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Impact of Urban Heat Island formation on electricity consumption over Delhi region

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ABSTRACT

Urban heat island (UHI) effect is a common phenomenon found in urban areas which is associated with the increased ambient temperature resulting from man-made alteration of the land. Urban structures with complex geometry, increased concretized surfaces and reduced natural land cover cause reduction in the rate of heat loss leading to increased temperature over urban areas and creating urban heat island (UHI). This study explores the temporal and spatial pattern of urban heat island (UHI) formation over Delhi. It is observed that the night-time surface temperature of central Delhi is higher in all months as compared to its surrounding rural areas. Thus, a nocturnal heat island forms over Delhi in all the seasons. The dense built-up area and impervious surfaces of Delhi are responsible for trapping heat which causes discomfort to humans, resulting in increased use of cooling devices with higher electricity consumption. Polynomial regression model based calculations show cooling load may be reduced up to 21-23% in summer months, 10 to 14 % in monsoon season, and 8 to 17 % in post-monsoon season if urban heat island effect is removed.

Introduction

Industrialization and economic growth lead to the process of urbanization. This involves the movement of people from the rural areas to the cities/towns in search of employment and is accompanied by significant modification in the land use and land cover of a local region. These modifications include the replacement of vast areas with soil and vegetation cover by impervious surfaces that inhibit the percolation of water into the soil. In the process, small rural structures and predominantly agriculture land in rural areas are replaced by densely packed high rise urban structures with complex geometry. These changes bring about reduction in soil moisture content over urban surfaces and a decrease in evapotranspiration (Priyadarsini 2012.). Further, the high rise buildings with complex geometry in the urban areas reduce the sky view factor, thereby reducing the efficiency of radiation loss in the long wave region (Oke 1981). This significantly decreases the rate of cooling of urban surfaces as compared to their rural counterparts. The extensive commercial, industrial, transportation activities over the urban region also lead to the emission of a large amount of waste heat and pollutants in urban atmosphere. All these changes alter the energy budget, leading to increased temperatures over urban areas as compared to the surrounding rural areas and create the so-called urban heat island (UHI).

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Gallo et al. (1993) reported the UHI effect over thirty-seven cities of the United States. Their results revealed that the difference in NDVI (normalized difference vegetation index) between urban and rural regions was the most important factor responsible for urban heat island formation. Similarly, Gaffin et al. (2008) also confirmed the formation of urban heat island over New York. Buyantuyev and Wu (2010) also revealed that during the nighttime, urban core was generally found to be warmer than its surrounding rural areas over Phoenix metropolitan region of Arizona, USA. Their results showed the important role of vegetation (day time) and pavements (night time) in explaining spatio-temporal variations of surface temperatures.

Besides their important role in regional climate and air quality, urban heat islands are known to cause thermal discomfort to humans. Urban communities respond to this increased thermal discomfort by employing energy devices (HVAC, Heating Ventilation and Air Condition) to make their indoor climate more comfortable. Thus, urban heat island formation in a city is expected to have a significant bearing on its energy demands (Priyadarsini 2012). Kolokotroni et al. (2007) used a building simulation program to study the cooling and heating load of air conditioning in office buildings located in different locations within London. It was observed that the effect of the UHI formation over the city on the energy used for heating and cooling depends on the degree of urbanization at a particular location, radial distance from the city center. Delhi, the capital city of India has witnessed rapid urbanization over the last few decades (Rahman et al 2011). Earlier studies (Pandey et al. 2012, Pandey et al. 2014) have shown the formation of nocturnal UHI over Delhi during most part of the year. Notable efforts to examine the relationship of electricity consumption of Delhi with weather parameters were made by Ramesh et al (1988) and Gupta (2012). However, there has not been any comprehensive effort till date to examine the impact of UHI on the electricity consumption in Delhi. The present study attempts to evaluate this impact with respect to the central district of Delhi.

Data Description

Study Area

India is expected to overtake China as the world's most populous country by 2050 (UN, 2017). Most of this growth in population will be absorbed in cities, resulting in an increased urbanization rate. Delhi is situated on the banks of river Yamuna (a tributary of the river Ganga) at a latitude of 28.38° N and the longitude of 77.17°E. It is spread over 1,483 sq Km and its population is 1.68 Crores with a density of 11,320 persons per sq km (Census 2011). More than half a million population resides in the Central district of Delhi (Census 2011). It includes the five sub-districts of Paharganj, Shankar Road, Patel Nagar, Darya Ganj, and Chandani Chowk. These sub-districts are highly populated and totally built-up areas.

Paharganj and Chandani Chowk are highly concentrated with both residential and commercial buildings like hotels, lodges, restaurants, dhabas and a wide variety of shops that sell books, clothing, electronics, consumer goods, shoes, and leather goods. Thus people come here from all over India for trading. Daryaganj is also a residential cum commercial area which is known for its books shops. Shankar road and Patel Nagar are totally residential areas. Population data of central Delhi given in the census data is actually an underestimate of the real population density of this area as most of the people throng this area during the day for commercial reasons. These people are not the residents of this area and include shopkeepers, street vendors, drivers of autorikshaws & e-rikshaws and visitors from other states as well. Thus, most of this area is highly congested in terms of vehicular and population density.

MODIS data

MODIS is a sensor mounted on the Terra and Aqua Satellites of NASA's EOS (Earth Observing System) Mission having 36 spectral channels in the range 0.405 and 14.385 µm, which provide information about the Earth Atmosphere, Ocean and Land Condition. Terra and Aqua are sun-synchronous, near-polar satellites having different equator crossing times i.e. 10.30am/pm and 1.30pm/am respectively, covering the whole earth's surface every 1-2 days (http://modis.gsfc.nasa.gov/data). MODIS has a swath resolution approximately 2330 km wide. In the present study, we have used the MODIS Aqua satellite product MYD11A2 Version 6, which provides an average 8-day per-pixel Land Surface Temperature with a 1 kilometer (km) spatial resolution in a 1200 x1200 km grid. The Land Surface Temperature (LST) data of MODIS are retrieved at 1 km pixels by the generalized split-window algorithm (Wan and Li 1997).

Maps of night-time Land Surface Temperature (LST) were created for the Delhi region for all seasons summer (April, May & June), winter (January & December), spring (February and March), post monsoon/autumn (September, October & November) and monsoon season (July and August) from Level 3 global data product (MYD11A2) acquired from MODIS Aqua satellite.

Estimation of Urban Heat Island Intensity (UHII)

The existence of an urban heat island is determined by calculating the urban heat island intensity, defined below:

$$\text{UHI Intensity} = \text{Temperature}_{\text{urban}} - \text{Temperature}_{\text{rural}}$$

For urban heat island intensity (UHII) estimation, the monthly average of nighttime land surface temperatures over the rectangular strips outside Delhi and over the central Delhi (Figure 1) was extracted for the period January 2017-December 2017 from the MODIS-AQUA monthly land surface temperature product (1 km resolution) MYD11A2. To estimate the UHII, the average temperature in the strip outside Delhi where mostly agriculture land use is predominant, was subtracted from the average temperature of the strip located over the central Delhi that is mainly comprised of dense built-up areas.

Electricity Consumption Data

Electricity is distributed in Delhi by three distribution companies, viz. BSES Rajdhani Power Limited, BSES Yamuna Power Limited, and Tata Power Delhi Distribution Limited. BSES Rajdhani distributes electricity in 19 sub-districts of South and South-West Delhi, BSES Yamuna distributes 14 sub-districts of the east and central Delhi, while NDPL distributes electricity in 13 sub-districts of North Delhi. For the present study, we used electricity consumption monthly data of 2017 for the Central Circle distributed by BSES Yamuna Power Limited which covers five areas viz. Pahar Ganj, Shankar Road, Patel Nagar, Darya Ganj, and

Chandani Chowk. The data comprised of the electricity consumption in all economic sectors (industrial, residential, and commercial) at the sub-district level of Delhi, because sectoral wise data was not available.

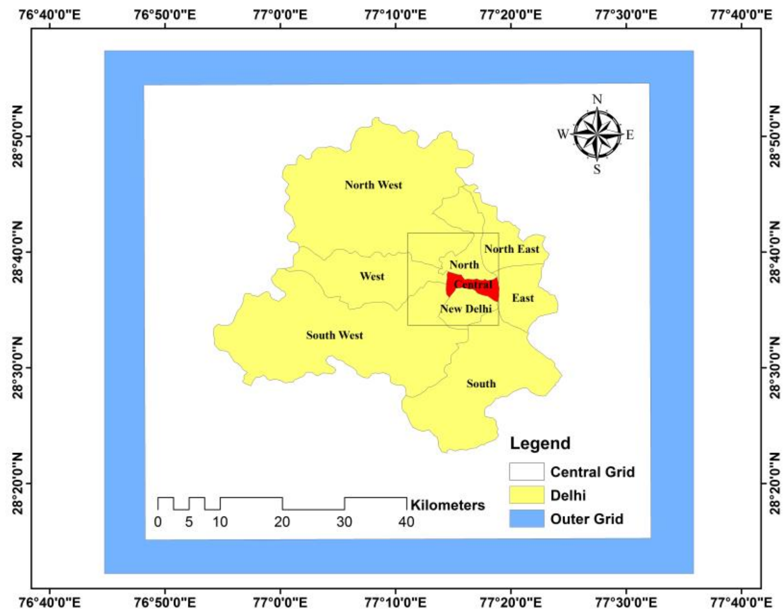


Figure1. Schematic diagram showing central part of Delhi (Central Grid) and outside (Outer Grid) for the estimation of urban heat island intensity (UHII).

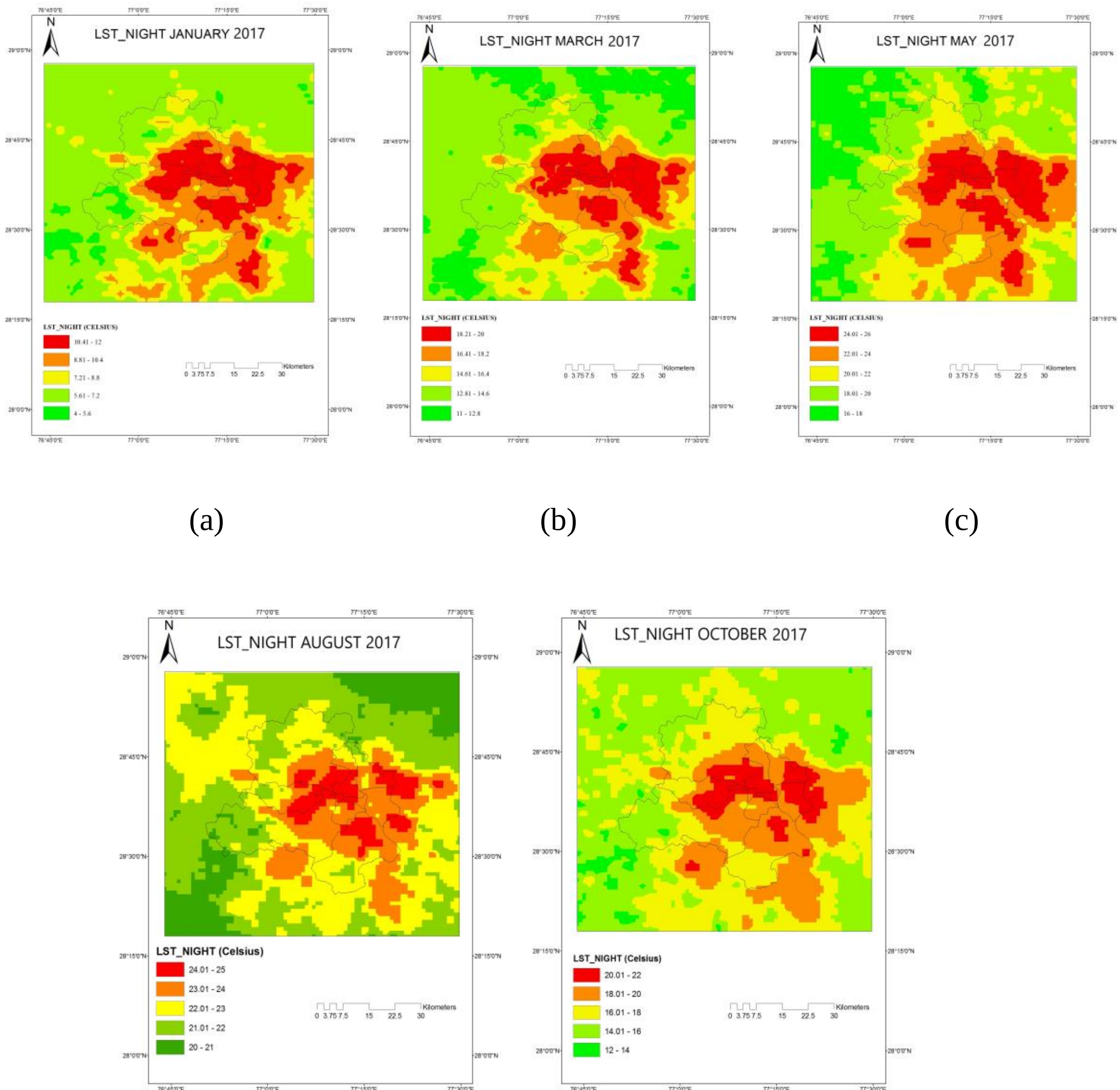
Results and Discussion

Night time land surface temperature variation

Spatial variation in night-time land surface temperature over central Delhi and its surrounding regions, for the different seasons, is shown in Figure 2 (a - e). It may be observed that in the month of January (figure 2 a), night-time surface temperatures over central Delhi were higher (10°C - 12 °C) as compared to those of the surrounding rural regions that ranged from 4°C to 7°C. The minimum night-time surface temperature (11°C -12°C) in the month of March (figure 2 b) was observed in the region lying North-East and South West of Delhi while in the central part of Delhi, the land surface temperature was observed to be in the range of 18°C to 20°C. This kind of temperature differential sustained till the month of May (figure 2 c). Maximum temperatures (24°C-26°C) occurred over central Delhi and minimum temperatures (16°C-20°C) were observed in some parts lying north-west and south-west of Delhi's surroundings.

In the month of August (figure 2 d), it was observed that the range of night-time temperatures over most parts of the study region reduced significantly. Maximum temperatures (~23°C - 25 °C) were observed over the central district of Delhi. In other parts of Delhi's surroundings, temperatures were found to lie in the range of 20 °C to 23°C. Night-time surface temperature variations during the month of October (figure 2 e) also depicted the clear existence of nocturnal heat island over central Delhi. Maximum temperatures over central Delhi ranged from 20 °C to 22 °C while minimum temperatures existed in Delhi's surroundings in the range of

12°C to 18 °C. So, it was observed that Delhi always has higher temperatures in the night as compared to the surrounding areas, which confirms the formation of a ‘nocturnal heat island’ in almost all the seasons. Badarinath et al. (2005) reported similar trends for the city of Hyderabad and found that heat island formations can be seen in the night time with core urban regions showing high temperatures. Pandey et al. (2012) also reported similar results and confirmed the formation of nocturnal heat island over Delhi which was found to be warmer by 4–7°C than the surrounding rural regions.



(a) (b) (c)

(d) (e)

Figure 2. MODIS night time land surface temperature over Delhi and it's surrounding for the month of (a) January (winter season); (b) March (spring season); (c) May (summer season); (d) August (monsoon season) and (e) October (Post monsoon season).

Variations of Urban heat island intensity

The monthly variations in night-time Urban Heat Island Intensity over Delhi and its surrounding regions, retrieved from MODIS AQUA satellite product MYD11A2 for different months for the year 2017 are shown in Figure 3. It is seen that temperatures over central Delhi were higher than the surrounding rural areas almost throughout the year during night-time. The plot reveals that the nocturnal UHII was the maximum (~ 4-5 °C) during the months of April and November. The nocturnal UHII was minimum (~ 1.5- 2°C) during the month of July.

The seasonal variations in the nocturnal UHI in this study were found to be similar to those for Mexico City by Cui and Foy (2012), who reported maximum values of night-time UHII for the dry season and minimum values for the wet season. Alonso et al. 2003 also revealed similar trends and found that during night-time the UHII values remained positive throughout the period. Their study reported nocturnal UHII to be highest during autumn and winter.

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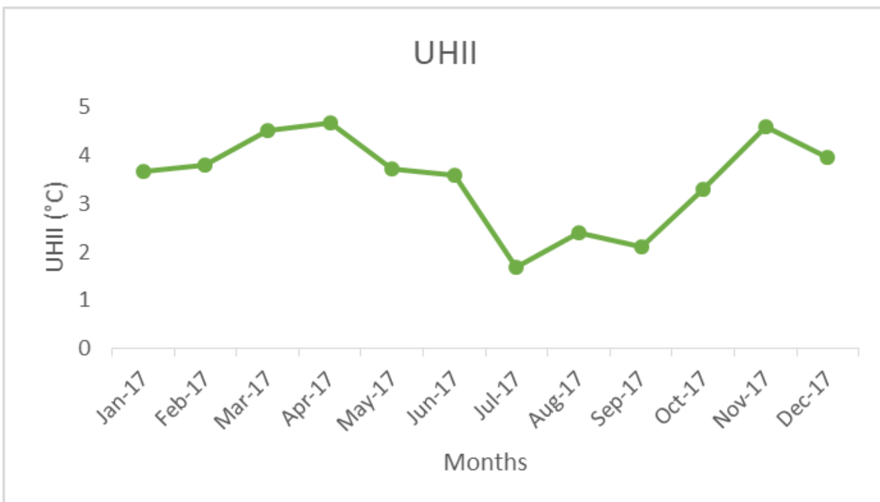

Figure 3. Monthly night time urban heat island Intensity for the year 2017.

Monthly electricity consumption pattern

Figure 4 shows the average monthly consumption of electricity in central Delhi for the year 2017. The graph shows a distinct pattern of electricity consumption rising up to 250 MU (1 MU = 1000 MWh) in summer season which is the result of increased use of cooling devices for thermal comfort. During monsoon season also consumption was observed to be high. This is because air temperature is not the only factor affecting thermal. There are other parameters like relative humidity, wind and precipitation which are equally important. Minimal electricity consumption can be seen in the months of January, February, November, and December, as in these months UHI plays a positive role and people don't require intensive usage of heating appliances. Similar monthly consumption pattern over Delhi has been reported by Gaur (2016).

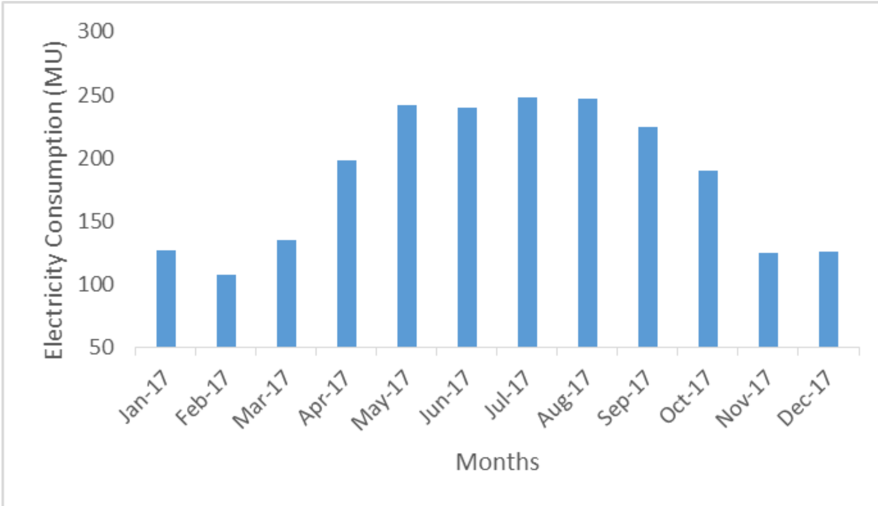

Figure 4. Monthly electricity consumption of central Delhi for the year 2017.

The relation between land surface temperature and electricity consumption

Many studies approached various methodologies to estimate the impact of UHI on energy consumption. The bottom-up and top-down approaches have been developed to estimate the energy consumption at multiple spatial scales from the building level to the city level and state level (Li et al. 2019). The bottom-up approaches include physical based and statistical models. In the present study, we have used a statistical model for the estimation of relationship between energy consumption and LST.

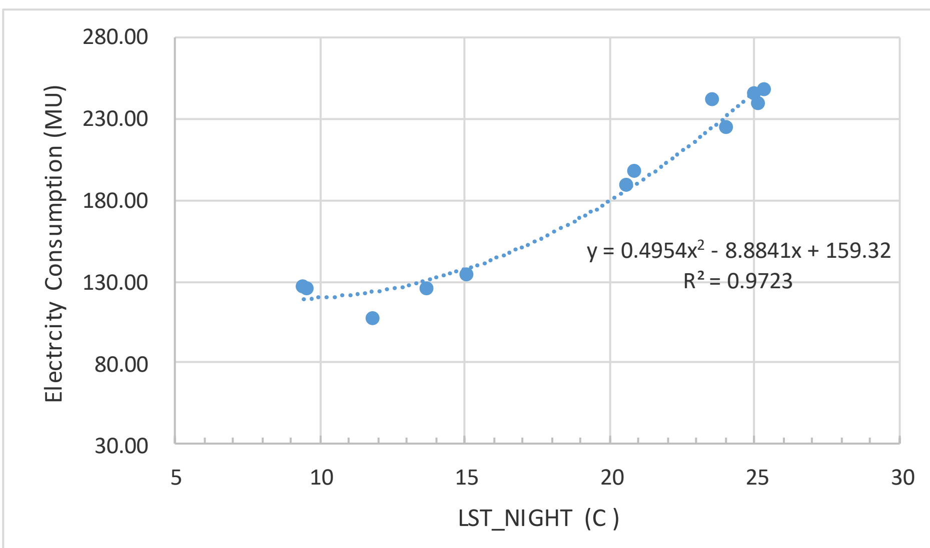

Figure 5. Scatter plot of monthly electricity consumption and night time land surface temperature.

Figure 5 shows the scatter plot between the electricity consumption and nighttime land surface temperature for central Delhi. It is seen that their relationship is well explained by the polynomial regression equation with $R^2 \sim 0.97$.

$$E = 0.495\,(T)^2 - 8.8841\,(T) + 159.32 \qquad (1)$$

Where, T is the temperature in Celsius and E is electricity consumption in Million Units. We have calculated the monthly electricity consumption with and without UHI effect by putting monthly LST value of the rural area and urban area for each month in the above Eq (1). The Net Energy saving potential for each month was computed from the equation given below.

Net saving potential = Energy consumption $_{\text{with UHI effect}}$ – Energy consumption $_{\text{without UHI effect}}$

Table 1. Monthly electricity consumption under with and without UHI effect and monthly net saving potential.

Months	UHII (°C)	Electricity Consumption under UHI impact (MU)	Electricity Consumption without UHI impact (MU)	Net Saving Potential (%)
January	3.7	119.6	124.6	-4%
February	3.8	123.4	120.0	3%
March	4.5	138.0	120.7	12%
April	4.7	189.0	145.0	23%
May	3.7	224.3	177.5	21%
June	3.6	248.9	197.6	21%
July	1.7	252.4	226.3	10%
August	2.4	246.2	211.1	14%
September	2.1	231.9	202.5	13%
October	3.3	186.3	153.7	17%
November	4.6	130.5	119.5	8%
December	4.0	119.6	125.2	-5%

Table 1 explains electricity consumption under UHI impact, non-UHI impact, and net saving potential for each month. Monthly electricity consumption for the summer months was observed to be between 189.0 –248.8 MU with UHI effect while removing the UHI effect, the consumption was calculated to be around 145–197.5 MU. When we reduce UHI effect from urban area by 3-4 °C, we found net saving potential on consumption or in other words consumption during these months was reduced by 21-23 %. Whereas during the monsoon months of July & August, the calculated consumption without UHI effect was observed to be 226 - 221 MU, however, higher consumption of 245 & 252 MU was observed under the UHI effect. Net saving potential on electricity consumption is observed to be 10 to 14 % in the monsoon season after removing the difference of 1-2 °C UHII from central Delhi.

During the post-monsoon season, 8 to 17 % net saving potential on consumption was seen over central Delhi without the UHI effect. Similarly, saving potential is positive during the spring season and it is observed to lie between 3-12 % when we remove the UHI effect from the urban region. UHI plays a positive role in the urban areas in terms of impact over the electricity consumption during the winter season as it reduces heating load on houses. Thus, more consumption (124-125 MU) can be seen without UHI impact rather than consumption (~119 MU) under the UHI impact during the winter season. Thus, a negative net saving potential (-4 % to -5%) was seen in these months. Many studies have reported similar results of UHI impact on building consumption. Radhi and Sharples (2013) reported that domestic energy consumption increased up to 10% in urban sites as compared to the rural sites in Bahrain due to UHI effect. Santamouris et al. (2001) also evaluated urban heat intensity impact on building cooling energy load. They reported that due to an increase in 10% mean urban heat intensity, the cooling load almost doubled in central Athens.

Conclusion

This study shows that central parts of Delhi experience increased night-time temperature as compared to the surrounding rural areas. A 'nocturnal heat island' is observed over Delhi in almost all the seasons though its intensity is seen to be the minimum during the monsoon months. Higher temperatures in the Delhi's center affect the cooling load of urban buildings as well. Polynomial regression model based calculations show that higher electricity consumption was under UHI effect rather than without UHI effect except for the winter months. Saving potential or cooling load may be reduced by up to 21-23% in summer months, 10 to 14 % in monsoon season, and 8 to 17 % in the post-monsoon season if UHII intensity reduces by ~3-4°C in summer, 1-2 °C in monsoon, and 2-4°C in the post-monsoon season. However, in the winter season UHI plays a positive role and reduces load on heating appliances. It may be possible to reduce energy consumption by applying UHI mitigation measures and energy conservation policies. The results of this study will provide valuable information for developing appropriate strategies to for energy conservation in megacities like Delhi.

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