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On the impact of urban heat island and global warming on the power demand and electricity consumption of buildings—A review

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ABSTRACT

Urban heat island and global warming increase significantly the ambient temperature. Higher temperatures have a serious impact on the electricity consumption of the building sector increasing considerably the peak and the total electricity demand. The present paper aims to collect, analyze and present in a comparative way existing studies investigating the impact of ambient temperature increase on electricity consumption. Analysis of eleven studies dealing with the impact of the ambient temperature on the peak electricity demand showed that for each degree of temperature increase, the increase of the peak electricity load varies between 0.45% and 4.6%. This corresponds to an additional electricity penalty of about 21 ($\pm$10.4) W per degree of temperature increase and per person. In parallel, analysis of fifteen studies examining the impact of ambient temperature on the total electricity consumption, showed that the actual increase of the electricity demand per degree of temperature increase varies between 0.5% and 8.5%.

1. Introduction

Increase of the near surface ambient temperature in cities is very well documented [1,2]. Urban overheating is the combined result of the urban heat island developed mainly in cities with a positive thermal balance and of the global warming which affects the urban climate as well. Although the impact of urban heat island is very well studied, the specific impact of the global warming on the urban climate is poorly understood [3]. Urban heat island studies are available for almost all major cities in the world and the corresponding urban heat island intensity is tabulated and reported by many authors [4,5]. The reported intensity of the UHI phenomena varies mainly as a function of the local topographical characteristics, the synoptic weather conditions, the urban characteristics like density, form and land use/cover, anthropogenic heat released, materials used, view factor, etc while it is also highly influenced by the characteristics of the selected rural station [6].

Urban warming has a serious impact on the energy consumption of the urban buildings by increasing the energy and the electric power necessary for cooling needs [7,8]. In parallel, higher ambient urban temperatures increase the concentration of certain pollutants like tropospheric ozone [9], deteriorate thermal comfort conditions in cities [10,11], exacerbate health and indoor environmental problems[12,13] and result in a serious increase of the global ecological footprint of the cities [14].

Weather variations have an important impact on the electricity demand and the general electricity market [15]. Several studies are carried out to examine the impact of various primary climatic parameters such as humidity, solar radiation, wind speed, etc., on the local electricity demand, while secondary climatic parameters such as the heating and cooling degree days are also considered [16,17]. In parallel, many economic, social and demographic indices such as the local Gross Domestic Product (GDP), the growth rate, the energy prices, the local manufacturing levels, etc., are also used as input parameters to estimate the electricity demand [18,19]. Most of the studies have concluded that ambient temperature is the parameter presenting the highest impact on the variation of the electricity demand [16].

The relation between the daily electricity consumption and the corresponding ambient temperature is not linear. It presents a high seasonality whereas the curve of the electricity demand obtains its peak value during the coldest period of winter in heating dominated zones or during the warmest summer period in cooling dominated zones. In winter, the relation between ambient temperature and electricity demand is negative as higher ambient temperatures decrease the need for heating. On the contrary, the relation is

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positive during the summer period where higher ambient temperatures increase the need for cooling. The respective curve between the electricity demand and the ambient temperature is usually of asymmetric U shape, where (a) the minimum consumption corresponds to the neutral climatic period when heating and cooling are insignificant and (b) the energy demand is almost inelastic to the temperature and (c) the maximum consumption corresponds to the periods of the lower and/or higher ambient temperatures depending on the local climate [20]. The threshold temperature over which the electricity consumption starts to increase, known as the inflection point of the response function, depends on the difference between the indoor comfort temperatures and the ambient ones. It is a strong function of the thermal quality of the building stock and of the indoor temperatures set for comfort. In a general approach, it is assumed that the inflection point is around 18.3 °C; however analysis of specific data for 15 European countries showed that it is close to 14.7 °C for the heating dominated countries and 22.4 °C for the cooling dominated zones [21].

Increasing use of air conditioning as a result of temperature increase and the improvement of the living standards had enforced and made more pronounced the correlation between the electricity demand and the outdoor ambient temperature above the threshold levels. The problem seems to be more significant in cooling dominated zones. In fact, a study examining the temperature elasticity of the electricity demand for six countries with warm climate (Australia, India, Indonesia, Mexico, Thailand, Venezuela), twenty one countries with mild climate (Austria, Belgium, Denmark, France, Germany, Ireland, Luxembourg, Netherlands, New Zealand, Switzerland, Greece, Hungary, Italy, Japan, Korea, Portugal, South Africa, Spain, Turkey, United Kingdom, United States), and four countries with cold climate (Canada, Finland, Norway, Sweden), concluded that the temperature elasticity for the warm countries is close to 1.7%, while for the mild and cold countries is 0.54% and 0.51%, respectively [22].

The aim of the present paper is to collect, analyze and present in a comparative way most of the important studies aiming to evaluate the impact of urban and global warming on electricity demand. Two type of articles are considered and presented: (a) those studying the impact of ambient temperature on the peak electricity demand and (b) those dealing with the impact of ambient temperature on the electricity consumption in a city or state.

2. The impact of high ambient temperatures on electricity demand

In order to manage the electricity consumption in an efficient way and forecast future electricity needs induced mainly by the urban overheating and global warming, utilities establish and use response functions to estimate the additional electricity needs per degree of temperature increase or the elasticity of the demand regarding the ambient temperature (increase of the ambient temperature by 1%). Response functions are mostly developed for the total electricity demand in a place; in rare cases the specific functions concerning the residential and commercial sectors are also available. Existing literature reports either the response function for the peak electricity demand or for the hourly, daily, monthly or even annual electricity consumption. Table 1 summarizes the existing literature with respect to the impact of ambient overheating on the peak electricity demand and electricity consumption. Twenty nine studies are analyzed and reported: eleven studies deal with the impact of ambient overheating on the peak electricity demand and eighteen studies discuss the impact of urban warming on the global electricity consumption.

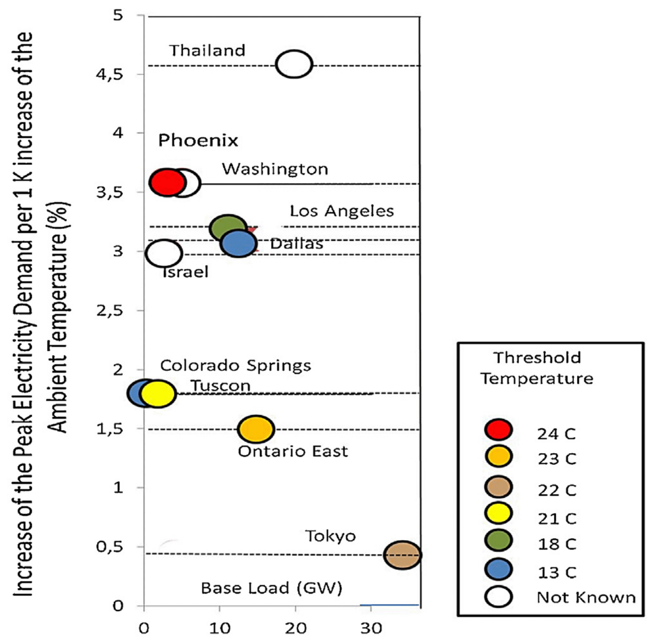

Fig. 1. Increase of the peak electricity demand (%) per degree of ambient temperature rise.

2.1. *Increase of the peak electricity demand*

Increase of the peak electricity demand is a serious problem for utilities as they are obliged to build additional power plants to satisfy the demand, a fact which increases the cost of the electricity generation. Data on the impact of ambient overheating on the peak electricity demand are available for Tokyo [23], Thailand [24], Ontario East Canada [25], Los Angeles, Washington, Dallas, Colorado Springs, Phoenix and Tuscon [26], Israel [27] and Pert of Carolina USA [28]. Fig. 1 summarizes the main results of the above studies. In particular, the base electrical load and its percentage rise per degree of ambient temperature increase is given. In parallel, the inflection point of the response functions i.e. the threshold temperature over which the cooling demands starts to increase is reported when known.

As shown, the rise of the peak electrical load per degree of ambient temperature increase, varies between 0.45% and 4.6%. The lower values are observed for Tokyo and the higher for Thailand. The average increase rate between all considered cases is close to 2.65% while the average increase of the electric load is 226 MW per degree of temperature increase. The base electrical load of the reported cases varied between 0.4 GW and almost 40 GW. Considering the average population of the considered cases, it is estimated that the average peak electricity penalty per person is close to 21 (±10.4) W per degree of temperature increase. The threshold ambient temperature over which the cooling demand starts to increase varied between 13 °C and 24 °C, but for most of the cases was above 18 °C. The inflection point temperature was not correlated to the rate of increase of the peak electricity demand.

As expected, the specific data indicates that the sensitivity of the electricity network on the additional cooling demand triggered by the ambient overheating depends highly on the degree of penetration of air conditioning in the considered area, the thermal quality of the building stock, the considered indoor comfort temperatures and the specific characteristics of the basic electricity load In the event that, the reported data of the basic peak electricity demand includes the consumption of the industrial sector, the sensitivity to the temperature increase is considerably lower given that the industrial production is not affected seriously by the temperature