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Determination of optimum thickness of nano and traditional insulation materials for building external walls by using degree-day approach for different climatic regions in Egypt

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Abstract

The usage of energy is one of the most critical challenges in modern life. The majority of the energy we use comes from fossil fuels which cause significant environmental degradation. One of the most effective ways of reducing energy use is using thermal insulation in building exterior walls but at a higher cost. Accordingly, this study discusses selecting the optimal thermal insulation and its thickness to increase building efficiency. The optimum insulation thickness is the thickness of insulating material that saves the most energy while costing the least. In this study, optimum insulation thicknesses of four cities from different regions of Egypt have been calculated for external walls using electricity as energy source. The calculations are made on 5 different traditional insulation materials and 2 nano insulation materials. Different cases have been considered: buildings cooled only, and both heated and cooled. It was found that Glass wool (GW) is the optimal insulation in all given locations, but its optimal thickness is very large and that will reduce the available used spaces which will reduce the rental income of buildings and reduce life cycle cost saving of building. Wherefore this study discusses also selecting the optimal thermal insulation and its thickness in the case of accounting for the impacts of space savings in life cycle saving of building, The results show that the nano insulation material vacuum insulated panels can be considered the optimum insulation in all cases when considering area saving as it achieved the maximum life cycle saving. Finally, the study reviewed the placing locations and installing insulation materials in buildings.

Keywords: Energy-saving, thermal insulation, life cycle costing, optimum thickness, payback period

1. Introduction

In hot climate countries like Egypt, energy consumption is rising every day due to the use of air conditioning in buildings to meet thermal comfort requirements, as well as inadequate building insulation, resulting in an energy crisis. Heating and cooling buildings consume nearly 50% of the total electricity consumption in Egypt for the residential and commercial building sectors, making this issue one of the most critical roadblocks to society's growth [1]. Building envelope components (Walls and roofs) must be designed and operated as passive systems over the life of the structure. The effect of building envelope depends on the selection of its consisting materials and their thicknesses, including the use of thermal insulation materials to increase the thermal resistance of the external walls. This study aims to determine the optimum insulation for exterior walls and its economical thickness. Optimization calculations are made for cooling, and combined heating and cooling of buildings, using the degree-day approach and lifecycle cost analysis (LCC). The approach of optimum thermal insulation thickness takes into account both the initial cost of the insulation as well as the energy cost savings during the insulation's lifetime. The value that delivers the lowest total life cycle cost corresponds to the optimum insulating thickness as represented in Figure 1. [2]

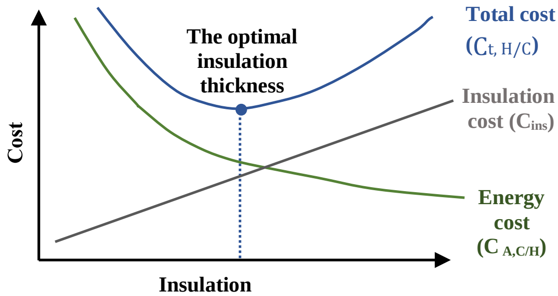


Figure 1. Calculation of the optimum insulation thickness based on the lowest total cost

In literature, there are several studies on optimum insulating thickness. For instance, a study conducted in 2011 discussed a literature review of the effect of some parameters such as (discount rate, inflation rate, fuel type, material lifetime, energy costs, building heating/cooling loads, the wall structure, and insulation material characteristics) on selecting the optimum insulation thickness [3]. Another research calculated optimum insulation thickness and repayment periods in 81 provinces of Turkey for four different fuels and five different insulation material [4]. The study conducted by Yuan et al. presented a proposal of optimum insulation thickness for the exterior walls of buildings in 32 regions of China to save energy [5]. They concluded that annual total energy cost can be reduced by increasing the thermal insulation thickness. In addition, another research examined optimum insulation thickness, energy savings, payback period, and CO2 emissions for poultry farm buildings' external walls located in Bandrma using different fuels and two different insulating materials were used in the calculations (expanded polystyrene and extruded polystyrene) [6]. The optimum insulation thickness was computed for different wall structures for two main cities in Saudi Arabia (Riyadh and Dammam) of residential buildings [7]. Depending on the kind of wall structure, the payback times for polystyrene were 2.3-2.7 years and 2-2.5 years for polyurethane in Riyadh. The findings demonstrate that residential building insulation in Saudi Arabia is cost-effective and should be installed since it would result in improved levels of comfort and reduced air-conditioning energy bills. Al-Tamimi in 2021, investigated the alternative positions for the insulation material and the optimum thickness for the three proposed strategies (on the roof only, on the walls only and on the roof and walls) [8]. The researcher uses the life cycle cost model to manage the optimum number of insulation levels and applied the method on a sample prototype villa in Najran City. The financial benefits of extruded polystyrene material (XPS) during its lifespan are used to select the optimum insulating thickness. The optimal insulation thicknesses of 8, 4 and 6 cm must be applied to the roof only, the walls only, and the roof and walls, respectively, according to the findings. These solutions can reduce yearly energy usage by 19.14 %, 7.51 %, and 29.77 %, respectively. There is also a significant reduction in CO2 emissions. Finally, the three best options had payback periods of 3.73, 12.14, and 6.39 years, respectively.

According to the literature review indicated above, the results of previous studies differ based on the individuality of each case and its unique climatic conditions. These studies focus on the traditional insulations only such as (expanded polystyrene and extruded polystyrene) but no studies focused on selecting optimum insulation of high-performance thermal insulation in buildings (nano-thermal insulating materials) such as aerogel, vacuum insulation panels (VIPs). And there are no studies also focused on determining the optimal insulating thickness for Egyptian buildings. In this study, the optimum insulation thickness of the external walls was calculated using a life-cycle cost (LCC) analysis for the main three (of eight) climate zones of Egypt as presented in Figure 2. (1) Cairo and Delta zone (Cairo city), (2) North coast zone (Alexandria city), and (6) the Southern zone (Aswan city). these cities were not chosen at random as the principal inquiry field cities. The reason for selecting Cairo and Alexandria where about 50% of the new construction projects implemented in Egypt are located in Cairo and Alexandria. Whereas Aswan is considered a very unique region in terms of climatic aspects compared to other regions [9]. Electricity is used as an energy source for heating/cooling as well as, five types of thermal insulation materials are used and their properties. The degree-day approach is used for estimating heating and cooling energy requirements.

2. Determination of degree-days HDD/CDD

In general, the degree-days approach is one of the more accurate ways to estimate building energy consumption. The difference between the average external temperature and the base temperature (T_b) is exactly related to the energy demand of the building, according to this approach. The heating and cooling degree days value describes the density of cold / heat in a specific period (month, year, etc.) by taking into consideration the outside air and base temperature. HDD / CDD can be expressed as the following functions (1),(2): [6,10]

$$HDD = \sum_{1}^{n} (T_b - T_o)^{+} \quad ; \text{ For } T_o < T_b \qquad (1)$$

$$CDD = \sum_{1}^{n} (T_o - T_b)^{+} \quad ; \text{ For } T_b < T_o \qquad (2)$$

T_o: is the temperature of the outside air. T_b : is the base temperature (In this study, the base temperature was taken 18°C). n: is the day's total number during the period. (In this study, n was taken 365 days). The + sign above the parenthesis indicates that only positive values should be counted, when $T_o > T_b$, the temperature difference is assumed to be zero.

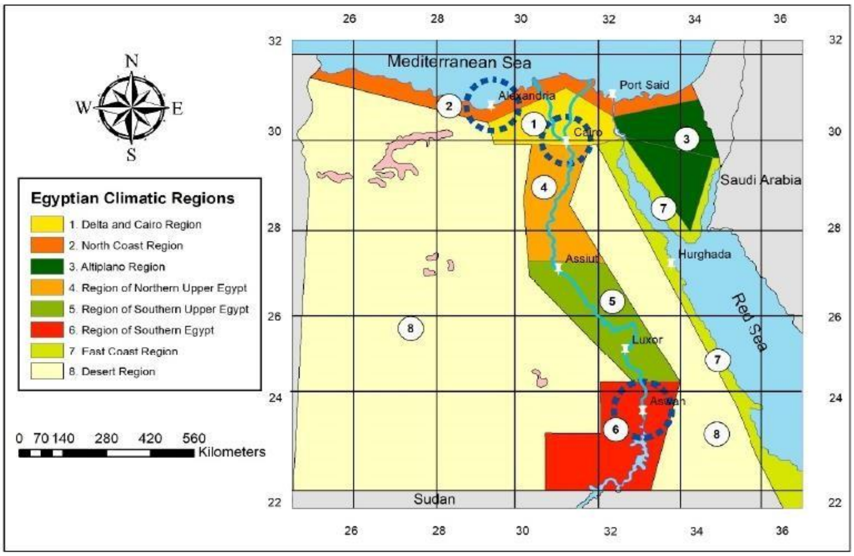


Figure 2. Climatic regions of Egypt [11]

3. Calculations of energy consumption

External walls, windows, ceilings (roofs), and air infiltration all contribute to heat loss in buildings. However, only heat loss through external walls was considered in this study. as wall insulation does not affect air ventilation or infiltration but raising resistance or reducing conductance reduces heat losses through walls. As a result, only wall losses will be included in the following optimization insulation thickness study. The following equations (3),(4),(5) may be used to determine the annual heat loss and gain via a unit area of the exterior wall [W/m2]: [12]

$$q_{A,H} = 86400 \cdot HDD \cdot U$$

(3)

$$q_{A,C} = 86400 \cdot CDD \cdot U \tag{4}$$

U: is the overall heat transfer coefficient [W/m^2K] expressed as [4]:

$$U = \frac{1}{R_i + R_w + R_{ins} + R_o} = \frac{1}{R_{tw} + R_{ins}} \tag{5}$$

R_i, R_o: are the inner and outer air's thermal resistances [m^2K/W], respectively. R_w: is the overall thermal resistance of wall materials without insulation [m^2K/W]. R_{ins}: is the thermal resistance of insulation materials [m^2K/W]. It may be calculated using the equation below [4]:

$$R_{ins} = \frac{x_{ins}}{k_{ins}} \tag{6}$$

x_i: is the insulation thickness, [m]. k_{ins}: is the thermal conductivity of insulation material, [W/mK].

The annual energy consumption for heating (E_H) and cooling (E_C) is estimated by dividing the annual heat loss by the system efficiency as equation (7),(8) [4]:

$$E_H = \frac{q_{A,H}}{\eta} \tag{7}$$

$$E_C = \frac{q_{A,C}}{COP} \tag{8}$$

η:is the efficiency of the heating system. COP: is the coefficient of performance of the cooling system.

4. Calculation of annual energy cost and the optimum insulation thickness

The Present-Worth Factor (PWF) will be calculated to determine cost accounting. It can be estimated using the following formulas (9), (10) depending on inflation and interest rates [4]:

$$If\ i \square g\ then\ r = \frac{i - g}{1 + g}\ ;\ If\ i \square g\ then,\ r = \frac{g - i}{1 + i} \tag{9}$$

$$PWF = \frac{(1+r)^N - 1}{r(1+r)^N}, \quad If\ i = g\ then\ PWF = \frac{N}{1+i} \qquad (10)$$

N: is the material lifetime [years]. i: is the interest rate, g is the inflation rate, r: is the actual interest rate

The annual energy cost for the unit area for heating ($C_{A,H}$) and cooling ($C_{A,C}$) are given by the following equations (11),(12) [4]:

$$C_{A,H} = \frac{86400\, HDD\, C_e}{(R_{tw} + R_{ins})\, H_u\, \eta} = \frac{E_H\, C_e}{H_u\, \eta} \qquad (11)$$

$$C_{A,C} = \frac{86400\, CDD\, C_e}{(R_{tw} + R_{ins})\, COP} = E_C\, C_e \qquad (12)$$

Hu: is the lower heating value, i: is the interest rate, g: is the inflation rate, r: is the actual interest rate.

The cost of exterior wall insulation is a function of its thickness. The overall cost of insulation including installation cost ($C_{t,\,ins}$) is calculated as following equation (13) [10]:

$$C_{t,ins} = C_{ins}\, x + C_{inst} \qquad (13)$$

Cins: is the cost of insulation material per unit volume. *Cinst:* is the installation cost.

According to the life cycle cost analysis, the total heating cost of an insulated building is determined as follows (14):

$$C_{t,H} = C_{A,H}\, PWF + C_{t,ins} \qquad (14)$$

The total cooling cost of an insulated building is estimated as follows equation (15):

$$C_{t,C} = C_{A,C}\,PWF + C_{t,ins} \qquad (15)$$

Finally, according to the life cycle cost analysis, the total heating and cooling cost of an insulated building is calculated as follows:

$$C_{t,H,C} = C_{A,H}\,PWF + C_{A,C}\,PWF + C_{t,ins} \qquad (16)$$

The calculation below is used to calculate the optimal insulation thickness for reducing overall heating /cooling costs. [13]

$$X_{opt,H} = 293.94\left(\frac{HDD\; C\; PWF\; k}{H_u\; C\; \eta\; C_{ins}}\right)^{1/2} - k_{ins}\,R_{tw} \qquad (17)$$

$$X_{opt,C} = 293.94\left(\frac{CDD\; C\; PWF\; k}{C_{ins}\; COP}\right)^{1/2} - k_{ins}\,R_{tw} \qquad (18)$$

The calculation below is used to calculate the optimal insulation thickness for minimizing total heating and cooling costs.

$$X_{opt,HC} = 293.94\left(\frac{CDD\; C\; PWF\; k}{C_{ins}\; COP} + \frac{HDD\; C\; PWF\; k}{H_u\; C\; \eta\; C_{ins}}\right)^{1/2} - k_{ins}\,R_{tw} \qquad (19)$$

The annual total net saving energy amount ($\$/m^2$) may be calculated as follows [14]

$$E_S = E_{nins} - E_{ins} \qquad (20)$$

E_{nins}: is the energy consumption at the non-insulation conditions (J/m). E_{ins}: is the energy consumption at insulation conditions (J/m).

The difference between the saved energy cost throughout the lifetime of insulation and the insulating cost is used to determine the life cycle savings (LCS). The total lifecycle savings may be expressed as eq.21 [15]:

$$LCS = PWF \cdot C_e \cdot \left[\left(\frac{1}{R_{tw}} - \frac{1}{R_{tw} + \frac{X_{ins}}{K_{ins}}} \right) 0.024 \cdot HDD + \frac{\left(\frac{1}{R_{tw}} - \frac{1}{R_{tw} + \frac{X_{ins}}{K_{ins}}} \right) 0.024 \cdot CDD}{COP} \right] - C_{ins} \qquad (21)$$

The payback period (years) for the insulation material can be calculated by applying eq. (22) [15]:

$$PP = \begin{cases} \dfrac{\ln \left[\dfrac{C_{ins} \cdot \left(k_{ins} R^2_{tw} + R_{tw} \cdot x_{ins} \right) (g - i)}{0.024 \cdot c_e \cdot \left(HDD + \dfrac{CDD}{COP} \right)} \right]}{\ln \left(\dfrac{1+i}{1+g} \right)} & ; i \neq g \\[2ex] \dfrac{C_{ins} \left(k_{ins} R^2_{tw} + \right) (1+i)}{0.024 \cdot c_e \cdot \left(HDD + \dfrac{CDD}{COP} \right)} & ; i = g \end{cases} \qquad (22)$$

In Table 1, the large quantity of CDDs indicates that cooling demand outnumbers heat demand. The number of cooling degree days is over six times that of HDDs. As a result, cooling consumes the majority of the energy consumed.

Table 1. Parameters of determining the optimum insulation thickness in different climate zones in Egypt

Location parameters

City	Climate zone	Latitude	Longitude	CDD_{18}	HDD_{18}
Cairo	Cairo and Delta zone	31.41E	30.11N	2299.3	309.9
Alexandria	North coast zone	29.95E	31.18N	1729.5	391.3
Aswan	the Southern zone	31.61E	22.38N	3582.9	243.2
Assiut	Southern Upper Egypt zone	31.01E	27.04N	2529	552.2

Physical characteristics of exterior wall materials parameters

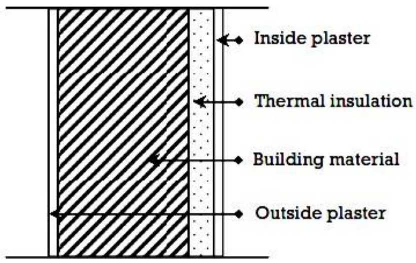


Figure 3. Wall section for the most commonly used external wall structure in Egypt

Wall material type	Thickness x (m)	Thermal conductivity k (W/mK)	Thermal resistance R (m^2K/W)
Internal plaster	0.02	0.87	0.022
clay bricks	0.25	0.711	0.351
Insulation layer			
External plaster	0.02	0.87	0.022
Inside Air Resistance	-	-	0.130
Outside Air Resistance	-	-	0.040
Total resistance (R_{wt})	-	-	0.567
the overall heat transfer (U)	1.761		

Properties of insulation materials parameters

Insulation type	Thermal conductivity k_{ins} (W/mK)	Cost of insulation, C_{ins} ($\$/m^3$)	Installation cost (labor & equipment)
1-Traditional Insulations			
Extruded polystyrene (XPS)	0.031	79	The cost of installation was considered to be the same for all studied thermal insulation materials kinds,
Expanded polystyrene (EPS)	0.039	53	
Glass wool (GW)	0.040	27	
Polyurethane(PUR)	0.024	118	

Polyisocyanurate(PIR)	0.023	105	hence it was not considered in the calculations.
2-Nano Insulations			
Vacuum insulated panels	0.004	2314	
Aerogel	0.014	1500	
Fuel parameters			
Fuel type	Electricity		
Price ($/kWh)	0.073		
lower heating value(Hu) J/kWh	3.599 *10^6		
The efficiency of the heating system (h)	0.99		
COP	2.5		
Economic parameters			
Interest rate (i)%	8.25		
Inflation rate (g)%	5.556		
Material Lifetime (N)	25		
Present worth factor (PWF)	18.32		

Sources: [16,17]

- Central Bank of Egypt, https://www.cbe.org.eg/en/EconomicResearch/Statistics/Pages/InflationRates.aspx (last accessed 9/1/2022).
- Global petrol prices, Egypt electricity prices, https://www.globalpetrolprices.com/Egypt/electricity_prices/ (last accessed 9/1/2022).

5. The placement and the installation methods of thermal insulation on the external walls

Insulation can be applied on the inside, outside, or in between the walls (sandwich wall) as shown in Figure 4. From the standpoint of thermal resistance, the position of thermal insulation in relation to mass is unimportant. Regardless of where it is in the assembly, each building component will have the same total thermal resistance for the same insulation type and thickness. Other thermal and practical advantages and disadvantages issues for insulation location include the following:

1. The placement of insulation on the inside

- Protected from the outside environment and harm by bulk. The structure, on the other hand, will be closer to the ambient temperature.
- The importance of expansion and contraction increases. Because of the unavoidable crossings and penetrations, there will be more 'thermal bridges.' As a result, all penetrations and joints must be sealed firmly.
- Potential heating advantages from the bulk of the building structure are minimised.

2. The placement of insulation on outside
   - Support for convective cooling in the summer and passive solar heating in the winter.
   - Allows extra solar and internal gains to be stored in bulk. However, because to exposure to the outside environment and damaging impacts, there is reduced durability.
3. The placement of insulation in the middle
   - Provides an even distribution of insulation throughout the component.
   - Allows for a trade-off between the advantages of the two layouts.
   - It can be used in freshly constructed structures, but it is neither practicable nor cost-effective in existing structures. [18]

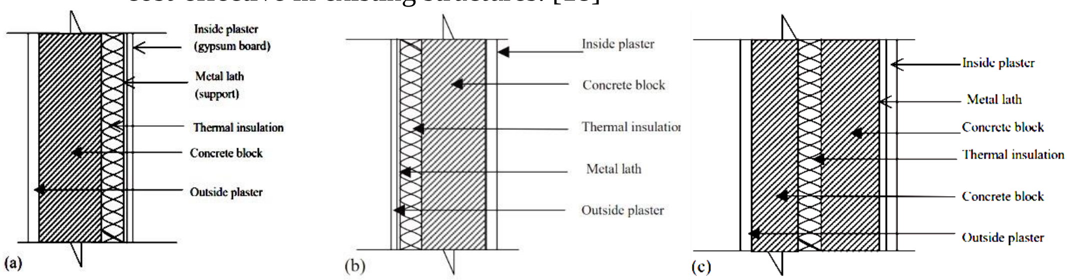
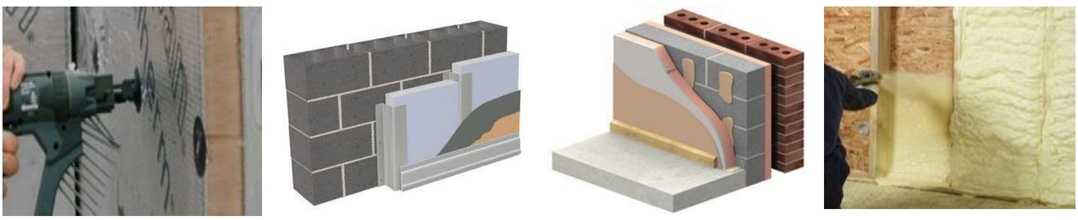


Figure 4. Methods for placing wall insulation. (a) the placement of insulation inside mass, (b) the placement of insulation outside mass, (c) the placement of insulation in the middle.

Insulation installation is determined by the kind of building, the insulating material used, and the position of the insulating material within the structure. There are a variety of ways to install the insulating material as shown in Figure 5, with the most popular techniques for concrete constructions being summarized below:

1. Nails: A special gun is used to drive nails into the concrete surface.
   The nail should be long enough to penetrate the thickness of the insulation (usually stiff foam) and secure it to the concrete surface. Washers are also used to secure metal lath to the insulation, allowing plastering to be applied over it. Additional metal siding or stucco coating is utilized on top of the metal lath for outdoor surface applications to protect the insulation from the elements.

2. Adhesives: for attaching stiff insulation boards to the wall surface (full adhesive bed is recommended). It is necessary to ensure that the surface is clean and that the adhesive used is compatible with the insulation being utilised.
3. Furring (Z-channels, T-channel metal furring, or wood furring): is used to attach two insulating stiff boards together. To keep the insulation in place, the furring can be stapled or fixed into the concrete.
4. Foamed-in-place: such as polyurethane or polyisocyanurate insulations that may conform to the contour of the building to which it is applied. This is appropriate for surfaces with uneven shapes. The thickness and R-value of foamed-in-place insulation, on the other hand, are difficult to manage.
5. Insulated concrete blocks with poured-in, blown-in, or foamed-in insulation in the cores, or concrete blocks containing insulating material in the concrete mix.
6. Insulating concrete is made up of rigid insulating foam that is inserted in the core (sandwich panel), or on one or both sides of the concrete panel and kept in place with plastic or steel rods and ties. This technique provides better and more consistent insulation, a tighter envelope, and quicker construction. However, it is more expensive than other building methods. [18]



(a) (b) (c) (d)

Figure 5. Methods for installing wall insulation. (a) Fixing insulation with nails using gun, (b) Fixing insulation using furring Z-channels, (c) Fixing insulation with adhesives, (d) foamed-in-place.

6. Results and Discussion

While increasing insulation thickness raises the original investment cost, it lowers the operational expenditures. In this study, optimal insulation thicknesses for exterior walls were computed using heating and cooling degree-day values for buildings that were only cooled, or both heated and cooled. For four cities in Egypt, the calculations were done for five traditional insulants and two nano insulants.

Table 2. illustrates the optimal thickness x_{opt} in the case of cooling only and heating & cooling demand, energy saving, life cycle saving (LCS), and payback period for some traditional and nano insulating materials for office buildings during a 25-year life cycle in Cairo, Alexandria, Aswan and Assiut located in Egypt.

	The case of cooled but not heated	**The case of both heated and cooled**

Insulation type	$X_{opt,C}$ (m)	Energy saving (kwh/m^2)	L.C.C ($\$/m^2$)	L.C.S ($\$/m^2$)	Payback period (Years)	$X_{opt,C.H}$ (m)	Energy saving (kwh/m^2)	L.C.C ($\$/m^2$)	L.C.S ($\$/m^2$)	Payback period (Years)
Cairo										
Extruded polystyrene (XPS)	0.09	32.529	15.62	36.407	3.07	0.107	44.76	18.30	51.43	2.67
Expanded polystyrene (EPS)	0.125	33.03	14.45	37.57	2.83	0.149	45.38	16.92	52.82	2.46
Glass wool (GW)	0.186	34.66	10.68	41.34	2.07	0.219	47.23	12.46	57.26	1.79
Polyurethane(PUR)	0.064	32.06	16.68	35.34	3.29	0.076	44.20	19.57	50.16	2.86
Polyisocyanurate (PIR)	0.067	32.55	15.52	36.51	3.05	0.08	44.81	18.18	51.55	2.65
Vacuum insulated panels (VIP)	0.005	26.74	27.82	24.21	5.77	0.006	37.81	33.03	36.71	5.03
Aerogel	0.009	20.65	37.89	14.13	8.41	0.011	30.26	45.75	23.99	7.36
Alexandria										
Extruded polystyrene (XPS)	0.076	23.75	13.36	25.77	3.52	0.099	39.03	17.10	44.39	2.84
Expanded polystyrene (EPS)	0.106	24.19	12.38	26.75	3.25	0.138	39.61	15.81	45.68	2.61
Glass wool (GW)	0.159	25.59	9.18	29.95	2.37	0.204	41.36	11.67	49.83	1.91
Polyurethane(PUR)	0.054	23.36	14.25	24.88	3.78	0.054	23.36	18.28	24.88	3.78
Polyisocyanurate (PIR)	0.057	23.80	13.28	25.85	3.50	0.074	39.07	16.99	44.50	2.82
Vacuum insulated panels (VIP)	0.004	18.66	23.42	15.70	6.59	0.006	33.35	30.76	30.73	5.34
Aerogel	0.006	12.58	31.29	7.83	9.55	0.01	30.05	42.23	16.29	7.79
Aswan										
Extruded polystyrene (XPS)	0.117	52.68	19.84	61.23	2.48	0.128	62.41	21.59	73.38	2.29
Expanded polystyrene (EPS)	0.162	53.31	18.33	62.74	2.29	0.177	63.09	19.94	75.03	2.12
Glass wool (GW)	0.238	55.32	13.49	67.58	1.66	0.26	65.28	14.65	80.32	1.54
Polyurethane(PUR)	0.083	52.05	21.22	59.85	2.66	0.091	61.74	23.10	71.86	2.47
Polyisocyanurate (PIR)	0.087	52.69	19.71	61.36	2.46	0.096	62.48	21.45	73.52	2.28
Vacuum insulated panels (VIP)	0.007	45.76	36.05	45.02	4.69	0.007	53.60	39.45	55.51	4.35
Aerogel	0.013	37.61	50.25	30.81	6.87	0.014	45.28	55.38	39.58	6.39
Assiut										
Extruded polystyrene (XPS)	0.095	36.09	16.45	40.77	2.94	0.123	58.05	20.83	67.95	2.37
Expanded polystyrene (EPS)	0.132	36.63	15.21	42.01	2.71	0.17	58.71	19.24	69.54	2.19
Glass wool (GW)	0.197	38.35	11.23	45.99	1.97	0.251	60.85	14.14	74.63	1.59
Polyurethane(PUR)	0.068	35.63	17.57	39.65	3.15	0.088	57.46	22.28	66.49	2.55
Polyisocyanurate (PIR)	0.071	36.13	16.34	40.88	2.92	0.092	58.11	20.69	68.08	2.36

Vacuum insulated panels (VIP)	0.005	29.42	29.44	27.78	5.52	0.007	50.11	37.94	50.83	4.49
Aerogel	0.009	22.72	40.33	16.89	8.05	0.014	42.33	53.14	35.63	6.59

As seen in table 2, glass wool (GW) is the optimum insulation material in all given locations with optimum thickness varies between 18.6 cm and 23.8cm, but these thicknesses are very large which will reduce the used areas and rental prices of buildings. Therefore, space savings and their rent costs must be taken into account when calculating the savings in life cycle costs and payback period to determine the best economical insulation material and its thickness.

Table 3 presented the rental costs of four selected cities in Egypt (Cairo - AlexandriaAswan-Assiut) for office buildings.

Table 3. Rent cost data of selected cities for office buildings *(1 USD = 15.7 EGP)*

City	**Rent cost ($\$/m^2$.year)**
Cairo	540
Alexandria	350
Aswan	230
Assiut	105

Source: https://www.propertyfinder.eg/ (last accessed 30/1/2022). https://www.semsarmasr.com/ (last accessed 30/1/2022). https://www.olx.com.eg/(last accessed 30/1/2022). https://aqarmap.com.eg/(last accessed 30/1/2022).

By comparing the use of conventional glass wool insulation material optimum thickness with the use of other nano and traditional insulation materials when considering space savings to determine the optimum insulation and its thickness in table 4.

Table 4. A comparative analysis of area-saving, life cycle savings between glass wool insulation optimum thickness in each case with nano and traditional insulation materials when space savings are taken into account for four selected locations in Egypt.

	The case of cooled but not heated			The case of both heated and cooled		
Insulation type	Area saving (m^2)	LCS ($\$/m^2$)	Payback period (Years)	Area saving (m^2)	LCS ($\$/m^2$)	Payback period (Years)
Cairo						
Extruded polystyrene (XPS)	126.311	162.718	0.687	147.363	198.793	0.691

Expanded polystyrene (EPS)	80.260	117.830	0.902	92.102	144.922	0.897
Glass wool (GW)	0.000	41.340	2.070	0.000	57.260	1.790
Polyurethane (PUR)	160.521	195.861	0.594	188.151	238.311	0.602
Polyisocyanurate (PIR)	156.573	193.083	0.577	182.888	234.438	0.583
Vacuum insulated panels (VIP)	238.149	262.359	0.532	280.253	316.963	0.583
Aerogel	232.886	247.016	0.481	273.674	297.664	0.593
Alexandria						
Extruded polystyrene (XPS)	70.782	96.552	0.939	89.544	133.934	0.941
Expanded polystyrene (EPS)	45.198	71.948	1.208	56.285	101.965	1.169
Glass wool (GW)	0.000	29.950	2.370	0.000	49.830	1.910
Polyurethane(PUR)	89.544	114.424	0.822	127.919	152.799	0.615
Polyisocyanurate (PIR)	86.985	112.835	0.802	110.863	155.363	0.808
Vacuum insulated panels (VIP)	132.183	147.883	0.700	168.854	199.584	0.822
Aerogel	130.478	138.308	0.541	165.442	181.732	0.698
Aswan						
Extruded polystyrene (XPS)	67.809	129.039	1.177	73.974	147.354	1.140
Expanded polystyrene (EPS)	42.591	105.331	1.364	46.514	121.544	1.309
Glass wool (GW)	0.000	67.580	1.660	0.000	80.320	1.540
Polyurethane (PUR)	86.863	146.713	1.085	94.709	166.569	1.066
Polyisocyanurate (PIR)	84.622	145.982	1.034	91.907	165.427	1.013
Vacuum insulated panels (VIP)	129.454	174.474	1.210	141.783	197.293	1.224
Aerogel	126.092	156.902	1.349	137.861	177.441	1.425
Assiut						
Extruded polystyrene (XPS)	26.096	66.866	1.793	32.747	100.697	1.599
Expanded polystyrene (EPS)	16.630	58.640	1.941	20.723	90.263	1.687
Glass wool (GW)	0.000	45.990	1.970	0.000	74.630	1.590
Polyurethane (PUR)	33.003	72.653	1.719	41.702	108.192	1.567

Polyisocyanurate (PIR)	32.236	73.116	1.633	40.678	108.758	1.477
Vacuum insulated panels (VIP)	49.121	76.901	1.994	62.425	113.255	2.015
Aerogel	48.098	64.988	2.092	60.634	96.264	2.439

7. Conclusions

Lately, there has been a lot of research published on determining the optimum thermal insulation thickness in various regions by analyzing various insulation materials. In this paper, the optimum insulation thickness for the external wall surface of office buildings for four selected cities namely Cairo, Alexandria, Aswan, and Assiut located in different climatic regions in Egypt was calculated by using the heating degree days and heating /cooling degree days method together with the life cycle saving analysis (LCS), energy-saving, and payback period. Extruded polystyrene (XPS), expanded polystyrene (EPS), glass wool (GW), rock wool, polyurethane and 2 nano insulation materials (vacuum insulated panels and aerogel) were used as insulation materials for office buildings. The main findings to be drawn from this study are:

- Raising insulation thickness saves energy until it reaches its optimal thickness, after that, it starts wasting money.
- Glass wool traditional insulation is considered the optimum thermal insulation in all of the selected locations, but because of its considerable thickness, it decreases available spaces, which reduces rental costs, making it uneconomical, thus the saving spaces were taken into consideration. When taking into account the costs of renting the saved space, the research showed the following results:
  - In Cairo, the economical insulation for the only cooled state is vacuum insulated panels nano insulation with thickness 0.005 m, or aerogel with thickness 0.009 m, which gives the quickest return on investment. For both heated and cooled case, the optimum insulation is vacuum insulated panels with thickness 0.006 m.
  - In Alexandria, the most cost-effective insulation for only cooled states is vacuum insulated panels nano insulation with a thickness of 0.004 m, which has the maximum life cycle saving, or aerogel with a thickness of 0.006 m, which provides the quickest payback. For both heated and cooled states vacuum insulated panels with a thickness of 0.006 m, which has the maximum life cycle saving, or polyurethane (PUR) with a thickness of 0.076, which has the fastest payback period, are the optimum insulation types.

- In Aswan, the most cost-effective insulation option in all cases is vacuum insulated panels nano insulation with a thickness of 0.007 m, or Polyisocyanurate (PIR) with a thickness of 0.087 m cooling case, or 0.096 m for both heated and cooled case.

- In Assiut, the economical insulation for all conditions is vacuum insulated panels with thickness 0.005 m for only cooled condition and 0.007 m for both heated and cooled condition, or Polyisocyanurate (PIR) with thickness 0.071 m for only cooled condition and 0.092 m for both heated and cooled condition.

- The research finally discussed the ways of placing and installing insulation materials in buildings.

Future works

Design a software application to make it easier to compute the optimum economic thermal insulation thickness by resolving the difficulty of calculating equations over and over again and considering the effects of installing insulation materials in buildings on the environment.

Nomenclature

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C Cost, $ U heat transfer coefficient, $W/m^2.°k$
CDD cooling degree-day, °C- day VIP Vacuum insulation panel
COP Cooling performance coefficient X material thickness, m
DD degree-day, °C- day ***Subscripts***
E annual energy consumption per unit area of A, C Annual, cooling
external wall J/m^2-year
EPS Expanded polystyrene A, H Annual, Heating
g inflation rate, % b base GW Glass wool C Cooling
h surface heat transfer coefficient, W/m^2K e Electricity
HDD Heating degree-day, °C- day H Heating
Hu Lower heating value, J/ kg, J/ m^3, J /kW h H, C Heating and Cooling
i Interest rate, % i inside
k coefficient of thermal conductivity, W/m. °k ins m^3 of Insulation
LCC life cycle cost inst installation
LCS life cycle saving nins non-insulation N Lifetime of
material, year o outside n The day's total number,days opt
Optimal thickness OIT optimal insulation thickness r
Actual interest rate
PP payback period, year S Saving
PIR Polyisocyanurate t total
PUR Expanded polyurethane w Wall
PWF present worth factor tw total wall excluding insulation material q heat transfer per unit
area of external wall, W/ m^2
R thermal resistance, $m^2.k/W$ ***Greek symbols***
T Temperature η heating system efficiency, %

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