



# Economic and environmental benefits of roof insulation in composite climate of India

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## General Note



Article is recommended to print as color version in recycled paper. *Save Trees, Save Climate.*

## ABSTRACT

From the view point of energy conservation in the built environment, thermal insulation is the most common and effective technique. In India, most of the air conditioned residential buildings have either little or no insulation at all. In this study, optimum insulation thickness (OIT) for extruded polystyrene insulation (XPS) material employed on reinforced cement concrete are determined for composite climatic zones of India. Additionally life cycle savings and payback period are calculated by using life cycle cost concepts. In the present study, a commonly used indoor design temperature (IDT) interval of 23 - 27°C is considered. For this range of IDT, OIT of XPS ranges from 0.025 to 0.042 m. Further, life cycle savings for the OIT varies from 240.0 to 663.0 Rs per m<sup>2</sup> of roof area, and payback period ranges from 2.2 to 3.2 years. Further carbon emissions are also estimated and by applying OIT on un-

insulated roof, CO<sub>2</sub> reduction of around 65 - 76% is observed, depending on the IDT. It is observed that determining optimum thickness of insulation material for roof is very significant for reducing the operational energy demand in the building sector.

**Keywords:** Optimum insulation thickness; Payback period; Life cycle cost analysis; Carbon emissions

## 1. INTRODUCTION

The cooling energy demand of a building is related to the thermal comfort level of its residents. Roof top is a leading heat gain area of the building from the environment. Several techniques are applied in order to maintain the thermal comfort level and bring down the energy demand of the buildings. Insulation application is one of the effective and popular techniques to trim down the building energy demand. Thus, Effective insulation of roof top plays an imperative role towards the energy consumption reduction for space cooling. Determining insulation optimum thickness, which will cut the energy demand as well as capital investment, is very significant. Hence, an attempt is made to generate a database for architects/construction industry practitioners to select the insulation thickness depending upon the combination of parameters.

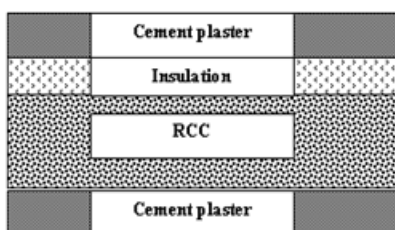
Many studies are reported in the literature for the assessment of the optimum insulation thicknesses on the building external walls and roof. Hasan [1] utilized the life cycle cost concept to optimize the insulation thickness for rock wool and polystyrene, as a function of degree days and structure thermal resistance, considering two typical wall structures for Israel. Satman and Yalcinkaya [2] determined heating and cooling degree-hours in order to forecast energy consumption of residential heating/cooling for Turkey. Comakli and Yuksel [3] reported a considerable energy saving of 12.113 \$/m<sup>2</sup> on the application of OITfor Turkey. Al-Sanea and Zedan [4] and Daouas [5] studied effect of wall orientation and insulation thickness on yearly transmission loads and reported that wall orientation had considerable effect on thermal behavior but comparatively smaller effect on the optimum insulation thickness.

Mahlia et al. [6] correlates the thermal conductivity and the OITfor different insulation materials for Malaysian conditions. Özkahraman and Bolattürk [7] reported an energy saving of 60% with a payback period of four years, by heat energy savings through the installation of porous tuff stone panels on external walls of buildings for Isparta. Dombaycı et.al. [8], [9] optimized the insulation thicknesses for five different fuel types and two insulation materials for Denizli and reported life cycle saving of 14.09 \$/m<sup>2</sup> as well as 41.53% reduction of CO<sub>2</sub> and SO<sub>2</sub> emissions when optimum insulation-thickness of expanded polystyrene is used with coal as an energy source. Using polystyrene as an insulating material, Bolatturk [10], [11] observed that life cycle savings (LCS) varied from 22% to 79%. Further, he reported that use of insulation in building walls with respect to cooling degree-hours is more significant for energy savings compared to heating degree-hours in Turkey's warmest zone. Ramesh et al. [12] obtained optimized insulation thickness of expanded polystyrene insulation on the basis of life cycle energy consumption in residential buildings in India.

From the literature, it is evident that relatively less attention has been paid to address the problem of roof insulation in Indian context. In the present study, an effort is made to determine the OITof extruded polystyrene insulation (XPS) for reinforced cement concrete (RCC) roof in compositeclimate of India. The life cycle savings (LCS) and payback periods are also presented herein.

## 2. THE CONVENTIONAL ROOF STURCTURE

Cooling appliances utilized for providing thermal comfort absorb heat produced by inmates, equipment and heat transmitted to the cooling space by the building envelope due to the external surroundings. Energy cost for running the cooling appliances that have high energy consumption is significant. Implementing a suitable insulation material to the building envelope will bring down the transmitted heat gain and therefore, minimize energy costs. In India RCC with cement plasters on its both sides is a popular technique of roof construction having no insulation material in-between. A typical composite roof structure is shown in figure1. Table 1 presents the physical and thermal characteristics of the external walls and its constituents.



**Figure 1** Cross sectional view of roof structure

**Table 1** Thermophysical properties of roof materials

S. No.	Material	Thermal conductivity (k, W/m K)	Thickness (m)	Thermal resistance (R, m <sup>2</sup> K/W)
1	External surface convection heat transfer coefficient	22.7 W/m <sup>2</sup> K [13]	-	0.044
2	Outer plaster	0.16 [12]	0.012[12]	0.075
3	XPS insulation	0.036 [11]	-	-
4	Reinforced Cement Concrete	2.5 [12]	0.12[12]	0.048
5	Inner plaster	0.16 [12]	0.012[12]	0.075
6	Internal surface convection heat transfer coefficient	8.29 W/m <sup>2</sup> K [13]	-	0.120

### 3. ECONOMIC ANALYSIS AND OPTIMUM INSULATION THICKNESS

The building opaque envelope is subjected to all the three heat transfer mechanisms: conduction, convection and radiation. Absorption of solar radiation by roof surface as well as temperature gradient leads to conduction heat transfer from exterior roof surface to interior roof surface of the building [19]. At the same time, convective heat transmission occurs between ambient air and the exterior roof surface, also between the interior roof surface and indoor air. The thermal gain load through the building external wall can be calculated by the following equation:

$$Q_r = UA(T_{sa} - T_{ia}) \quad (1)$$

where,  $Q_r$  is the heat gain by building roof (W);  $U$  is the overall heat transfer coefficient of roof (W/m<sup>2</sup> K);  $A$  is the roof surface area (m<sup>2</sup>);  $T_{sa}$  is outside sol air temperature (°C) and  $T_{ia}$  is indoor design air temperature (IDT) (°C).

The net resistance of roof,  $R_r$  (m<sup>2</sup> K/W), can be expressed as:

$$R_r = \frac{1}{h_i} + \frac{x_1}{k_1} + \frac{x_2}{k_2} + \dots + \frac{x_n}{k_n} + \frac{1}{h_e} \quad (2)$$

where,  $h_i$  and  $h_e$  are convection heat transfer coefficient for interior and exterior surface of cooled space, respectively.  $k_1, k_2, \dots, k_n$ , are thermal conductivity of different layer of wall, and  $x_1, x_2, \dots, x_n$ , are their thicknesses respectively.

Building annual energy consumption can be estimated by using degree-hours method under static conditions. Hourly temperature profile for whole year is generated using eQuest v.3.6 based on DoE-2 [14], with IWEC weather data [15] as an input. The cooling degree hours (CDH) values at different IDT are shown in Table 3. The total annual energy consumption of cooling system per unit area of external wall ( $E_c$ , kWh) can be calculated as [11]:

$$E_c = \frac{U * CDH}{COP} \quad (3)$$

where, COP is coefficient of performance of cooling system.

The difference between the overall heat transfer coefficients of non-insulated and insulated walls is expressed as:

$$\Delta U = U_{un-ins} - U_{ins} = \frac{1}{R_r} - \frac{1}{R_r + R_{ins}} \quad (4)$$

where,  $R_{ins}$  is the insulation thermal resistance, which can also be expressed as  $x/k_{ins}$ . Here  $x$  is the insulation thickness (m),  $k_{ins}$  is the thermal conductivity of insulation material (W/mK).

Life-cycle cost analysis is frequently applied for evaluating the cost effectiveness of the projects. A method proposed by Duffie and Beckman [16] for calculating life-cycle cost is referred to as the  $P_1$ - $P_2$  method. Here,  $P_1$  is a multiplier that establishes the present value of future energy costs. It depends upon discount rate  $d$ , electricity cost inflation rate  $i$ , and life time period  $N$ . The value of  $P_1$  can be estimated as:

$$P_1 = \begin{cases} \frac{1}{(d-i)} \left[ 1 - \left( \frac{1+i}{1+d} \right)^N \right], i \neq d \\ \frac{N}{1+i}, i = d \end{cases} \quad (5)$$

$P_2$  is the ratio of life cycle expenditures incurred owing to the additional capital investment to the preliminary investment. It is defined as [16]:

$$P_2 = 1 + P_1 M_s - \frac{R_v}{(1+d)^N} \quad (6)$$

where,  $M_s$  is the ratio of the annual maintenance and operation cost to the original first cost,  $R_v$  is the ratio of the resale value to the first cost. In this study,  $P_2$  can be taken as 1 if the maintenance and operation costs are assumed to be zero.

Total cost of insulation ( $C_{ins}$ ) depends on the cost of insulation material per unit volume ( $C_i$ , Rs/m<sup>3</sup>) and insulation thickness and expressed as;

$$C_{ins} = C_i * x \quad (7)$$

The life cycle cost (LCC) of the insulation material and the energy consumption can be estimated as:

$$LCC = P_1 C_e E_c + P_2 C_{ins} \quad (8)$$

where,  $C_e$  is the cost of electricity (Rs./kWh). Savings over life cycle (LCS) is the difference between the conserved energy cost over the lifetime and the insulation disbursed and expressed as;

$$LCS = P_1 C_e E_c - P_2 C_{ins} \quad (9)$$

Utilizing equations (9) or (10), the optimum thickness of insulation is obtained and expressed as:

$$x_{opt} = \sqrt{\frac{C_e k_{ins} CDH}{P_2 C_i COP}} - R_w k_{ins} \quad (10)$$

By setting Eq. (10) equal to zero, the payback period of insulation cost  $N_p$ , for cooling is expressed as:

$$N_p = - \frac{\ln \left\{ 1 - \frac{P_2 C_i (d-i) (R_w x + k_{ins} R_w^2) COP}{C_e CDH} \right\}}{\ln \left( \frac{1+i}{1+d} \right)}, i \neq d \quad (11)$$

$$N_p = \left\{ \frac{P_2 C_i (1+i) (R_w x + k_{ins} R_w^2) COP}{C_e CDH} \right\}, i = d \quad (12)$$

#### 4. RESULTS AND DISCUSSIONS

Selection of suitable insulation material along with its optimum thickness is the key issue for any energy efficient and economic building construction. The present work deals with estimation of optimum insulation thickness, LCS and payback period for XPS insulation applied roof structure for cooling loads in composite climatic of India. Table 2 shows the parameters used for the LCC calculations.

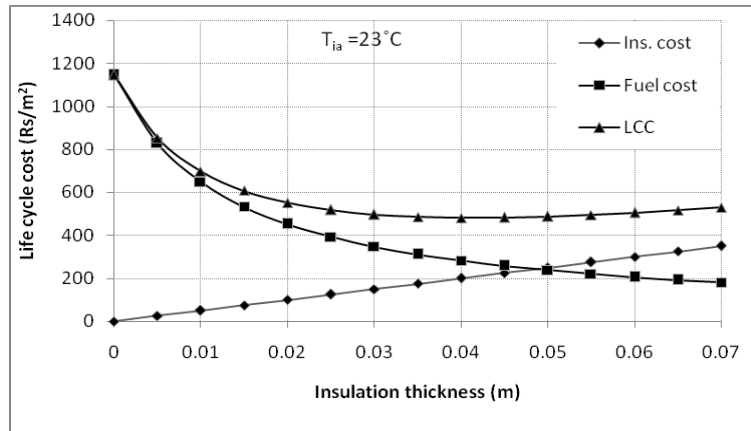
**Table 2** Parameters used in the LCC calculations

Parameters	Values
Life time (N)	10 years [3]
Cooling system coefficient of performance (COP)	3.0

Cost of electricity ( $C_e$ )	4 Rs/kWh
Price increase rate of electricity (d)	10%
Discount rate (i)	8%
Insulation Cost ( $C_i$ )	5000* Rs/m <sup>3</sup>

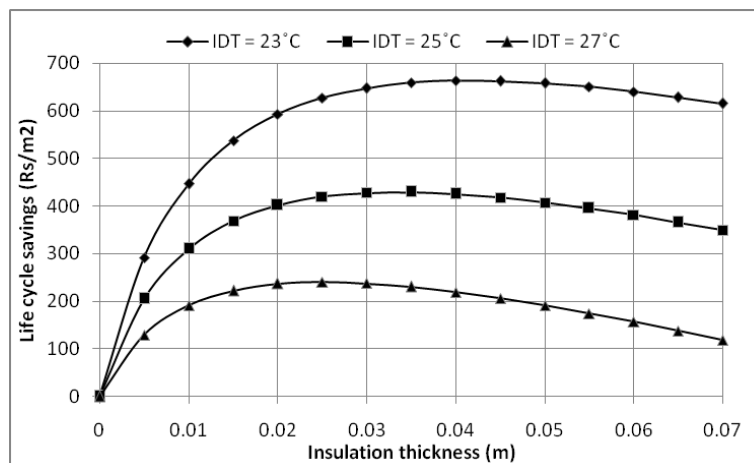
\* Local market cost

Figure 2 depicts the variation LCC with respect to insulation thickness of XPS insulation material for RCC roof at 23°C IDT. It has been seen that increasing the insulation thickness will result in a continuous decrease in fuel cost as well as linear increase in insulation cost. Sum total of fuel cost and cost of added insulation material will render LCC. Minimizing of the LCC provide optimum insulation thickness. For instance, the OIT comes to be 0.042 m. OIT for different IDT is given in table 3. With the increase in thermal comfort temperature, the required cooling degree hours goes downhill. It is observed that increase in CDH results in increase in OIT as it is directly proportional to half order power of CDH.



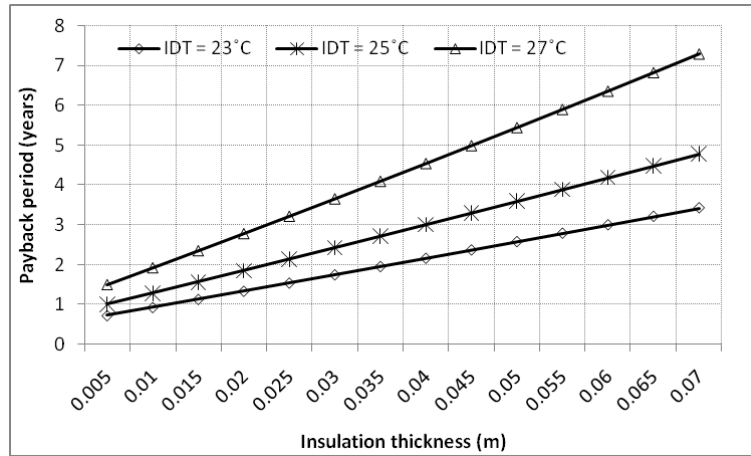
**Figure 2** Variation of life cycle cost with insulation thickness

The effect of insulation thickness on LCS for XPS insulation for different IDT is demonstrated by figure 3. It is seen that LCS attains its maximum value at optimum insulation thickness. Variation of payback period with insulation thickness for RCC roof for different IDT is shown in figure 4. The payback period varies with insulation thickness linearly. Insulation with maximum LCS, have the lowest payback period.



**Figure 3** Variation of life cycle cost with insulation thickness

Difference in payback period for per degree change in thermal comfort temperature also increases with increase in insulation thickness. Eqn. (11) shows that payback period is direct function of insulation thickness and having an inverse relation to cooling degree hours. But per degree change in cooling degree hours is more for lower side of IDT. And so the difference in payback period for per degree change in thermal comfort temperature is less for thin insulation.



**Figure 4** Effect of insulation thickness on payback period

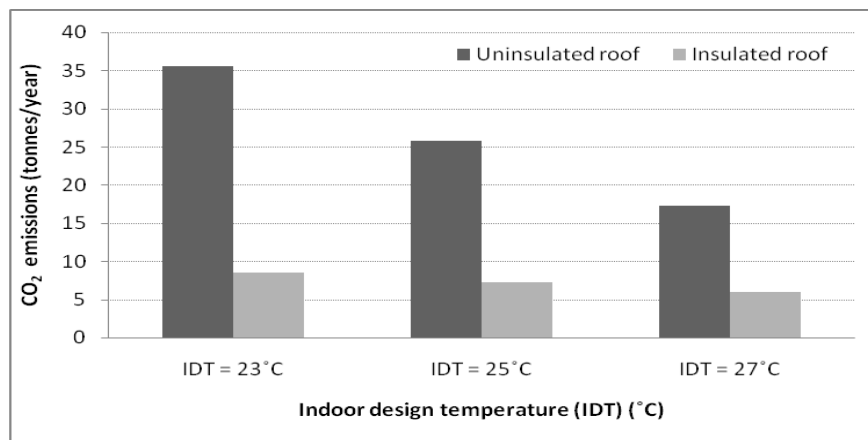
The values for OIT with corresponding LCS and payback periods for the selected climatic zones and the insulation material chosen for the analysis are shown in table 3. It is seen that with the increase in IDT payback period also increases. Therefore lower the set indoor thermal comfort temperature higher will be the economic benefits of insulation.

**Table 3** OIT, LCS and payback period at various IDT

Indoor design temperature (°C)	CDH (°C-hours)	Optimum insulation thickness (m)	Life cycle savings (Rs/m <sup>2</sup> )	Payback period (years)
23	37152	0.042	663.36	2.2
25	26904	0.034	429.05	2.6
27	18048	0.025	240.35	3.2

Energy conservation through building insulation is an effective and environmental friendly technique, which has the potential to contribute significantly in the development of sustainable buildings. In India, around 54% [17] of power generation is from coal based thermal power plants. The average intensity of CO<sub>2</sub> emission from coal thermal power plants is 1.04 tCO<sub>2</sub>/MWh [18]. The total mitigation of carbon emission for a lifespan of insulation is calculated as follows:

$$\text{CO}_2 \text{ emission mitigated (tonnes/year)} = 1.04 \text{ (tCO}_2\text{/MWh)} \times \Delta E \text{ (MWh/year)} \quad (13)$$



**Figure 5** CO<sub>2</sub> emissions comparison for different IDT

As insulation thickness increases, CO<sub>2</sub> emissions decrease because of the increase in energy savings. It is seen that the curves are steep at thinner insulation and gradually becomes asymptotic with insulation thickness. By applying optimum insulation thickness on un-insulated roof, CO<sub>2</sub> reduction of around 65 - 76% is observed, depending on the IDT as shown in figure 5.

## 5. CONCLUSIONS

The present study, deals with estimation of optimum insulation thickness, payback periods and life cycle savings utilizing LCC analysis for XPS insulation in composite climatic zone of India, with regard to cooling applications. It is observed that with the increase in IDT, results in a decrease in OIT as well as LCS. The payback period shows a linear relation with insulation thickness. Insulation having maximum LCS, attain the lowest payback period. Therefore lower the set indoor thermal comfort temperature higher will be the economic benefits of insulation but high initial capital payout for insulation. Thicker insulations have high potential of CO<sub>2</sub> emissions saving because of the increase in energy savings. When optimum insulation thickness is applied CO<sub>2</sub> reduction of around 65 - 76% is observed, depending on the IDT. Choosing any random value of insulation thickness except the optimum one, will increase the LCC and reduce the LCS, thereby increasing the payback period. Therefore, the selection of the appropriate insulation material and its optimum thickness is expected to provide maximum benefit in terms of energy saving, emission reduction and economic aspects.

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