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On the energy impact of urban heat island and global warming on buildings

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ABSTRACT

Urban heat island and global warming increase ambient temperature and modify the energy budget of buildings. The magnitude of the modification has been evaluated in a large number of articles, under different climatic and building boundary conditions. This paper collects, analyzes and classifies existing knowledge regarding the energy impact of urban heating to buildings and calculates preliminary indicators and impact figures. Based on the analysis of the impact studies, it is found that in average the cooling load of typical urban buildings is by 13% higher compared to similar buildings in rural areas. Four specific energy impact indicators, the global energy penalty per m^2, the global energy penalty per m^2 and degree of UHI, the global energy penalty per person and the global energy penalty per person and per degree of the UHI are defined and calculated. The variability of the heating and cooling loads of typical buildings is evaluated for the period 1970–2010. The average increase of the cooling demand is 23% while the corresponding average reduction of the heating is 19%. In total, the average energy consumption of typical buildings for heating and cooling purposes increased by 11% for the same period.

1. Introduction

Urban heat island and global warming increase the near surface ambient temperature in cities [1]. Urban heat island is extremely well documented and relevant studies exist for most of the major cities in the world [2]. On the contrary few studies are available on the specific impact of the global warming on the urban climate [3]. The magnitude of the urban heat island expressed as the urban heat island intensity depends on many parameters like the topographic characteristics of the city, the weather conditions, the urban density, the anthropogenic heat released, the thermal and optical characteristics of the used materials in the city fabric, the urban form and land use while its is very influenced by the specific characteristics of the selected reference – rural station [4].

Urban warming has serious consequences on the energy, environmental and social balance of cities. The most serious impact is associated to the significant increase of the peak and total electricity demand especially for cooling purposes [5,6]. In parallel, urban warming is associated to increase the concentration of urban pollutants and in particular of the tropospheric ozone [7], worsen thermal comfort conditions in outdoor spaces [8,9], enhance health and mortality problems [10,11], and significantly increase the urban ecological footprint [12].

The magnitude of the specific energy impact of urban warming depends on many parameters such as the intensity of the urban overheating, the type and characteristics of the buildings under consideration and the local microclimate. Increase of the urban temperatures may exacerbate the energy demand for cooling purposes; however, the heating needs may be reduced as well. The specific energy impact of urban warming, under various climatic boundary conditions and for many types of buildings, has been analyzed in a wide number of studies. The methodology used, the period of the analysis, as well as the outcome of the studies vary substantially between the various studies, a fact which results in difficulties regarding the intercomparison of results and the extraction of solid conclusions, especially in the event that classification and normalization is not performed. In addition to the classification and normalization, a clear need is recognized so as to propose and standardize new global indicators expressing properly the specific energy penalty.

The present paper aims to investigate in depth existing knowledge on the energy impact of urban warming, the latter as caused by the urban heat island the global warming. To this end, results

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as published in several articles are collected, classified and analyzed; in addition new energy impact indicators are defined and calculated.

2. Estimating the energy impact of urban warming

The impact of high ambient temperatures on the energy consumption and the environmental quality of buildings is a quite well investigated area. Recent research mainly focus on two different categories of studies aiming to evaluate the energy impact of urban heat island and global warming:

(a) Studies aiming to evaluate the energy impact of the urban heat island. These studies rely on the use of climatic data as collected from urban and rural or suburban stations in order to evaluate in a comparative way the precise energy needs of reference buildings.
(b) Studies aiming to evaluate the temporal evolution of the energy penalty to buildings as imposed by the global urban warming. These studies are mainly based on the use of long series of past and current climatic data as collected from reference meteorological stations.

For both categories of studies, two types of specific methodologies are proposed and used. The first methodology focuses on the evaluation of the specific energy impact calculated for one or more reference buildings, like a small or a large office, a typical residence, etc. In this case, detailed or simplified energy simulation techniques are used to calculate the energy load of the building. The second methodology attempts to estimate the energy impact implied on the whole building stock of a specific geographical zone. This is performed by using methods like statistical energy modeling or detailed mapping and simulation of the building stock. As a result of the various categories of studies and types of methodologies, climatic related energy impact studies for buildings involve four 'groups' of investigations classified according to the climatic problem under investigation and the evaluation methodology used. In the following chapters the main results of existing studies on the energy impact of high urban temperatures on buildings are analyzed on the basis of the classification described above, and are presented accordingly.

2.1. The energy impact of heat island on various types of buildings using urban and rural climatic data

Identification of the heat island characteristics in an urban area requires knowledge of the spatial distribution of the ambient temperature. In most of the cases, a climatic station usually located in a thermally undisturbed suburban or rural area is selected as the reference one. The maximum difference between the urban and the reference station is known as the heat island intensity and is used to characterize the local heating and overheating conditions. Although, detailed heat island studies are available for a wide number of cities around the world, energy impact studies using urban and rural climatic data are quite limited. Thirteen studies are published on the topic concerning five cities in Europe (Athens, London, Munich, Rome, Volos), four US cities and states (Boston, New York, California, Texas), and two other cities in the rest of the world, Melbourne Australia and Bahrain. Details of all studies and the main results are given in Table 1. In most of the cases, ten, the comparative analysis was performed for reference residential buildings while the rest of the cases referred to offices. As it concerns the number of climatic stations used, only three studies were based on data from just two stations, the reference and an urban one, five studies used data from three to five stations while six studies used climatic inputs from more than twenty stations. The magnitude of the warming in the considered cities is not reported in the same way in all studies and comparisons are quite difficult. Some studies give the average maximum UHI intensity as measured in summer while many others report the average annual temperature difference between the urban and reference stations. Reported average maximum summer urban heat island intensities range between 3.5 K and 7 K while the annual average temperatures differences were between 1 K and 3 K. To evaluate the energy needs of the buildings, eight studies employed dynamic simulation techniques, three studies were based on empirical parametric models and two studies calculated the energy needs using simply the corresponding degree days. Three studies calculated the energy load of the buildings without considering the efficiency of the heating and cooling systems, three studies calculated the necessary primary energy while the rest calculated the delivered energy. Most of the studies, nine, calculated the energy impact of UHI during both the winter and summer periods, heating and cooling load, three studies concentrated just on the cooling impact and one study estimated the impact on the heating demand. In parallel, two studies estimated the increase of the peak electricity demand during the summer period and another study investigated the possible decrease of the COP (coefficient of performance), of air conditioners caused by warming. Details and results of all studies are presented below.

2.1.1. Presentation of the cases under consideration

Heat island characteristics in Athens Greece are very well studied. Almost 30 stations are placed in urban and suburban locations in and around the city measuring ambient temperature and allowing the estimation of its spatial distribution. According to [13], the average maximum intensity of heat island during the summer period is around to 6–8 K. High urban temperatures are observed in the central and western parts of the city characterized by high urban density, increased anthropogenic heat and considerable absence of green areas. The energy impact of the heat island phenomenon is studied in many ways. Santamouris et al. [13], has used hourly data from 30 climatic stations and calculated the spatial distribution of the heating and cooling load for a typical office building during the summer and winter period of 1996. As it concerns the cooling load it was found that the monthly load in the center of the city was about 120% higher than the respective load at the reference zone, while the corresponding heating load in the center was reduced by 38%. As it concerns the peak electricity load for cooling purposes, it increased from 13.7 kW/m^2 in the reference areas to 27.5 kW/m^2 in the center of the city. Finally, the heat island caused a serious reduction of the minimum COP values of the air conditioning systems. In particular, while the minimum COP of the air conditioners in cooling mode was 102% in the reference station, it decreased to 75% in the areas associated to the highest intensity of heat island.

In another study presented by Hassid et al. [14], the cooling as well as the peak electricity demand of a residential building with four apartments was calculated using climatic data from four different stations located in Western Athens where heat island is usually established, and two other reference stations located in suburban zones of the city. Data for 1997 and 1998 were used. For 1997, it was found that the cooling demand of the residential building in western Athens was 41 kWh/m^2/y, while in the reference station was almost 70% lower. In parallel, the peak electricity demand for cooling in western Athens was calculated close to 30.6 W/m^2/y, almost 100% higher than in the reference zone. For 1998, a significantly warmer year than 1997, the electricity demand was much higher in all zones of the city and the corresponding differences were reduced. In particular, the cooling demand in western Athens was 45.4 kWh/m^2/y almost 29% higher than in the reference area. In