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Installation of roof-top solar PV modules and their impact on building cooling load

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Abstract

It has been shown by many researchers that over a long term there has been a slow but steady rise of ambient temperature within the Indian sub-continent. Due to an increased economic prosperity there has been an accompanied increase in the urban heat island effect. Furthermore, urbanisation of large cities in India has also led to higher population densities. The above factors had the combined effect of a significant increase of cooling load of buildings.

The high density of dwellings and other building construction has resulted in shading of walls. However, the flat roof spaces are exposed to an uninterrupted solar radiation regime and this in turn leads to generation of high sol-air temperatures which cause higher cooling loads. Presently, it has been argued that roof spaces are one of the major contributors to building cooling load.

In this article the reasons behind the phenomenal rise in the installation of air-conditioners in India are reviewed. The dual role of roof-top PV systems in electricity generation and reduction of building cooling load due to the shading they provide is then investigated.

Keywords

Climate change, Solar PV modules, Building cooling load, CO_2 emissions

1. Introduction

India lies in the southern portion of Asia. It is a peninsula, surrounded on three sides by water and one side with land. India lies between 8°4' and 37°6' North latitude and 68°7' and 97°25' East longitude. It covers nearly 2 million square km of land area. In 2011 the population of India was 1.241 billion with an annual growth rate of 1.37%.

India is a fast growing country with a large economy. India's electricity demand is increasing at the rate of 8.5%. It will be presently shown that large part of the electricity demand in urban areas is due to a phenomenal rise of air-conditioner installations in buildings.

India depends heavily on fossil fuels like coal and oil to meet its rapidly growing energy demand. All major power plants in India are based on thermal systems which provide three fifths of India's energy needs. Amongst the renewable energy sources, India is beginning to exploit solar, wind and biomass technology. Solar energy, however, is the most abundant and stable source of energy available in India, i.e. most parts of India receive 4-7kWh/m^2-day of solar radiation. The development of solar PV technology was initiated in the year 1994 and by early 2013 had reached a cumulative capacity of 1.5 GW. This pales into insignificance though when compared to the UK which has a matching PV capacity with a mere 5% population ratio and yet an annual solar energy income of 0.9-1.3 kWh/m^2-day! There are signs of a vibrant growth in the Indian PV sector though with plants as large as 5GW planned in the Indian state of Gujarat alone [1]

In the present article, a method for selection of design solar radiation and outdoor ambient temperature for production of sol-air temperature is presented. Design tables for sol-air temperature for five key Indian locations, shown in Fig. 1: Delhi, Bhopal, Ahmadabad, Bhubaneswar and Chennai, are then presented. The production of the latter tables was based on the recently measured data set for solar radiation and ambient temperature that has been made available by the NASA [2] and the India Meteorological Department [3]. Furthermore, those solar radiation, ambient temperature and sol-air temperature tables were then used to study the impact of the installation of PV modules on roof-tops towards sustainable electricity generation and their potential towards the reduction of building cooling load due to the shading provided by the modules.

Insert Figure 1

2. The combined impact of climate change, Urban Heat Island effect and economic prosperity on building cooling demand

2.1. Climate change

It has been shown by several researchers [4, 5, 6,7,8] that over a long term there has been a slow but steady rise of ambient temperature within the Indian sub-continent. Most of the studies have shown that a positive change in temperature with different rates has occurred for different cities within the past century. On the regional scale, Kothawale and Rupa Kumar [9] have examined a surface temperature over India from 1901 to 2003 and reported that annual mean, maximum and minimum temperature had a rise of 0.2^{o}C per decade. Sarker and Thapliyal [10] reviewed climate change over the previous 80 years and indicated a warming trend in temperature. The study by Srivastava et al. [11] on decadal trends in climate over India has shown much larger increasing trends of maximum temperatures than the minimum temperatures. Pant and Kumar [12] analysed the data for 1881–1997 and showed that there was a significant warming trend of 0.57°C per hundred years. Sinha Ray and De [13] have summarized their work by indicating an increasing trend of 0.35°C over the last 100 years. Figure 2 shows the rising trend of annual-averaged maximum, minimum and mean temperature for Chennai which is one of the five locations that are presently under discussion.

Insert Figure 2

2.2. Urban Heat Island effect

The phenomenon of Urban Heat Island is recognised as a direct consequence of urbanisation [14, 15, 16, 17, 18, 19, 20]. Urbanisation of large cities in India has also led to higher population densities and rise in temperature [21, 22]. Indian government backed research has shown that both Delhi and Mumbai, are becoming "urban heat islands", with significantly different climates to their surrounding rural areas. The Delhi-based Energy Research Institute (TERI) has shown that within the past 15 years temperatures in both cities have risen by 2-3ºC. The on-going study, based on NASA [2] satellite readings, also showed the cities to be 5°C - 7°C warmer than the surrounding rural areas on summer nights [23].

2.3. Rising economic prosperity and the use of air-conditioners

With one of the fastest growing economies in the world, India recorded an average economic growth rate of 7% for the period 2000-2003 [24]. The Indian middle-class population of around 450 million is getting used to an affluent lifestyle.

The Korean air-conditioner manufacturer, LG Electronics claims that in year 2012 India became the world's largest importer of its units. With a present market penetration of a mere 3% the 2012 recorded sales were 900,000 units and the annual energy consumption for cooling of buildings was 25 TWh [25]. It is not difficult to guess the increase in sales and energy consumption that would take place in the future years once India joins the club of developed countries!

In a landmark article that explores the strong correlation that links the deployment of air-conditioners within homes to economic prosperity and cooling degree-days McNeil and Letschert [26] have provided some interesting data for India. They have shown that with 3,120 cooling degree-days India has the potential capacity to have 99% market saturation once economic prosperity comes on a par with the western world. The latter work is somewhat flawed though as the base temperature that was used for obtaining cooling degree days was set at 18°C. The adaptive comfort theory [27, 28] suggests that the latter indoor temperature could be as high as 26°C for the Indian sub-continent. The personal experience of three of the four authors of this article confirms the latter comfort temperature. However, even with a lower cooling degree-days profile it is evident that there will be an ever increasing deployment of air-conditioners in India.

A further link that has been studied by the above research team is the one between availability of air-conditioners and household income and a strong relationship was demonstrated once again. Based on the latter relationship the forecast is a trebling of domestic air-conditioners between the years 2013 and 2030. Figure 3 presents the rising prosperity profile for India.

Insert Figure 3

The above factors have had the combined effect of a significant increase of cooling load of buildings [29].

3. Roof-top installation of PV modules

3.1. Status and trends

India is planning to raise its solar electricity generation capacity by eightfold by the year 2017 [30].

In December 2012, Ministry of New & Renewable Energy (MNRE) [31] released a policy document regarding the next phase of its solar mission. One of the areas that the policy document stresses upon is the rooftop PV segment, with the possible deployment of up to 1GW of rooftop projects; both for off-grid and grid connected systems. The newly formed Solar Energy Corporation of India (SECI) has started the process to allocate 10 MW of rooftop PV projects in 6 locations - Delhi, Bhubaneswar, Haryana, Chhattisgarh, Karnataka and Tamil Nadu.

Other recent developments include the state of Gujarat that has taken first steps by making its capital, Gandhinagar, a model solar city. By partnering with the private sector, it will generate 5 MW of peak power entirely from Solar PV rooftop system by 2013 and Tamil Nadu which has set a target of 1GW-peak rooftop solar generation from residential and multi-storied housing sector.

Attention may be also drawn to a parallel project that was completed in India's neighbouring country, China where Canadian Solar has completed a 30MW rooftop PV installation in City of Suzhou. The rather large-scale project spanned 129 buildings, with a total surface area of approximately 500,000 square meters. The rooftops were mixed surfaces, with 200,000 square meters of steel structured rooftops and 300,000 square meters of concrete rooftops. The project was completed in June 2013, with full-grid connectivity provided through July and August of the same year. The first year's electricity generation was projected to be over 32GWh/annum [32].

3.2. Price drop of PV modules

Figure 4 shows the installed prices for 2-5 kW capacity PV roof top systems for residential applications in different countries. In India, the price of the equivalent PV system is USD 3,500/kW, which is about the same as the price in China. In Italy, France, Spain and US that price is USD 6,000/kW. Portugal has the highest price at USD 7,000/kW [33].

Insert Figure 4

The Figure 5 shows the historical price reduction of crystalline silicon photovoltaic cells.

Insert Figure 5 [34]

The industry quoted rule seems to be that the cost of photovoltaic cells falls by 20% with each doubling of global manufacturing capability.

In April 2013 the present research team completed a design and installation of a complete PV system in Madurai, a city in the Indian state of Tamil Nadu. Figure 6 shows a view of the installed PV modules. The total cost for the 1.5kWpeak electricity generation and battery storage system was Indian Rupees 294,000 (USD 4,809). This translates to $3,206/kWpeak.

Insert Figure 6

Presently, with the view to assess the economic viability of rooftop PV system for India a price quote for a complete system was obtained from a local installer. That information is provided in Table 1.

Insert Table 1

4. Sol-air temperature and building cooling load

4.1. Sol-Air Temperature

Solar radiation absorbed at the outside, opaque surfaces of buildings such as walls and roofs is partly transmitted to the interior of the building. The absorbed radiation has the same effect as a rise in the outside temperature. CIBSE Guide [35] defines the sol-air temperature as 'the outside temperature which, in the absence of solar radiation, would give the same temperature distribution and rate of energy transfer through the wall or roof as exists with the actual outside air temperature and incident radiation'. The CIBSE Guides A [36] and J [37] provide extensive guidance on estimation method for sol-air temperature, a resume of which is presented below.

For a given amount of cloudiness, C the horizontal- and vertical surfaces long-wave radiation loss (I_{lwl},W/m^2) are respectively given as,

$$I_{lwl} = 93 – 79\ C \qquad \text{Eq. (1)}$$

$$I_{lwl} = 21 – 17\ C \qquad \text{Eq. (2)}$$

The sol-air temperature, t_{eo} may then be obtained as follows:

$$t_{eo} = (\alpha\ I_{surface} – \varepsilon\ I_{lwl})R_{so} + t_{ao} \qquad \text{Eq. (3)}$$

where α is the solar absorptance, $I_{surface}$ the incident solar irradiation (W/m^2), ε the long-wave emissivity, R_{so} the outside surface resistance (m^2-K/W) and t_{ao} the outdoor temperature (Celsius).

The London based Chartered Institution of Building Services Engineers recommends the use of hourly sol-air temperature tables for cooling load estimation and these are obtained for the design 'maximum' irradiances that are exceeded on 2.5% of occasions in each month (CIBSE, 2014). The sol-air temperatures are then obtained using coincident dry-bulb temperature. Note that CIBSE recommends α=0.9 for dark- and 0.5 for light coloured surfaces and ε = 0.9.

4.2. Building Cooling Load

This is the rate at which sensible and latent heat must be removed from the space to maintain a constant space air temperature and humidity. Cooling loads result from many conduction, convection, and radiation heat transfer processes through the building envelope and from internal sources and system components. The building components that contribute towards the cooling load may include (a) external walls, roofs, windows, skylights, doors, partitions, ceilings, and floors, (b) internal lights, people, appliances, and equipment, (c) air and moisture leakage or admittance by means of ventilation, and (d) energy transfer from duct leakage, fans and pumps.

The sum of all space instantaneous heat gains at any given time does not necessarily equal the cooling load for the space at that same time. Time delay effects are experienced due to radiant energy absorbed by walls, floor and furniture and re-release as convective gains.

The relevant work of two leading professional bodies that provide guidance on the estimation of building cooling load is briefly mentioned here.

4.2.1. The work of ASHRAE

The Atlanta based American Society for Refrigerating, Heating and Air- conditioning Engineers provides extensive guidance on building cooling load estimation. In its most recent edition of Guide to Fundamentals (ASHRAE, 2009) the following two methods are cited.

The 'Heat Balance Method' for obtaining cooling load involves calculating a surface-by-surface conductive, convective, and radiative heat balance for each room surface and a convective heat balance for the room air. The Radiant Time Series (RTS) method is a simplified method for performing design cooling load calculations that is derived from the heat balance method. It replaces the historical 'transfer function' method that was used by ASHRAE for several decades. Figure 7 presents a synopsis of the ASHRAE procedure for obtaining building cooling load. Note that one of the essential element in this regard is the knowledge of sol-air temperature for the opaque elements of the building envelope.

Insert Figure 7

4.2.2. The work of CIBSE

Section A5 of CIBSE Guide A provides the algorithmic details for obtaining building cooling load. For the opaque surfaces, the transmission of fluctuations in outdoor sol-air temperature is calculated using a decrement factor ‘f’ which is the attenuation of a thermal wave that is travelling through an element of building structure. Thus, if a cyclic wave of amplitude λ enters at one side of an element, after a period of Φ hours a wave of reduced amplitude fλ will emerge at the other side. Both ‘f’ and Φ are characteristics of the material and its thickness. Guide A provides tables of properties for construction materials.

5. Weather data for Indian locations

5.1. Outdoor temperature and solar radiation

NASA-NREL has recently provided hourly global irradiation data for Indian locations that cover the period up to year 2008. Those irradiation values were obtained using Atmospheric Optical Depth (AOD) data set that was in turn developed using satellite data. The latter data sets were compared with ground-truth data from NASA's Aeronet network, and Indian Space Research Organization (ISRO) data made available by the Solar Energy Center (SEC) of India's Ministry for New and Renewable Energy and from additional sites with data published in the literature. The data set presently used in this work for any given month was selected based on completeness of satellite data and performance compared with available ground-truth data.

5.2. Sol-Air temperature tables for India

Table 2 provides geographical and other details of the locations under discussion. Using established Statistical Procedures that have been laid out by CIBSE Guide A (2014) and employing the SPSS software time series of daily total irradiation were prepared for each of the five locations from which the 97.5th percentile value for daily total irradiation and the corresponding date was identified. Table 2 includes the latter information.

Insert Table 2

Figure 8 shows the plot of Sol-air temperature and its constituting components.

Insert Figure 8

Tables 3 through 7 present Sol-air temperature data for the chosen locations. To date these tables have not been available for any Indian location.

Insert Tables 3, 4, 5, 6, 7

6. Impact of roof-top PV modules on cooling load

As identified in Section 4, availability of hourly irradiation and Sol-air temperature profile for the design day enables estimation of cooling load due to external building fabric. In the present work only the cooling load due to roof has been obtained. Wall induced solar heat load has not been considered in view of the argument presented in Section 5, i.e. wall shading due to a combination of high density of construction and high solar altitude when the sun's intensity is at its peak. The high density of construction for one Delhi suburb is shown in Fig. 9.

Insert Figure 9

A computer simulation routine was presently developed for solving the classical transient heat conduction problem with hourly Sol-air temperature data and roof construction details provided to the routine. The routine has its roots in an earlier work of one of the present authors [38]. Table 8 and Fig. 10 respectively provide details of the property data and thermal model for the elements of roof construction.

Insert Table 8 and Figure 10

The problem at hand is a classical one-dimensional heat conduction problem and for computer application may be analysed using a finite-difference method. This method is described in detail in reference [38]. The minimum time increment for the forward-marching scheme in such a case is obtained via Eq. 4,

$$Fo\ (1 + Bo) \leq 0.5 \qquad \text{Eq. (4)}$$

Where Fo is the Fourier number ($=\frac{\alpha t}{Lc^2}$), and Bo is the Biot number ($=\frac{hLc}{k}$). The Fourier and Biot number are respectively, the dimensionless time and the ratio of resistance to conduction within the solid to surface convective resistance. Note that α is the thermal diffusivity ($\frac{m^2}{s}$), L_c the characteristic length (m), h the surface convection heat transfer coefficient ($\frac{W}{m^2-K}$) and k the thermal conductivity ($\frac{W}{m-K}$) of the roof constructional material.

Using the information provided in Table 8 and Figure 10 an optimum time increment for analysing the present transient problem was found to be 120 Sec.

The above simulation program was executed to obtain the cooling load profile for each of the five Indian locations for the respective design day. A sample plot of the transient conduction process and the propagation of the thermal wave is shown in Figures 11 and 12 respectively for the case of a conventional, light-coloured flat roof with - and without shading provided by PV modules.

Insert Figures 11 and 12

In each case a 90 m^2 roof area for an average-sized family residence has been used.

Table 9 presents the result obtained from cooling load simulation for the two cases: (a) roof irradiated by sun, and (b) roof shaded by PV array. The reduction in energy required for roof-induced cooling is dramatic as a result of shading, i.e. from 73% for Chennai to 90% reduction in energy demand for Delhi. Thus, roof-top PV arrays offer a twin advantage of electricity generation and reduction of energy consumed for roof-induced cooling load.

Insert Table 9

Table 10 presents further information on the energetic, economic and environmental impact of the proposed roof-top PV array.

Insert Table 10

Table 11 includes data that has been used for preparation of Table 10.

Insert Table 11

7. Discussion

Reference is made to Figures 11 - 12 and Tables 9 - 10. The latter Tables have demonstrated that on one hand, a remarkable reduction of building cooling load can be achieved by roof shading provided by PV modules and on the other hand, a significant energy generation may be achieved. The main contributor to the dual return may be traced to the high solar energy income for the Indian Sub-Continent. To shed further light Figures 13 and 14 have been prepared. Figure 13 compares the sol-air temperature profile for Indian location against London, which has a temperate, maritime climate. At peak times, the difference between sol-air temperature for India and London appears to be 26 - 32 Celsius. It is a known fact that there is a growing prevalence of the use of air-conditioning for cooling even in London.

Insert Figure 13

With the above temperature incline for Delhi and other Indian locations, compared to London, it is therefore not surprising to experience a growing demand for cooling. Another point worth mentioning here with respect to Figure 13 is that the coastal locations of Chennai and Bhubaneswar seem to have slighter cooler profile when compared to the remaining three in land locations.

Figure 14 presents the stark difference of the differential between rooftop and outdoor ambient temperature profile for Delhi when compared with London. Whereas a comparatively weak English sun generates a temperature differential of only 13 Celsius, in contract a corresponding Figure of 25 Celsius is noted for Delhi. The sole reason for the above phenomenon is, once again, the high intensity of solar radiation for Delhi.

Insert Figure 14

Figure 15 presents the Delhi demand profile for the electricity grid. The peak demand occurs around 3pm when the air-conditioners for offices and residential buildings start to run at full capacity as the thermal wave arrives indoors (see Figure 12). The reported peak load for Delhi on 5th July 2012 was 5.6GW, which occurred at 3pm. [41]. A considerable part of this load may be attributed to cooling of buildings, as the following analysis shall demonstrate.

Insert Figure 15

Refer to Table 8 that showed Delhi population to be close to 17 million. Being the capital city with a considerable affluence, it may be safely assumed that at least 15% of the population would use air-conditioning. Using a compressor rating of 1.33kW for a split system as shown in Table 11, the cooling load for the city would thus be of the order of over 3GW. The latter load though could be shaved off by 90% if roof shading was provided as shown in Table 9.

8. Conclusions

The CIBSE method to obtain sol-air temperature with solar radiation and outdoor ambient temperature has been obtained. Design tables for sol-air temperature for five key Indian locations were then obtained. These tables are based on the recently presented data by the NREL-India Meteorological Department consortium. The ambient- and sol-air temperature tables were then used to study the impact of the installation of roof-top PV modules on sustainable electricity generation and their potential towards the reduction of building cooling load due to the shading provided by the PV modules.

A computer simulation routine was presently developed for solving the classical transient heat conduction problem with hourly Sol-air temperature data and roof construction details provided to the routine. This program was executed to obtain the cooling load profile for each of the five Indian locations for the respective design day. The computer simulation demonstrated that the energy required for roof-induced cooling load decreased between 73-90% after installation of the PV system.

The PV system is expected to generate annual solar electricity of at least 11.9MWh from a 90 square metre roof-top, for each of the five Indian locations.

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Table 1
Price quote for roof-top PV system for India

Component	Cost, INR	Cost, USD	Ratio of total system cost
Monocrystalline modules	350,000	5,600	0.44
5kVA grid tied inverter	250,000	4,000	0.31
Cables and module support	100,000	1,600	0.13
Transportation and installation	100,000	1,600	0.13
Total cost	800,000	12,800	

Note: Modules cost = $1.4/Wp and system cost = $3.2/Wp
INR = Indian Rupee, USD = US Dollar

Table 2
Locations chosen for the present study

Location (city)	State	Latitude, N	Longitude, E	State population, 2011 Census
Delhi	Delhi	29.02	77.38	16,753,235
Bhopal	Madhya Pradesh	23.25	77.42	72,597,565
Ahmedabad	Gujarat	23.03	72.62	60,383,628
Bhubaneshwar	Odisha	20.27	85.84	41,947,358
Chennai	Tamil Nadu	13.08	80.27	72,138,958

Table 3

Sol-air temperature table for Delhi (based on CIBSE recommended 97.5 percentile daily radiation method)

Time, hour	Radiation, W/m^2	Ambient temperature, C	Sol-air temperature, C
0	0	23.8	18.0
1	0	23.1	17.3
2	0	22.6	16.7
3	0	22.1	16.3
4	0	22.0	16.1
5	0	22.3	16.4
6	88	23.0	20.2
7	288	24.2	28.5
8	491	26.1	37.4
9	702	28.2	46.9
10	866	30.5	55.0
11	960	32.8	60.5
12	977	34.5	62.8
13	938	35.6	62.6
14	845	36.0	59.7
15	670	35.6	53.2
16	462	34.6	44.9
17	255	33.1	36.1
18	65	31.2	27.7
19	0	29.4	23.6
20	0	27.9	22.0
21	0	26.5	20.6
22	0	25.4	19.5
23	0	24.5	18.7

Table 4

Sol-air temperature table for Bhopal (based on CIBSE recommended 97.5 percentile daily radiation method)

Time, hour	Radiation, W/m^2	Ambient temperature, C	Sol-air temperature, C
0	0	28.0	22.2
1	0	27.2	21.4
2	0	26.6	20.8
3	0	26.2	20.3
4	0	26.0	20.1
5	0	26.3	20.5
6	73	27.1	23.8
7	291	28.5	32.8
8	527	30.5	43.1
9	724	32.8	52.3
10	879	35.5	60.4
11	975	38.0	66.2
12	1006	39.8	69.2
13	964	41.1	69.0
14	863	41.6	65.9
15	698	41.1	59.7
16	491	40.0	51.3
17	258	38.3	41.5
18	47	36.3	32.0
19	0	34.2	28.4
20	0	32.5	26.7
21	0	31.0	25.1
22	0	29.7	23.9
23	0	28.8	22.9

Table 5

Sol-air temperature table for Ahmadabad (based on CIBSE recommended 97.5 percentile daily radiation method)

Time, hour	Radiation, W/m^2	Ambient temperature, C	Sol-air temperature, C
0	0	29.5	23.7
1	0	28.8	23.0
2	0	28.3	22.4
3	0	27.8	22.0
4	0	27.7	21.8
5	0	28.0	22.1
6	28	28.7	23.8
7	226	30.0	32.0
8	453	31.8	41.8
9	661	33.9	51.2
10	837	36.4	59.8
11	954	38.6	66.2
12	1004	40.3	69.6
13	984	41.5	70.1
14	895	41.9	67.4
15	745	41.5	61.7
16	546	40.5	53.7
17	321	38.9	44.3
18	100	37.1	34.7
19	0	35.2	29.4
20	0	33.7	27.8
21	0	32.2	26.4
22	0	31.1	25.2
23	0	30.3	24.4

Table 6

Sol-air temperature table for Bhubaneswar (based on CIBSE recommended 97.5 percentile daily radiation method)

Time, hour	Radiation, W/m^2	Ambient temperature, C	Sol-air temperature, C
0	0	26.3	20.4
1	0	25.6	19.8
2	0	25.1	19.3
3	0	24.8	18.9
4	0	24.7	18.8
5	1	24.9	19.1
6	125	25.5	24.0
7	399	26.6	34.7
8	622	28.2	44.2
9	809	30.1	52.6
10	940	32.2	59.3
11	1000	34.2	63.3
12	929	35.7	62.3
13	850	36.7	60.6
14	733	37.1	56.8
15	556	36.7	50.3
16	330	35.8	41.5
17	91	34.4	31.8
18	0	32.8	27.0
19	0	31.2	25.4
20	0	29.9	24.0
21	0	28.6	22.8
22	0	27.6	21.8
23	0	26.9	21.0

Table 7

Sol-air temperature table for Chennai (based on CIBSE recommended 97.5 percentile daily radiation method)

Time, hour	Radiation, W/m^2	Ambient temperature, C	Sol-air temperature, C
0	0	30.0	24.2
1	0	29.4	23.5
2	0	28.9	23.0
3	0	28.5	22.7
4	0	28.4	22.5
5	0	28.7	22.8
6	61	29.3	25.6
7	282	30.4	34.4
8	521	32.0	44.4
9	722	33.9	53.3
10	874	36.1	60.8
11	963	38.1	65.9
12	978	39.6	67.9
13	919	40.6	66.9
14	792	41.0	62.8
15	609	40.6	56.0
16	390	39.7	47.5
17	149	38.3	37.7
18	0	36.7	30.8
19	0	35.1	29.2
20	0	33.7	27.8
21	0	32.4	26.6
22	0	31.4	25.6
23	0	30.7	24.8

Table 8
Thermo-physical data for roof construction material used in India

Element	Density, kg/m^3	Specific Heat, J/kg-K	Thermal Conductivity, W/m-K	Thermal Diffusivity, m^2/s
Cement mortar	1860	780	0.72	4.96E-07
Common brick	1920	835	0.72	4.49E-07
Reinforced concrete	2000	880	1.37	7.78E-07

Table 9
Roof induced cooling load (kWh) for a 97.5th percentile day

	Delhi	Bhopal	Ahmadabad	Bhubaneswar	Chennai
Roof irradiated by sun	33.2	45.3	46.8	37.4	45.3
Roof shaded by PV array	3.4	10.5	12.4	5.8	12.3

Table 10
Energetic, economic and environmental impact of the proposed roof-top PV array

Location	Annual solar electricity output, kWh	Income, USD	CO_2 Emission Saved, Tonnes [39]
Delhi	13011	1041	11320
Bhopal	12421	994	10806
Ahmadabad	12722	1018	11068
Bhubaneswar	11920	954	10371
Chennai	12383	991	10773

*Income = energy sold to grid per annum

Table 11
Data required for preparing Table 10

$COP_{cooling}$ [40]	2.8
$Q_{evaporation}$	3.73 kW
Design outdoor temperature (ºC)	40.5-46
$W_{compressor}$ (kW)	1.33
Design indoor dry bulb temperature (ºC)	24
Design indoor wet bulb temperature (ºC)	19.4

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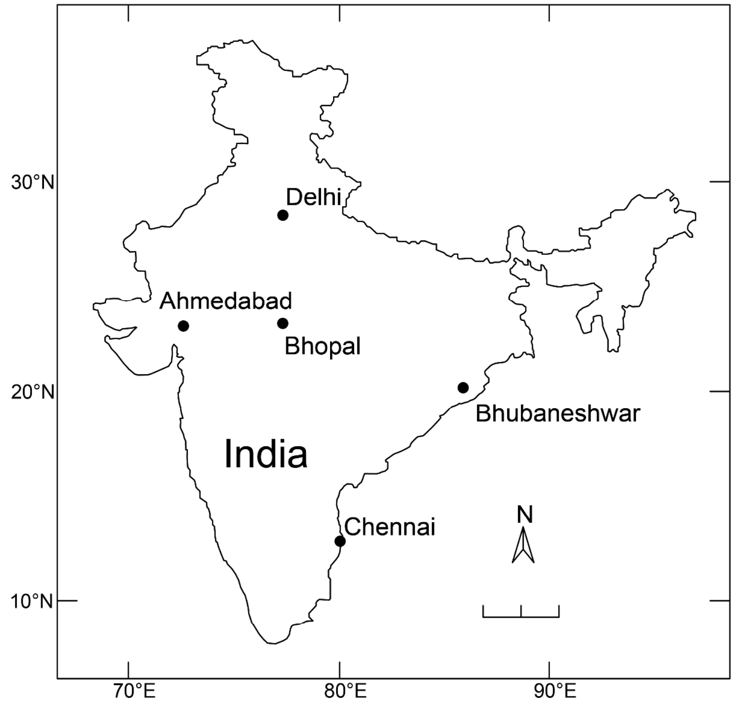
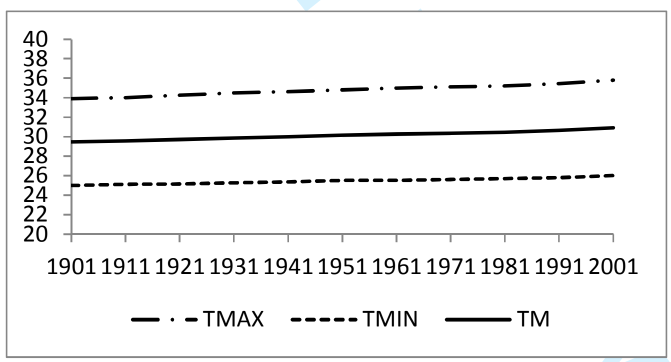


Fig. 1. Five Indian locations chosen for this study.



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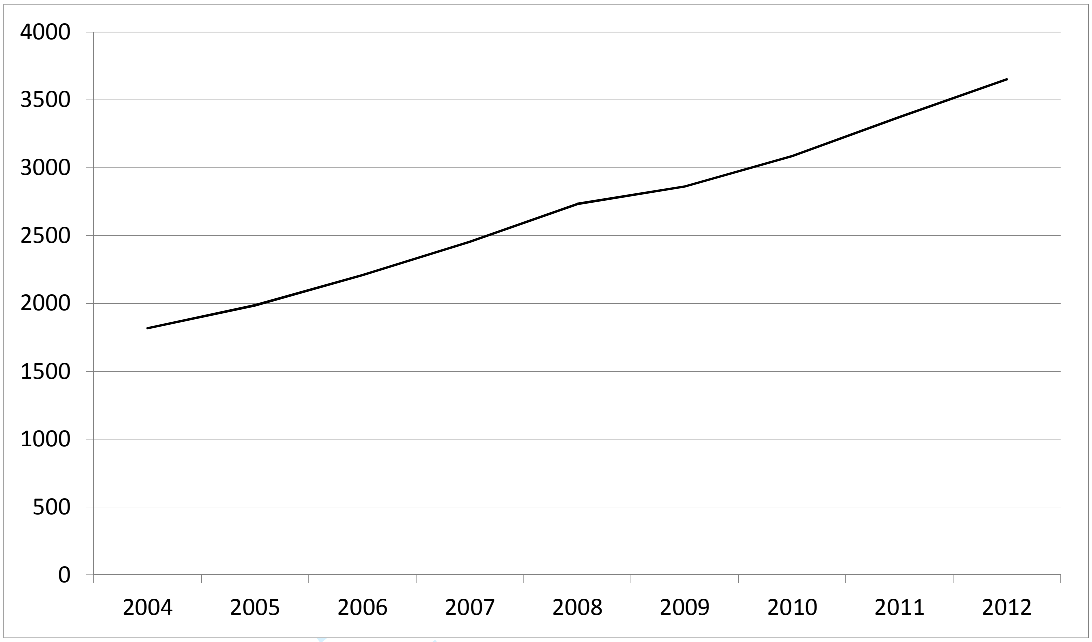
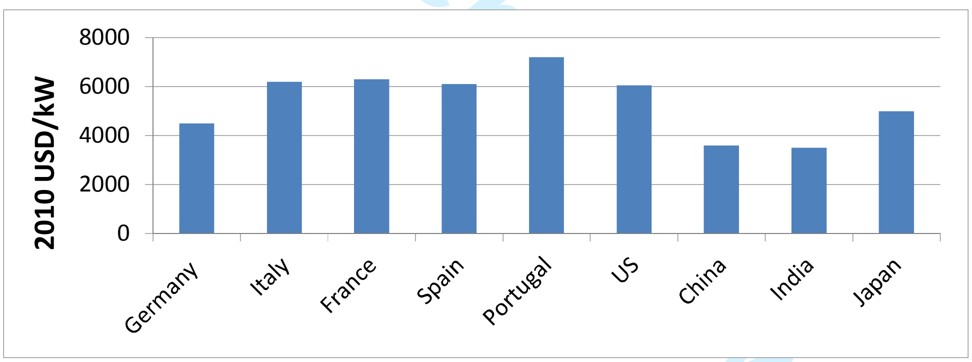


Fig.3.The rising Purchasing Power Parity, PPP (US Dollars) for India.



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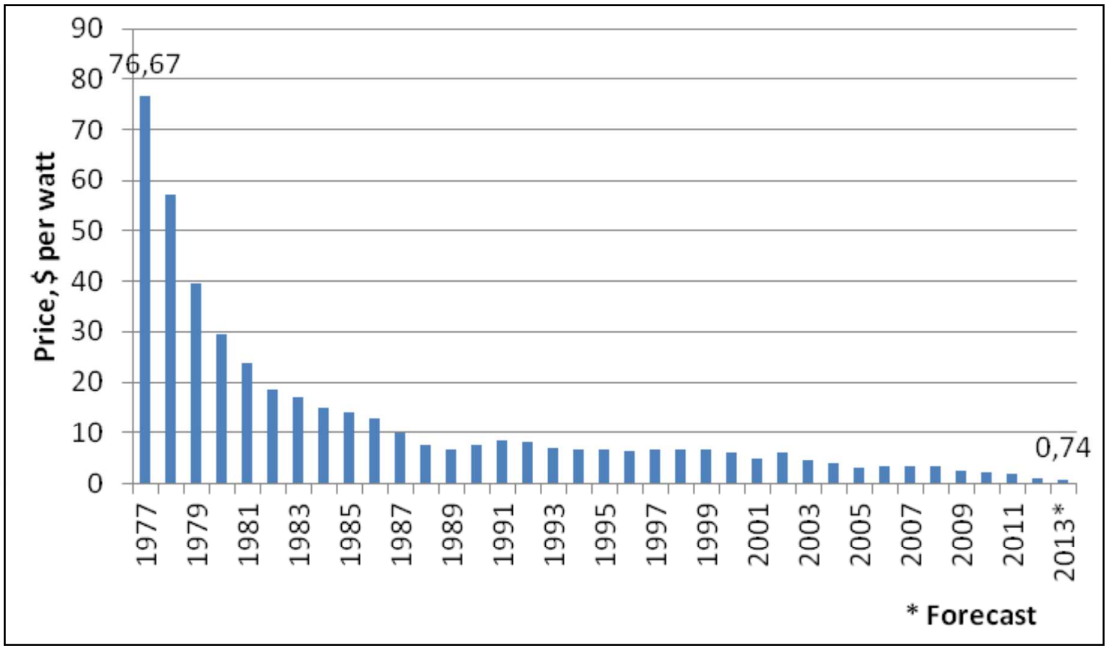

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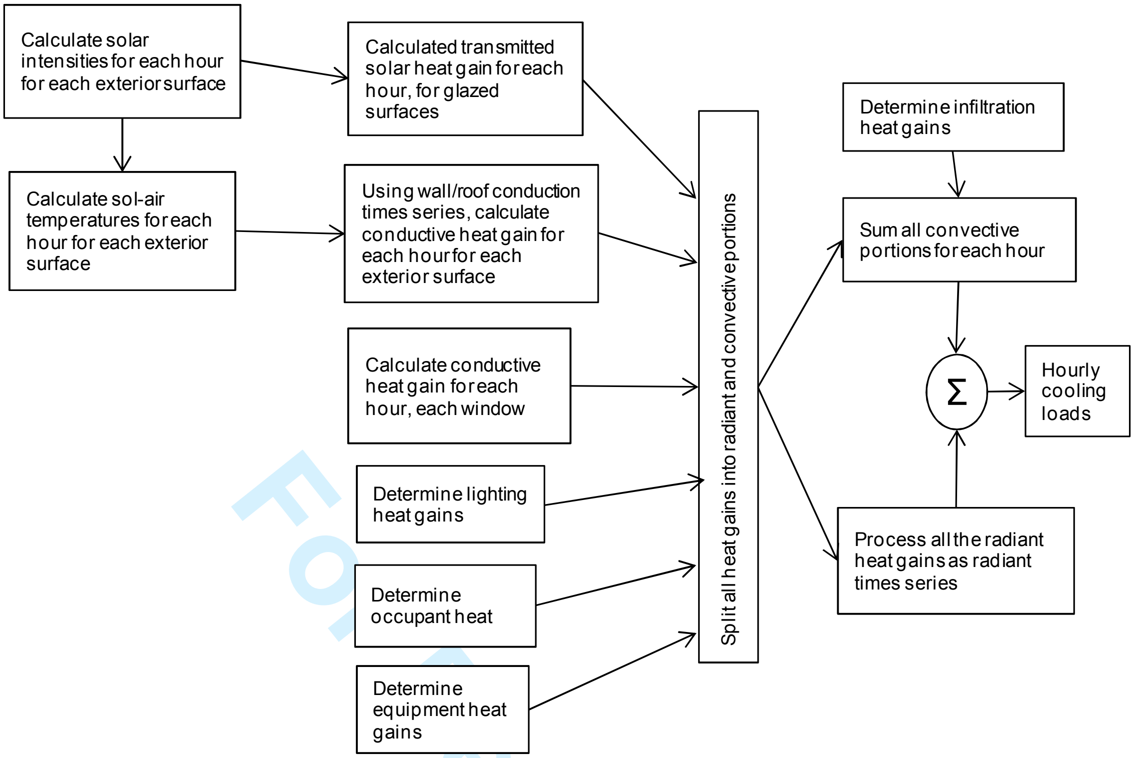

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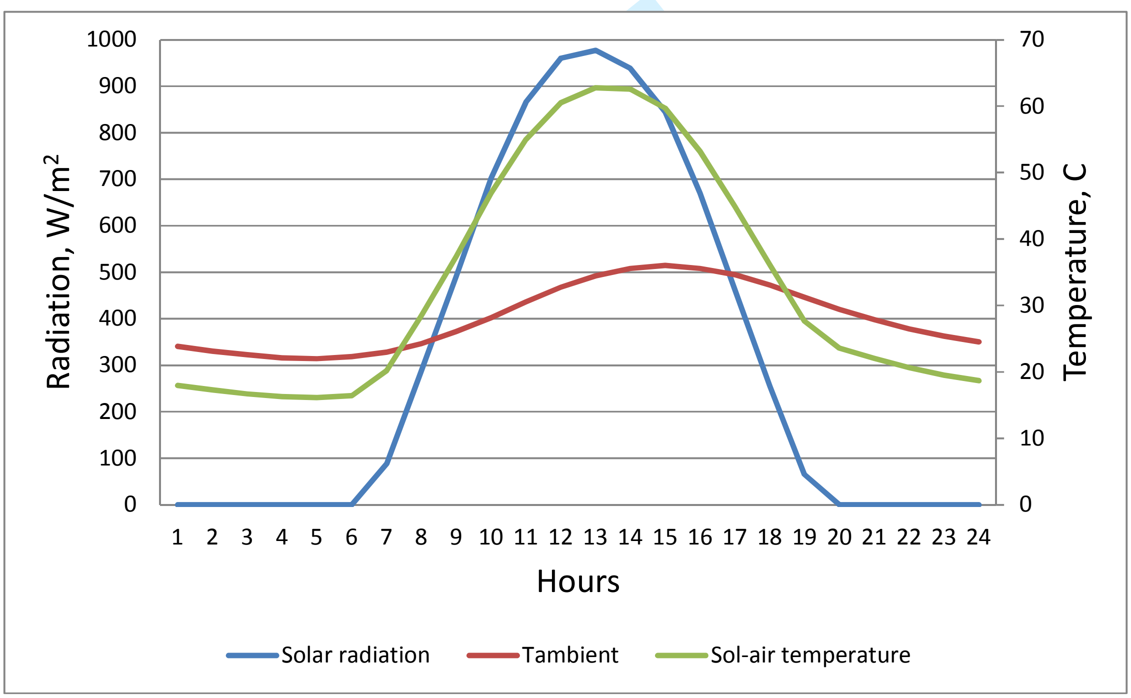

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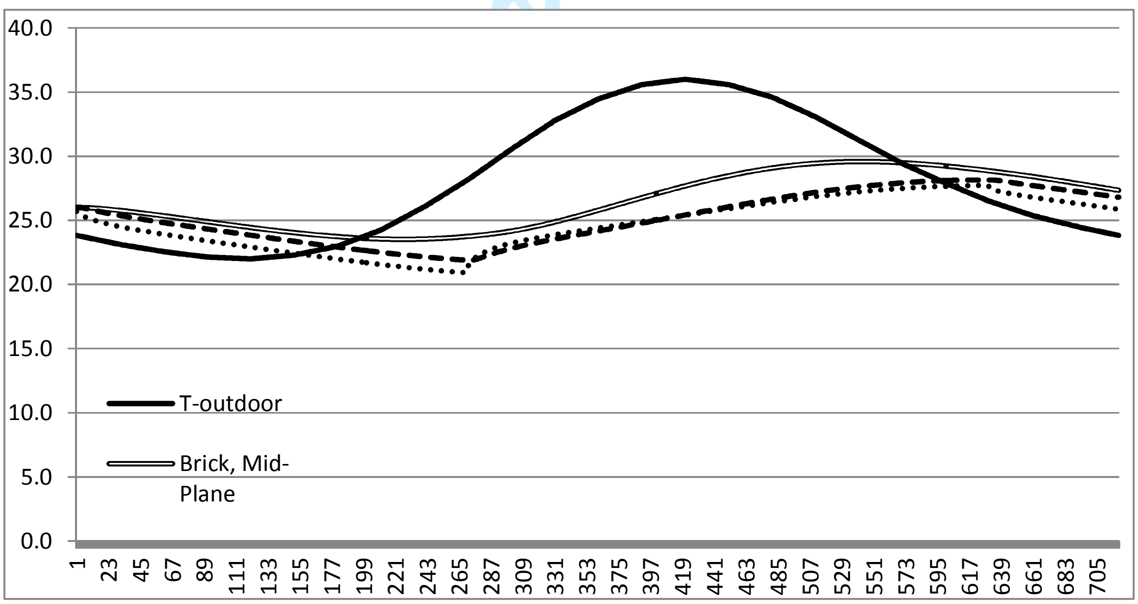
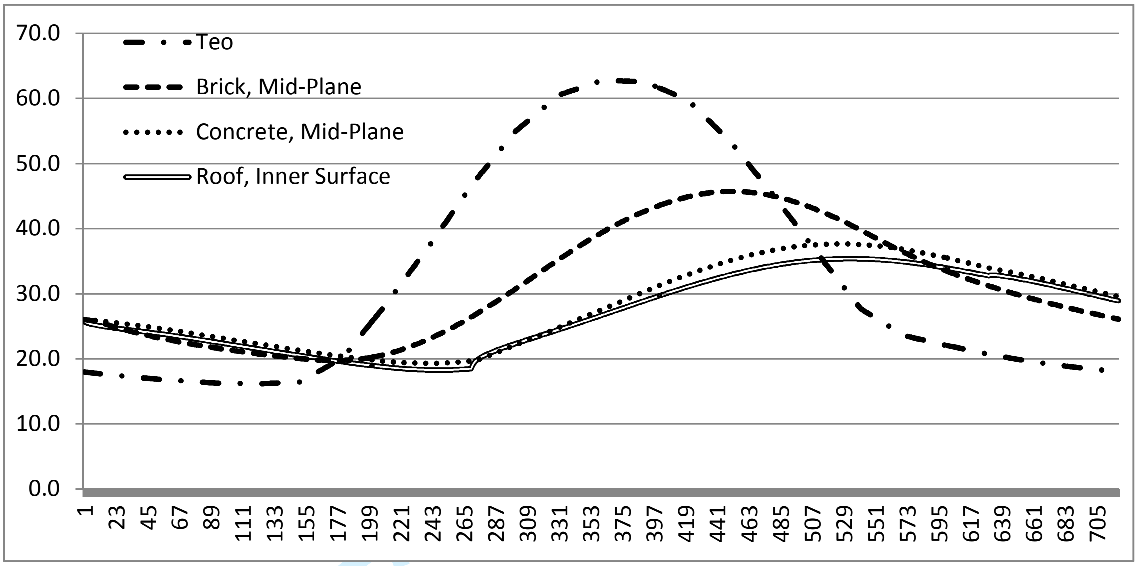


Fig.11. Thermal wave propagation for a flat roof under shade provided by a 7 kWp array. Note: The thermal loading in this case is due to outdoor-indoor temperature difference.



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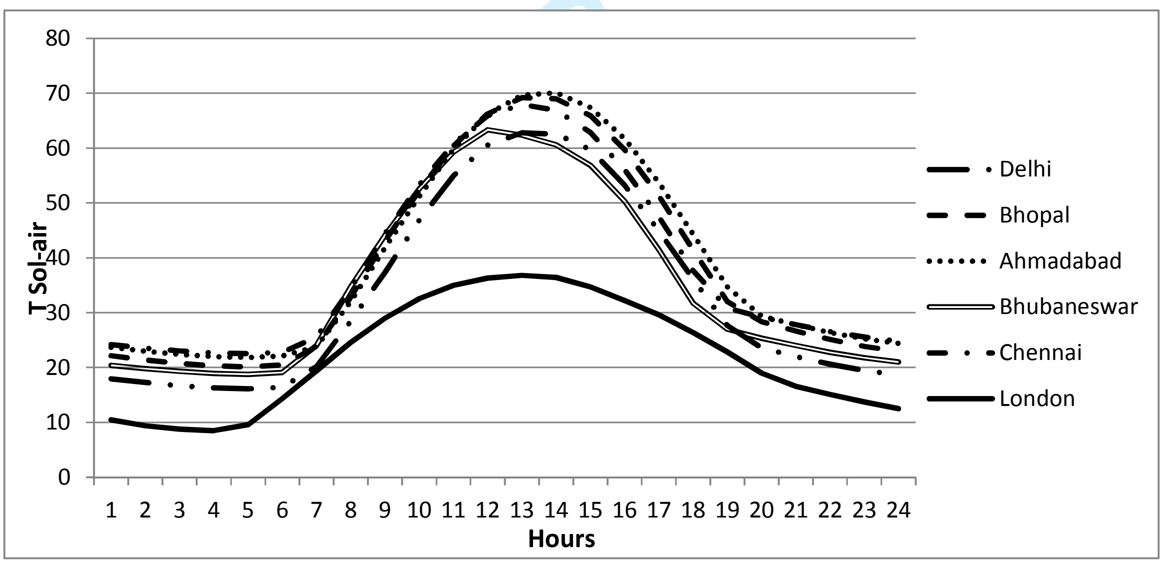

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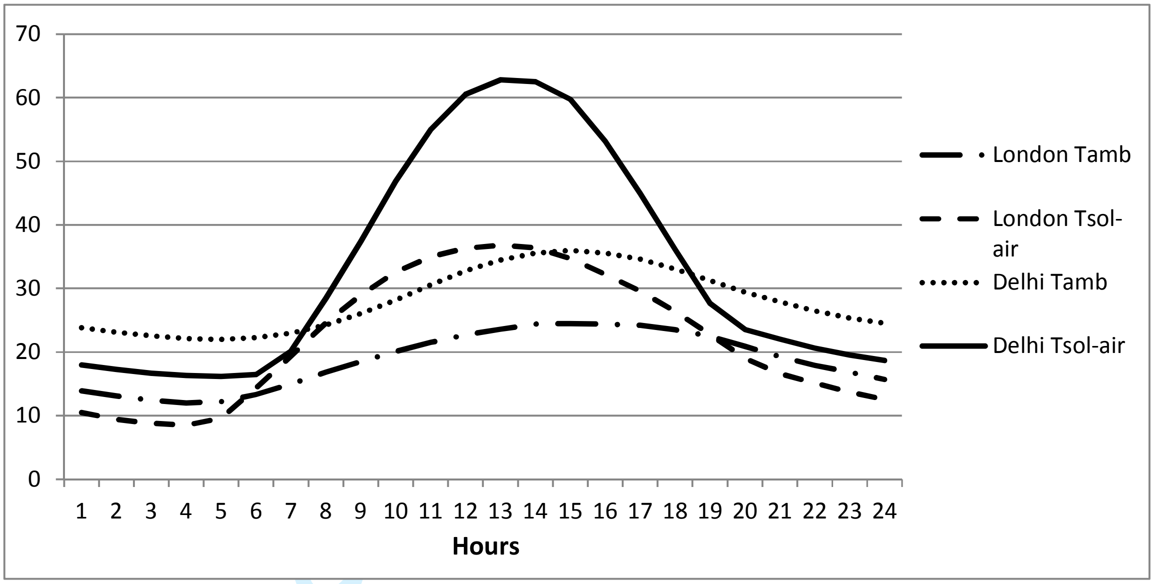

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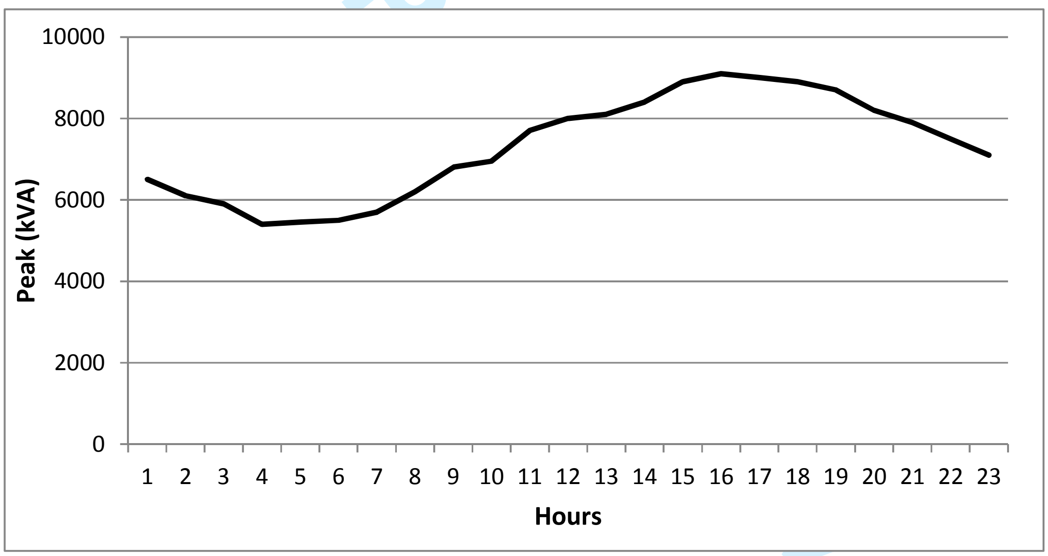

Fig.15. Typical electricity demand profile for the month of July for Delhi grid.