

An Optimum Thermal Insulation Type and Thickness for Residential Buildings in Three Different Climatic Regions of Saudi Arabia

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Abstract Efficient thermal insulation in the harsh desert climate of Saudi Arabia, where the cooling requirement of buildings is dominant, is very important from the aspect of energy efficiency. Through its eco-friendly properties, thermal insulation is one of the most efficient strategies for reducing energy use while providing the desired thermal comfort. In this study, the impact of thermal insulation type and thickness on reducing the annual energy consumption was evaluated for a sample prototype building located in three Saudi cities. DesignBuilder energy simulation tool has been used for more investigation such as the insulation cost benefits using the life-cycle cost model to knowing when to stop adding insulation. Results showed that applying thermal insulation to the walls and roof leads to a significant reduction in the total costs for all four insulation types. The results show that energy cost savings vary from 5.6 \$/m² to 9.7 \$/m² depending on the city climatic condition. On the other hand, the highest payback period value with 8.8 years in Khamis Mushait (Moderate climate), while the lowest value reached 4.7 years in Gazan (Hot-humid climate).

Keywords Thermal Insulation, Cooling Loads, Energy Consumption, Saudi Arabia, Residential Buildings, DesignBuilder

1. Introduction

The rapid development, urbanization and growth of the construction industry in the Kingdom of Saudi Arabia (KSA) contributed to the generation of 86 GW of electricity during the year 2018 to meet the needs of the growing population [1]. The Kingdom also plans to increase its electricity generation capacity to 120 GW by 2032 to meet the increasing electricity demand [2]. During the last decade, the concept of energy-efficient design has become imperative due to the country's dependence almost entirely on fossil fuels to generate electricity, which is recognized as unsustainable due to their depleting supplies [3].

Compared with other developed countries, the serious view of the issues of energy consumption, energy performance and energy efficiency have not been given serious consideration of study and research except during the past few years. On the other hand, the Saudi population reaches 34.2 million inhabitants, lives in an area of 2 million km², and a population growth rate of 2.1% [4]. Based on statistical authority in 2018 [5] the statistics of the residential units in the KSA have reached 5,466,910 units. The relatively young demographic (over 60% are aged between 15 and 26), which may increase housing demand in the coming few years [6]. The Kingdom's vision 2030 through the housing program has achieved a gradual increase in the rate of Saudi

homeownership from 47% in 2016 to 62% in 2020, in line with their needs and financial capabilities [7, 8]. Besides, the government introduced several reforms and legislations to encourage both local and foreign developers to build 1.5 million homes in the country by 2025 [9]. It is also expected that the rate of ownership of buildings will increase to 70% by 2030. On the other hand, Saudi residential sector consumes about 45% of the total electricity sold (figure 1.), whereas the world average is 31% [10].

Approximately, 70% of existing residential buildings are not thermally insulated [11]. Therefore, nearly 70% of household energy is used for cooling purposes alone [3]. In all Saudi operating districts, residential consumption is dominant. However, it reaches a maximum of 82.3% of the total consumption in the Southern Operating District where this study is carried out [1].

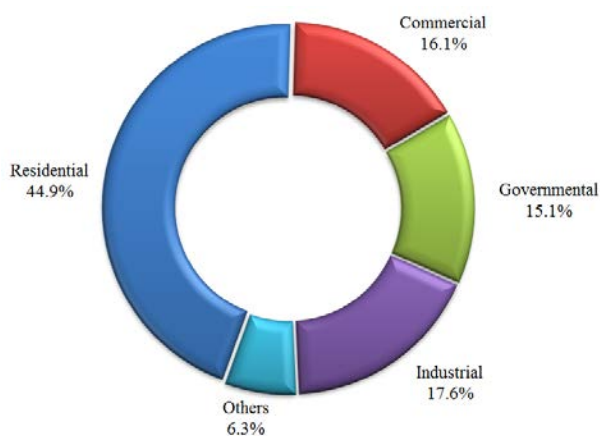


Figure 1. Distribution of consumption by class-kingdom-wise

Building envelope components such as walls and roofs must be designed and operated as passive systems over the lifetime of the building. The most effective way of reducing energy domain in hot-arid climate is achieved by applying thermal insulation to the solid components of the building envelope [12]. Using proper thermal insulation in building envelope does not only contribute to reducing the required air-conditioning system size in desert areas but also in reducing the annual energy consumption, extending the periods of thermal comfort [13]. Although some studies [14-17] during the past few years have shown an increasing interest in improving energy efficiency in Saudi buildings by studying thermal insulation and its applications in building envelopes, only a few studies discussed the cost and the payback benefit of the insulation material.

This study aims to determine the optimum insulation type and thickness to be installed in the walls and roofs of residential buildings in three different climatic regions in the KSA. This determination was based on an economic model, in which a lifecycle cost analysis was conducted using four types of insulation material applies in steps of 2 cm thickness. Thus, this work contributes significantly to

best practices of using thermal insulation in residential building envelope under varied climate conditions of the KSA or similar.

2. Previous Studies

Representative research on the optimization of thermal insulation in building envelopes is reviewed with emphasis on recent studies. Most of the studies in the literature had used the degree day to calculate the thickness [18-20]. A study [21], investigates some of the important factors related to residential energy consumption such as weather conditions, types of dwellings, building envelopes, air-conditioning (A/C) systems. The work is based upon an analysis of the actual monthly electricity consumption for 115 dwellings in Dhahran city, Eastern Province of KSA for the year 2012. The investigated buildings include 62 apartments, 28 villas and 25 traditional houses. The results show that half of the apartments are not thermally insulated, and more than 75% of the surveyed traditional houses were without insulation. Dissipate that the use of thermal insulation started two decades ago in KSA, the optimum type, thickness and position of the thermal insulation and its efficiency are still questionable. A survey study covered 7,120 householders for all Jordanian regions conducted by Mohsen et al. to evaluate the energy consumption in residential buildings. The results showed that applying polystyrene insulation for both walls and roofs of Jordanian dwellings can increase energy saving by up to 76.8% [22].

Kemal and Bedri investigated the optimum insulation thickness for the coldest cities of Turkey. The optimization was based on the lifecycle cost analysis. The results showed that when 10 cm of thermal insulation thickness was applied, a saving up to 12 US\$/m² of wall area can be achieved over a lifetime of 10 years [20]. Saleh et al. evaluated the performance of three different arrangements and thicknesses in the hot-dry climate of Riyadh based on cooling and heating loads. He utilized a predefined computer program using the thermal response factor method. This result showed better thermal performance when locating the insulation within the outer side of the building envelope. Al-Sallal [23] compared two types of roof insulation (i.e. polystyrene and fiberglass) in warm and cold climates in the USA. The study found that the payback period in cold climates is shorter than that in warm climates. Aldossary et al. [24] analyzed the patterns of the annual energy consumption in three (detached houses) and three apartments located in the hot humid city of Jeddah. The simulation results showed that the average consumption of residential buildings in Saudi Arabia is 185.4 kWh/m²/y. The study concluded that high energy consumption was due to the lack of thermal insulation. It is widely known that

increasing thermal insulation thickness leads to a reduction in energy consumption for cooling and heating spaces. However, the most significant point is knowing when to stop adding the insulation layers. The economic approach to find the optimum thermal insulation thickness is to use a life-cycle cost assessment. This approach is widely used in building construction as an energy-efficient technic to determine the optimum insulation thickness where the total cost (i.e. energy cost and the initial cost of the insulation material) is at the minimum [19, 25].

It should be noticed that the results obtained in the previous studies were varied according to the specificity of each individual case with their own climatic condition. Therefore, the choice of Najran, Gazan and Khamis Mushait as the main investigation field cities has not been made randomly. These cities represent hot-dry with desert subzone, hot-humid with a maritime climate and subtropical with mountainous, respectively. Several cities in Saudi and Gulf countries have a climate similar to these three cities. Thus, the results of the present study can serve as a standard for the design, construction and operation of

buildings in these different regions. As presented in figure 2, these cities are located in the Southern Province of the country.

3. Climate Conditions of Saudi Southern Region

Najran, Gazan and Khamis Mushait are three cities representing the three regions called Southern region where residential building responsible for about 82.3% of the total electricity consumption among the other building types, which not studied before. These cities are representing the climatic region of the KSA hot-arid, hot-humid and temperate climates respectively. Several cities in the Kingdom have a climate similar to that of these three cities. The three cities that represent the three climate zones of Saudi Arabia are shown in Figure 2. Moreover, the location information and climate characteristics of the three selected cities are given in Table 1.



Figure 2. Map of Saudi Arabia and selected cities in this study.

Table 1. Climate characteristics of selected locations [26]

Location	Geographic coordinates			Air temperature			Relative humidity			Global Horizontal Irradiance (GHI)/day		
	Latitude (°N)	Longitude (°E)	Elevation (m)	Min (°C)	Max (°C)	Mean (°C)	Min (%)	Max (%)	Mean (%)	Min (kW/m ²)	Max (kW/m ²)	Mean (kW/m ²)
Najran	17.3	44.1	1213	10.7	36.4	26.6	10.5	96.8	24.6	0.99	8.60	6.77
Gazan	16.6	42.3	4	24.1	35.9	30.3	26.6	100	69.5	1.42	7.55	5.64
Khamis Mushait	18.3	42.7	2051	2.7	34.3	18.9	17.1	100	52.3	0.49	8.72	5.99

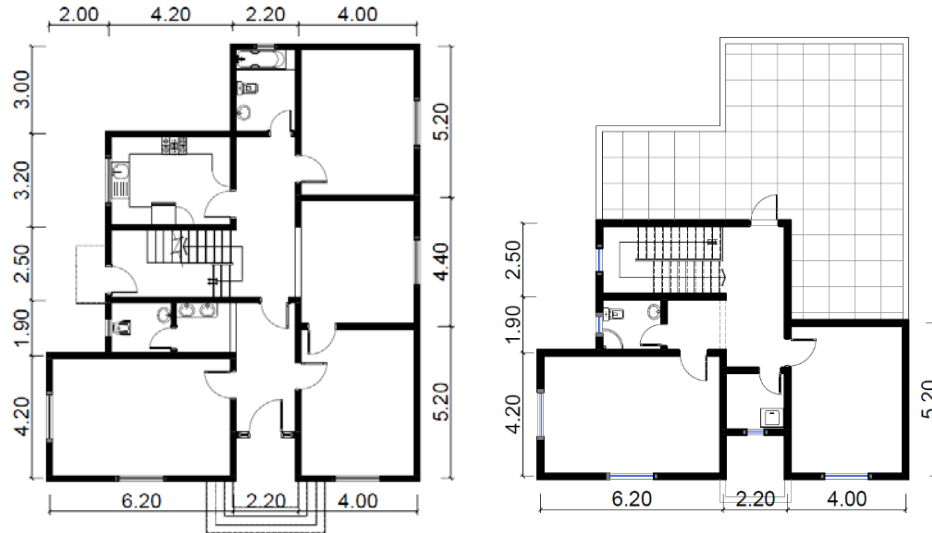


Figure 3. Ground and first floor plans of the typical villa

4. Research Methodology

4.1. Building Characteristics

The residential building considered in this study is a prototype villa developed by the housing authority of the KSA, under the name “Model A”, which is constructed and duplicated with a huge number exceeds 12,000 units in 35 cities all over the kingdom [7]. Since this is a standard floor plan for various housing estates developed by the Saudi Housing Authority, there is no fixed location or orientation. The typical building’s data were obtained from two sources: (i) review of building plans approved by the housing authority, (ii) site visits to the housing campus, to conduct information related to building systems (types and operation), schedules of occupancy, and house appliances. The case study building comprises two stories, with a built floor area of 238 m² and a total land area of 500 m². Fig. 3 illustrates the floor plans and a photo of the case study. In addition, the annual energy consumption data are collected for 15 villas occupied by families in Najran city from the electricity & cogeneration regulatory authority for the year 2018. The average annual electricity consumption was 183.93 kWh/m²/y. The material and construction characteristics used in the building are summarized in Table 2. Moreover, the

specifications of air-conditioning and lighting systems for the base-case model are shown in Table 3.



Figure 4. Perspectives of the typical villa and rendered building model

Table 2. Building construction specifications for the building

Characteristics	Description
Number of stories	Two
Total height	7.0 m
Gross floor areas	238 m ²
Gross wall area	357 m ²
Gross roof area	140 m ²
WWR	6.4%
Type of glass (U-value = 6.121 W/m ² K)	Single Clear 6mm.
External walls from outside to inside (U-value = 1.65 W/m ² K)	20 mm Plaster 200 mm Concrete block 20 mm Plaster (light)
Internal partitions	200 mm Concrete blocks 20 mm Plaster (light)
Roof from outside to inside (U-value = 3.644 W/m ² K)	20 mm Cemented tiles 13 mm Mortar 50 mm Sand stone 150 mm Reinforced concrete 13 mm Plaster (light)
Ground floor	13 mm Ceramic tiles 13 mm Mortar 100 mm Light reinforced concrete 5 mm Asphalt insulation 50 mm Concrete high density 150 mm Base-course stone
Number of occupants	6

Table 3. HVAC and lighting systems characteristics for the base case model

Characteristics	Description
System type	Cons. volume DX air-cooled A/C system
Thermostat setting	24°C for cooling
COP	2.17
Lighting	3.0 kW (lower level), 2.0 kW (upper level)
Appliances	2.0 kW (lower level), 1.0 kW (upper level)

4.2. Building Simulation Method

Computer-based simulation is the best technique by which building design and its operation can be accurately evaluated [27, 28]. Rendering for the energy models of the prototype was carried out using DesignBuilder, an hourly building simulation tool [29]. The energy model has been calibrated based on the monthly energy consumption compared to the real-time consumption obtained from the utility bills of the year 2019. The calibration procedure of the villa located in Najran shows a good agreement between simulated results from the building model and actual data with a relative error of about 5.3%. The impacts of varied investigated cases were also modeled and calculated using DesignBuilder software under three weather files of Najran, Gazan and Khamis Mushait. These weather files used in the simulation analysis for each city are based on average data of 10-20 years provided through the USA, Department of Energy (DOE) website.

4.3. Selection Criteria of Insulation Material

There are many parameters to be addressed when selecting thermal insulation, including durability, compressive strength, water vapour absorption, fire resistance, ease of application, and thermal conductivity [30]. However, the thermal transmittance (U-value) and the cost are the most important criteria when considering thermal performance and energy conservation issues. In this study, four common and available thermal insulations in the Saudi market are selected for more investigation. The properties of those materials are shown in table 4.

The selection of optimum thermal insulation type and thickness of building walls/roofs is based on three major steps. The first step is determining the annual energy consumption, while the second step is selecting optimum thickness through an economic analysis method. The final step is carrying out the payback period.

Table 4. Material properties

Code	Type of Insulation	Density (kg/m ³)	Thermal conductivity (W/m-K)	Fire resistance	Cost \$/m ³
FG	Fiberglass (sand & recycled glass)	12–56	0.04–0.033	Good	178-252-350-304
RW	Rockwool (natural rocks)	40–200	0.037	Excellent	148-215
PETH	Polyethylene	35-40	0.041	Poor	164-205
EXTp	Extruded Polystyrene (closed cell foam)	26-45	0.032–0.030	Poor	182

4.4. Payback Calculation

The optimum economic thickness of insulation material can be determined as the thickness for which the cost of the added increment of insulation is just balanced by increased energy savings over the lifetime of the project [31]. Thermal insulation costs are satisfactorily defined. However, it can be changed within KSA regions depending on the suppliers, time, and various economic approaches. Local suppliers through direct contact provided the cost of each thermal insulation type proposed in this study. The annual energy consumption and its contribution to the annual energy saving and payback were calculated based on the following equations:

$$SE = (EC_{bc} - EC_{sc}) / EC_{bc} * 100 \quad (1)$$

$$C_{se} = (EC_{bc} - EC_{sc}) * 0.05 \quad (2)$$

$$P_b = C_{im} * 12 / C_{se} \quad (3)$$

Where:

SE = Saved Energy (kWh)

EC_{bc} = Energy consumption in the base case (kWh/y)

EC_{sc} = Energy consumption in the simulated case (kWh/y)

C_{se} = Cost of saved energy (\$US)

0.05\$US = Electricity tariff for residential buildings in KSA (per kWh)

P_b = Duration of the payback per month

C_{im} = Total cost of the insulation material (\$UD)

12 = Number of months.

5. Results and Discussion

To validate the model, a comparison between the simulated monthly energy and the actual consumption from the utility bills of the base case under the climate condition of Najran city is illustrated in figure 5. The

annual Energy Efficiency Index (EEI) was 183.93 kWh/m²/y whereas the result from the simulation program was 193.07 kWh/m²/y. The value of 9.14 kWh/m²/y represents the energy consumption gap between measured and simulation results, which show a good agreement with relative errors of approximately 5.3%. The same base case energy modeled in Najran was also simulated under weather conditions of Gazan and Khamis Mushait. The simulation results show significant variations in EEI according to the climate condition of each city. The EEIs were 193.07, 273.11, and 121.01 kWh/m²/y in Najran, Gazan and Khamis Mushait respectively.

5.1. Impact of Thermal Insulation Strategy on Energy Conservation

After direct contact with specialized suppliers in the field of thermal insulation in Najran, it is found that XPS Extruded Polystyrene is commonly used especially for roof insulation in the Saudi Arabia construction industry due to its reasonable costs and ease in manufacturing and installation. Therefore, at this stage, XPS Extruded Polystyrene was used to assess the impact of thermal insulation on energy conservation. To investigate the impact of thermal insulation, two cases are modelled (Coded: I2, I3) and compared with the base case i.e. with no insulation material (Coded: I1). The criteria of each case, the impact of thermal insulation on energy consumption and the percentage of saved energy for the three cities are illustrated in table 5. The results show that a maximum energy saving occurs when applying full insulation in roofs and walls (Code #I3). This result is correct for all cities. The maximum saving of 32.08%, 38.35% and 16.4% achieved at Najran, Gazan and Khamis Mushait respectively. The impact of the thermal insulation is minimal in Khamis Mushait as the weather is relatively mild compared with Najran and Gazan.

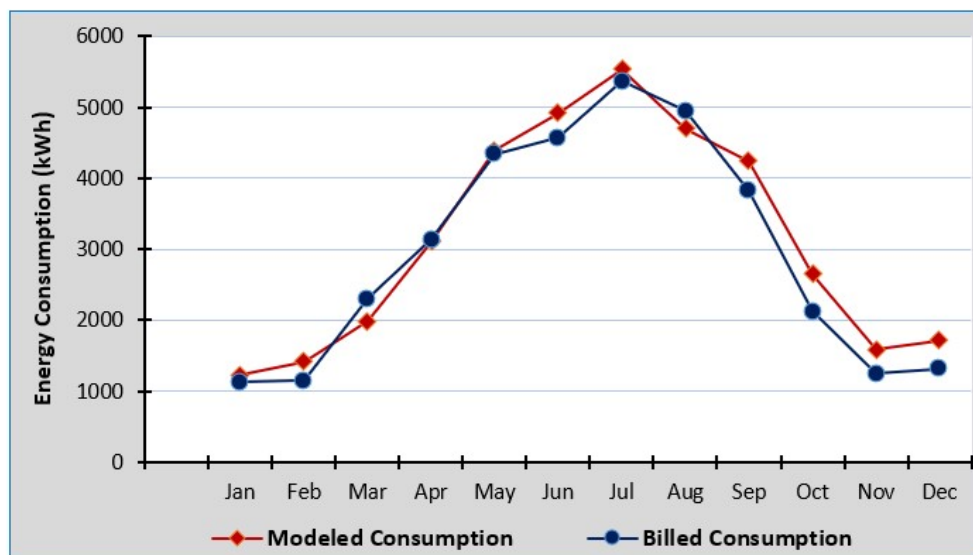

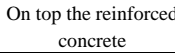



Figure 5. Comparison between simulation results and billed consumption for the base case

Table 5. Impact of thermal insulation on energy conservation in the three investigated cites

Code	Description	Insulation type	Insulation Thickness	Insulation Position	Najran		Gazan		Khamis Mushait	
					*ECp	">%SE	*ECp	">%SE	*ECp	">%SE
I1	NO Insulation (BC)	----	----	----	193.07	0	273.11	0	121.01	0
I2	Only Roof Insulation	XPS Extruded Polystyrene	Roof 14 cm	 <p>On top the reinforced concrete</p>	154.11	20.18	209.02	23.47	104.32	13.79
			Roof 14 cm	 <p>On top the reinforced concrete</p>						
I3	The whole building is completely insulated (roof and walls)	XPS Extruded Polystyrene for Roof and Wall	Walls 6 cm	 <p>Centre of the wall</p>	131.13	32.08	168.37	38.35	101.17	16.40

* ECp Energy Consumption (kWh/m²/Y)

* %SE Percentage of Saved Energy (%)

5.2. Impact of Thermal Insulation Type on Energy Consumption

In this section, the energy efficiency index of the base case villa located in the three different cities is evaluated using a different alternative wall and roof designs that cover a wide range of thermal insulation characteristics as illustrated in Table 6. The investigated types of thermal insulation have a fixed thickness of 6 cm in the wall’s center for all cases. The result shows that a reduction in energy consumption of about 16% to 38% can be achieved depends on the climate conditions of each city. A closer look at the percentage of saved energy shown in table 6, indicates that thermal insulation type results in significant reductions in the annual EEI. The results indicate that the use of any type of thermal insulation in the three cities is an effective strategy to reduce annual energy consumption with negligible variation between the largest and lowest performance of each type. These variations were 4.3%, 5.6% and 1.4% in Najran, Gazan and Khamis Mushait respectively. For the hot-dry climate of Najran, the reductions in annual energy consumption due to the use of different types of thermal insulation ranges between 27.3% and 31.6%. For the hot-humid climate of Gazan, these reductions are likely to be similar to the results found in Najran, ranging between 32% and 37.6%. For the temperate climate of Khamis Mushait, on the other hand, these reductions are the lowest which ranging between 14.4% and 15.8%. It is also clear that the minimum reduction in energy consumption occurred when applying Rock Wool types under varied climatic conditions. However, XPS polystyrene and fiberglass

performed almost the same especially in hot-dry and temperate climates.

5.3. Impact of Thermal Insulation Thickness on Energy Consumption

To assess the impact of thermal insulation thickness on energy consumption, XPS polystyrene was used due to the reasons mentioned in section 5.1. The thicknesses for which the tests were carried out started from 2 cm to 14 cm in steps of 2 cm in both centers of the walls and on top of the reinforced concrete of the roof. Table 7 shows the percentage variation in yearly energy consumption with different thickness of XPS insulation in Najran, Gazan, and Khamis Mushait. The results show that energy consumption decreases with increasing insulation layers. However, the decrease is sharp at the beginning and becomes more gradual with increased thickness.

On the other hand, the life cycle cost model is used to manage the optimum thermal insulation thickness. The impact of insulation thickness on the total cost over the lifetime of 20 years is illustrated in figure 6 (a, b, c). The cost of the energy reduces with the increase of insulation thickness. Based on the total cost, the optimum insulation thicknesses for both roofs and walls for the villa located in Najran, Gazan and Khamis Mushait are 6, 8 and 2 cm, respectively. Table 6, shows that applying the optimum insulation layers leads to the highest total cost savings of 29.8, 37.7 and 11.5% in the three cities respectively. Besides, the payback periods as shown in table 8 for the three optimum alternatives are 6.4, 4.7 and 8.8 years, respectively.

Table 6. Impact of thermal insulation types on energy saving in the three cites

Code	Insulation type	U-value (W/m ² -k)	Najran		Gazan		Khamis Mushait	
			*ECp	**%SE	*ECp	**%SE	*ECp	**%SE
T1	NO Insulation (BC)	---	193.07	0	273.11	0	121.01	0
T2	XPS Polystyrene	0.030	135.59	29.77	176.84	35.25	102.67	15.16
T3	Fiber Glass	0.040	136.17	29.47	178.02	34.82	102.69	15.14
T4	Rock Wool	0.040	140.32	27.32	185.76	31.98	103.59	14.40

* ECp Energy Consumption (kWh/m²/Y)

** %SE Percentage of Saved Energy (%)

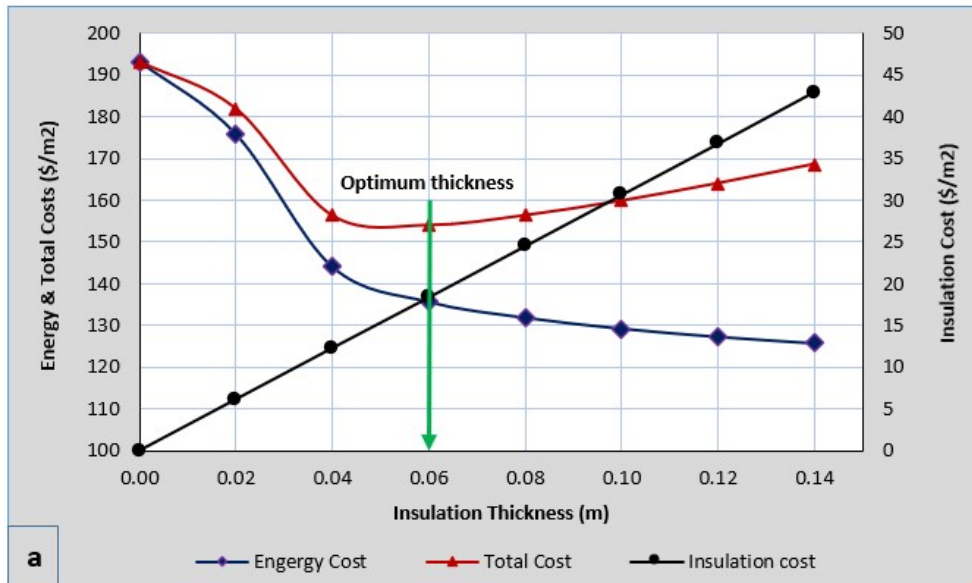
Table 7. Impact of thermal insulation thickness on energy saving

Thickness (cm)	Total U-value (W/m ² -k)		Total Insulation cost USD/bldg	Najran			Gazan			Khamis Mushait		
	Roof	Wall		*ECp	**%SE	***ECt	*ECp	**%SE	***ECt	*ECp	**%SE	***ECt
0.0	3.644	1.650	0.0	193.07	0.00	193.07	273.11	0.00	273.11	121.01	0.00	121.01
2.0	1.159	0.837	1457.9	175.74	8.98	175.74	209.02	23.47	209.02	107.15	11.45	107.15
4.0	0.689	0.561	2915.8	144.04	25.39	144.04	187.84	31.22	187.84	104.09	13.98	104.09
6.0	0.490	0.422	4373.7	135.59	29.77	135.59	176.84	35.25	176.84	102.67	15.16	102.67
8.0	0.381	0.338	5831.6	131.82	31.72	131.82	170.01	37.75	170.01	101.79	15.88	101.79
10.0	0.311	0.282	7289.5	129.19	33.09	129.19	165.29	39.48	165.29	101.17	16.40	101.17
12.0	0.263	0.242	8747.4	127.24	34.10	127.24	161.82	40.75	161.82	100.68	16.80	100.68
14.0	0.228	0.212	10205.3	125.70	34.89	125.7	159.14	41.73	159.14	100.29	17.12	100.29

* ECp Energy Consumption (kWh/m²/Y)

** %SE Percentage of Saved Energy (%)

*** ECt Energy Cost for life time (\$/m²/20y) at 0.05\$US Electricity tariff for residential buildings in KSA (per kWh)



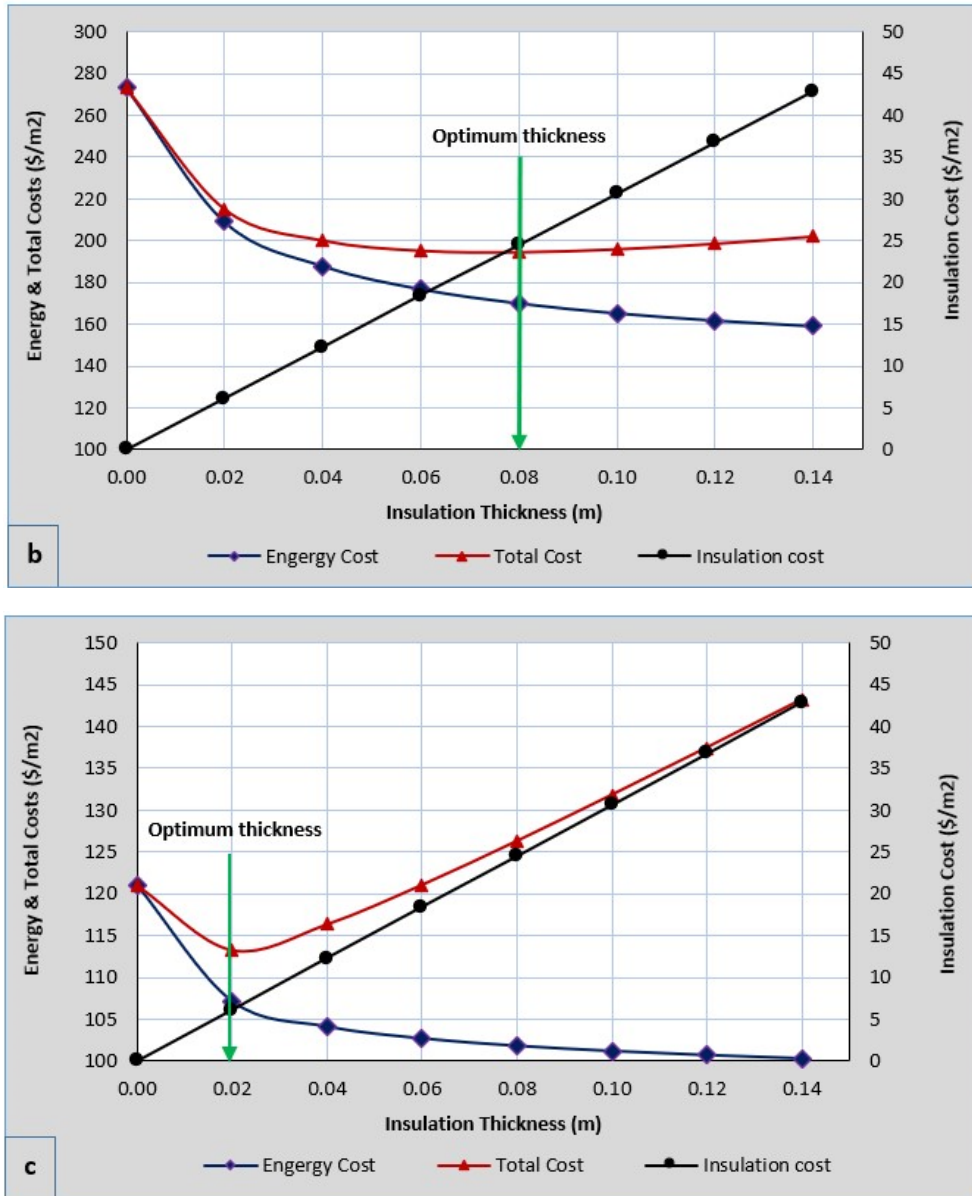


Figure 6. Variations of insulation cost, energy cost and total cost with the insulation thickness of: (a) Najran, (b) Gazan, and (c) Khamis Mushait.

Table 8. Optimum insulation thickness, savings and payback period for different cities

Name of the City	Optimum thermal insulation (m)	Insulation cost (\$/building)	Saved energy (kWh/m ² /y)	Cost of saved Energy (\$/y)	Payback Period (years)
Najran	0.06	4373.70	13680.24	684.01	6.39
Gazan	0.08	5831.60	24537.80	1226.89	4.75
Khamis Mushait	0.02	1457.90	3298.68	164.93	8.84

6. Conclusions

The optimum thickness of the thermal insulation is essential, not just to save the operation cost, but also to reduce the construction cost. In the present study, which was carried out through a typical villa using the DesignBuilder simulation tool, the optimum thickness of the thermal insulation of walls and roof was investigated. Four different insulating materials were selected to be applied in three Saudi cities, which fully reflect the diversity of the climate in the country. The amount of saved energy over a period of 20 years was also calculated. The results showed that the energy efficiency of the building is directly proportional to the total cost of the insulating material, so that the total energy cost of the optimum cases ranged between 7.7, 9.7 and 5.6 \$/m²/y in Najran, Gazan and Khamis Mushait respectively. According to the climate regions the study found that the optimum thicknesses for thermal insulation are 2, 6 and 8 cm for the three cities respectively. On the other hand, the highest payback period value with 8.8 years is in Khamis Mushait (Moderate climate), while the lowest value is reached 4.7 years in Gazan (Hot-humid climate).

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