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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. For this purpose, the CIBSE method to obtain sol-air temperature with solar radiation and outdoor ambient temperature has been used. Sol-air temperature for five key Indian locations (Delhi, Bhopal, Ahmadabad, Bhubaneswar and Chennai), based on the recently presented data by the NREL-India Meteorological Department consortium, were then obtained.

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.

Practical application: The present work reviews the reasons behind the phenomenal rise in the installation of air-conditioners in India. The dual role of roof-top PV systems in electricity generation and reduction of building cooling load due to the shading they provide has been investigated. The computer simulation demonstrated that the energy required for roof-induced cooling load decreased between 73-90% after installation of the PV system. The method used in this work has the advantage that it enables the user to obtain cooling load estimates using a general transient heat conduction

approach. Moreover, all software was developed within MS-Excel environment, this is also an additional advantage as the cost associated with purchase and training of proprietary building energy software can be prohibitive for many consultants who are based in developing countries.

Keywords

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

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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.

India is endowed with rich solar energy resource. Because of its location between the Tropic of Cancer and the Equator, India has an average annual temperature that ranges from 25°C – 27.5 °C. Being a tropical country, India has huge potential for solar power generation. The average intensity of solar radiation received on India is 200 MW/km^2 with 250–325 sunny days in a year **[1]**. India receives 4-7kWh/m^2-day of solar radiation, a fairly large amount of radiation as compared to many parts of the world especially Japan, Europe and the US where development and deployment of solar technologies is far ahead of India **[2]**.

Europe has dominated the global PV market for years but the rest of the world clearly has the biggest potential for growth. This was highlighted by market developments that saw Europe's share of the global market being reduced from 74% in 2011 to 55% in 2012. Driven by local and global energy demand, the fastest PV growth is expected to continue in China and India, followed by Southeast Asia, Latin America and the MENA countries **[3]**.

New installations of PV systems in the rest of the world accounted for 13.9 GW in 2012, compared to 8 GW in 2011 and 3 GW in 2010. China took first place among these countries with 5 GW installed, followed by the USA with 3.3 GW and Japan with a maximum of 2 GW. All are expected to continue growing in 2013, with China as one of the two top markets in 2013. Australia expanded rapidly in

2012 with around 1 GW of new installations. India installed 1.5 GW since the development of solar PV technologies was initiated in the year 1994, finally realising a part of its huge potential [3]. There are signs of a vibrant growth in the Indian PV sector though with plants as large as 5 GW planned in the Indian state of Gujarat alone [4].

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 [5] and the India Meteorological Department [6]. 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 [7,8,9,10,11] 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 [12] 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 [13] reviewed climate change over the previous 80 years and indicated a warming trend in temperature. The study by Srivastava et al. [14] on decadal trends in climate over India has shown much larger increasing trends of maximum temperatures than the minimum temperatures. Pant and Kumar [15] 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 [16] 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 **[17,18,19,20,21,22,23]**. Urbanisation of large cities in India has also led to higher population densities and rise in temperature **[24,25]**. 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 past 15 years temperatures in both cities have risen by 2-3ºC. The on-going study, based on NASA **[5]** satellite readings, also showed the cities to be 5°C - 7°C warmer than the surrounding rural areas on summer nights **[26]**.

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 **[27]**. 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 **[28]**. 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 **[29]** 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 **[30,31]** 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 **[32]**.

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 **[33]**.

In December 2012, Ministry of New & Renewable Energy (MNRE) **[34]** 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 **[35]**.

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 **[36]**.

Insert Figure 4

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

Insert Figure 5 **[37]**

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 **[38]** 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 **[39]** and J **[40]** 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,

$I_{lwl} = 93 – 79\ C$ Eq. (1)

$I_{lwl} = 21 – 17\ C$ Eq. (2)

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

$t_{eo} = (\alpha\ I_{surface} – \varepsilon\ I_{lwl})R_{so} + t_{ao}$ 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

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.

4.2.3. Comparison of Load Calculation Procedures **[41]**

Simultaneous to the development of the CIBSE admittance method in the UK was the development of other methodologies in various countries, most notably North America, where all air plant needed to be sized to accommodate the growing market for air conditioning in offices.

The need in the UK was different, primarily aimed at sizing wet heating systems and predicting possible summertime overheating for offices in a time when large windows were fashionable. These differences led to alternative approximations and approaches being taken to arrive at practical manual calculation techniques. A good example of this could be the early ASHRAE methods which were based on internal air temperature. The mathematical treatment of heat flow through walls was also calculated differently, as the British method assumed a sinusoidal input and response whilst the North Americans opted for a time series analysis combined with conduction transfer functions.

Among the various ASHRAE methods, the RTS method and the CIBSE admittance method are the most similar in terms of application. The RTS method is noted for its suitability in calculating the peak cooling load in a defined zone on a particular design day. Extreme cooling loads tend to be overestimated in this as in the admittance method; however, as both assume that the same weather occurs every day. Furthermore it does not have the ability to model the re-radiation of long wave radiation from the interior back out into the environment, an important measure when dealing with a room with extensive glazing. It works on the assumption that the energy entering a zone remains stored in the fabric until it is later dissipated as part of a convective cooling load.

Although the HB method is the most accurate, it is unusable for interacting zones in a large building due to the added complexity of calculation. Energy re-radiation is addressed by simultaneous solving of internal and external surface temperatures hourly. This method is similar to the RTS method in that it assumes the same weather pattern is repeated each day, making it impossible to calculate annual energy or overheating frequencies. As ‘design day’ calculations, both the RTS and HB methods are most effectively employed in modular offices with mixed air cooling strategies and do not adapt well to calculating the cooling load on rooms with displacement-type air conditioning systems or chilled ceilings.

There are other publications showing procedures for sizing cooling equipment and calculating energy use from a number of different countries which can be similar in terms of modelling the physics from first principles or which may use an adaptive technique based on a simple steady state calculation.

In Germany, although the VDI 2078: Computation of Cooling Load for Air-conditioned Areas uses a times series solution of the underlying physics, it differs significantly from the HB method. Instead of making calculations of the necessary intermediate data from first principles, the VDI 2078 procedure adapts data from standardised solutions of ‘lightweight’ and ‘heavyweight’ offices. In application, it is similar to the HB and RTS methods and is suited to modular offices.

The Dutch standard NEN 2919: Energy Performance of Non-Residential Buildings — Determination Method is vastly different in approach, based on the hypothesis that the cooling loads can be calculated when only steady state conditions are taken into account before modifying results with coefficients to account for thermal capacity.

Along these lines, the Italian UNI 10375: Method for calculating the summer internal temperature of environments. It has been proved that simplified adaptive methods are less precise and flexible than those based on hourly simulation.

5. Weather data for Indian locations

In this section, using established procedures that have been laid out by CIBSE, sol-air temperature with solar radiation and outdoor ambient temperature are obtained. Design tables, based on the recently presented data by the NREL-India Meteorological Department consortium, for sol-air temperature for five key Indian locations (Delhi, Bhopal, Ahmadabad, Bhubaneswar and Chennai) are obtained.

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 **[42]** 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. Sol-air temperature tables were generated using CIBSE proposed Eqs. 1-3. Note that the above-mentioned 97.5 percentile days are cloudless regimes as has been evident to the present research team from processing of data for a large number of locations.

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 **[43]**. 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 **[44]**. 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. Note that in this respect Eq. 4 is used to obtain the minimum time increment for the iterations.

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

Insert Figures 11 and 12

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. The savings in the work of compression of the cooling plant has been obtained as a quotient of cooling load savings and a COP of 2.8 (see Table 10).

Note that there may be an incremental rise of ambient temperature around the PV modules due to their heat rejection. However, this effect is unlikely to be very significant as the rejected heat would be dissipated rapidly through convection.

It is worthwhile to point out though is that the present analysis shows the potential for cooling load reduction due to shading of the roof. The reduction in the total building energy cooling load will however be of a smaller proportion.

Insert Table 9 and 10

Table 11a presents further information on the energetic, economic and environmental impact of the proposed roof-top PV array. The solar electricity output shown in column 2 was obtained by running a simulation program that takes in to account the variation of PV cell efficiency as a function of cell temperature. The cell temperature in turn is computed as a function of the prevalent ambient temperature and solar irradiance. To do this the characteristics of a leading module manufacturer (Schott) were used and these are shown in Table 11b. Columns 3 and 4 were respectively produced by using an electricity rate of Indian Rupees 5/kWh (8 US cents/kWh) and CO_2 electricity generation intensity of 870g/kWh.

Insert Tables 11a and 11b

7. Discussion

Reference is made to Figures 11 - 12 and Tables 9 – 11a. 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

5.6 GW, which occurred at 3pm. [47]. 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 1.33 kW for a split system as shown in Table 10, the cooling load for the city would thus be of the order of over 3 GW. 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 presently used to produce design tables for five key Indian locations. 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 11.9 MWh from a 90 square metre roof-top, for each of the five Indian locations.

The advantage of the present method is that it enables the user to obtain cooling load estimates using a general transient heat conduction approach. The thermo-physical data that is required for external roof and wall construction is easily available in standard Heat Transfer texts or engineering guides provided by institutions such as CIBSE or ASHRAE. In developing countries varied types of building construction materials are employed. These construction materials may not necessarily conform to design tables associated with methods such as ASHRAE’s heat balance (HB) method. The present method would fill-in that gap. In the present work all software was developed within MS-Excel environment and this is also an additional advantage as the cost associated with purchase and training of proprietary building energy software can be prohibitive for many consultants who are based in developing countries.

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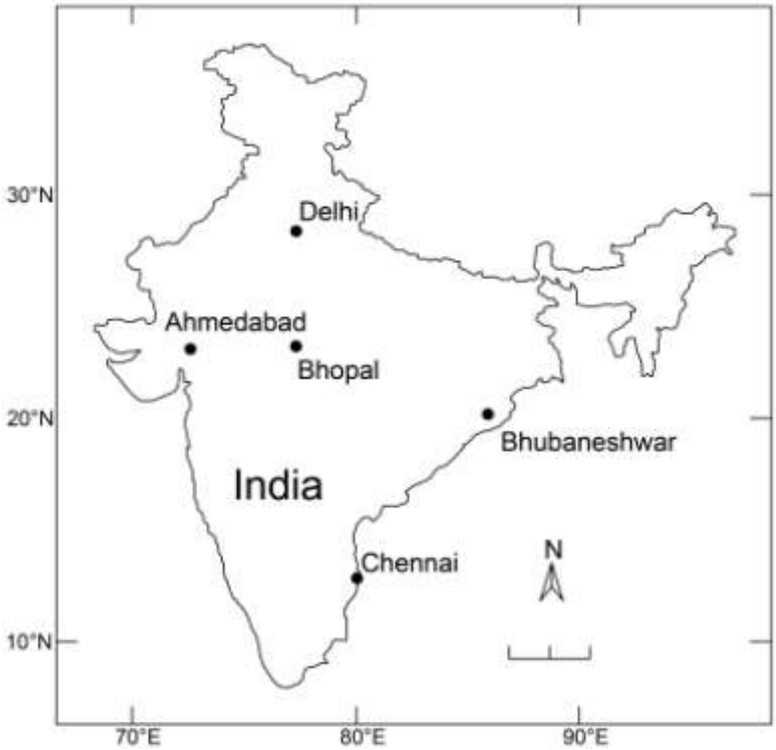

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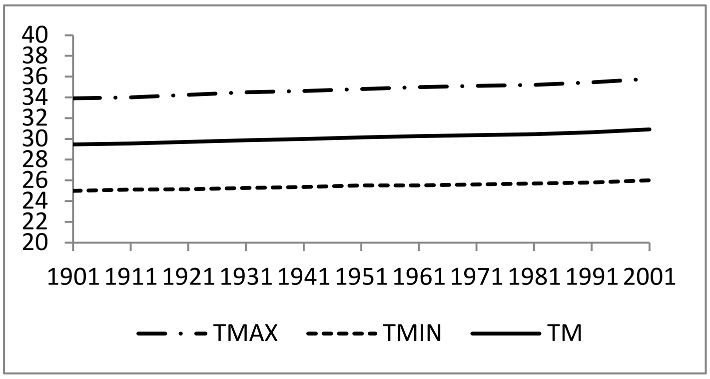

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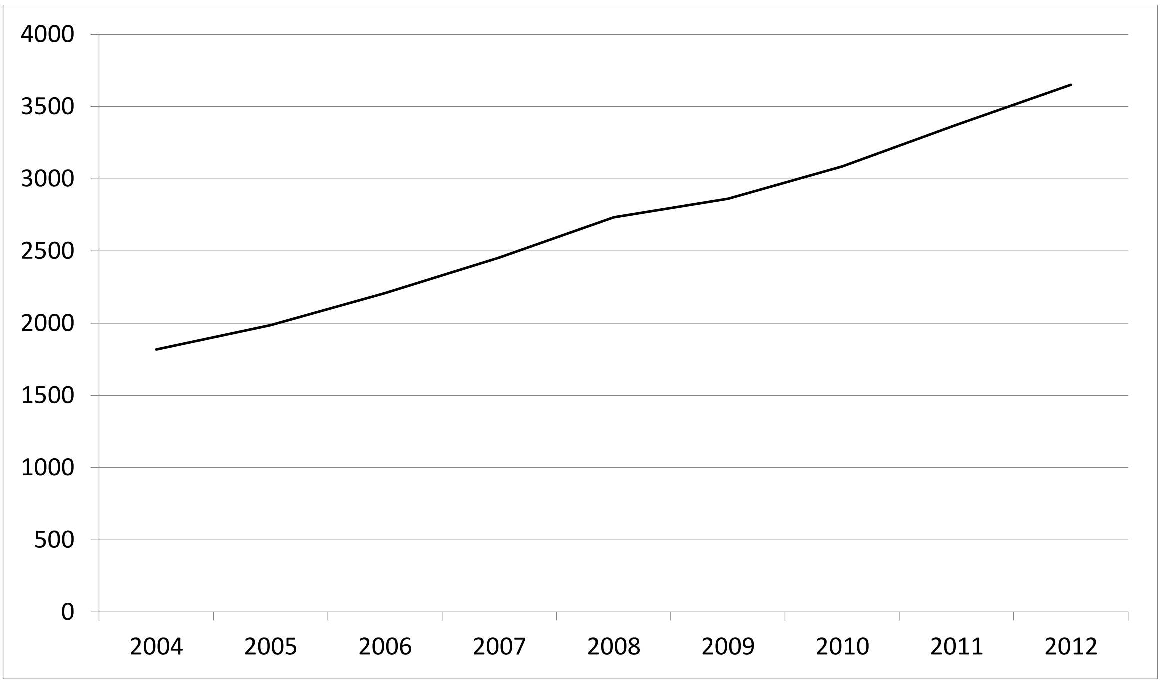

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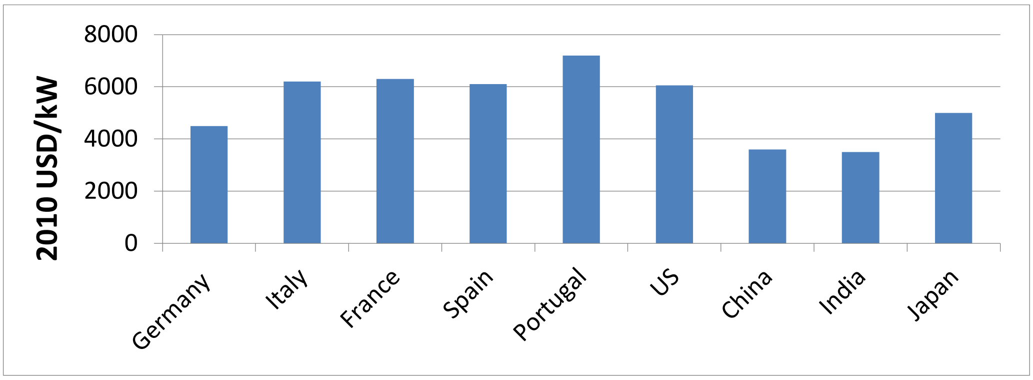

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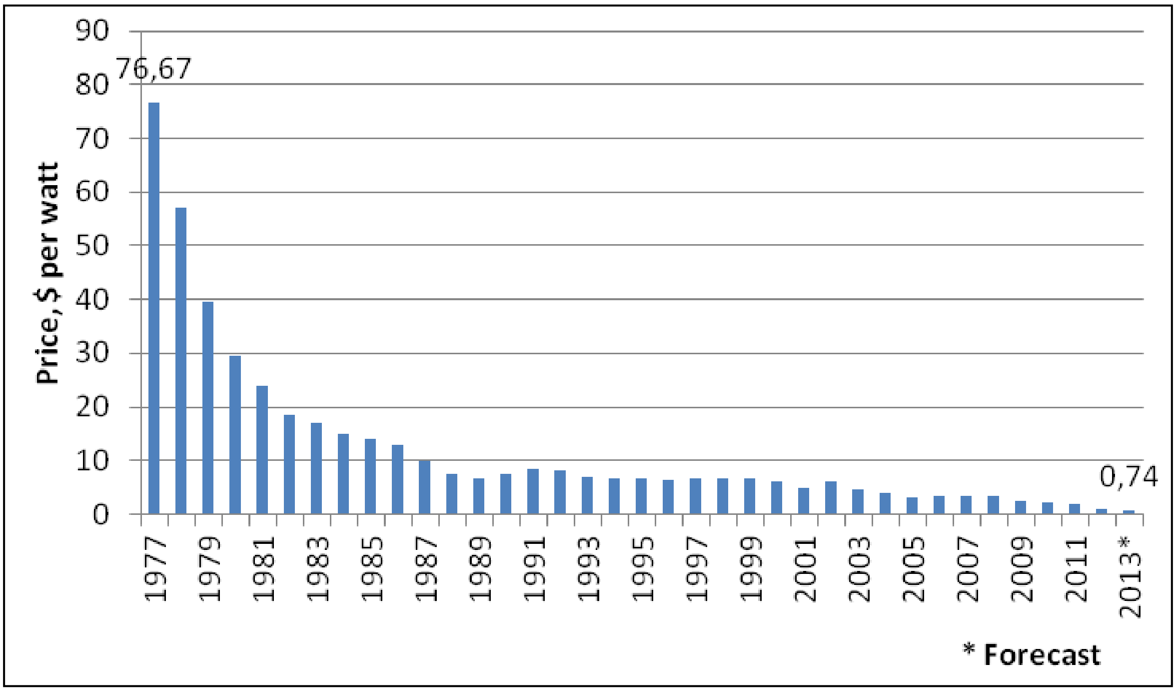

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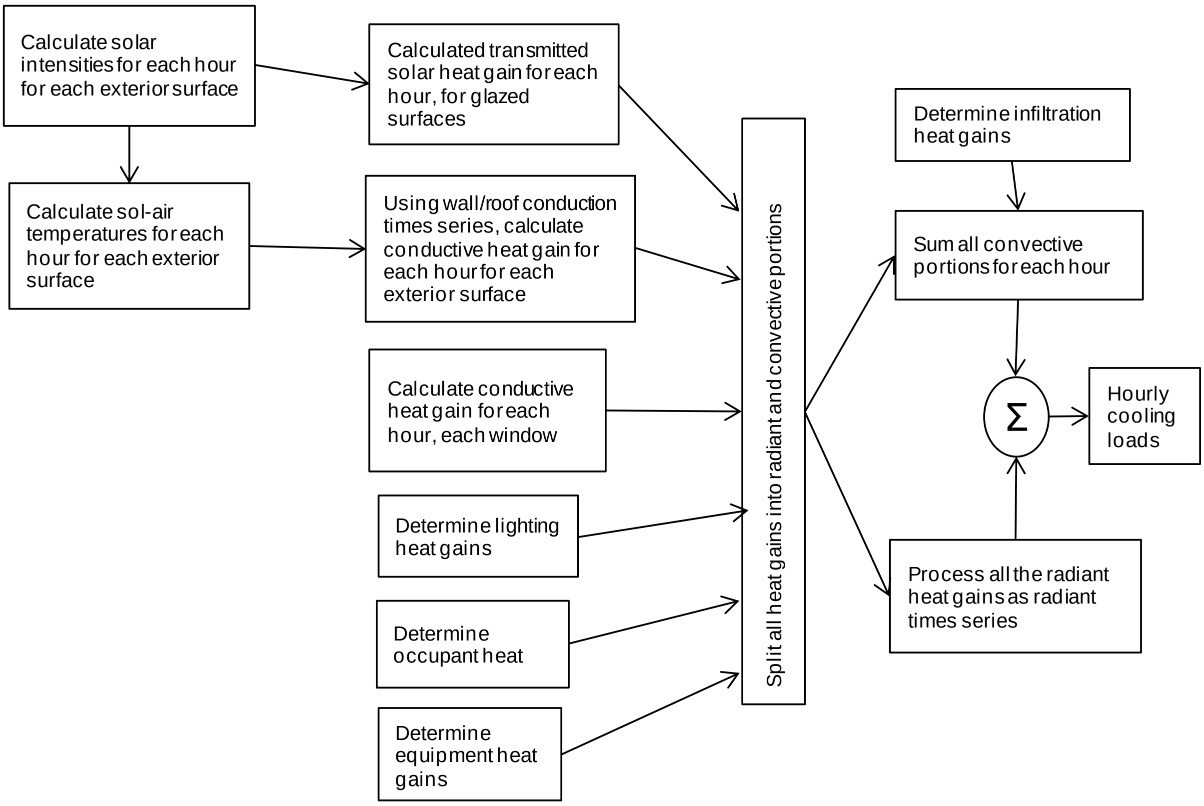

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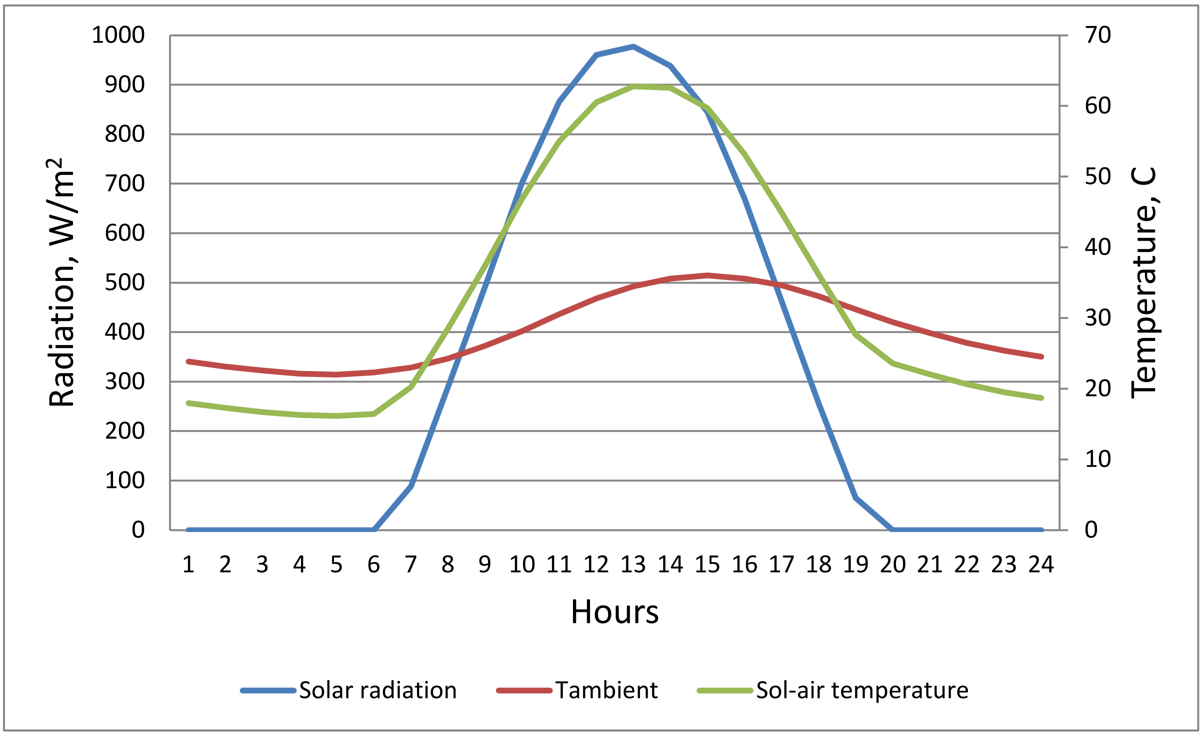

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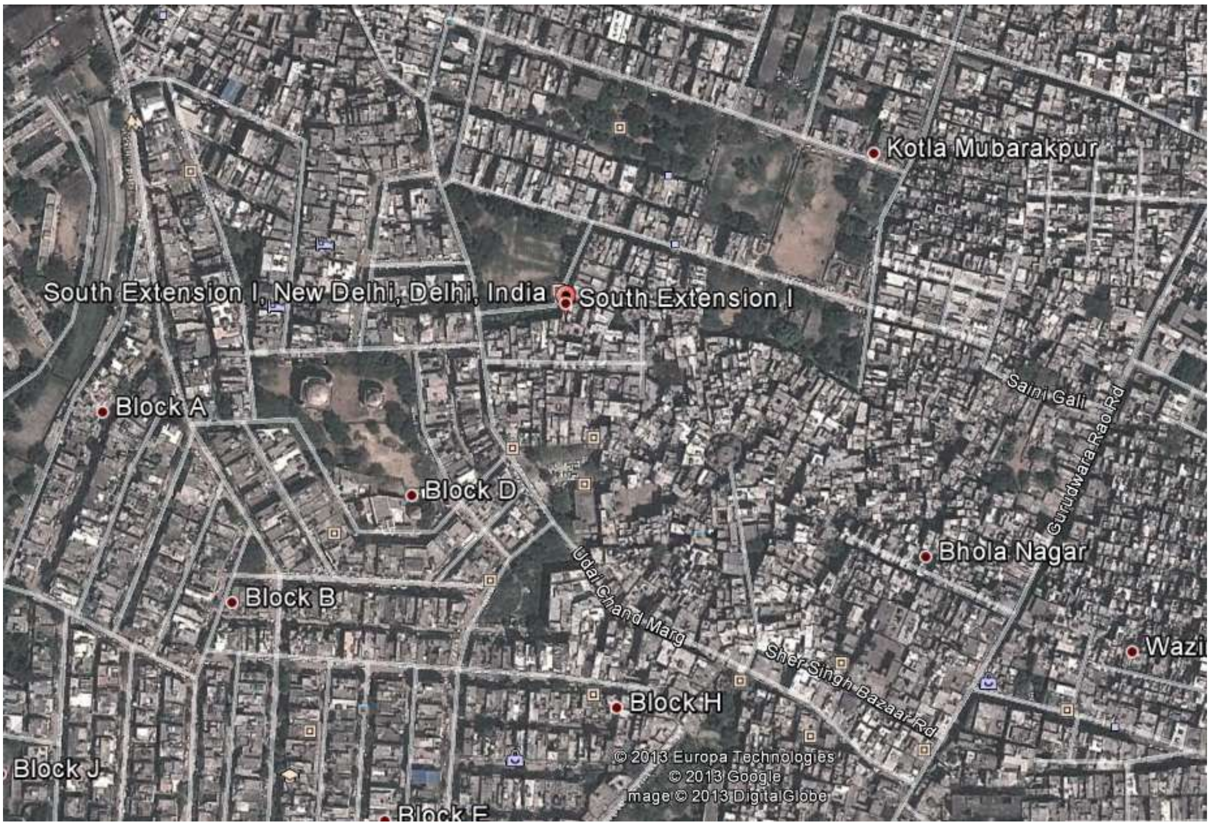

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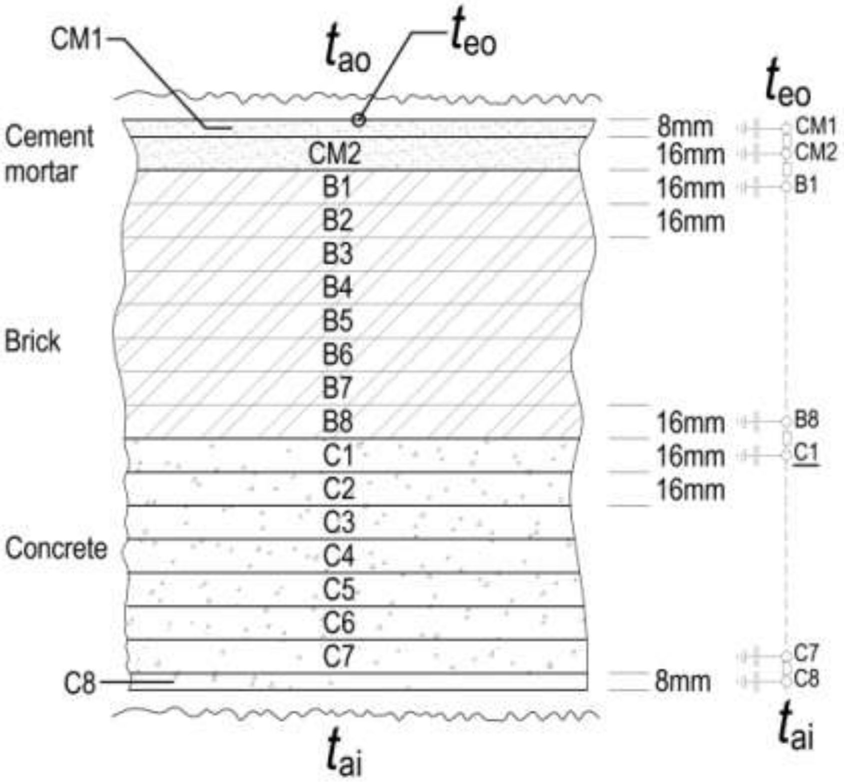

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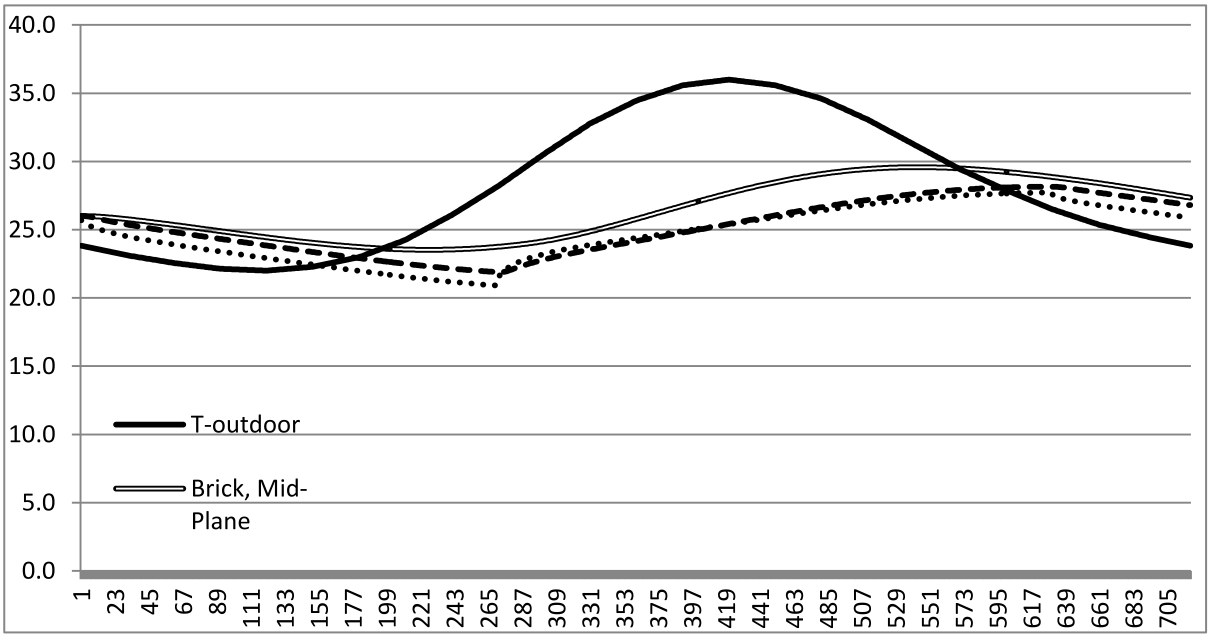

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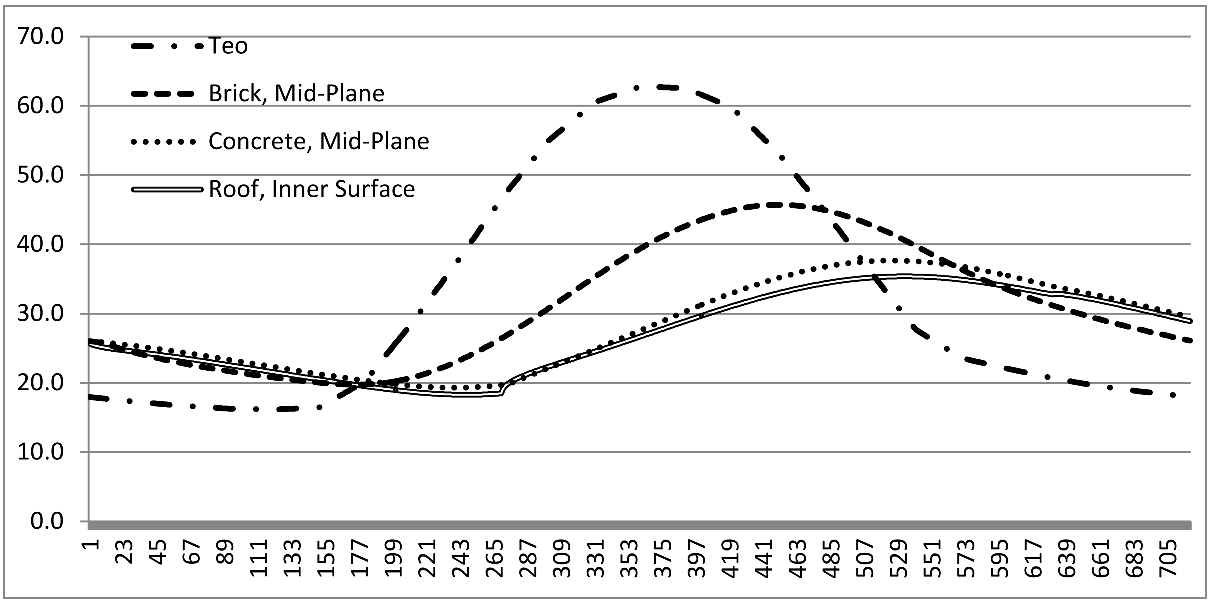

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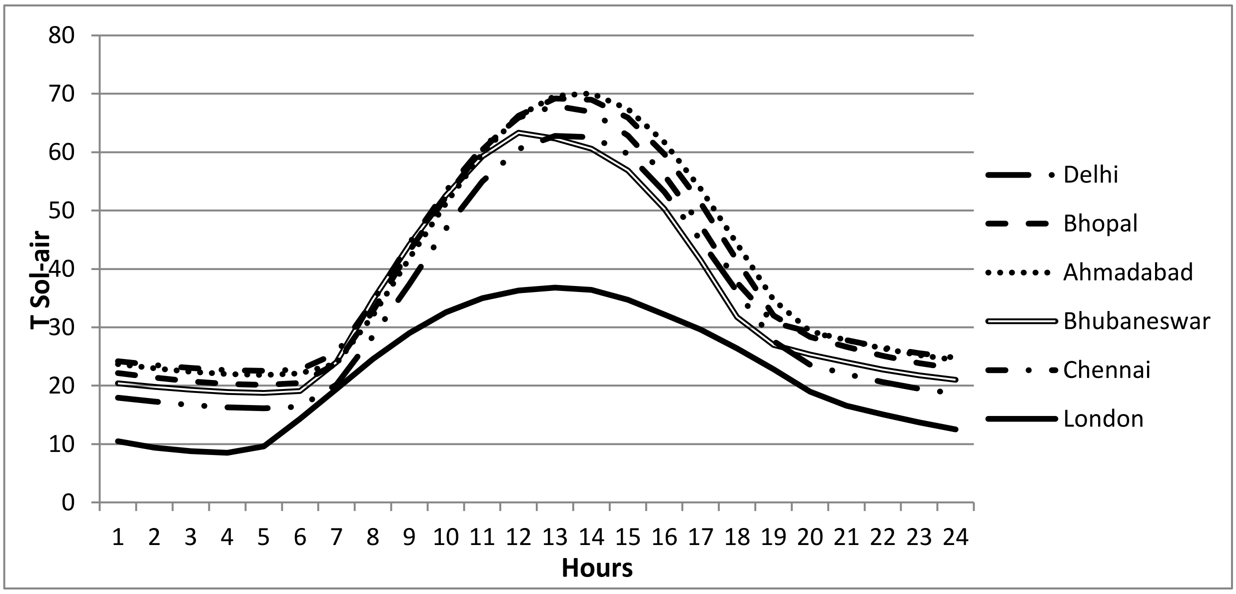

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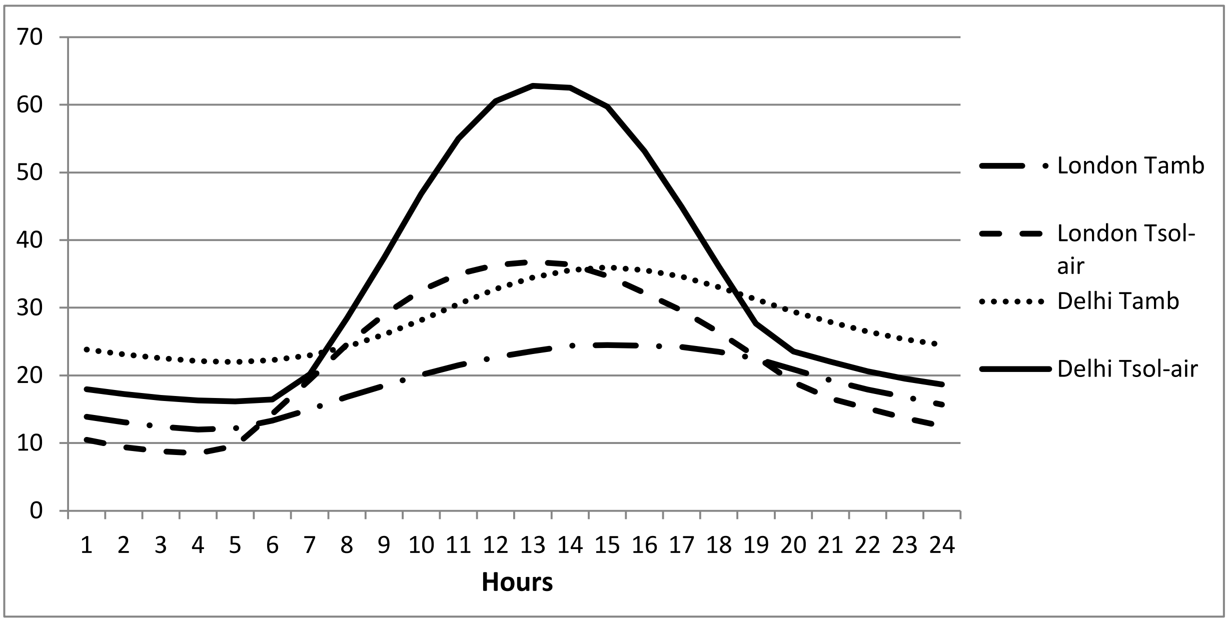

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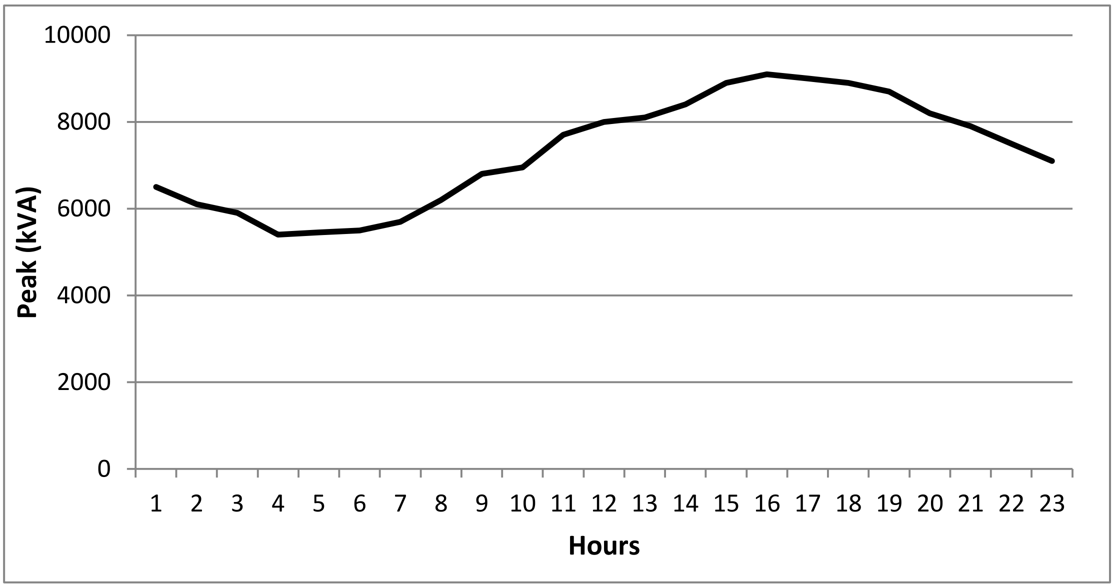

Fig.15. Typical electricity demand profile for the month of July for Delhi grid [47].

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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
Cooling Load Savings	29.8	34.8	34.4	31.6	33
Electricity Saved in Work of Compression	10.6	12.4	12.3	11.3	11.8

Table 10
Data required for preparing Table 9 **[46]**

$COP_{cooling}$	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

Table 11a
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 [45]
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 11b
Characteristics of Solar Panels Used

Characteristics	Values
T_{ref}	25^{o}C
I_{sc}	5.35A
V_{oc}	45V
P_m	190W
I_m	5.14A
V_m	37V
m_{Isc}	0.0005A/^{o}C
m_V	-0.0035V/^{o}C
Efficiency	14.8%
Area	1.27m^2
NOCT	45 ^{o}C

*NOCT = Nominal Operating Cell Temperature

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OASYS South Asia project

The Off-grid Access Systems for South Asia (or OASYS South Asia) is a research project funded by the Engineering and Physical Sciences Research Council of UK and the Department for International Development, UK. This research is investigating off-grid electrification in South Asia from a multi-dimensional perspective, considering techno-economic, governance, socio-political and environmental dimensions. A consortium of universities and research institutes led by De Montfort University (originally by University of Dundee until end of August 2012) is carrying out this research. The partner teams include Edinburgh Napier University, University of Manchester, the Energy and Resources Institute (TERI) and TERI University (India).

The project has carried out a detailed review of status of off-grid electrification in the region and around the world. It has also considered the financial challenges, participatory models and governance issues. Based on these, an edited book titled "Rural Electrification through Decentralised Off-grid Systems in Developing Countries" was published in 2013 (Springer-Verlag, UK). As opposed to individual systems for off-grid electrification, such as solar home systems, the research under this project is focusing on enabling income generating activities through electrification and accordingly, investing decentralised mini-grids as a solution. Various local level solutions for the region have been looked into, including husk-based power, micro-hydro, solar PV-based mini-grids and hybrid systems. The project is also carrying out demonstration projects using alternative business models (community-based, private led and local government led) and technologies to develop a better understanding of the challenges. It is also looking at replication and scale-up challenges and options and will provide policy recommendations based on the research.

More details about the project and its outputs can be obtained from www.oasyssouthasia.dmu.ac.uk or by contacting the principal investigator Prof. Subhes Bhattacharyya (subhesb@dmu.ac.uk).

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