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Assessing the urban heat island and its energy impact on residential buildings in Mediterranean climate: Barcelona case study

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ABSTRACT

The Urban Heat Island (UHI) effect is particularly concerning in Mediterranean zone, as climate change and UHI scenarios foresee a fast growth of energy consumption for next years, due to the widespread of air conditioning systems and the increase of cooling demand. The UHI intensity is thus a key variable for the prediction of energy needs in urban areas.

This study investigates the intensity of UHI in Barcelona (Spain), the densest Mediterranean coastal city, and its impact on cooling demand of residential buildings.

The experimental analysis is based on temperature data from rural and urban Weather Stations and field measurements at street level. The maximum average UHI intensity is found to be 2.8 °C in winter and 1.7 °C in summer, reaching 4.3 °C at street level. Simulations performed with EnergyPlus indicate that the UHI intensity increases the sensible cooling load of residential buildings by around 18%–28%, depending on UHI intensity, amount of solar gains and cooling set point.

In the light of the results, the UHI intensity in Mediterranean context should be properly considered in performing energy evaluations for urban contexts, since standard meteorological data from airport weather stations are not found to be accurate enough.

1. Introduction

One of major concerns of our days is to reduce energy consumption and environmental footprint of cities and buildings. In Mediterranean climate, this issue is more and more associated with the summer season. The widespread use of air conditioning in residential buildings has led to a fast increase of electricity consumption over the last few decades [1]. This trend is particularly alarming, because electricity consumption is growing much faster than Gross Domestic Product (GDP), primary energy consumption and population growth [2]. Furthermore, climate change and urban warming contribute to raise the cooling energy consumption even more in this context. In effect, the predicted climate scenarios for the next 100 years [3] foresee an increase of tropical nights (>20 °C) and hot days (>35 °C) for the Mediterranean basin. So, the combination of global warming with the so-called "urban heat island" (UHI) effect makes the energy issue particularly concerning in Mediterranean basin.

Higher temperatures cause a significant increase of the buildings' energy consumption, since they affect the already onerous cooling demand [4–10]. It is indeed estimated that temperate and mid-latitude climates will experience the largest increase in annual energy consumption due to climate change and UHI scenarios, because cooling will be needed also in autumn and spring periods [11,12]. The UHI intensity is therefore a crucial variable for the estimation of buildings energy performance in Mediterranean climate. Nonetheless, it is still rather overlooked in the practice of energy assessment.

The aim of this paper is to quantify the average UHI intensity in a dense urban area facing the Mediterranean Sea and its impact on cooling energy demand for residential buildings. To this purpose, the city of Barcelona, Spain, has been selected as case study.

1.1. Background

Urban climate and UHI have been widely investigated in the last decades [13,14] and several studies have been conducted in the Mediterranean zone. According to the review by Santamouris [15], the UHI intensity varies between 2 °C and 10 °C in this context.

The UHI intensity was firstly investigated in Greece, in the area of Great Athens, by considering air temperature data collected from

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a network of urban and sub-urban weather stations between 1996 and 1998 [16–18]. A strong UHI intensity was recorded in summer during the daytime, when the temperature difference between suburban weather stations and urban stations reached up to 15 °C in locations far away from surrounding buildings. During the night time, the temperature difference was smaller ranging between 2 °C and 5 °C. More recently, Giannopoulou et al. [19] reported a variation of the UHI intensity in Athens between 3.0 °C and 5.3 °C during the day time and between 1.3 °C and 2.3 °C during the night time. Kolokotsa et al. [20] studied the UHI in the Hania, Greece, finding a maximum daily UHI intensity of 8 °C and an average urban-rural temperature difference of almost 2.6 °C. A further study was conducted by Giannaros and Melas in the coastal city of Thessaloniki [21], who identified a maximum UHI intensity between 2 °C and 4 °C. An average maximum UHI intensity of 2 °C was found also in Volos, a medium-sized coastal city in central Greece [22].

In Spain, an early study on the UHI intensity in Barcelona was carried out by Moreno-Garcia in the 90s [23], based on air temperature data (daily maximum and minimum) recorded by two fixed meteorological stations during the period 1970–1984. The average difference between urban and rural temperature was found to be +1.4 °C (+2.9° C referring to the average daily minimum), while the maximum UHI intensity exceeded 8 °C. According to the study, the average UHI intensity was slightly greater during winter months.

In Italy, the UHI intensity was firstly investigated in Rome by Colacino and Lavagnini [24], using daily minimum temperature data measured from a network of urban and rural weather stations over the period 1964–1975; the UHI intensity was found to be approximately 2.5 °C during winter and 4.3 °C during summer. More recently, Bonacquisti et al. [25] reported an urban-rural temperature difference of around 3 °C, with a maximum of 5 °C in summer, during night-time. These results were confirmed by additional studies carried out in Rome [26–28], which detected an average UHI intensity between 3 °C and 4 °C, with a peak intensity of 4.5 °C in summer. Besides experimental studies, some numerical analysis on the UHI over the metropolitan region of Rome and the influence of the sea breeze on the urban boundary layer have been recently presented [29,30].

For what concern the Mediterranean area, it has to be mentioned also the work carried out in Tel Aviv, Israel, by Saaroni et al. [31]; the authors found that the UHI intensity in the coastal city varies between 5 °C at street level and only 2.5 °C at roof level, thanks to the mitigating effect of the Sea breeze.

Several studies on the UHI also detected a spatial variability of urban temperatures, mainly due to building density, presence of parks, water bodies or orographic characteristics of the different areas within the city [32–34]. Many relationships between the UHI intensity and the canyon geometry have also been identified [35–40]. However, results on this topic are still contradictory, being strictly dependent on the reference climate and the methodologies adopted in the studies.

Differently, many studies agree on the negative impact of the UHI on the building energy performance. According to the studies scrutinized by Santamouris in a recent review [41], the UHI determines an average increase of 11% of the annual energy demand (23% for the cooling load). The same author used hourly data of air temperature recorded in the city of Athens to calculate the energy loads for an office building with TRNSYS model [17]; the results showed an increase of about 120% of the monthly cooling load for the building in the city centre with respect to the suburban location and a decrease of the heating load by 38%. Another study by Hassid et al. [8] estimated the impact of the UHI on residential cooling loads in Athens, using the energy model DOE2.1E. and climate data from four urban stations and two rural stations; an increase of the sensible cooling loads of about 15–50% was found with urban temperatures instead of rural temperatures.

Akbari et al. [42] investigated the energy-saving potential of different heat island reduction strategies, for about 240 locations in the US.A. According to calculations with DOE-2.IE model, the potential energy saving was about 12–25% for residential buildings, 5–18% for office buildings and 7–17% for retail stores. Bueno et al. [43], instead, presented a new "urban canopy and building energy model" to evaluate the change of energy demand of residential buildings under different UHI scenarios; results showed a 5% increase of cooling demand per 1 K increase in the maximum UHI effect at night.

The impact of the UHI on buildings energy performance has been widely investigated also in tropical climates. Ignatius et al. [38] estimated the UHI intensity in the city of Singapore with the "STEVE" tool and calculated its impact on buildings energy performance with the "Integrated Environmental Solutions" (IES) software; the analysis showed that the cooling load for an office building increased by 8% under an average UHI intensity of about 1–2 °C, and up to 3.5 °C with regard to the maximum temperatures. Chan [44] studied the impact of the UHI on the cooling load calculation for an office building and a typical residential building in Hong Kong; the study was carried out with EnergyPlus model (using a modified input weather file to take into account the UHI effect) and showed an average 10% increase in air-conditioning demand in both cases.

In Mediterranean climate, the impact of UHI on buildings energy performance was studied by Fanchiotti et al. [27] for residential buildings in Rome, using temperature measurements over the period July–September 2011 as input for simulations with TRNSYS model; results showed an increase of the cooling loads up to the 57% for a maximum UHI intensity of about 4.5 °C. With the same methodology, Magli et al. [45] estimated the impact of the UHI on the cooling loads of a university building in Modena (Northern Italy), finding an increase of about 10% for the urban situation compared to the suburban one.

The UHI effect determines an increase of overall energy demand of building stock even in colder climates. Many studies highlighted the negative impact of UHI on cooling loads and risk of overheating for buildings in London [46–49]. Kolokotroni et al. [50] used measurements of air temperature to run simulations for an office building with the energy model TAS; the results showed that in London area the cooling load is 25% higher than the rural load, while the heating load is reduced only by 22%. Dorer and Allegrini [51] analysed the cooling and heating demand for office and residential buildings in Basel, Swiss, using TRNSYS model and urban and rural air temperatures; the results showed an increase of the cooling demand in the urban environment up to 10 times as much as the rural one, while the reduction of the heating demand was much less significant.

In the light of these findings, standard meteorological data seem to be rather inaccurate to run energy simulations of buildings in urban areas, since they refer to out-of-town weather stations- normally airports- that cannot detect the UHI effect [38,44,47,52].

2. Methodology and case studies

This study investigates the UHI intensity at the local scale and the microscale [53] in Barcelona city and the relating impact on energy performance of buildings during summer time.

The assessment of the UHI intensity at local scale is based on the comparison of air temperature measurements from urban and rural fixed weather stations. The variability of the UHI intensity at microscale has been instead investigated through field measurements in different urban canyons.The temperature data at urban and rural sites have been then used as input for a set of energy simulations with EnergyPlus [54,55], by means of the Design Builder