Comparison of building energy performance in three urban sites using field measurements and modelling in Kayseri, Turkiye

B I Toren[1], T Sharmin[1]
[1] Welsh School of Architecture, Cardiff University

* Corresponding author email: torenbi@cardiff.ac.uk

Abstract. Despite the fact that the interrelationships between urban microclimates and energy demand have been recognised, there are not many processes that combine microclimatic boundary conditions to estimate energy consumption in parametric morphological investigations. Therefore, this paper will demonstrate a simple step-by-step methodology to incorporate the effect of urban microclimate on building cooling energy demand in semi-arid climatic areas. In this study, the combination of ENVI-met, Urban Weather Generator (UWG) and Rhino grasshopper are used to investigate the connection between microclimate and energy in the climatic environment of Kayseri. This coupling's potential is investigated across compact high-rise, midrise and low-rise buildings, focusing on the cooling requirement on the hottest days. The comparative study shows how and to what extent urban geometry, building height in this case, contributes to modifying the magnitude of microclimate impact on building cooling performance.

1. Introduction

The urban environment's features, particularly the local microclimate, are altered by the city's rapid expansion in development. The worldwide demographic growth in urbanised areas has been causing global energy consumption, which is predicted to increase by 22 to 46% by 2060 [1]. Predicting the impact of the urban form on the local microclimate, which affects not only outdoor thermal comfort but also building energy use, demand, and building thermal resilience, is one of the key issues throughout the urban design process. The analysis of the energy performance of buildings and their effects on the environment must increasingly consider the local climatic conditions, according to previous empirical and theoretical research [2- 4]. Many researchers have focused on ways to measure the effect of urban microclimates on energy usage during the last 20 years. These studies, which address various scales and resolution levels, range from relatively simple validated methods in which TMY weather data for the energy simulation is modified by a predictive microclimatic calculation method, such as the Canyon Air Temperature (CAT) model or the Urban Weather Generator (UWG) model [5], to more complex methods in which Building Energy Simulation (BES) and microclimatic simulation tools are coupled to achieve greater reliability. The Urban Weather Generator (UWG) is a methodology and software tool applied for the estimation of hourly local urban canopy air temperature and humidity. This estimation is based on factors such as cityscape geometry and urban land use. Boccalatte et al. [6] examines the Urban Heat Island (UHI) phenomenon through the utilisation of the Urban Weather Generator tool (UWG). The analysis focused on comparing the intensity of the urban heat island (UHI), which refers to the increase in air temperature in urban areas compared to rural areas. The energy consumption for heating and cooling in a residential building has been evaluated within the EnergyPlus simulation environment, considering various urban weather conditions and district characteristics. Regarding the two urban configurations under consideration, it is observed that the enhanced design exhibits a marginal reduction of 2.2% in annual energy consumption compared to the reference case. However, when analysing the division of heating and cooling load, the disparity increases to approximately 8%, with contrasting patterns observed for heating and cooling requirements.

The comprehensive examination of the urban microclimate necessitates the utilisation of Computational Fluid Dynamics (CFD) tools capable of simulating intricate heat and mass transfer mechanisms. The ENVI-met model is a prognostic microclimate model that has been specifically developed to simulate the complex interactions among surfaces, plants, and air within an urban setting [7]. The use of this method is prevalent in the estimation and evaluation of outdoor thermal comfort [8], [9] , as well as in the examination of the influence of the urban microclimate on building energy consumption [2], [10].

The automated extraction and flow of simulation input parameters to various simulation engines, as well as the management or post-processing of their outputs, are all provided by Grasshopper without any direct link. In urban parametric research, this potent characteristic may be efficiently used to create many iterations [3], [11]In this regard, Ladybug tools have introduced new capabilities; these plugins offer a substantial collection of Grasshopper components interacting with various validated simulation engines (for example, Radiance for daylight, EnergyPlus for energy modelling, Open-FOAM for Computational Fluid Dynamics (CFD), and most recently Envi-MET for microclimatic modelling), which can now be easily coupled for sophisticated environmental evaluations. In this study, the authors use the capabilities of digital technologies to present a novel coupling approach between ENVI-met, UWG, and Energy Plus using Grasshopper for an efficient and automated microclimatic and energy performance evaluation. This procedure is used in the semi-arid climate of Kayseri, Turkey. This paper presents and discusses the results obtained from running the analytic workflow on three distinct typologies, each with three density scenarios, following a comprehensive description of the workflow. This paper concludes by engaging in a discussion regarding the potential for implementing this workflow, as well as exploring potential avenues for future research and development.

2. Methodology

Figure 1 depicts the steps taken in the analytical process, during which the energy model was run utilising three distinct weather data inputs: The first one is the EPW file from the airport, the second one is the urban EPW weather file generated by UWG, and the last one is the microclimatic data generated by ENVI-met using the Rural EPW weather file as the input. The study determined that the 21st of June was the weekday with the lowest dry-bulb temperatures throughout the cooling season based on the EPW file of Erkilet Kayseri Airport, which is indicative of Kayseri's semi-arid climate. This method was used to determine the cooling requirement precisely for that day.

Kayseri (Fig.2) is a major industrialised city in Turkey's Central Anatolia. Kayseri has a cold semi-arid climate, as classified by the Koppen climate classification (BSk), or a temperate continental climate, as classified by the Trewartha climate classification (Dc). Winters are cold and snowy, while summers are hot and dry with cool evenings. The city of Kayseri has its highest average temperatures during the month of July, with temperatures peaking at 30°C. Conversely, the lowest average temperatures are observed in January, with temperatures dropping to an average low of -6°C. Specifically, July experiences an average low of 13°C and January encounters an average high of 4°C, thus illustrating the extreme thermal contrast across the seasons in this region.

 2600 (2023) 032007 doi:10.1088/1742-6596/2600/3/032007

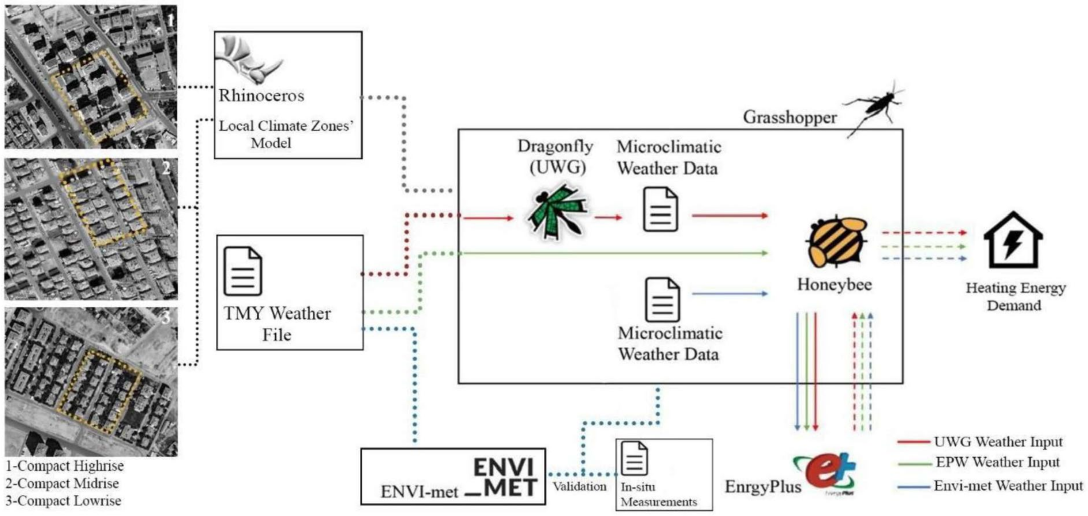

Figure 1. Framework of the study

2.1. Microclimatic Measurement

The data collection was done in June. The in-situ measurement instruments are HOBO and Tiny Tag data loggers for the temperature and humidity, and the loggers recorded data every ten minutes (Fig.1). Besides, hand hotwire anemometer was used for wind speed. The shelters were used to protect the data loggers from direct sunlight. These measurements used for validation of the data from Envi-met.

Figure 2. The equipment for in-situ measurements and location of Kayseri

2.2. Simulation Tools

ENVI-met: After modelling the sites on Rhino, microclimatic data for three local climate zones are generated for the worst-case scenarios using ENVI-met. The procedure for preparing input data for ENVI-met microclimatic modelling (version 5.1.1) was carried out using a specific set of components within the Grasshopper platform. The Area Input (.INX) and Simulation (.SIM) Files are generated automatically for each iteration by these parts from a variety of source files. The provided inputs include the geometric characteristics of the structures, rural climatic variables such as wind speed, wind direction, hourly air temperature, and relative humidity, along with the ENVI-met model variations. In this specific instance, the grid density was established at 5 metres. After each simulation, the results were expeditiously uploaded to the Grasshopper platform.

Urban Weather Generator: In parallel to Envi-met simulation, Urban Weather Generator (UWG) is used to generate the urban EPW weather file. Next, ENVI-met and UWG data are compared with actual measurements carried out on-site for validation purposes which are further used to calibrate the input rural EPW data for UWG to generate the annual urban EPW data containing microclimate effects. For each iteration, energy modelling purposes involved making use of both modified EPW files and the original 'rural' EPW file. The direct and diffuse solar radiation values have been retained from the original EPW file. Although ENVI-met generates related outputs, the disparities in data resolution and data structure between the microclimate outputs and Energy Plus inputs prevent being included in the coupling process at this stage.

Cooling Demand Evaluation: A comprehensive assessment of cooling energy demand was carried out employing the Grasshopper Ladybug Honeybee and Dragonfly components set. This evaluation connected three distinct EPW files (representing rural, urban, and microclimatic conditions) for each typology. In addition, the assessment encompassed three different floor area ratio (FAR) scenarios. The energy simulations were carried out for residential buildings in accordance with the hypothesis that the urban heat island (UHI) phenomenon primarily impacts the cooling demand of residential structures, primarily due to nighttime occupancy patterns. The parameters used in the energy model were established based on the baseline definitions outlined in Mangan et. al [12] which complied to the Turkish energy savings in buildings code. However, it is important to note that this study also considered the inclusion of window-driven natural ventilation.

3. Results and Discussion

This section analyses the microclimate result and the cooling demand of each zone with different height. In comparison to the rural EPW file, the results of the UWG air temperature measurements (shown in orange) indicate a nighttime air temperature increase of up to 1.5 degrees occurring at 10pm, showing UWG capacity to identify Urban Heat Island (UHI) effect. Similar effect was noted in [13]. The difference in temperature between this climate zones appears to be quite small (up to 0.5 degrees), which indicates that the impact of urban geometry characteristics on UHI as measured by UWG is almost insignificant. The ENVI-met microclimatic EPW file recorded a larger night-time temperature increase of up to 3 degrees but also a temperature drop of up to 1.5 degrees during the daytime, with larger variances amongst local climate zones.

Figure 3 depicts a summary of the day's cooling requirement, which was compiled on the 21st of July. When the ENVI-met microclimatic weather file was utilised (in blue), the findings indicate that there was a significant increase of up to 49% in the amount of cooling energy demand that was required. These results are not completely consistent across all of the possible density and different climate zones configurations; larger cooling load differences were reported in the high-rise typology, which corresponds to the higher UHI intensity that was computed in the figure 3. The growth in the amount of self-shading provided by the urban environment is the primary factor behind the decline in the amount of cooling that is required at increasing densities in both midrise and high-rise typologies.

However, for the same cases, the rise in night-time temperatures in higher density highlights a phenomenon of heat storage in the urban canyons which might increase the magnitude of UHI, which is a trade-off that should be further studied in longer time segments. This trend is significantly more distinct when using the ENVI- met microclimatic weather file in comparison the rural EPW. In the C. high-rise and C. low rise typologies, the UWG weather file resulted in the highest cooling requirement of the three different weather file inputs. These findings imply a differential impact of urban microclimatic variables on energy performance as measured by these three methodologies, findings that require additional investigation and validation. All three simulation techniques (rural, urban, and microclimatic) showed the same pattern with an almost constant cooling demand due to the compact urban form and continuous mutual shading in all density scenarios above a floor area ratio of 2.

IOP Publishing
2600 (2023) 032007 doi:10.1088/1742-6596/2600/3/032007

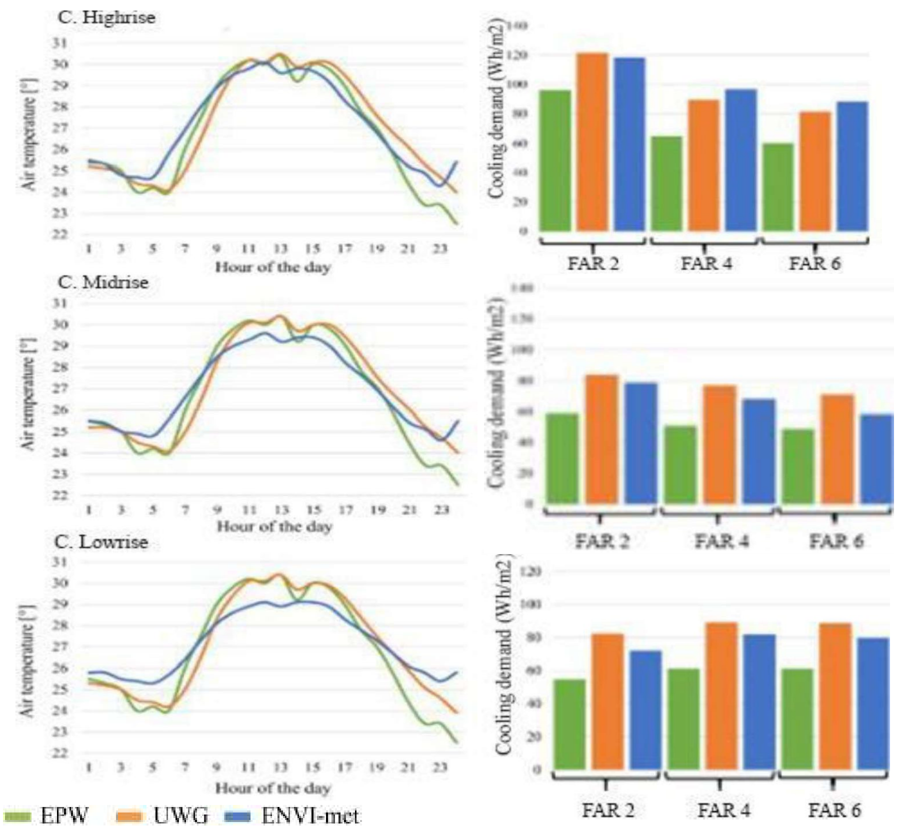

Figure 3. Daily air temperature and Daily cooling demand for recorded for three different weather files

4. Conclusion

The advancement of parametric computational tools has played a crucial role in enabling the automated integration of urban performance analysis tools. This has resulted in a more efficient integration of microclimatic factors within design processes prioritising performance-driven outcomes. This article presented a parametric approach to accounting for the UHI impact in an energy evaluation of 9 distinct scenarios, using Envi-met's outputs of air temperature and relative humidity. The necessity of include microclimatic data in energy analysis is shown by the observation of UHI intensities as high as three degrees and associated variations in cooling demand as high as 49%. The study contrasted the effects of dense urban settings on cooling demand. It demonstrated how and to what degree building geometry contributes to vary the amount of microclimate influence on building energy performance.

During the design process of dense urban districts and structures, this workflow, which was designed in the widely used Grasshopper parametric environment, may be simply copied and yield valuable performative indicators. Future applications and development of this workflow should investigate the impact of wind flows on energy performance, refine the process by which short- and long-wave radiation outputs from ENVI- met can be imported into EnergyPlus, and deal with the massive discrepancy in computational time (from 7 hours to 20 minutes) between coupled and uncoupled energy modelling.

Acknowledgements
This article is extracted from part of Basak Ilknur Toren PhD thesis.

References

[1] H. Leng, X. Chen, Y. Ma, N. H. Wong, and T. Ming, 'Urban morphology and building heating energy consumption: Evidence from Harbin, a severe cold region city', *Energy Build*, vol. 224, p. 110143, Oct. 2020, doi: 10.1016/J.ENBUILD.2020.110143.
[2] S. Tsoka, K. Velikou, K. Tolika, and A. Tsikaloudaki, 'Evaluating the Combined Effect of Climate Change and Urban Microclimate on Buildings' Heating and Cooling Energy Demand in a Mediterranean City', 2021, doi: 10.3390/en14185799.
[3] J. Y. Deng, N. H. Wong, and X. Zheng, 'Effects of street geometries on building cooling demand in Nanjing, China', *Renewable and Sustainable Energy Reviews*, vol. 142, p. 110862, May 2021, doi: 10.1016/j.rser.2021.110862.
[4] J. Yang, Y. Yang, D. Sun, C. Jin, and X. Xiao, 'Influence of urban morphological characteristics on thermal environment', *Sustain Cities Soc*, vol. 72, p. 103045, Sep. 2021, doi: 10.1016/j.scs.2021.103045.
[5] J. Natanian, D. Maiullari, A. Yezioro, and T. Auer, 'Synergetic urban microclimate and energy simulation parametric workflow', *J Phys Conf Ser*, vol. 1343, no. 1, 2019, doi: 10.1088/1742-6596/1343/1/012006.
[6] A. Boccalatte, M. Fossa, L. Gaillard, and C. Menezo, 'Microclimate and urban morphology effects on building energy demand in different European cities', *Energy Build*, vol. 224, p. 110129, Oct. 2020, doi: 10.1016/J.ENBUILD.2020.110129.
[7] E. Consumption, 'Energy Consumption', pp. 1–15, 2021.
[8] S. Achour-Younsi and F. Kharrat, 'Outdoor Thermal Comfort: Impact of the Geometry of an Urban Street Canyon in a Mediterranean Subtropical Climate – Case Study Tunis, Tunisia', *Procedia Soc Behav Sci*, vol. 216, pp. 689–700, Jan. 2016, doi: 10.1016/j.sbspro.2015.12.062.
[9] J. Natanian, P. Kastner, T. Dogan, and T. Auer, 'From energy performative to livable Mediterranean cities: An annual outdoor thermal comfort and energy balance cross-climatic typological study', *Energy Build*, vol. 224, p. 110283, Oct. 2020, doi: 10.1016/J.ENBUILD.2020.110283.
[10] S. Yang, L. (Leon) Wang, T. Stathopoulos, and A. M. Marey, 'Urban microclimate and its impact on built environment – A review', *Build Environ*, vol. 238, p. 110334, Jun. 2023, doi: 10.1016/J.BUILDENV.2023.110334.
[11] Y. Ibrahim, T. Kershaw, P. Shepherd, and I. Elwy, 'A parametric optimisation study of urban geometry design to assess outdoor thermal comfort', *Sustain Cities Soc*, vol. 75, p. 103352, Dec. 2021, doi: 10.1016/J.SCS.2021.103352.
[12] S. D. Mangan, G. Koclar Oral, I. Erdemir Kocagil, and I. Sozen, 'The impact of urban form on building energy and cost efficiency in temperate-humid zones', *Journal of Building Engineering*, vol. 33, p. 101626, Jan. 2021, doi: 10.1016/J.JOBE.2020.101626.
[13] G. Mills, 'Urban climatology: History, status and prospects', *Urban Clim*, vol. 10, no. P3, pp. 479–489, Dec. 2014, doi: 10.1016/J.UCLIM.2014.06.00