Urban overheating and impact on the built environment

Mat Santamouris
Anita Lawrence Chair on High Performance Architecture, Faculty of Built Environment, University of New South Wales, Sydney, Australia
m.santamouris@unsw.edu.au

Abstract: The present article aims to analyse and discuss the quantitative and qualitative impact of ambient and urban overheating in the built environment and in particular: on the peak electricity demand, the cooling and heating energy demand of buildings, the electricity consumption during the hot period, the energy impact on the electricity generation and supply systems and the transmission networks, the direct and indirect effects on outdoor air environmental quality as well as the energy and environmental impact on low income and vulnerable population. The existing literature on the topic, more than 250 published articles, has been analysed, classified and discussed. All results and conclusion are tabulated.

1. Introduction
Urban heat island is the most documented phenomenon of climate change. Increased ambient temperatures are experimentally documented in more than 400 major cities around the world. The average amplitude of urban overheating is between 4 to 5°C, while values up to 10°C are reported for several cities. Parallel, to the local warming, the global climatic change increases the frequency and the amplitude of heat waves and the other extreme climatic phenomena. Several studies have shown that there is a synergetic effect between the local and global climate change resulting in a significant increase of the amplitude of the urban overheating. Future projections foresee a very significant global overheating, that may have a tremendous impact on the built environment and put under serious stress urban citizens and energy infrastructures, (1).

Urban and ambient overheating have a serious and well quantified impact on the global built environment. It is well documented that increase the cooling energy consumption of buildings, (2), raises the peak electricity demand during the hot period and oblige utilities to build additional power plants and increase the cost of electricity supply, (3), increase the concentration of harmful pollutants like the tropospheric ozone and the emission of pollutants by the power plants, (4), have a serious impact on the quality of life of vulnerable and low income population and threat their health, (5), and increases significantly the heat related mortality and morbidity, (6).

Numerous studies have been performed and published aiming to document and quantify the specific impact of the current and future urban and ambient overheating in the built environment. The present paper, has collected and analysed almost all of the known existing studies has assess their conclusions and results and has classified the reported quantitative impact in a comprehensive way.

2. Energy Impact of Urban and Ambient Overheating
The various implications of ambient and urban overheating in the built environment are summarised in Table 1, (7). Based on the analysis of almost 100 published studies, the quantified impact of the urban
and ambient overheating on the energy demand of buildings as well as on the electricity generation and supply systems and the associated transmission networks, is given in Table 2.

Table 1. Implications of ambient and urban overheating on demand and supply side components of electricity. Adapted from (7).

| Demand System Component | Ambient and Urban Overheating Effect | Implications |
|-------------------------|-------------------------------------|--------------|
| Cooling Load of Buildings | Higher ambient temperature in summer | Increase of the cooling demand of buildings |
| Peak electricity Demand | Higher ambient temperature in summer | Increase of the peak electricity demand |
| Load Duration curves | Important change of air conditioning profile | Higher demand curve peaks and much greater load variability may increase chances of breaching the market price cap |
| Non-temperature sensitive demand | Increased cooling water temperatures | Generation curtailments and potential interruption of power to avoid blackouts |

| Supply system component | Overheating Effect | Implications |
|-------------------------|-------------------|--------------|
| Thermal Electricity Generation Plants and Components | Increased Ambient Temperatures, Increased Water Temperatures | Decreased efficiency of electricity generating equipment like gas turbines, coal power plants, etc. |
| Transmission Network | Higher ambient temperatures and longer spells of dry weather | Power disruptions, increased cost of adaptation designs. Reduced equipment lifetime. Reduce the power carrying capacity of transmission lines and may cause disruptions because of the power line sagging |
| Substations and Transformers | High Ambient Temperatures | Increases losses within substations and transformers |
| Fuel Stock | High Ambient Temperatures | Coal stocks may spontaneously combust or self-ignite |
| Power Plants | Increased Ambient temperature and Extreme events, Increase of the peak electricity demand | Utilities have to built additional power plants to cover the peaks. Increased cost of electricity production during the peak hours |

As shown in Table 1, urban heat island increases the average the cooling load of buildings by 12 %, while the mean cooling penalty is estimated close to 2.3 kWh/m²/y and degree of temperature increase. In parallel, it is assessed that the cooling load of reference buildings has increased by 23 % since 1970 because of the global and local overheating. Using numerous relevant studies, several indices have been proposed and quantified. It is characteristic that the Global induced energy penalty per person and degree of temperature increase is found close to 78 kWh/p/C.
It is also estimated that the impact of the actual overheating increases in average the peak electricity demand during the warm period by an equivalent of 21.9 W per person and per degree of temperature increase. A very significant impact is also found regarding the systems of electricity generation and supply. Overheating reduces significantly the performance of the thermal power plants and limits considerably the capacity of the transmission systems, while it increases dramatically the cost of the necessary investments to avoid power supply problems.

Table 2. Quantified Implications of ambient and urban overheating on demand and supply side components of electricity. Adapted from (7).

| Demand Side Component | Overheating Effect | Average Implications |
|-----------------------|--------------------|-----------------------|
| Cooling Load of Reference Buildings | Urban Heat Island | Average increase of the cooling load by 12 % compared to reference climatic conditions |
| | Combined Impact of Urban Heat Island and Global Climate Change | Average cooling penalty close to 2.3 kWh/m2/y and per degree of temperature increase |
| Cooling Load of Reference Buildings | Combined Impact of Urban Heat Island and Global Climate Change | Increase of the average cooling load of reference buildings by 23 % or 11 kWh/m2/y, between 1970 and 2010 |
| | Combined Impact of Urban Heat Island and Global Climate Change | Decrease of the heating needs by 19 %, and increase of the total heating and cooling demand by 11 %, for the period 1970-2010 |
| Future Cooling Load of Reference Buildings | Global Climate Change | The Global Energy Penalty per unit of city surface, GEPS, varies between 0.13 to 5.5 kWh/m2, with an average value close to 2.3 ±(1.5) kWh/m2. |
| | Combined Impact of Urban Heat Island and Global Climate Change | The Global Energy Penalty per city surface and degree of temperature increase, GEPSI, varies between 0.12 to 2.22 kWh/m2/C, with an average value close to 0.73±(0.64) kWh/m2/C. |
| | Combined Impact of Urban Heat Island and Global Climate Change | The Global Energy Penalty per Person, GEPP, varies between 104 to 305 kWh/p, with an average value close to 230±(120) kWh/p. |
| | Combined Impact of Urban Heat Island and Global Climate Change | The Global Energy Penalty per person and degree of temperature increase, GEPP, varies between 20 to 154 kWh/p/C, with an average value close to 78±(47) kWh/p/C. |
| Peak Electricity Demand | Global Climate Change | For actual reference cooling loads close to 50 kWh/m2/y, the average expected future increase of the cooling demand per degree of temperature increase is close to 6 kWh/m2/C. |
| | Combined Impact of Urban Heat Island and Global Climate Change | For actual reference cooling loads close to 150 kWh/m2/y, the average expected future increase of the cooling demand is close to 12 kWh/m2/y. |
| Supply Side Component | Overheating Effect | Average Implications |
|-----------------------|--------------------|-----------------------|
| Future Cooling Load of Reference Buildings | Global Climate Change | For actual reference cooling loads close to 50 kWh/m2/y, the average expected future increase of the cooling demand per degree of temperature increase is close to 6 kWh/m2/C. |
| | Combined Impact of Urban Heat Island and Global Climate Change | For actual reference cooling loads close to 150 kWh/m2/y, the average expected future increase of the cooling demand is close to 12 kWh/m2/y. |
| Peak Electricity Demand | Global Climate Change | The additional peak electricity demand per degree of temperature increase varies between 0.45 % to 12.3 % . |
| | Combined Impact of Urban Heat Island and Global Climate Change | The average additional electricity demand per person and temperature increase is close to 21.9± (11.8) W/C/person. |
| | Combined Impact of Urban Heat Island and Global Climate Change | The average increase of the peak electricity demand is around 3.7 % or 215 MW per degree of temperature increase |
Power Output of Coil and Gas Power Plants

A temperature increase of 1 °C reduces the power output of coal and gas power stations by 0.6 %.

Power Output of Nuclear Plants

A temperature increase of about 1 °C decreases their power output by 0.8 %.

Carrying Capacity of Electric Transmission Network

The expected increase of the ambient temperature by 2040-2060 may decrease the mean summertime transmission capacity in the USA by 1.9%–5.8% relative to the 1990–2010 period.

Additional Investments on Electricity Capacity

Increased ambient temperatures and extreme phenomena, may cause 14–23 % additional investments on electricity capacity in USA, relative to a non–climate change scenario for the years between 2010-2055.

Assessment of the potential future impact of global and local warming on the demand and supply energy systems, shown that it is extremely high and may affect considerably the whole balance and economics of the energy sector.

3. The Impact of Local and Global Overheating on the Environment and the Ambient Air Quality

Higher ambient temperatures act as catalysts and result in higher concentration of harmful pollutants like the tropospheric ozone. Table 3, reports the result of more than 50 published studies aiming to assess and quantify the specific direct and indirect impacts of ambient overheating on the global environmental quality. As it concerns the direct effect of overheating on air quality, this is mainly focussed on the increase of the ozone concentration at the ground level. Ozone is toxic atmospheric gas and may damage significantly the human health. As shown, during heat waves the concentration of ozone is found to increase significantly and up to 20 %, while the number of ozone episodes above the allowed threshold concentration is increasing considerably. A serious future increase of the concentration of the ground level ozone is also foreseen by many studies as a result of the expected global climatic change.

As it concerns the indirect effects of the ambient overheating, several studies have demonstrated that the emission of harmful pollutants by the power plants is increasing significantly during the hot season. A considerable future increase of the emitted pollutants by the electricity generation systems is foreseen by several studies considering that the used fuels will not change significantly.

Table 3. Quantified Implications of ambient and urban overheating on ambient air quality, Adapted from (7).

| Air Quality Component | Overheating Effect | Implication |
|-----------------------|------------------|-------------|
| Ozone concentration   | Global Overheating – Heat Waves | Increase of the ozone concentration between 9.6 - 20 % during heat waves, |
| Ozone Concentration   | Combined Impact of Urban Heat Island and Global Climate Change | Increase of the ambient temperature by 1 % increases the number of days exceeding the ozone concentration threshold by 10 %, |
4. Impact of Overheating on Low Income and Vulnerable Population

Increased ambient temperatures have a serious impact on the indoor environmental quality of low income households while may increase considerably the necessary cooling energy demand to satisfy the additional cooling needs induced by the ambient overheating. It is well known that low income population lives in less protected houses presenting a non-appropriate energy and environmental performance. Increase of the ambient temperature obliges low income population to consume additional energy to achieve indoor comfort or to live under unacceptable indoor conditions and very high indoor temperatures. Table 4, summarises the conclusions and results of almost 40 published studies aiming to assess experimentally the impact of overheating on the energy and environmental quality of low income and vulnerable population.

As shown, the few low income households able to cover the cost of electricity for cooling purposes, has to spend almost the double budget than the average population because of the poor housing and energy conditions.

Table 4. Quantified Implications of ambient and urban overheating on low income and vulnerable population. Adapted from (7).

| Component                  | Overheating Effect                                  | Implication                                                                 |
|----------------------------|-----------------------------------------------------|------------------------------------------------------------------------------|
| Cooling energy cost        | Combined impact of Global and Regional Climate Change| The cost of air conditioning in low income houses may increase up to 100 % relative to the average conditions |
| Indoor Temperature         | Combined impact of Global and Regional Climate Change| Indoor peak temperatures in low income houses during heat waves may exceed 40 C. |
However, most of the studies shown that vulnerable population is not able to satisfy the cooling needs and is forced to live under very high indoor temperatures. As reported, indoor temperatures recorded in numerous monitoring campaigns, may reach or exceed 40 C, while extremely long spells with indoor temperature continuously above 30 C are recorded and reported. Exposure to high indoor temperatures put in risk and threatens the life of the vulnerable population while it increases dramatically the heat related mortality and morbidity especially in aged population groups.

5. Conclusions
Urban and ambient overheating has a very serious impact in the built environment. This is documented through numerous studies that have quantified the specific impact on the peak electricity demand, absolute cooling energy consumption, performance of supply and distribution networks, outdoor environmental quality and also the energy and social impact on low income and vulnerable population. In parallel, a very important research is carried out to identify and document the impact of high ambient temperatures on heat related mortality and morbidity.

The overcome and counterbalance the specific impact of ambient overheating, appropriate mitigation and adaptation technologies are developed and implemented in numerous large scale projects all around the world. Analysis of the impact of the used mitigation technologies indicate that can contribute highly to alleviate the effects of the current and future overheating. Future research should concentrate on the deeper understanding and documentation of the actual and future impact of urban and ambient overheating, the development of appropriate and efficient mitigation technologies as well as on the assessment of their impact on the global building environment.

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