using standard TMY data and projected weather data, followed by integrating this modified weather data into urban building energy simulations. This architect-friendly approach highlights the importance of considering UHI effects in studies of building energy.

The Capitol East neighbourhood, characterized as an Open Low-rise area, was modelled in detail, integrating both built and vegetative elements such as trees and grass areas to accurately represent the urban landscape. This detailed modelling, in conjunction with the method of integrating the LCZ classification system with the UWG model, allowed for the creation of weather data that not only reflected present conditions but also anticipated future shifts in UHI intensity.

The following phase of urban building energy modelling provided crucial findings, specifically regarding the UHI's influence on energy consumption within the modelled buildings and the differential impacts on residential and commercial sectors. Specifically, the simulations estimated a 9.81% decrease in overall energy use, a 16.32% reduction in heating loads, and a 49.79% rise in cooling loads when comparing the UHI-influenced current weather data to future projections. Moreover, the UHI effect on the residential sector was particularly notable, as evidenced by an increase in cooling load of 75% in future scenarios, which decreased to 62% with the inclusion of UHI effects. The commercial sector, while also impacted, showed a consistent increase in cooling load of approximately 36% across both current and future scenarios, with and without UHI.

The findings highlight significant challenges that urban planners and policymakers must navigate due to evolving climate conditions, underlining the importance of sustainable design practices that address both heating and cooling requirements. Future research should aim to apply this methodology across diverse climatic regions to uncover the different impacts of UHI in varying settings. Moreover, this study's focus was limited to a selected neighbourhood characterized as LC6-Open Low Rise. Broadening the scope of this research to include other LCZ built types, particularly downtown areas typically comprising compact high or mid-rise buildings, would offer deeper insights into the UHI effect on a range of building typologies, including mixed-use and office buildings.

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