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On the relation between urban climate and energy performance of buildings. A three-years experience in Rome, Italy

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HIGHLIGHTS

- Summer urban heat island up to 2.8 °C and winter urban heat island up to 1 °C.
- Reduction of urban heating degree days up to 18%.
- Increase of urban cooling degree days up to 157%.
- Building cooling energy increase by 22–26% per urban heat island degree.
- Building heating energy reduction by 18–24% per urban heat island degree.

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ABSTRACT

Climatic conditions strongly affect the energy performance of buildings, and due to the synergy between global climate change and the Urban Heat Island (UHI) effect, the climatic conditions inside and outside the city are highly different. However, weather data collected at airports are commonly used for building energy simulations and these data do not take into account real temperature distribution in cities. Many studies in the literature address the topic but mostly considering only a couple of urban and non-urban stations. In this paper, the urban climate in Rome, Italy, is analysed after monitoring of the air temperature and relative humidity in four selected neighbourhoods and one reference station from October 2014 until September 2017. Rome is characterised by a composite urban pattern and high variability of building types, of which the four selected areas are representative. The heating degree days decrease up to 18% and cooling degree days increase up to 157% in the urban area with respect to the rural reference and the area most affected by the UHI is the city centre. The UHI is more intense in summer than in winter (average increase between 0.7 °C and 1 °C); while the diurnal and nocturnal UHI depends on the season and the neighbourhood. Then, the energy performance of a representative apartment block and a typical office building was computed using the measured data. Regarding the predicted energy performance, comparing the four urban sites and the reference site, the UHI causes a reduction of heating consumption up to 21% in residential building and 18% in the office building. An increase of cooling consumption up to 74% is instead computed for the residential building and up to 53% for the office building.

1. Introduction

Buildings are responsible for the highest energy consumption and CO_2 emissions in Europe, with a share of respectively 40% and 36% [1]. Energy policies were developed in the past years to achieve relevant energy savings in the building sector. In the EU, for instance, the Energy Performance of Building Directive [2] outlines a general framework for assessing the energy performance of new buildings and existing buildings to be renovated. In Italy, as in most European countries, the first measure which has been set is the improvement of the energy performance for space heating since it is considered the most energy consuming service [3]. Global climate change, however, is outlining new scenarios, based on a strong increase of cooling demand in buildings. The trend is exacerbated by urban sprawl, which leads to the generation of the Urban Heat Island (UHI) effect, namely the strongest local climate change, defined as the increase of urban temperature compared to that of the countryside surrounding the city, due to urban sprawl, in increasing synergy with global warming [4–7]. The magnitude of UHIs

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Nomenclature

UHI	Urban Heat Island
UCI	urban cooling island
TMY	Typical Meteorological Year
GIS	geographic information system
CCZ	city centre zone
SP1	semi-peripheral zone 1
SP2	semi-peripheral zone 2
PE	peripheral zone
RE	reference station
HDD	heating degree days
CDD	cooling degree days

depends on several aspects: urban texture and morphology, radiative and thermal properties of the construction materials which create favourable conditions for absorption and storage of solar irradiation, local wind speed and direction, anthropogenic heat, the presence of green areas and water. The choice of the extra-urban microclimatic reference also play an important role in the assessment of UHI [8–10]. UHI is crucial for several applied energy issues: to predict the energy performance of single buildings and whole districts; to provide realistic microclimatic data for reliable energy system assessments at different scales; to adequately implement urban overheating mitigation strategies.

Climate change is reshaping the energy performance of building and cities. The variation of the energy performance of buildings for space heating and cooling in the future (till the year 2030) was investigated by Cartalis et al. [11]. With a simulation model which assesses climatic changes on the basis of climatic scenarios they found that heating and cooling degree days will decrease and increase, respectively, compared to the respective amounts for the year 1990. The limitation of these climatic models, as highlighted by the authors, is due to the lack of data in existing and future emission inventories of greenhouse gases and the impossibility of predicting potential changes in the future.

In another study, Lam et al. [12] assessed the impact of climate change on the electricity consumption for air conditioning of a commercial building stock in subtropical Hong Kong by using 1979–2008 meteorological data. They developed a regression based on measured data and they estimated the energy consumption from 2009 to 2100, computing a mean increase of 12.5% of electricity consumption for the 92-year period. Ahmed et al. [13] computed that in the State of New South Wales, Australia, the electricity demand will increase by 2050 between 2.7% and 4.5% during summer and spring season because of global climate change.

Greater impacts are computed when the thermal response of the city is investigated. A comprehensive review by Santamouris [14] screened many relevant studies finding that the impact of UHI on cooling loads is statistically significant and account for about 13% on the average. The influence of urban temperatures on the energy use for air conditioning in arid regions was explored by Radhi and Sharples [15] in Bahrain. They used numerical modelling to assess wind flow, temperatures and heat distribution fluxes, showing an increase by up to 10% of the electricity consumption for cooling in urban regions from April to October. Zhou et al. also achieved similar results for the city of Beijing in 2005, where it was assessed that air conditioning, due to the influence of the local climate (UHI, relative humidity and cumulative effect), is responsible for approximately the 12% of total summer electricity consumption, reaching the 20% during peak periods [16]. The UHI in Beijing was studied considering the average temperature of the entire urban area and the average temperature of several locations in the surrounding rural areas. The impact of UHI in London was studied by Kolokotroni et al. [17,18], who computed the energy performance of an office building using hourly temperature data recorded by 20 microclimatic stations within the urban canopy layer during one year of monitoring (1999–2000). They found that cooling increased between 27% and 45% and heating loads are reduced by more than 60% in the city centre. In Modena, Italy, Magli et al. [19] considered a rural and an urban reference station recording hourly temperature data for one year. The heating energy loads of a commercial building associated with the rural station was 20% higher than the urban one, while the cooling loads decreased by about 10%. Street et al. [20] developed a similar analysis for the city of Boston, U.S.A., using temperature data from one urban station and two rural stations; heating loads decreased by 14% in the urban station for a detached house, while the cooling demand increased by about 3–9%. An analysis of residential buildings was carried out by Chen et al. [21] for the city of Melbourne, Australia, comparing urban and rural temperature measured by two stations from a one-year campaign. They found that the UHI causes an increase of cooling uses by 10% and 17% for respectively existing and new buildings, and the analogous space heating decrease is respectively 5% and 7%. Paolini et al. [22] for a residential building, representative of the building stock of Milan, Italy, computed the heating, cooling and dehumidification loads with urban and rural data for seven years (2002–2008), including the European heat wave of 2003. They found that the UHI reduces heating loads by 12–16% and dehumidification loads by 74–78%, while it increases cooling loads by 39–41%. They found the largest gap in cooling needs to occur right during heatwaves, with a greater indoor urban-rural air temperature difference during the heatwave than during the seven-year average. This finding is consistent with the synergy between heat islands and heatwaves [23]. Giannopoulou et al. [24] have recorded temperature from 25 fixed stations in Athens in the year 2009 to analyse the characteristics of the heat island phenomenon during the summer season. The stations were grouped into five zones, showing statistically different mean and maximum daily air temperatures among the five areas. Data from the literature about the impact of the urban heat island on the peak electricity consumption were reviewed by Santamouris et al. [25]: average results show an increase between 0.45% and 4.6% per each degree of ambient temperature rise.

According to these studies, it emerges the importance of the quality of meteorological data to accurately predict the energy and thermal response of buildings in the real urban or rural context [26]. This is particularly critical for cities, whose climatic data are often collected at airports, outside of the urban belt, and thus are not representative of the urban local climate conditions. The impact of seven different climatic input files for two years on energy consumption of a residential building in Athens was evaluated by Hassid et al. [27]. Their results show high differences in cooling energy consumption and peak power due to the different input files in particular when comparing Athens meteorological year with measured data in urban areas.

Starting from the evident impact of the UHI on building energy consumption, relevant studies were addressed to estimate the potentials of mitigation strategies [28]. A large simulation study on mitigation strategies for five pilot cities in the USA was carried out by Akbari and Konopacki [29], where direct impacts (building related technologies) and indirect effects (energy savings arising from reduced urban temperatures) were computed. They calculated the annual cooling savings and heating penalties, showing the predominance of the former with intensities varying according to the selected technology and the climatic zone. Ihara et al. [30] analysed countermeasures to the UHI and benefits to the energy performance of office buildings using annual meteorological and building energy models for calculating the year-round environmental impacts. It was found that the use technologies based on an increase in albedo cause a reduction in the cooling demand but also an increase of heating demand, resulting in a null global impact on energy consumption. Furthermore, humidification and the