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Economic Optimization of Roof Insulation in Three Climates in Morocco

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Abstract — *worldwide, building's energy consumption is considered as a relevant international issue. More than one third of energy demand is due to achieving acceptable conditions of thermal comfort and lighting in buildings. One of the most effective ways to reduce the annual energy consumption is the implementation of insulation in the envelope. Thereby, this paper investigated the optimum insulation thickness determination for conventional roof in Ifran, Casablanca and Marrakech. Extruded polystyrene was considered as insulation material.*

Keyword — Building; Roof; Thermal insulation; Energy saving; Optimum insulation thickness.

Introduction

In today's world, energy is considered as one of the thorniest and daunting challenges. Future energy growth is affected by many factors, mainly: economic growth, population growth, energy prices and fuel availability, technologies that improve efficiency and develop new renewable, also environmental and emissions regulations and standards [1]. The International Energy Agency has collected startling data on energy consumption trends. The forecasts agree on an important growth in the demand for energy during the thirty years to come [2]. World net electricity generation increases by 69% from 21.6 trillion kilowatt-hours (kWh) in 2012 to 25.8 trillion kWh in 2020 and to 36.5 trillion kWh in 2040 [2]. Electricity is the world's fastest-growing form of end-use energy consumption, as it has been for many decades [2]. The Fifth Assessment Report from the Intergovernmental Panel on Climate Change states that human influence on the climate system is clear (IPCC, 2013) [3]. In 2013, the global emissions of carbon dioxide have reached 35.3 trillion tonnes (Gt) of CO_2. This represents an increase of 0.7 Gt compared to the previous year. [4]. All sectors are concerned, but the building sector requires a special attention because, it offers a significant potential to improve energy efficiency through the use of insulation and energy-efficient systems. The buildings sector, including residential and commercial end users, consumes 20% of the total delivered energy consumed worldwide. World Energy Outlook (2016) points out that, under its reference scenario, total world energy consumption in buildings increases by an average of 1.5%/year from 2012 to 2040 [2]. In Morocco building energy usage is one of the main drivers of energy demand growth, according to the figures published by the Moroccan Agency for energetic efficiency the building sector is the second largest energy consumer and accounts for approximately 28% of the final energy consumption [5]. For this reason, energy efficiency in buildings is today a prime objective for energy policy in Morocco. Many researches related to the optimization of building envelope have been carried out. Axaopoulos et al [6] used the Transient System Simulation Program in order to determine the optimum insulation thickness for the external walls, with different composition and orientation, of a residential building, for both heating and cooling period, taking into consideration the wind speed and direction. According to the results, it was demonstrated that the optimum insulation of external walls may be calculated by using the appropriate economic parameters and the results of a transient simulation, it was also concluded that for any type of wall and orientation, the optimum insulation thickness varies between 7.1cm and 10.1cm. The impact of cool and green roofs on the overall energy performance of buildings in different localities at Mediterranean latitudes was analyzed by Zinzi and Agnoli [7] using Energy Plus software. They reported that the use of cool and green roofs helps to an annual energy savings from -13.7 to 41.7 %. Shanmuga et al [8] optimized the insulation thickness on wall of buildings by using the degree day's concept. Their study was carried out in five cities located in India by comparing three different insulation materials. According to their results, expanded polystyrene was found to be a suitable material for all five cities. Using Design Builder software Jiandong Ran et al [9] compared and analyzed the indoor temperature and energy consumption of the typical rural residence in Chongqing of different thermal insulation roofs. The results show that the energy saving rate value of light insulation roofing on the top floor can be increased to 40%-50% with the combination of night time ventilation and intermittent air conditioning to cooling. For heavy insulation roofing, the reasonable thickness of aerated concrete layer for the roof is 100-150mm, the heat transfer coefficient of roof is between 0.94 W / (m· K) and 1.25 W / (m· K). And the energy saving rate limit value of the aerated concrete roof is estimated below 40%. Daouas determined the optimum insulation thickness and the resulting energy savings for two typical roof structures and two types of in solution materials [10]. He reported that the hollow terracotta-based roof insulated with rock wool presents the optimum insulation thickness (7.9 cm) with an energy savings of 58.06 %. Jraida et al [11] determined the optimum insulation thickness for a typical external wall by using the optimization method based on life cycle cost analysis over a lifetime of 20 years of the building, six cities are chosen to represent the six zones of Morocco and three different insulation materials are selected. It was found that the optimum insulation thickness range from 2.3cm and 10.7cm, the energy saving range from 5.86 and 73.88$/m^2, and payback period range from 4.88 and 11.06 years. Glass wool is considered as the optimal among the three insulation materials. Furthermore, it is seen that as the optimal insulation thickness rises, the energy saving increases and payback period decreases. And similarly to the other studies, it was observed that the economic parameters as inflation rate, interest rate, cost of insulation and cost of electricity have a significant effect on optimal insulation thickness and energy saving.

As can be seen from literature survey, the determination of optimum insulation thickness in the roof had never been investigated in Morocco. Accordingly, the purpose of this study is to determine the optimum insulation thickness of the roof and the related energy saving and payback period for three different cities located in three different climatic zones in Morocco by using degree-hour concept and life cycle cost analysis. Extruded polystyrene is used as insulation material.

Methodology

Using the degree-hour concept, the yearly heating and cooling loads were calculated. The P1-P2 method was used in economic analysis to find the optimum insulation thickness and the related energy saving and payback period. The roof structure used in the calculation consists of 2cm tiles, 10cm cement mortar, 16cm concrete slab and 2cm plaster. The annual energy consumption for heating per unit area of roof can be calculated by using heating degree-hour numbers [12]:

$$E_h = \frac{10^{-3}\, U\, HDH}{\eta}, \qquad (1)$$

Similarly, the annual cooling requirement per unit area of roof can be calculated as follows:

$$E_c = \frac{10^{-3}\, U\, CDH}{EER}, \qquad (2)$$

Where η is the efficiency of the heating system and EER is the energy efficiency ratio of cooling system and U is the overall heat transfer coefficient of roof (W/m^2 K) which can be calculated as follows:

$$U = \frac{1}{R_i + R_w + R_{ins} + R_o} \qquad (3)$$

Where, Ri and Ro the thermal resistance of interior and exterior air film respectively and Rw, the thermal resistance of non-insulated roof. Ri and Ro are set to be 0.1612 m^{2}K/W and 0.0617 m^{2}K/W, respectively [10]. The thermal resistance of insulation material can be calculated as follows:

$$R_{ins} = \frac{x}{k} \qquad (4)$$

In the present study, the P1-P2 method is used for calculating the optimum insulation thickness [17]. P1 is the ratio of life cycle cost (savings) to the first-year electricity cost (savings), which is equal to the present worth factor of a series of Ne future payment with the market discount rate d and inflation rate i. P1 can be calculated by the following equation [13]:

$$\mathrm{P1} = \mathrm{PWF(Ne, i, d)} = \sum_{j=1}^{Ne} \left(\frac{1+i}{1+d}\right)^j = \begin{cases} \frac{1}{d-i}\left[1-\left(\frac{1+i}{1+d}\right)^{Ne}\right] & i \neq d \\ \frac{Ne}{1+i} & i = d \end{cases} \qquad (5)$$

P2 is the ratio of the life cycle expenditures incurred because of the additional capital investment to the initial investment and can be defined as [13]:

$$\mathrm{P2} = D + (1-D)\frac{\mathrm{PWF}(N_{min}, 0, d)}{\mathrm{PWF}(N_L, 0, m)} + M_s\,\mathrm{PWF(Ne, i, d)} - \frac{R_\upsilon}{(1+d)^{N_e}} \qquad (6)$$

where D is the ratio of down payment to initial investment, Ms is the ratio of the first year miscellaneous costs (insurance maintenance) to initial investment, Rv is the ratio resale value at the end of the analysis period to initial investment, NL is term of loan and Nmin is the year over which mortgage payments contribute to the analysis period. The cost of building insulation per unit area can be determined as in reference [14]:

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

where C_i is the cost of insulation ($/m3). Therefore, the total heating and cooling cost for the building as the present worth value for Ne years can be given by:

$$\mathrm{LCT} = 10^{-3}.P_1.C_E.U.\left(\frac{HDH}{\eta} + \frac{CDH}{EER}\right) + P_2.C_i.x \qquad (8)$$

where C_E is the unit price of electrical energy ($/kWh). The energy saving cost for insulated building is the difference between the energy cost of non-insulated and insulated building, respectively.

$$\mathrm{LCS} = 10^{-3}.P_1.C_E.\left(\frac{1}{R_w} - \frac{1}{R_w + x/\lambda}\right).\left(\frac{HDH}{\eta} + \frac{CDH}{EER}\right) + P_2.C_i.x \qquad (9)$$

The value of the optimum insulation thickness is calculated by setting the derivative of Eq (9), with respect to x, equal to zero [15].

$$x_{op} = \sqrt{\frac{10^{-3}.P_1.\lambda.C_E}{P_2.C_i}.\left(\frac{HDH}{\eta} + \frac{CDH}{EER}\right)} - R_w.\lambda \qquad (10)$$

The payback period of investment can be calculated by setting the net energy saved cost to be zero [15]:

$$\begin{cases} N_p = \dfrac{ln\left[1 - \left(P_2 C_i(\lambda R_w^2 + R_w x)(d-i)\right)/\left(10^{-3}.C_E.\left(\frac{HDH}{\eta} + \frac{CDH}{EER}\right)\right)\right]}{ln(1+i/1+d)} \\ N_p = \dfrac{P_2 C_i(\lambda R_w^2 + R_w x)(1+i)}{10^{-3}.C_E.\left(\frac{HDH}{\eta} + \frac{CDH}{EER}\right)} \end{cases} \qquad (11)$$

Results

An economic analysis is carried out in order to determine optimum insulation thickness of extruded polystyrene where annual energy requirement are considered and calculated based on degree hour method. The cooling and heating degree hour for the three cities were determined in our previous work [16] and are listed in Table 1. The investigation is carried out for a typical roof structure under the climatic conditions of Ifran, Casablanca and Marrakech. Considering the thermal properties provided in Table 2, the total heat transfer coefficient for the typical roof without insulation is estimated to be U=1.98W/m^2.K. The parameters used in calculations are given in Table 3.

Table 1. Climate characteristics of referenced cities

City	Elevation (m)	Longitude (deg)	Latitude (deg)	HDH (°C-days)	CDH (°C-days)
Ifran	1663.8	-5.17	33.50	45764.40	12402.24
Casablanca	27	-7.61	33.58	30622.56	7073.76
Marrakech	463.5	-8.03	31.62	18092.16	25001.52

Table 2. The parameters used in calculations

Parameters	Value
Rw (m^{2}k/W)	0.502
Cins ($ /m 3)	320.17
CE ($/kWh)	0.115
EER	3.2
η	2.8
i	2.1
d	2.25
Ne (YEAR)	20
D	1
Ms	0
Rυ	0
P1	19.28
P2	1

Table 3. Thermo-physical properties of building materials

Materials	Thermal Conductivity (W/m.K)	Density (kg/m^3)	Capacity (j/kg.K)
Tiles	1.70	2300	1000
Cement mortar	1.15	1800	840
Concrete Slab	1.23	1300	1000
Plaster	0.351	1500	1000
Extruded polystyrene	0.038	35	1180

Table 4. Optimum insulation thickness, total cost, annual energy saving and payback period

City	Optimum Insulation Thickness (m)	Minimum Total cost ($/m^2)	Payback Period (years)	Life Cycle Saving ($/m^2)	Life Cycle Saving (%)
Ifran	0.0486	35.6129	4.4188	54.0512	60.28
Casablanca	0.0365	27.8485	5.4843	30.4513	52.23
Marrakech	0.0386	29.2061	5.2624	34.0926	53.85

The obtained results of optimum insulation thickness of extruded polystyrene as well as the related values of minimum total cost, life cycle saving and payback period, considering 24h operation of cooling and heating equipments, are summarized in Table 4. Considering the cities, optimum insulation thicknesses of extruded polystyrene ranged from 0.0365 to 0.0486 m over a lifetime of 20 years. The total cost and life cycle saving obtained while applying the optimum insulation in the three cities vary from 27.84$/m^2 to 35.61$/m^2 and 30.45$/m^2 to 54.05$/m^2, respectively. When the optimum insulation thickness of the roof is applied the payback period for Ifran is 4.41 years, it reaches up to 5.48 years for Casablanca and 5.26 years for Marrakech. Figure 1 shows variation of the optimum thickness of extruded polystyrene to DH, which is function of climate and energy efficiency of cooling and heating equipments and can be calculated as follows:

$$DH = \frac{HDH}{\eta} + \frac{CDH}{EER} \quad (12)$$

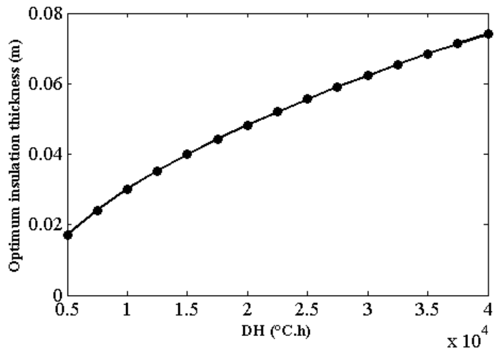

Figure 1. Effect of DH on optimum insulation thickness

According to the results, it is apparent that the degree-hour value has a strong effect on the optimum thickness. In fact, it is clearly seen that the higher the DH is the higher the optimum insulation thickness will be. The relation between the DH values and optimum thickness is in the form of:

$$X_{op} = 0.00005\ DH^{0.6982} \quad (13)$$

The coefficient of determination of Equation (13) is

$$R^2 = 0.9962$$

Furthermore, the variation of the optimum thickness of insulation with the Present Worth Factor and the thermal resistance of the roof are presented in Figure 2 and 3, respectively for the three cities. One can notice from those curves that the optimum insulation thickness increases with the increase of the Present Worth Factor whose value is related to the lifetime, inflation rate and interest rate. Contrariwise, it is seen that when the thermal resistance of the roof is higher, the optimum insulation thickness become lower. The determination of optimum insulation thickness is affected by many uncertain factors such as cost of electricity, cost of insulation, inflation rate and discount rate. Accordingly, a sensitivity analysis is carried out in order to investigate the effect of modification of those uncertain factors on the optimum insulation thickness. The results presented in Figure 4 show that optimum insulation thickness is sensitive to change in the uncertain factors. It's important to notice that the effects of cost of insulation and cost of electricity are much more important than inflation rate and discount rate, which is in a good agreement with the conclusions reported in reference [12].When cost of electricity and insulation increase by 80%; optimum insulation thickness rises by 44.03% and drops to 32.71%, respectively. However, when inflation rate and discount rate increase by 80%, optimum insulation thickness rises by only 10.69% and drops to only 10.90%, respectively.

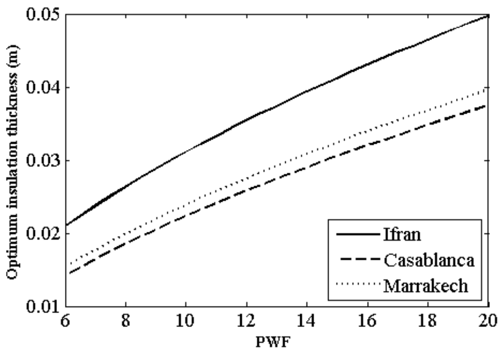

Figure 2. Effect of PWF on optimum insulation thickness

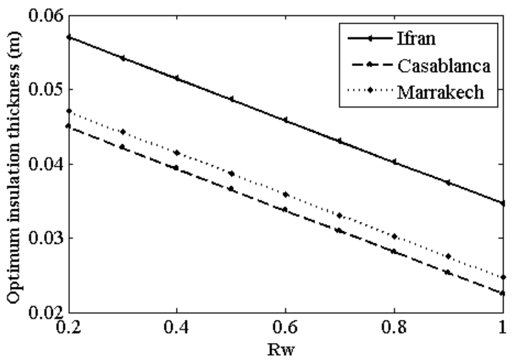

Figure 3. Effect of PWF on optimum insulation thickness

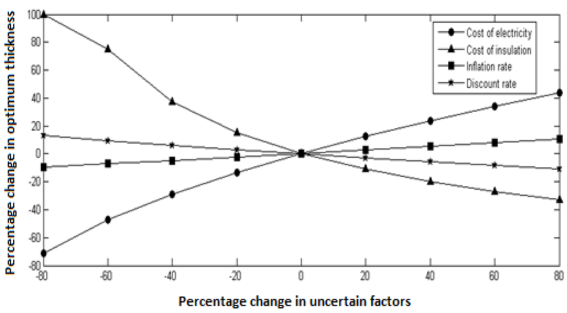

Figure 4. Effect of variation of four uncertain factors on optimum insulation thickness

Conclusion

The results presented for the considered cities revealed that the optimum insulation thickness of extruded polystyrene varies between 0.0365 and 0.0486 m, the energy savings vary between 52.23 and 60.28% and the payback periods vary between 4.41 and 5.48 years. The findings showed also a significant effect of degree-hour value, present worth factor and thermal resistance of the roof on the optimum insulation thickness whose value increases with the increase of DH and PWF and decreases with the increase of R_w. Furthermore, it was found that optimum insulation thickness is sensitive to change in the uncertain factors. The effects of cost of insulation and cost of electricity are much more important than inflation rate and discount rate.

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