Thickness optimization for building walls in Morocco: Economic and Environmental analysis

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ABSTRACT : *The accelerated urbanization process in Morocco has steadily increased the amount of energy consumed in buildings over the last years. Thermal insulation is one of the effective ways to reduce the energy demand and to improve the energy efficiency. Therefore, in the present paper, optimum insulation thickness of three different insulation materials is investigated for six locations in Morocco and four heating energy sources. Likewise, the potential of abatement of fuel consumption and emissions achieved by introducing optimal thickness is analyzed. The overall results show that the optimum thickness is in the range of 0.013-0.077 m, the energy cost saving in the range of 1.77-38.70$/m² and the payback period in the range of 6.06-13.67 years, depending on the city, the energy source and the insulation material. Furthermore, it was demonstrated that applying optimized thickness for proper insulation material leads to a significant mitigation in fuel consumption and greenhouse gas emissions.*

KEYWORDS *–Building, Morocco, Optimum insulation thickness, Energy cost saving, Fuel consumption and emissions.*

I. INTRODUCTION

Major environmental problems are currently facing the world as a result of human activities and energy use [1,2]. The atmospheric concentrations of important greenhouse gasses have increased over the last few centuries [3]. The global CO2 concentration in the atmosphere has increased over the past 36 years (1979-2014), with an average growth of 1.74 ppm/year [3], and it is predicted that the global carbon emissions will exceed 40 billion tons by 2030 [4]. Besides the increase of the greenhouse gas emissions in the atmosphere, future predictions by the energy information administration (EIA) indicate that the world energy consumption will grow by 56% between 2010 and 2040 [5]. The global electricity demand will rise by 60% between 2015 and 2040, accounting for 55% of the world's energy demand growth [6]. Subsequently, research on efficient minimization of energy consumption has become indispensable more than ever before.

Among others, the conservation of energy has become a priority for Morocco, especially with the increase of total population that was last recorded at 33.8 million people in 2014 from 11.6 million in 1960, changing 186% during the last 50 years [7]. Fossil fuels like natural gas, coal and oil present about 81% of the Morocco's electricity production [8]. According to the international energy agency (IEA) the electricity demand grew at an average annual rate of 6.7% from 2003 to 2013 leading to an energy consumption of 32.015 GWh. Moreover, the country's total greenhouse gas emissions were estimated at 72.51 MtCO2 in 2012 and are expected to increase [9]. The renewable energies and energy efficiency are among the priorities axes to contribute to the energy bill reduction. Transportation, building and industry are the three-major energy consuming sectors in Morocco [10], in which the building sector has the largest energy conservation potential [11, 12]. In this respect, one possible solution to reduce the level of energy consumption in buildings and abate the emission of greenhouse gases in the atmosphere is to apply an insulation layer in building walls [13-16]. Thereby, Morocco's agency for energy efficiency (AMEE) has launched different energy efficiency programs in the building sector and has established a new climatic zoning map for Morocco in partnership with the national center of meteorology; as a result, the country was segmented into six climatic zones [17,18].

Often, no insulation is applied in the Moroccan buildings;however, the new thermal comfort standards have increased the need of insulation materials. In this country, relatively, little works on the subject of the optimization of building envelop are conducted. Guechchati et al. [19], Benhamou and Bennouna [20] and Jraida et al. [21] studied the effect of thermal insulation and other parameters on annual energy consumption in Oujda city, Marrakech city and Casablanca city, respectively using TRNSYS simulation program. Idchabani et al. [22] calculated the heating energy requirements for typical Moroccan building, using the degree-day values of five Moroccan winter climate zones. Using regressing approach from a set of dynamic simulation of the building behavior, Romani et al [23] developed meta-models of heating and cooling energy needs for single-family houses in six Moroccan climate zones. However, based on author's knowledge, the optimization of insulation thickness and the analysis of the environmental impact using different insulation materials and energy sources have not been conducted until now in our country. In this vision, the first objective of this paper is to determine the optimum insulation thickness of the six referenced cities in Morocco (Agadir, Tangier, Fes, Ifran, Marrakech and Errachidia). Based on daily temperature data, the annual heating and cooling degree-days of selected cities are taken for base temperatures of 18°C for heating and 21°C for cooling as shown in Table 1 [24]. Accordingly, a comparative study of three different insulation materials (glass wool, extruded polystyrene, and cork) (Table 2) and four types of heating energy sources (coal, fuel oil, natural gas and LPG) is established, the optimization is based on the life cycle cost analysis. The second target of this work is to predict the annual abatement in greenhouse gas emissions because of the application of the optimum insulation thickness.

Table 1 - Climate characteristics of selected cities

Zone	City	Elevation (m)	Longitude (deg)	Latitude (deg)	DD_H (°C-days)	DD_C (°C-days)
1st zone	Agadir	74.50	-9.40	30.32	331	475
2n zone	Tangier	15.40	-5.92	35.73	708	395
3rd zone	Fez	571.3	-4.98	33.97	1067	568
4th zone	Ifran	1663.8	-5.17	33.50	2224	183
5th zone	Marrakech	463.5	-8.03	31.62	567	967
6th zone	Errachidia	1037.2	-4.40	31.93	1001	1238

Table 2 - Properties of insulation materials

Insulation materials	Conductivity (W/m K)	Density (Kg/m^3)	Capacity (kJ/Kg.K)	Cost (\$/m3)
Glass wool	0.038	24	0.837	228.69
Extruded polystyrene	0.028	35	1.18	320.17
Cork	0.035	120	0.48	279.51

II. LITERATURE REVIEW

Thermal insulation is one of the most valuable tools in improving the energy efficiency level of buildings [25-27]. A large number of research studies in different countries have been conducted to determine the economic and the environmental benefits when the optimum insulation thickness is applied. One of these studies is carried out by Dombayci [28] who investigated the environmental impact of optimum insulation thickness in external walls for the case of Denizli, Turkey. In the theoretical calculations, coal was used as the fuel source and expanded polystyrene as the insulation material. The results proved that energy consumption and fuel emissions decreased by 46.6% and 41.53%, respectively when the optimum insulation thickness is used. Along the same lines, Ucar and Balo [29] calculated the optimum insulation thickness and emissions of CO2, SO2, CO and NOX from the combustion of coal over a lifetime of 10 years for the four different wall types in the city of Elarzig, Turkey. It was found that 82% of reduction in emissions of CO and NOX is achieved when optimum insulation thickness is applied. Mahlia and Iqbal [30] conducted a detailed study on the potential cost savings and emission reductions in the Maldives achieved by installing different insulation materials of optimum thickness and air gaps in building's walls, according to the results, it was shown that installing fiberglass in its optimum thickness without an air gap in the wall can reduces the fuel consumption and exhaust emissions by 65%. Moreover, with an introduction of 6 cm of air gap a further decrease is observed (more than 77%). Taking into account both the economic and the environmental benefits, Dylewski and Adamczyk [31] investigated insulation layer thickness by introducing the so called meta-criterion and analyzed the effect of four heat sources types. The analysis showed that the best results are obtained by thermal insulation made of polystyrene foam and ecofiber. Shekarchian et al. [32] determined the cost benefits and emissions reduction obtained by applying the optimum insulation thickness on the external wall in Malaysia, it was found that the insulation material at its optimum thickness reduces the fuel consumption significantly and decreases the exhaust emissions; fiberglass-urethane was considered as the suitable insulation material. Additionally, three scenarios were introduced in order to predict the potential emission production fluctuation for over the next 20 years. It was concluded that the increase in the contribution of renewable power plants on one hand, and phasing out of the conventional thermal coal plants on the other will substantially lead to a decrease of CO2 emission in long term. For different wall orientations during winter period, Ozel [33] analyzed the effect of building insulation from thermal, economic and environmental point of view, in the coldest city of Turkey, by using a computer model based on an implicit finite difference procedure, according to the results it is seen that the yearly heating loads decrease when the wall is insulated, the obtained insulation thickness for south, north, east and west is 9.2, 10.2, 9.8 and 9.8 cm, respectively. Additionally, it is seen that when optimum insulation thickness is applied fuel consumption and emissions for south north east and west facing wall decrease by 85.5%, 86.7%, 86.3% and 86.3%, respectively. Tettey et al. [34] discussed the effect of different insulation material types on the primary energy and CO2 emission of a multi-storey residential building in Sweden. It was shown that the use of cellulose fiber in the optimum version instead of rock wool reduces the primary energy use by approximately 6-7% and CO2 emission by 6- 8%. Moreover, a reduction of about 39% in the total fossil fuel use for insulation material production was observed. Cuce et al. [35] analyzed the optimum insulation thickness of aerogel and its environmental impacts for the climatic conditions of Nottingham, UK considering different fuel types as energy source. It was concluded that aerogel insulation yields higher mitigation in greenhouse gas emissions with remarkably slimmer insulation thicknesses, it provides 86.4% and 55.2% reduction in CO2 emissions for non-insulated and insulated cavity walls, respectively. Barrau et al. [36] studied different optimization point of views using a simplified analytical method in order to quantify the impact of the insulation material characteristics of the manufacture process on the economic, energetic and environmental optimum insulation thicknesses, the results obtained show that the insulation thickness depends in a large way on the unitary costs associated to the fabrication of the materials, moreover it was demonstrated that the differences for energetic or environmental optimization assessments are larger than for the economic one. Islam et al. [37] evaluated the effects of various alternative wall, floor and roofing assemblages to select an optimized house designs for typical Australian houses using life cycle costing and life cycle environmental impact, it was observed that when the base house design was improved, with the optimal wall, floor and roofing designs, the performance increased and the environmental impact decreased by up to 20% for the same life cycle cost.

III. WALL ENERGY CONSUMPTION

In the present study, Calculations are made for a wall structure, consisting of an insulation layer in the middle of two hallow brick layers and two cement plasters on the inside and outside. Thermal properties of building materials, obtained from [19], are given in Table 3. The convective heat transfer coefficient at the indoor and the outdoor wall surfaces are taken to be 9 W/m² K and 22 W/m² K respectively [27].

Table 3 - Thermo-physical properties of wall materials

Wall structure	Thickness (m)	Conductivity (W/m K)	Resistance (m² K/W)
Cement	0.015	1.153	0.013
Hallow brick	0.150	0.200	0.75
Cement	0.015	1.153	0.013
R_i			0.11
R_o			0.045
R_{wt}			0.931

The annual heating and cooling transmission loads per unit area (J/m²) from building walls are calculated from Eqs. (1) and (2), respectively, using heating and cooling degree-days [38].

$$Q_H = 86400.U.DD_H \quad (1)$$
$$Q_C = 86400.U.DD_C \quad (2)$$

Where DD_H is the heating degree-days and DD_C is the cooling degree-days (°C. day). U is the overall heat transfer coefficient (W/m² K) of the wall defined by:

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

Where R_i and R_o are the inside and outside air film thermal resistances, respectively (m^2 K/W), R_w, is the summation of the total internal resistance of the composite wall materials without insulation (m^2.K/W) and $Ri_{ns}$is the thermal resistance of insulation layer (m^2 K/W) which can be expressed by:

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

Where x is the insulation thickness (m) and k is the thermal conductivity of insulation material wall (W/m K). Thus, U can be expressed as follow:

$$U = \frac{1}{R_{wt} + \frac{x}{k}} \quad (5)$$

With R_{wt} is the sum of R_i, R_w and R_o.

The annual heating energy requirement per unit area can be written as:

$$E_H = \frac{Q_H}{\eta_s} = \frac{86400\, DD_H}{\left(R_{wt} + \frac{x}{k}\right)\eta_s} \quad (6)$$

The annual cooling energy requirement per unit area can be calculated using equation analogous to equation (7).

$$E_C = \frac{Q_C}{COP} = \frac{86400\, DD_C}{\left(R_{wt} + \frac{x}{k}\right)COP} \quad (7)$$

Where $\eta_s$is the efficiency of the heating system and COP is coefficient of performance of cooling system.

IV. ECONOMIC MODEL

In literature, several financial methods have been proposed and used for evaluating and optimizing the thickness of thermal insulation, one of the most commonly used methods, as seen in literature review [28-33], is the life cycle cost analysis (LCCA) that evaluates the cost of a system or a component over its entire lifetime (LT). The total cost is obtained in its present value using the Present Worth Factor (PWF) calculated as [39]:

$$PWF = \sum_{j=1}^{L_T} \left(\frac{1+i}{1+d}\right)^j = \begin{cases} \frac{1+i}{d-i}\left[1 - \left(\frac{1+i}{1+d}\right)^{L_T}\right] & i \neq d \\ \frac{L_T}{1+i} & i = d \end{cases} \quad (8)$$

The PWF takes into account the effect of the inflation rate i and interest rate d, over the lifetime of the building. In this study, the lifetime is considered as 20 years. The inflation and the interest rates are taken as 2% and 2.5%, respectively, according to the published record of Central Bank of Morocco [40].

The life cycle total cost (LCT) is equal to the sum of the energy consumption during the time of existence of the building and the cost of insulation material [41].

$$\mathrm{LCT} = \mathrm{C_{En}}\,\mathrm{PWF} + \mathrm{C_{ins}} \tag{9}$$

Where C_{ins} ($/m²) is the cost of insulation material and C_{En}($/m² year) is the yearly cost of energy consumption per unit area given by:

$$\mathrm{C_{En}} = \left(\frac{86400.\mathrm{U.DD_H}}{\mathrm{H_u}.\eta}.\mathrm{C_f} + \frac{86400.\mathrm{U.DD_C}}{\mathrm{COP}}.\frac{\mathrm{C_E}}{(3.6\times10^6)}\right) \tag{10}$$

Where C_f is the fuel cost in ($/kg) or ($/m^3) and C_E ($/kWh) is the cost of electricity. 3.6×10^6 is added as conversion of units. The cost of electricity and the COP are taken as 0.115$/kWh and 2.5, respectively. Current prices and lower heating values of fuel types with the efficiency of the heating systems used in these calculations are provided in Table 4.

Table 4 - Cost, lower heating values and system efficiencies for different fuel types

Fuel type	Cost ($/kg)	H_u (J/kg)	η (%)
Coal	0.327	26800000	65
Fuel oil	0.625	40193280	80
Natural gas	0.450	34541000	93
LPG	0.815	45576000	90

The cost of insulation is given by the following equation:

$$C_{ins} = C_i.x_i \tag{11}$$

Where C_i is the cost of insulation material in ($/m^3) and xi is the insulation thickness. Thus, combining Eqs. (9), (10) and (11) the life cycle total cost can be rewritten as follows:

$$\mathrm{LCT} = \mathrm{PWF}\left(\frac{86400.\mathrm{U.DD_H}}{\mathrm{H_u}.\eta}.\mathrm{C_f} + \frac{0.024.\mathrm{U.DD_C}}{\mathrm{COP}}.\mathrm{C_E}\right) + \mathrm{C_i.x_i} \tag{12}$$

The value of the optimum insulation thickness is calculated by setting the derivative of Eq (12), with respect to x, equal to zero.

$$\mathrm{x_{op}} = \sqrt{\frac{\mathrm{PWF.k_i}}{\mathrm{C_i}}.\left(\frac{86400.\mathrm{DD_H}}{\mathrm{H_u}.\eta}.\mathrm{C_f} + \frac{0.024.\mathrm{DD_C}}{\mathrm{COP}}.\mathrm{C_E}\right)} - \mathrm{R_{wt}.k_i} \tag{13}$$

The life cycle saving (LCS) is calculated from the difference between the total cost when the wall is non-insulated and the total cost when it is insulated with optimum thickness as reported by Daouas [42].

$$\mathrm{LCS} = \mathrm{PWF}\left(\frac{86400.\left(\frac{1}{R_{wt}} - \frac{1}{R_{wt}+\frac{x}{k}}\right).\mathrm{DD_H.C_f}}{\mathrm{H_u}.\eta} + \frac{0.024.\left(\frac{1}{R_{wt}} - \frac{1}{R_{wt}+\frac{x}{k}}\right).\mathrm{DD_C.C_E}}{\mathrm{COP}}\right) - \mathrm{C_i.x_i} \tag{14}$$

As pointed out by Ozkahraman and Bolatturk[43], the payback period, which is the time needed for the cumulative energy cost saving to equal the total initial investment, can be calculated by the following equation:

$$Payback_p = \begin{cases} \dfrac{\ln\left(1-\left(\frac{d-i}{1+i}\right).\left(\frac{C_{ins}}{A_S}\right)\right)}{\ln\left(\frac{1+i}{1+d}\right)} & if\ i \neq d \\ (1+i)\dfrac{C_{ins}}{A_S} & if\ i = d \end{cases} \quad (15)$$

Where A_s (\$/m2) presents the saved energy over the lifetime divided by the PWF.

V. ENVIRONMENTAL ANALYSIS

Conventional fuels contain primarily hydrogen and carbon in element form or in various compounds (hydrocarbons). Their complete combustion produces mainly carbon dioxide CO_2 and water, however small quantities of carbon monoxide (CO) and partially reacted flue gas constituents. Most conventional fuel also contains small amounts of sulfur, which is oxidized to sulfur dioxide (SO_2) or trioxide (SO3) [44]. The constants of the general combustion equation for different fuel types are shown in Table 5.

$$C_xH_yO_zS_pN_q + \alpha X(O_2 + 3.76N_2) \dashrightarrow x\,CO_2 + \frac{y}{2}H_2O + pSO_2 + YO_2 + ZN_2 \quad (15)$$

Table 5 - The constant of the general combustion equation for different fuel types

Fuel type	X	y	z	p	q
Coal	7.243	5.159	0.362	0.015	0.085
Fuel oil	7.143	10.318	0.000	0.0717	0.0242
Natural gas	1.040	4.0865	0.000	0.000	0.008
LPG	3.700	4.100	0.000	0.000	0.000

Neglecting CO and NOx emissions, the constants of X, Y and Z are obtained using the expression below [43]:

$$X = x + \frac{y}{4} + p - \frac{z}{2} \quad (16)$$

$$Y = (\alpha - 1).x + \frac{y}{4} + p - \frac{z}{2} \quad (17)$$

$$Z = 3.76\alpha.\left(x + \frac{y}{4} + p - \frac{z}{2}\right).\frac{q}{2} \quad (18)$$

As reported by Ucar and Balo [29], the emission rate of combustion products per 1kg of fuel burned can be calculated by:

$$ER_{CO_2} = \frac{x.M_{CO_2}}{M_f} \equiv kg\,CO2\ /kg\,fuel \quad 19$$

$$ER_{SO_2} = \frac{p.M_{SO_2}}{M_f} \equiv kg\,CO2\ /kg\,fuel \quad 20$$

Where MCO2, MSO2 and Mf are the weight of molecule for CO_2, SO_2 and fuel. The molecule weight of fuel can be calculated as follows:

$$M_f = 12x + y + 16z + 32p + 14q \quad (21)$$

The total emission of CO_2 and SO_2 can be calculated using the fuel consumption mf:

$$m_{CO_2} = \frac{x.M_{CO_2}}{M_f}.m_f = \frac{44.x}{M_f}.m_f \quad (22)$$

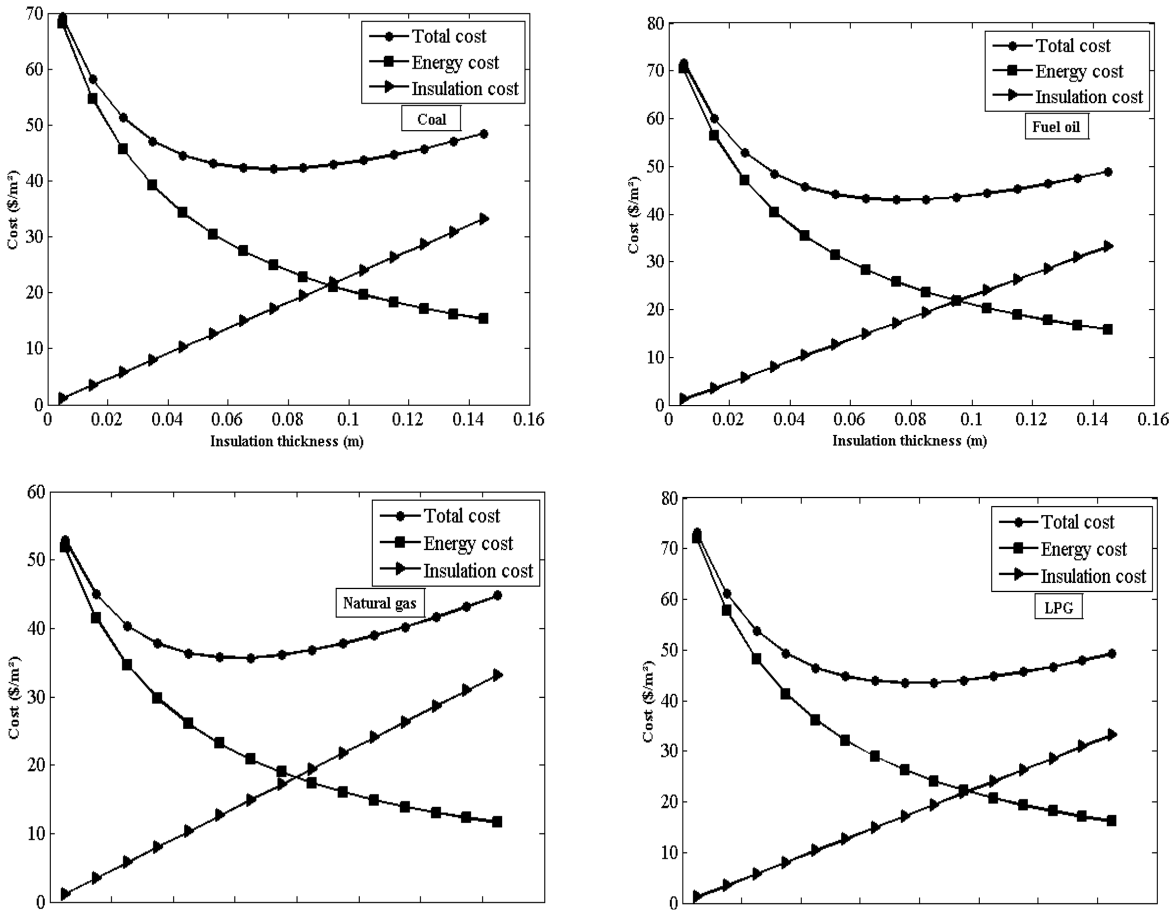
$$m_{SO_2} = \frac{p.M_{SO_2}}{M_f}.m_f = \frac{32.P}{M_f}.m_f \quad (23)$$

The yearly fuel consumption can be calculated by:

$$m_f = \frac{86400.U.DD_H}{H_u.\eta} \tag{24}$$

VI. RESULTS AND DISCUSSION

The energy performance in buildings should be evaluated taking into account not only energy but also economic and environmental considerations. Therefore, in this study, economic and environmental analysis for a typical wall structure under different climatic conditions of Morocco are investigated. The calculations are made on the basis of three different insulation materials (glass wool, extruded polystyrene and cork) and four different heating energy sources (coal, fuel oil, natural gas and LPG).



It is clearly appeared from the calculated results that the energy cost is inversely proportional to insulation thickness, whilst the insulation cost increases linearly with increasing insulation thickness. Additionally, it is observed that the total cost, which is defined as the sum of energy cost and insulation cost, firstly decreases to a minimum value and then starts to increase with increasing the insulation thickness. This is true with all types of energy sources. The optimum insulation thickness is the one that ensures this minimum of the total cost. Figure 1 illustrates this for glass wool as the insulation material and Ifran as the sample city.

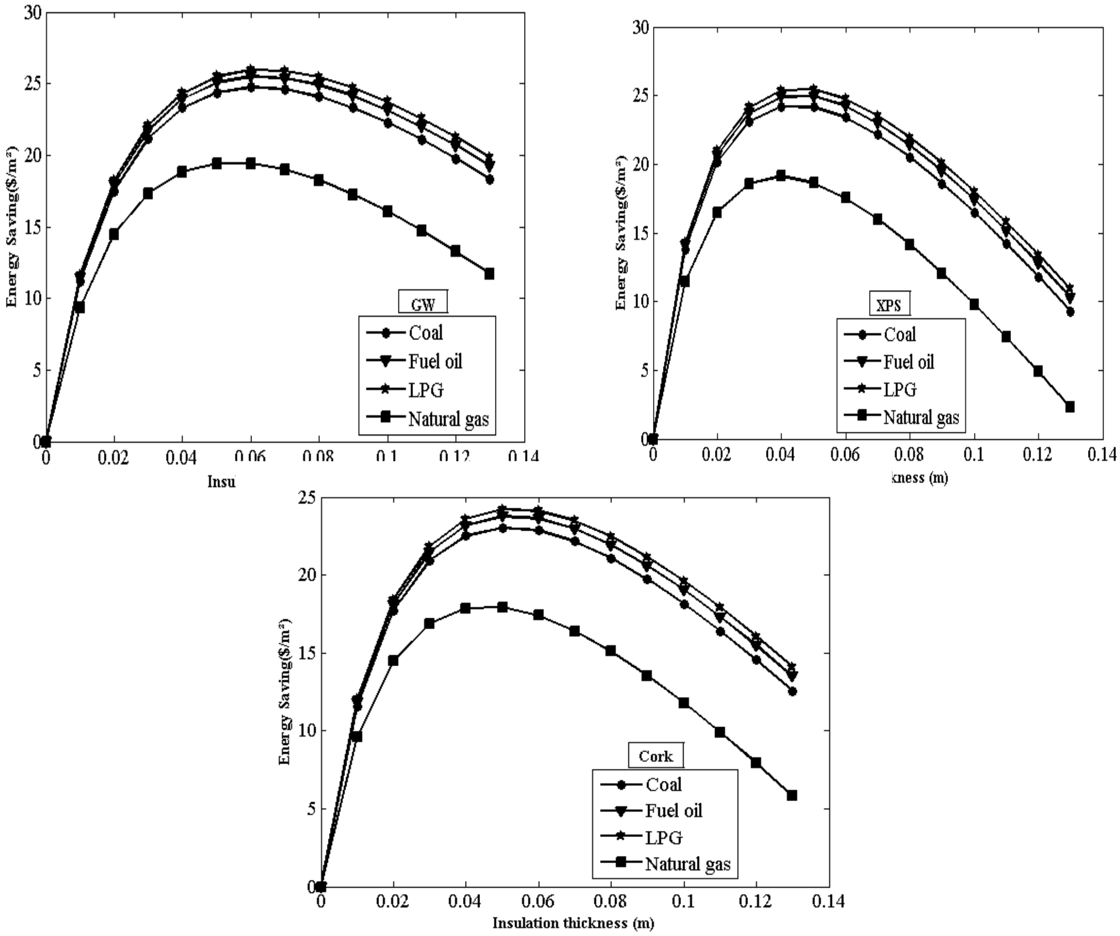


Figure 1 - Energy saving versus insulation thickness for different fuel types and insulation materials in Errachidia city

The effect of insulation thickness on energy cost saving for different fuel types and insulation materials are shown in Figures 2. As can be seen, with increasing insulation thickness, the energy cost saving is observed to be increasing. It increases to a maximum point and then it tends to reduce. This point is referred to the optimum insulation thickness. Beyond this point an increase in the insulation thickness is not economic. Moreover, it is observed that the highest energy cost saving is possessed by LPG and fuel oil, while the lowest energy cost saving is provided by natural gas and coal, which has also been demonstrated by Cuce et al. [34]. On the other hand, when the glass wool, extruded polystyrene and cork are compared, it appears that glass wool has the highest level of energy cost saving potential while cork has the lowest.

For each city, the optimization results for given fuels and insulation materials are summarized in Table 5 and 6. From these tables, it is obvious that cities having higher degree-days require larger layers of insulation. As it can be seen from the results, the optimum thicknesses of the six cities are 0.013-0.023 m in Agadir, 0.020-0.037 m in Tangier, 0.030-0.053 m in Fez, 0.043-0.077 m in Ifran, 0.028-0.045 m in Marrakech, 0.039-0.063 m in Errachidia, regarding of the insulation materials and energy sources. When compared with the others, LPG gives the highest optimum thicknesses; however, natural gas gives the lowest values. The optimum thicknesses of insulation materials from high to low in turn are glass wool, cork and extruded polystyrene. Additionally, it is understood from the tables that the thicker the optimum thickness is, the higher the energy cost saving goes which is in good agreement with results presented in literature [27-33]. The energy cost savings vary from 1.77 $/m² to 38.70 $/m². Besides, it is seen that in each city the energy cost savings are obviously different. The highest and lowest energy cost savings appeared in Ifran using LPG as energy source and glass wool as insulation material and Agadir using natural gas as energy source and cork as insulation material, respectively.

Furthermore, as expected, it is observed from the tables that the higher the energy cost saving is the shorter the payback period will be. Accordingly, the shortest payback period belongs to LPG which range from 11.79 to 12.52 years in Agadir, 9.54 to 10.13 years in Tangier, and 7.78 to 8.26 years in Fez, 6.06 to 6.44 years in Ifran, 8.55 to 9.09 years in Marrakech and 6.93 to 7.36 years in Errachidia depending on the insulation materials. However, coal and natural gas give relatively longer values. Glass wool is the most economical insulation material of the three due to the lowest payback period and thus the highest energy cost saving, while cork was found to be the least economical.

Table 6 - The optimum insulation thickness, energy cost saving and payback period for three different insulation materials and four different heating energy sources in Agadir, Tangier and Fez

Fuel type	Optimum insulation thickness (m)			Energy cost saving ($/m²)			Payback period (years)		
	GW	EXP	Cork	GW	EXP	Cork	GW	EXP	Cork
Agadir									
Coal	0.0226	0.016	0.0177	3.2912	3.1315	2.6920	11.98	12.18	12.72
Fuel oil	0.0231	0.0163	0.0182	3.4439	3.2805	2.8302	11.87	12.04	12.62
Natural gas	0.0187	0.0132	0.0144	2.2651	2.1330	1.7732	12.85	13.07	13.67
LPG	0.0234	0.0166	0.0184	3.5440	3.3782	2.9211	11.79	11.99	12.52
Tangier									
Coal	0.0354	0.0253	0.0289	8.1075	7.8558	7.1500	9.74	9.90	10.36
Fuel oil	0.0363	0.0259	0.0296	8.5866	8.2684	7.5439	9.62	9.76	10.21
Natural gas	0.0286	0.0203	0.0229	5.2790	5.0763	4.5121	10.82	10.98	11.49
LPG	0.0369	0.0264	0.0301	8.8012	8.5389	7.8023	9.54	9.70	10.13
Fez									
Coal	0.0509	0.0366	0.0424	16.7968	16.4336	15.4054	7.95	8.08	8.45
Fuel oil	0.0521	0.0374	0.0433	17.5408	17.1696	16.1182	7.85	7.98	8.33
Natural gas	0.0425	0.0304	0.0350	11.6878	11.3851	10.5320	8.84	8.98	9.39
LPG	0.0528	0.0379	0.0439	18.0.267	17.6504	16.5841	7.78	7.91	8.26

Table 7 - The optimum insulation thickness, energy cost saving and payback period for three different insulation materials and four different energy sources in Ifran, Marrakech and Errachidia

Fuel type	Optimum insulation thickness (m)			Energy cost saving ($/m²)			Payback period (years)		
	GW	EXP	Cork	GW	EXP	Cork	GW	EXP	Cork
Ifran									
Coal	0.0743	0.0535	0.0627	35.7610	35.2300	33.7168	6.23	6.32	6.62
Fuel oil	0.0762	0.0549	0.0642	37.5400	36.9960	35.4449	6.13	6.23	6.50
Natural gas	0.0603	0.0433	0.0504	23.4971	23.0672	21.8459	7.17	7.28	7.60
LPG	0.0773	0.0557	0.0653	38.7011	38.1487	36.5734	6.06	6.16	6.44
Marrakech									
Coal	0.0439	0.0314	0.0362	12.4594	12.1468	11.2652	8.68	8.81	9.22
Fuel oil	0.0445	0.0319	0.0368	12.8298	12.5126	11.6175	8.60	8.74	9.14
Natural gas	0.0391	0.0280	0.0321	9.8846	9.6064	8.8241	9.25	9.41	9.83
LPG	0.0449	0.0322	0.0371	13.0713	12.7511	11.8474	8.55	8.70	9.09
Errachidia									
Coal	0.0618	0.0445	0.0518	24.7449	24.3036	23.0496	7.04	7.16	7.48
Fuel oil	0.0628	0.0451	0.0526	25.4958	25.0478	23.7745	6.98	7.08	7.41
Natural gas	0.0549	0.0394	0.0458	19.5014	19.1098	17.9997	7.60	7.71	8.07
LPG	0.0634	0.0456	0.0531	25.9849	25.5326	24.2469	6.93	7.05	7.36

As reported by Yildiz et al. [45], insulation application to external walls of a building must be feasible both economically and environmentally, thus the second target of this paper was to analyze the annual abatement in fuel consumption, CO2 emissions and SO2 emissions due to the use of thermal insulation. The constants of general combustion equation for selected fuels (Coal, fuel oil, natural gas and LPG) are shown in Table 5. It is deduced from the results that by the increase of the insulation thickness, we observe a noticeable decrease in the fuel consumption and the emission level which can be explained by the fact that thicker insulation material brings to a lower energy requirement, hence lower fuel consumption and greenhouse gas emissions. Besides, it was observed that coal possesses the highest level of CO2 emissions, while LPG and natural gas are very close to each other and give the lowest values. This can be seen in figures 3, 4 and 5 where glass wool was chosen as the insulation material and Ifran as the sample city.

Table 8 and 9 illustrate the values of fuel consumption and emissions obtained at the optimum insulation thickness for the selected cities and insulation materials. According to the results, it is found that the yearly fuel consumption varies between 0.451 and 4.053 kg/m² year, the CO_2 emission varies between 1.514 and 12.978 kg/m² year and the SO_2 emission varies between 0.0104 and 0.1005 kg/m² year representing a percentage of reduction that range between 39.85% and 87.84%, depending on the city, the fuel type and the insulation material. The obtained results show also that the lowest values of fuel consumption and emission are obtained when LPG is used as energy source and glass wool as insulation material, however the highest values are obtained when coal is used as energy source and cork as insulation material.

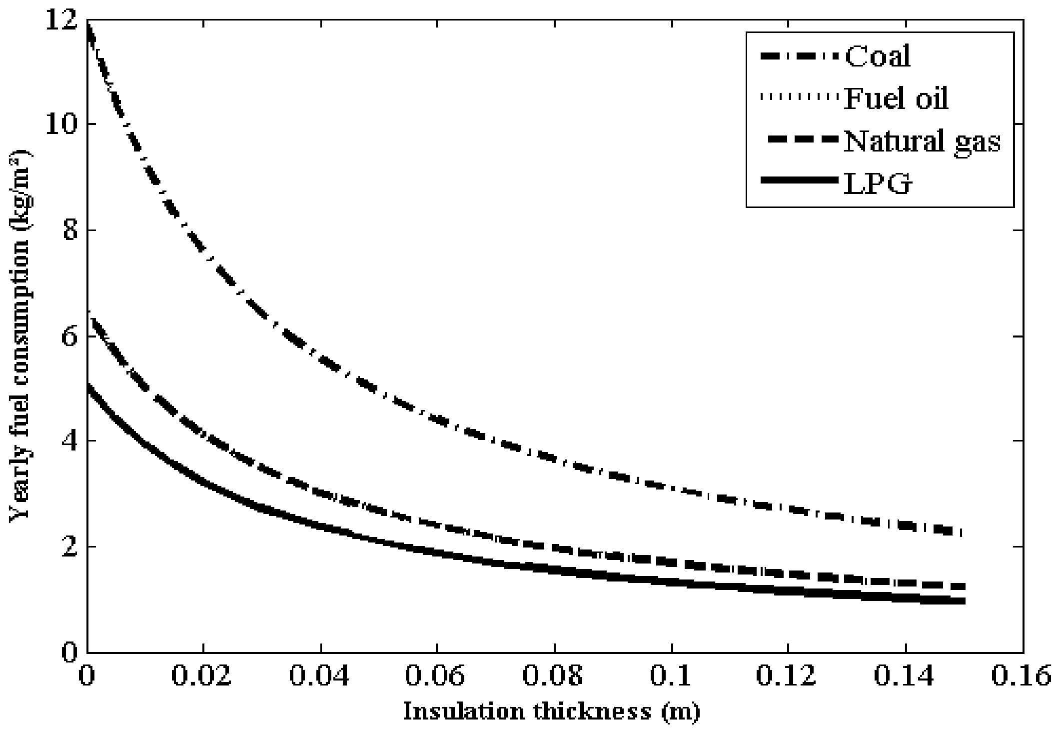


Figure 2 - Variations of the annual fuels consumption with glass wool insulation thickness for Ifran city

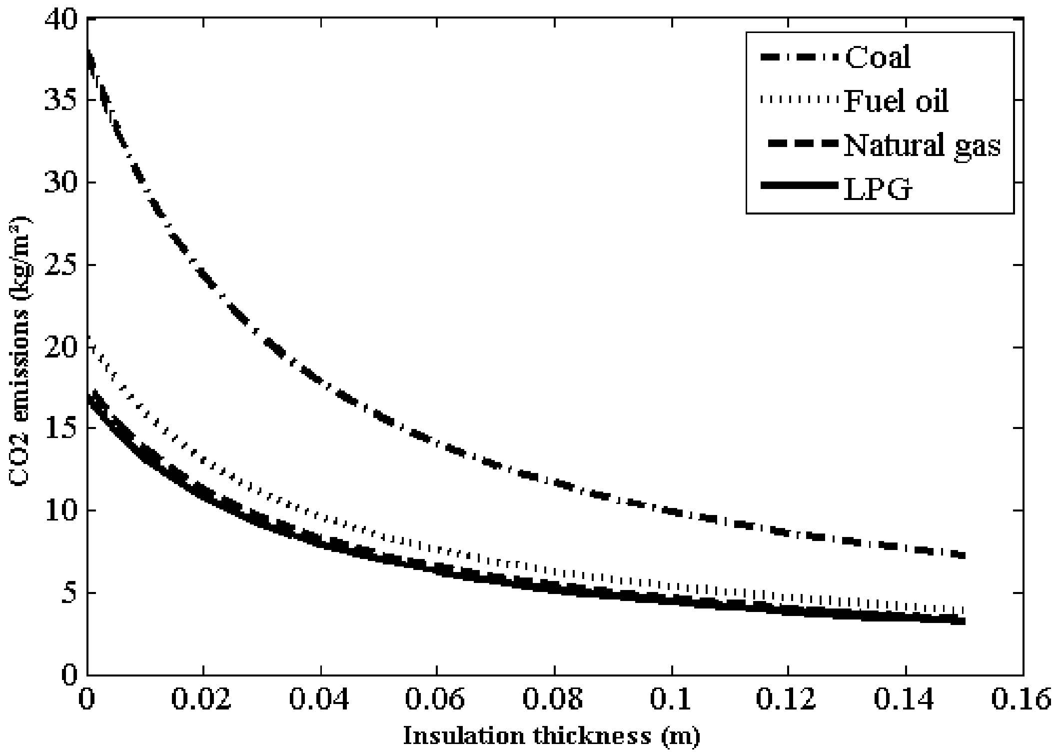


Figure 3 - Variations of the annual CO_2 emissions with glass wool insulation thickness for Ifran city

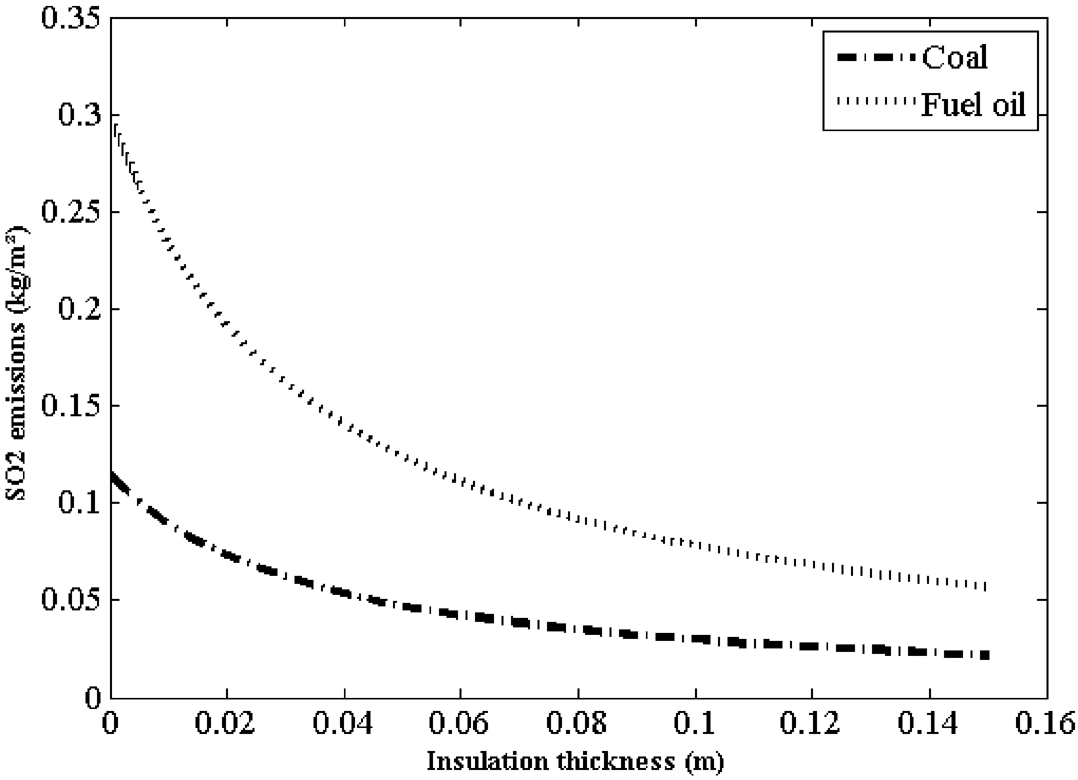


Figure 4 - Variations of the annual SO_2 emissions with glass wool insulation thickness for Ifran city

Table 5 - Fuel consumption and emissions obtained at the optimum insulation thickness for coal and fuel oil.

City	Fuel consumption and emission **(kg/m² year)**	Coal			Fuel oil		
		GW	XPS	Cork	GW	XPS	Cork
Agadir	Fuel consumption	1.077	1.093	1.144	0.578	0.588	0.613
	CO_2 emission	3.447	3.501	3.661	1.842	1.874	1.954
	SO_2 emission	0.010	0.011	0.011	0.027	0.027	0.028
Tangier	Fuel consumption	1.886	1.915	2.000	1.009	1.026	1.071
	CO_2 emission	6.039	6.132	6.404	3.214	3.267	3.413
	SO_2 emission	0.018	0.019	0.019	0.047	0.048	0.050
Fez	Fuel consumption	2.332	2.366	2.471	1.246	1.265	1.323
	CO_2 emission	7.466	7.574	7.912	3.969	4.031	4.214
	SO_2 emission	0.023	0.023	0.024	0.058	0.059	0.062
Ifran	Fuel consumption	3.823	3.883	4.053	2.036	2.067	2.162
	CO_2 emission	12.241	12.431	12.978	6.485	6.585	6.886
	SO_2 emission	0.037	0.038	0.039	0.095	0.096	0.101
Marrakech	Fuel consumption	1.349	1.371	1.432	0.725	0.736	0.769
	CO_2 emission	4.318	4.389	4.584	2.310	2.345	2.449
	SO_2 emission	0.013	0.013	0.012	0.034	0.034	0.036
Errachidia	Fuel consumption	1.942	1.971	2.060	1.042	1.059	1.106
	CO_2 emission	6.218	6.310	6.596	3.312	3.372	3.522
	SO_2 emission	0.019	0.019	0.020	0.048	0.049	0.051

Table 6 - Fuel consumption and emissions obtained at the optimum insulation thickness for natural gas and LPG.

City	Fuel consumption and emission (kg/m² year)	Natural gas			LPG		
		GW	XPS	Cork	GW	XPS	Cork
Agadir	Fuel consumption	0.626	0.635	0.664	0.451	0.458	0.479
	CO_2 emission	1.716	1.743	1.821	1.514	1.537	1.608
Tangier	Fuel consumption	1.132	1.151	1.202	0.785	0.796	0.833
	CO_2 emission	3.105	3.157	3.298	2.633	2.673	2.797
Fez	Fuel consumption	1.401	1.424	1.487	0.969	0.871	1.029
	CO_2 emission	3.844	3.906	4.080	3.252	3.304	3.454
Ifran	Fuel consumption	2.377	2.416	2.524	1.580	1.605	1.676
	CO_2 emission	6.521	6.627	6.925	5.305	5.387	5.625
Marrakech	Fuel consumption	0.779	0.790	0.826	0.566	0.574	0.600
	CO_2 emission	2.136	2.168	2.265	1.899	1.927	2.015
Errachidia	Fuel consumption	1.134	1.152	1.203	0.811	0.824	0.862
	CO_2 emission	3.111	3.161	3.300	2.724	2.766	2.892

VII. CONCLUSION

The main aim of this study was to optimize the thicknesses of insulation layers in a building external wall in six locations in Morocco (Agadir, Tangier, Fez, Ifran, Marrakech and Errachiadia). Four different types of energy sources as coal, fuel oil, natural gas and LPG, and three different insulation materials as glass wool, extruded polystyrene and cork are evaluated in the optimization work. The main results of this paper show that the optimum insulation thicknesses, energy cost savings and payback periods present significant variations due to fuel types, insulation materials and the climatic conditions of each city. Besides, it is observed that applying optimum insulation thickness in cities having higher degree-day is more beneficial in terms of energy cost savings. Additionally, it is seen that the highest energy cost saving occurred due to the fuels is provided by LPG, while the lowest energy cost saving is obtained by natural gas. On the other hand, glass wool was considered as the most economical insulation material of the three while cork was found to be the least economical. The study has also demonstrated that when optimum insulation thickness is applied the percentage of reduction in fuel consumption varies between 39.85% and 87.84%, depending on the city, fuel type and insulation material. The taking account of the obtained results by the building designers is essential for building energy efficiency in Morocco. The results must be viewed as specific to the thermal and economic parameters used in this study.

Future works should consider the influence of renewable forms of heating and cooling supply on the optimum insulation thickness.

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