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Evaluating carbon payback time by optimizing insulation materials for different orientations: A cradle-to-gate life cycle assessment (LCA)

Abstract:

The EU aims to reduce greenhouse gases emissions by 80%–95% compared to 1990 levels by 2050. Therefore the life cycle concept has gained widespread acceptance as a model for evaluating the environmental impact of goods and services. This study, the optimal thickness of various insulation materials for external walls, roofs, and floors using a Mediterranean climate zone's hot summers and mild winters for a hypothetical residential building for four cardinal orientations was determined. The criteria for determining the optimum thickness represent a turning point in terms of cooling energy consumption (electricity). The optimum thickness of nine different types of insulation materials was defined using the aforementioned approach. These materials included aerogel, polyisocyanurate (PIR), polyurethane (PUR), extruded polystyrene (XPS), expanded polystyrene (EPS), phenolic foam (PF), cellulose fiber (cellulose), mineral wool (MW), and glass wool (GW). The purpose of this paper is to calculate the carbon payback time (CPBT) using the cradle to gate life cycle assessment (LCA) method by considering the global warming potential (GWP) of insulation materials at their optimum thickness. The CPBT is calculated as the ratio of the total building's GWP to the GWP of savings from cooling and heating (electricity and natural gas). The results indicated that when evaluating the average CPBT for four cardinal orientations (FCO), aerogel has the longest carbon payback time of 2.34 years, and GW has the shortest CPBT of just 0.09 years. Aside from cost payback time, the findings of this study provide a new perspective on selecting appropriate thermal insulation.

Keywords: Orientation, Optimum insulation thickness, Global warming potential, Life cycle assessment, Cradle to gate, Carbon payback time

PUR	polyurethane	GWP	global warming potential
PIR	polyisocyanurate	CPBT	carbon payback time
XPS	extruded polystyrene	FCO	four cardinal orientation
EPS	expanded polystyrene	EC	energy consumption
Pf	phenolic foam	TIM	thermal insulation material
Cellulose	cellulose fiber	λ	thermal conductivity
MW	mineral wool	LCA	life cycle assessment
GW	glass wool	OIT	optimum insulation thickness

1. Introduction:

Concerns have been raised about sustainable development due to a considerable increase in energy consumption (EC) and greengouse gases (GHG) emissions as a result of population growth and improved quality of life (1). Industry, building (residential/commercial), transportation, and agriculture are the four sectors that contribute the most to EC (2).

According to the United Nations Environment Program, buildings use around 40% of global energy, 25% of global water, and 40% of global resources. Buildings also account for about 1/3 of worldwide greenhouse gas emissions (3). Furthermore, the International Energy Agency forecasted a 50 % rise in global energy use by 2030. In reality, with regard to the expansion of new structures and a lack of energy-efficient technology and sustainable development plans, the rising energy demand is expected to be greater in developing countries and fast-growing cities (4). By 2050, because of many countries' stimulus plans, renewable energy projects have become feasible energy-generating options (5)

Buildings may reduce energy usage by thermally insulating the envelopes to reduce heating and cooling loads (6). Hence, regardless of the kind of structure, thermal insulation material (TIM) is a fundamental construction ingredient for maintaining sustainability and occupant comfort. TIM plays an essential role and is a reasonable first step toward reducing the levels of energy necessary to maintain a comfortable interior temperature and, as a result, achieve energy efficiency (2). All TIM used in building applications have low thermal conductivity (λ), typically less than 0.1 W/mK (7)(8). By using high-performance TIM, heat losses may be greatly reduced throughout the building's walls and roof, hence raising the building's energy efficiency. Since the quantity of material required to manufacture TIM grows as the insulation thickness in the building's envelope increases, the environmental effect and expense of producing insulation materials are expected to rise. As a result, efforts should be concentrated on optimizing the thickness of insulating materials in order to reduce the EC of the building. (9). Typically the thickness of the insulation material is determined by the average ambient temperature of the location, the insulation materials (λ), and the cost (10). Increased insulation thickness reduces energy consumption, CO_2 emission, and expenses connected with energy consumption (11). The optimal position and distribution of the insulating material layer are not the only factors that contribute to the reduction of heat losses in a building's construction. As a result, externally insulated walls with the optimum insulation thicknesses (OIT) allow for considerable savings in annual energy consumption (E_{An}) of heating and air conditioning systems (12). Conclusions are reached showing a 68–89% reduction in the annual fuel consumption and emissions by the application of an OIT, depending on the type of insulation (13). The effect of insulation thickness on fuel consumption, payback period, and pollutant emissions for different insulations and fuels was studied, and a 50-54% reduction in CO_2 emissions was reported for extruded polystyrene foam (14).

The life cycle concept has gained widespread acceptance as a model for evaluating the environmental impact of goods and services. As a result, LCA is often used to refer to the climate change mitigation advantages of alternative goods and services (15)(16). When considering the environmental benefits associated with an insulator's life cycle, it is necessary to conduct proper evaluations to ensure that the impacts associated with the phases of production and disposal are offset by the benefits associated with the use phase, such as energy and carbon dioxide (CO_2) emission savings (17). CO_2 will cause the greenhouse effect and lead to climate warming (18)(19).

The majority of previous research has concentrated on determining the OIT in terms of LCA costing and payback period. The new aerogel super insulation of humid subtropical climate was investigated as a model, establishing the entire LCA model to exploit emission The economic optimum insulation thickness for various insulating materials was found for external walls with varied topologies and orientations, taking into account the heating and cooling time, as well as the wind speed and direction in Cyprus. Finally, The OIT determined for any wall topology, and orientation ranges between 4.25 cm and 15.5 cm, with a payback period of 5.47 years to 12.11 years (20). Determining the optimal PUR, EPS, and Rockwool thickness in Morocco through a comprehensive analysis based on energy, environmental, and economic criteria (21). A. Dombayci et al. define the optimal thickness of polystyrene and PUR for the external wall of the housing in the selected province's four distinct temperature zones (22). Based on a multi-objective optimization study, the OIT for four-layer insulation by using twelve typical insulation materials resulted in almost 70% energy savings (23). Based on the amount of energy and the reduction in energy grade in a residential case study in Tiajin, China, a mathematical model was developed to determine the optimal environmental insulation thickness for minimizing the annual total environmental impact. They discovered that GW is more beneficial than EPS and rock wool after evaluating three different types of thermal materials (24). A Chinese college building investigated the life cycle economics perspective of some type of thermal insulation, and the results were saving 21.52%, 3.78%, and 25.34% for heating load, total load, and total cost per unit, respectively (25) Marta Braulio et al. in a life cycle cost methodology determined OIT of building’s envelope, in order to achieve energy demand reduction during the operating phase (26). Another study found a 4 cm insulation thickness for external walls in Iran (27).

Other research examined LCA from an environmental perspective and CPBT, with a greater emphasis on cradle-to-grave assessment in this research. Utilizing LCA analysis to aid in decision-making in order to optimize building design (28). Assess the environmental effect and EC of renewable and non-renewable primary energy in the manufacture of standard thermal insulation materials: XPS and EPS, PUR, expanded cork agglomerate, and expanded lightweight clay aggregates (2). Calculating the energy and CPBT of various retrofit scenarios in a Turin, Italy school building (29). Xinyi Li et al. The whole-life performance of solid wall insulation is evaluated in separation from the diversity of building types found in the pre-1919 Victorian house stock. Eight commercially available insulation materials were investigated (30). An LCA study that compares the environmental impact includes the GWP and the primary energy use, from the material production stage to the building operational phase (50 years) for three hypothetical buildings, a standard residential building, a regular well-insulated building and a building insulated with VIPs (31). Noelia Llantoy et al. Comparative LCA of three distinct insulating materials (PUR, XPS, and MW) was conducted to determine the environmental profile of each material type in the Mediterranean continental climate. The EPS had the highest environmental effect, whereas MW had the best environmental performance (32). And another study has determined that stone wool and EPS are the most impactful materials (33). The examination of the environmental performance of insulation using LCA revealed that cellulose had the best performance of all the insulations (34). Duygu Evin and Aynur Ucar use four different insulation materials to simulate twenty different energy demand scenarios for four distinct climate zones in Turkey, with a GWP indicator based on the LCA (35). A quantitative evaluation of several TIM used in construction was conducted, ranging from the most commonly used to novel, extremely efficient materials (36). Another study is on the environmental impact of construction during the component manufacturing, installation, and transportation phases (33). There are numerous studies examining the effect of different orientations on building energy demand, the current study does not direct much attention to the reasons for the differences in energy consumption due to different orientations.

The purpose of this study is to determine the CPBT for FCO. The following steps are highlighted to reach the ultimate result.

First step is to determine the optimum thickness of a compendium of thermal insulations while taking into account the electricity consumption (EC) turning point for six different K-Values in FCO. Then, these points are used to calculate the energy saving in terms of electricity and gas consumption (GC). The next step is finding GWP of unit Kg of each TIM through a cradle-to-gate LCA, as well as for 1 kWh generation electricity and natural gas production through previous studies. The final step is evaluating the CPBT for four different orientations and identifying the optimum orientation in terms of energy usage and CPBT.

2. Case study:

Valencia city in Spain which has a Mediterranean climate with hot summers and mild winters selected for the location of this study. The multi-family dwelling block, which makes up 43% of the residential stock and was constructed between 1950 and 1980, is the most typical type of Spanish housing stock (37). For this paper a six-floor hypothetical residential building [Fig. 1] with a single dwelling unit on each floor measuring 14.3 m in width and 14.1 m in length and 3 m in height for a floor [Fig.2], as well as a ground floor for parking. The amount of λ mentioned for different wall materials in this article are based on the regulations stipulated in the Código Técnico de la Edificación (CTE) and the data provided in the Catálogo de Elementos Constructivos. The CTE, also known as the Technical Building Code, is a set of regulations and guidelines that govern building design, construction, and habitability in Spain. It establishes requirements for various aspects such as health, safety, energy efficiency, and acoustic performance. The Catálogo de Elementos Constructivos, or Catalog of Construction Elements, provides valuable technical information and values for specific construction solutions in accordance with the CTE (38). The external wall layers are cement plaster, concrete block, thermal insulation, and gypsum from outermost to innermost, respectively, with relevant λ and thickness [Fig.3], and the roof layers [Fig.4] and for the floor [Fig. 5]. For the glazing area, 20 mm thickness with λ=051 W/m K is considered. Other Executive layers are not simulated due to their negligible effect. The total area of the building that requires insulation is 1397 m^2, which includes external walls, the roof, and the first floor that is in contact with an unconditioned area (car parking).

Fig.1. A 3D view of the hypothetic building model

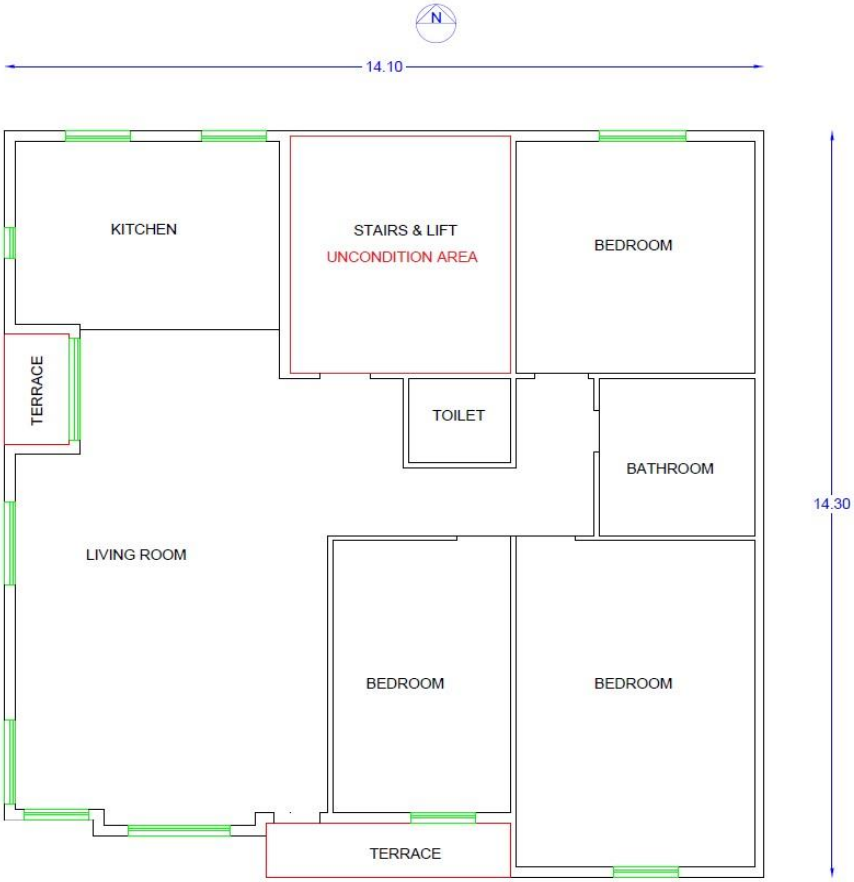


Fig.2. Plan of single housing unit

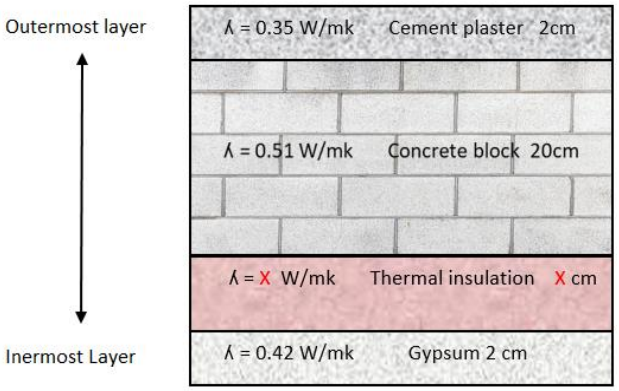


Fig.3. External wall Layers

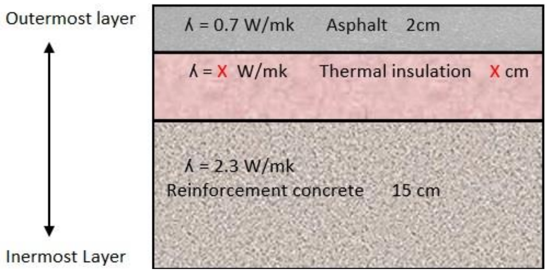


Fig.4. Roof layers

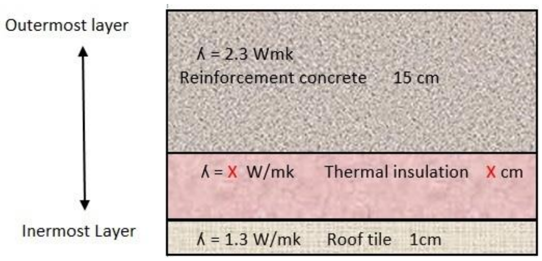


Fig.5. Floor Layers (first floor)

In the current study, natural gas is used for heating and electricity for cooling. Moreover, the heating setpoint temperature is 12-22 °C, and the cooling setpoint temperature is considered 24-28 °C. window-to-wall ratio for north, east, south, and west is 22%, 30%, 15%, and 0 %, respectively.

3. Methodology

3.1 Simulation Process

Natural gas and electricity are used in order to heat and cool the current building, and Design Builder 7.0.0.082 is used for simulation energy in this paper. Nine different types of insulation with different λ are simulated in this section, including EPS, PUR, GW, MW, XPS, PF, PIR, cellulose, and aerogel [Table1]. In the first step, an uninsulated building was simulated to determine the annual energy consumption In the subsequent stage, the aforementioned insulations are simulated by random thicknesses to find the OIT. As long as insulation thickness increases, GC decreases; however, when insulation thickness exceeds the OIT, EC increases again; this point is referred to as the OIT. In this study, it was assumed that the same insulation is used throughout the building and that the OIT is used in the whole part of the building. For each insulation with a related λ, energy savings in the OIT in terms of cooling and heating were obtained. This procedure was repeated for FCO in order to determine which orientation was the most environmentally friendly in terms of EC and CPBT.

3.2. Designing of OIT

The OIT of the model is defined as a parameter set that leads to the least response parameter. This point is usually estimated by solving the least-squares problem of the model parameters. In this study, the model parameters are thickness (X_1) and K-value (X_2) of the TIM, and the response parameter is EC (Y). The model response Y can be estimated by polynomial regression fitting of the input parameters:

$$Y = \sum_{j=0}^{q} \sum_{i=0}^{p} \beta_{i,j} X_1^i X_2^j \tag{39) (1}$$

where $\beta_{i,j}$ are constant coefficients and q and p are orders of the regression function. $\beta_{i,j}$ maybe determined by fitting equation (1) to sample points $[\{X_1, X_2\}_l, Y_l]$, l=1:d where d is the sample size. In this study, the response Y_l for each selected sample point is calculated by Design Builder software. Finally, the OIT for a given λ and also the optimum conductivity for a given thickness can be determined by solving equations (2) and (3), respectively.

$$(\frac{\partial Y}{\partial X_1})_{X_2\ Cons.} = \sum_{j=0}^{q} \sum_{i=1}^{p} (i)(\beta_{i,j} X_1^{i-1} X_2^j) = 0 \tag{2}$$

$$(\frac{\partial Y}{\partial X_2})_{X_1\ Cons.} = \sum_{j=1}^{q} \sum_{i=0}^{p} (j)(\beta_{i,j} X_1^{i} X_2^{j-1}) = 0 \tag{3}$$

3.3. LCA methodology

The LCA is a tool for evaluating and assessing the potential environmental impact of products or processes (40). The research analyzed the cradle-to-gate aspect of LCA and the embodied environmental impact. This method entails only the manufacturing phase (A1-A3), which is extracting raw materials or recycling them (A1), transporting them to the factory (A2), and the manufacturing process (A3). The ISO 14040 standard defines the overall LCA approach, which consists of four iterative phases, including goal and scope definition, inventory analysis, impact assessment, and interpretation (41). The LCA methodology used in this study was based on the impact of GWP, using a cradle-to-gate embodied carbon approach, due to the negligible carbon emissions associated with transporting from gate to site, which accounts for less than 1% of cradle-to-site carbon emissions for 100 km (30).

Calculating the cradle-to-gate GWP of insulation materials involves conducting a life cycle assessment LCA that considers the environmental impacts from raw material extraction to manufacturing. Here are the key steps:

1. Define the Scope: Determine the study boundaries, including the functional unit and stages to be included.
2. Inventory Analysis: Collect data on inputs, outputs, and emissions at each stage of the insulation material's life cycle.
3. Emissions and Impact Assessment: Quantify emissions and resource consumption data, applying impact assessment methods to calculate GWP.
4. Data Quality and Uncertainty Analysis: Evaluate data reliability and address uncertainties or gaps to ensure accurate results.
5. Interpretation and Reporting: Analyze and compare GWP values to identify insulation materials with lower environmental impacts. Present findings transparently, considering limitations and assumptions (42) (43).

The values of Table 1 have been extracted from credible sources and represent a comprehensive overview. Each GWP value in the table corresponds to a specific reference number, which can be found in the reference section of the paper.

In this research, we aim to achieve more precise outcomes by referring to Spain-specific sources as they account for variations in insulation density and global warming potential (GWP) caused by different manufacturing facilities and countries of origin (Table 1), as well as The GWP of electricity consumption in Spain in 2014 was calculated as 0.287 kg CO_2 eq / kWh. This assessment took into account the proportional representation of different energy sources in total electricity production. Specifically, the energy mix comprised of various sources, with 21% coming from nuclear energy, 17% from coal thermal power, 10% from natural gas combined cycle, 16% from hydro energy, 19%

from wind power, 3% from solar energy, 2% from combined heat and power oil, 10% from combined heat and power gas, and 2% from combined heat and power wood (44) It is important to note that in order to accurately determine the exact GWP of natural gas, a comprehensive assessment must be conducted, considering the carbon emissions associated with its extraction, transportation, and. The National Energy Technology Laboratory (NETL) calculated the GWP of natural gas to be 0.506 kg CO_2 eq / kWh (45). Unlike the other study, this one does not use a whole LCA to determine the CPBT; instead, it uses an annual simulation to determine the CPBT for each insulation at the optimum thickness; there are approximately the same energy savings for all of them. Because after a certain level of EC, which is considered OIT in this paper, EC increases again, and the associated GC for all types of insulation is approximately similar. With the total volume or weight of insulation and the associated energy savings, the GWP of each group was compared to determine the CPBT equation (4). Where the CPBT has shown the density (ρ) of insulation in the OIT ,whole insulation area (S) which is 1397 m^2 for this building, annual gas-saving (S_G) and annual electricity saving (S_E).

$$CPBT=\frac{\rho\times OIT\times S\times GWP}{(S_G\times GWP)+(S_E\times GWP)} \qquad (4)$$

Table.1. The characteristics of different insulation materials

Insulation material	ρ (kg/ m3)	ʎ (W/m K)	Cradle-to-gate GWP (kgCO_2eq/kg)	Ref.
EPS	15	0.04	3.29	(30)(46)
PUR	30	0.028	4.26	(30)(46)
GW	12	0.04	1.35	(30)(46)
MW	140	0.038	1.60	(47)(46)
XPS	35	0.03	5.21	(2)(46)
PF	30	0.04	7.02	(48)(46)
PIR	29	0.023	3.68	(49)(46)
Cellulose	48	0.04	1.83	(50)(46)
Aerogel	122	0.017	8.20	(51)(46)

4. Result and discussion:

4.1. Orientation analysis

The orientation of a building with the sun's path can affect its ability to naturally heat the building envelope via solar gain (52). The case study building was simulated in FCO without insulation to determine annual heating and cooling consumption, as well as to establish a benchmark for comparing insulations and defining the OIT in terms of EC.

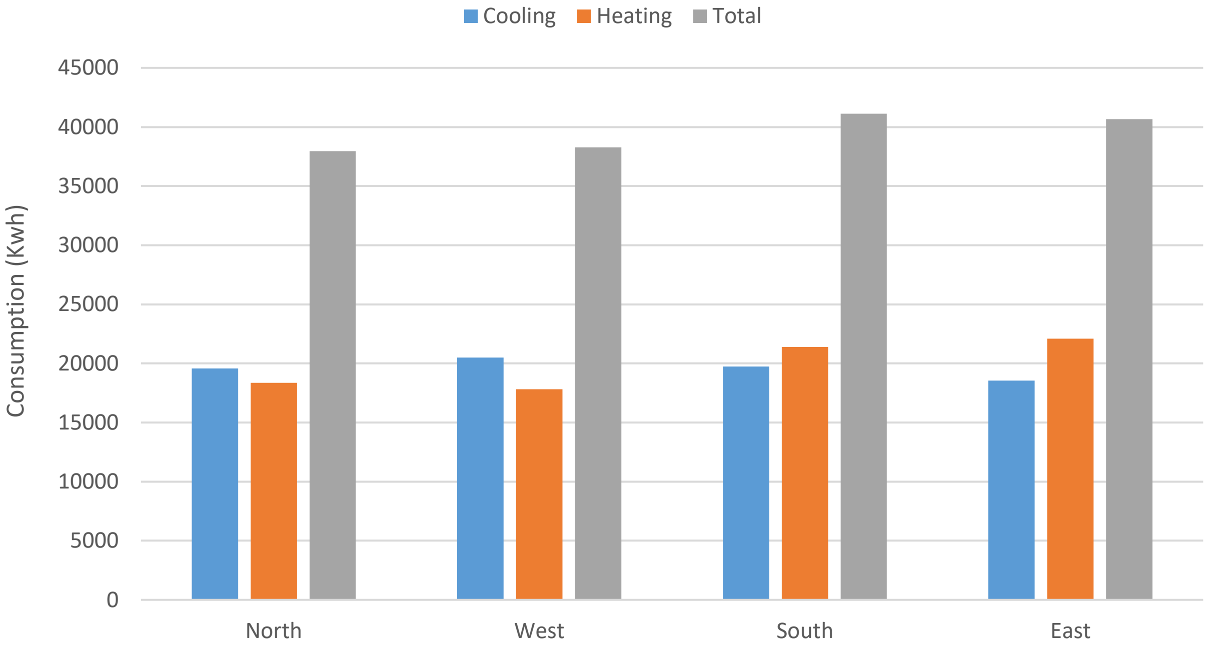
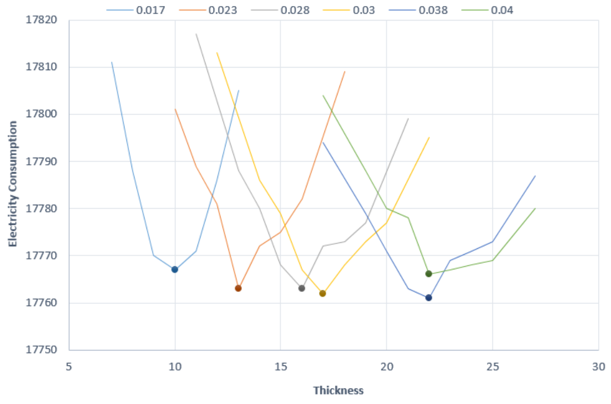


Fig.6. Cooling, heating, and whole E_{An} of cooling and heating without insulation

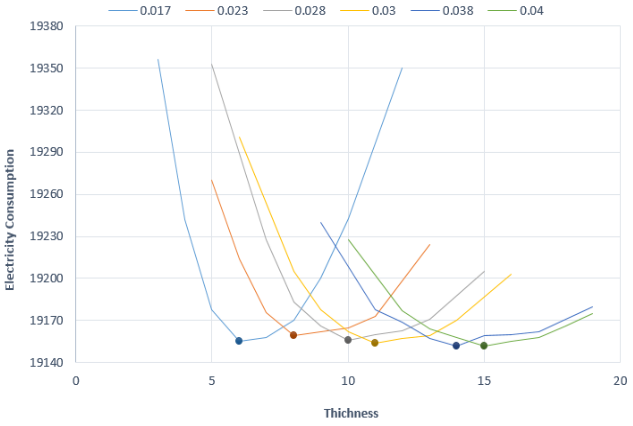
As illustrated in Fig.6, the north direction has the lowest energy demand for cooling and heating at 37945 kwh, followed by the west, east, and finally south at 38293, 40654, and 41132 kwh, respectively. In terms of cooling, the east orientation requires the least energy 18559 kwh, followed by the north 19505 kwh, the south 19744 kwh, and the west 20488 kwh. Related to heating energy demand, the optimal orientation is west, north, south, and east, with 17805, 18355, 21388, and 22095, respectively. Due to a variety of reasons can affect energy consumption for different orientations including the high k-value of wall layers which causes heat island in the summer (53), which a single reason is a subject of several studies this paper is not going to discuss it. As well as the goal of the current paper is not to focus on the reasons for different energy consumption for different orientations. According to the above information, a thicker insulation layer at the optimum point is expected for the east orientation due to the highest energy demand in this direction.

4.2. OIT for different orientation

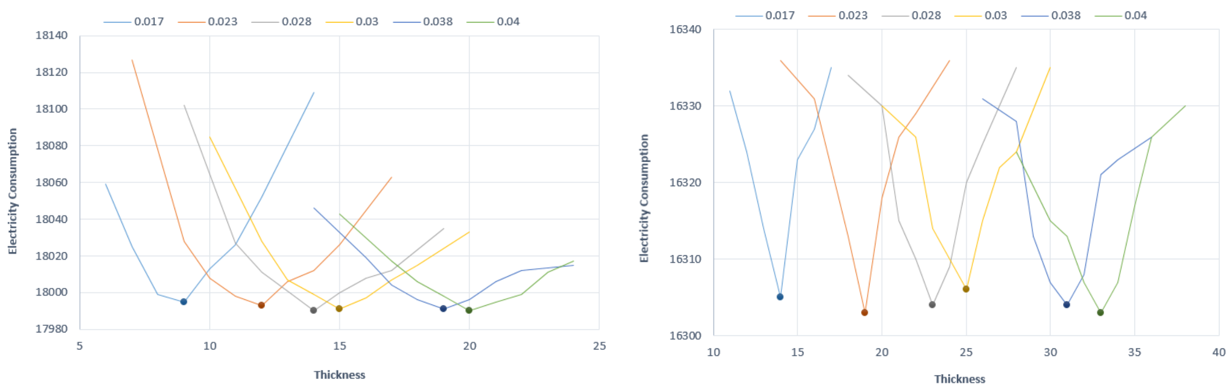
The OIT for each insulation was calculated using the associated λ, as well as the optimum thickness and related EC for cooling for six different λ: 0.017, 0.023, 0.028, 0.03, 0.038, and 0.04 (W/(m·K)). The remaining three insulations have the same λ (0.04) as those mentioned. As indicated in [Fig.7], OIT and associated electricity consumption for the north orientation, as well as for the west, south, and east orientations, the optimum thickness of each insulation is at the same level of EC. For instance, when the λ is 0.017 W/(mK), electricity consumption increases significantly in the thicknesses before and after the optimum thickness, whereas when the λ is 0.04 W/(mK), increasing electricity in those thicknesses before and after the OIT is not intensive, particularly after that. The impact of insulation on overheating can vary depending on the influence of other factors, leading to both decreases and increases in overheating(54). As previously stated, the building is located in a hot summer climate zone, which clarifies why there is no remarkable energy saving, as the building requires more energy for cooling (55).



North



West



South

East

Fig.7. OIT for six different λ in FCO and related EC

4.3. Result of polynomial regression fitting

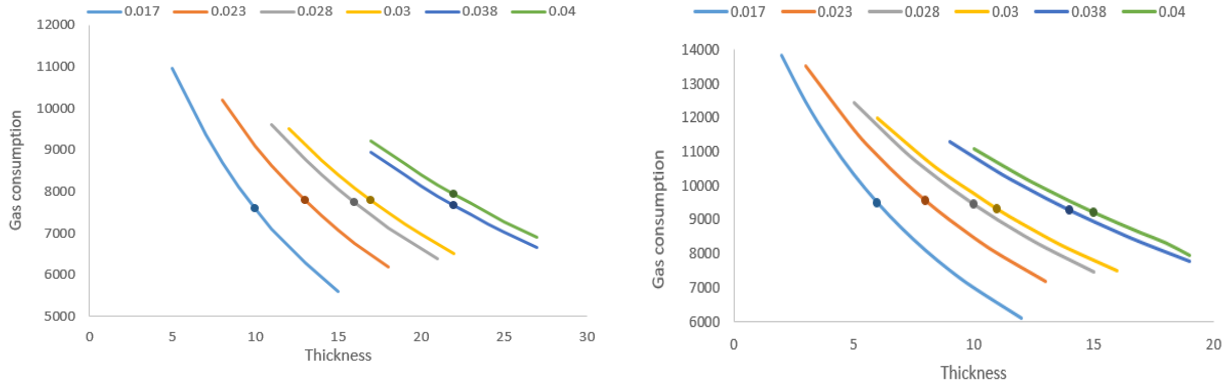
In [Table.2], the results for OIT determined using polynomial regression fitting have been compared to those extracted from Design Builder software in the north orientation. the proposed methodology can simulate the optimum point with high precision (±1 mm)

Table.2. Comparing OIT calculating by polynomial regression method and Design Builder software

λ (W/(m·K))	0.017	0.023	0.028	0.03	0.038	0.04
Polynomial regression fitting (mm)	11	14	17	18	22	23
Design builder (mm)	10	13	16	17	22	2

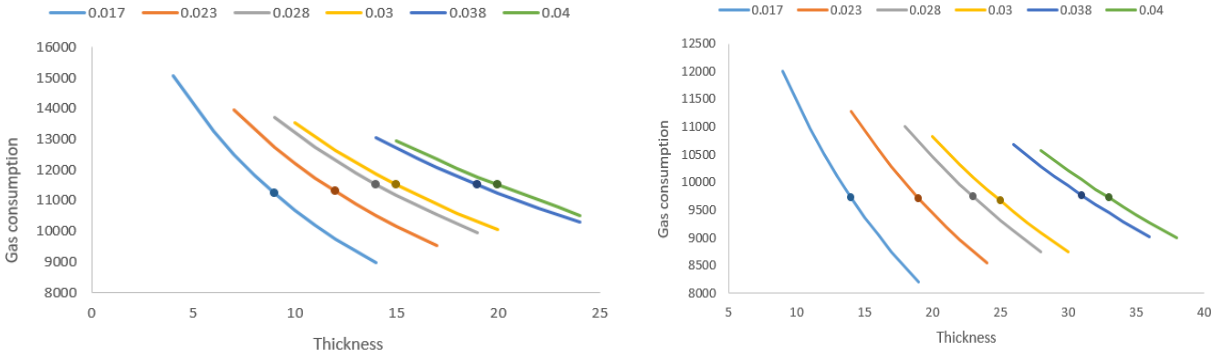
4.4. Gas consumption of four cardinal orientation

The cumulative annual heating load index and the thickness of the insulation layer per unit area of the building have a negative linear relationship, which means that the cumulative annual heating load index decreases linearly as the insulation layer thickness increases(25). Additionally, GC for the above-mentioned λ is depicted in [Fig.8] for FCO. Thus the point in the charts indicates GC at the optimum thickness. As illustrated in the preceding figures, unlike electricity, GC decreases linearly with increasing thickness. Unlike the cooling, all orientations follow the same pattern versus thickness variable, a steeper slope for reducing and increasing for lower λ. Furthermore, the highest energy savings in the optimum thickness are found in the east orientation at 36%, the north at 33%, the south at 29%, and the west at 26% [Fig.9]. The higher energy savings percentage equates to a higher demand for heating energy for the related orientation, as well as a thicker layer of insulation, in that order.



North

West



South

East

Fig.8. GC for FCO in OIT

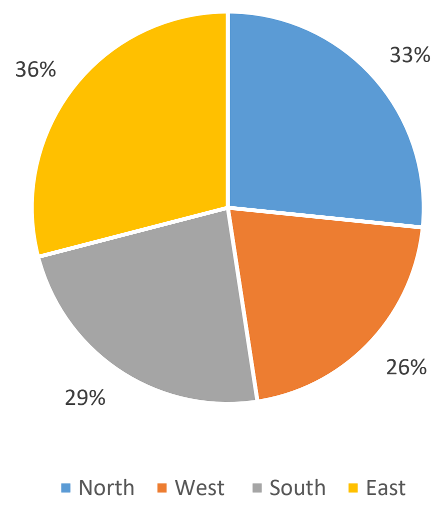


Fig.9. Saving energy for FCO in OIT

4.5 Calculating CPBT

This study employs cradle–to–gate GWP data obtained from reputable sources such as the inventory of carbon energy databases, journal articles, and environmental product declaration. The concept of CPBT measured in years refers to the duration required for a system to offset its initial environmental impact over the entire lifespan [52].The optimum thickness for all orientations, the CPBT of insulation is defined as the weight of all insulation required for the building multiplied by the relevant GWP, and the GWP of energy savings from cooling and heating in the OIT. The findings presented in [Table 3] indicate that the insulation rankings are consistent across different orientations. For the north orientation, aerogel has the longest CPBT with 2.35 years, followed by MW with 1.19 years, PF with 1.1 years, XPS with 0.73 years, PUR with 0.49 years, Cellulose with 0.46 years, PIR with 0.33 years, EPS with 0.26 years, and GW with the shortest CPBT of 0.09 years. In the west orientation, the CPBT values are as follows: aerogel1.83 years, MW 1 year, PF 0.93 years, XPS 0.6 years, Cellulose 0.39 years, PUR 0.39 years, PIR 0.25 years, EPS 0.22 years, and GW 0.08 years. The south orientation demonstrates that aerogel has the highest GWP, resulting in a CPBT of 2.23 years, while MW has a CPBT of 1.14 years, PF has 1.07 years, XPS has 0.7 years, Cellulose has 0.49 years, PUR has 0.45 years, PIR has 0.32 years, EPS has 0.25 years, and GW has the lowest CPBT of 0.08 years. As anticipated, the east orientation exhibits the longest CPBT due to its higher EC compared to other orientations. In this orientation, aerogel has the longest CPBT of 2.84 years, followed by MW 1.5 years, PF 1.41 years, XPS 0.93 years, PUR 0.6 years, Cellulose 0.59 years, PIR 0.41 years, EPS 0.3 years, and GW with the shortest CPBT of 0.11 years. As depicted in [Figure 10], the CPBT for the west orientation exhibits the shortest duration compared to other orientations, despite having thinner insulation. Although the energy savings in this orientation are lower than in other orientations, the CPBT is minimized. Conversely, aerogel, with its density of 122 kg/m^3) and a high GWP of (8.2 (kgCO_2eq/kg)), possesses the longest CPBT, even though it has the minimum thickness among other insulation types. On the contrary, GW, with a density of 12 kg/$m^3$and a low GWP (1.35 (kgCO_2eq/kg)), receives the shortest CPBT.

Following the west orientation, the south, north, and east orientations demonstrate progressively longer CPBT values. In summary, the CPBT for all insulation materials indicates that GW has the shortest average CPBT at 0.09 years (FOC). EPS follows with a CPBT of 0.27 years, then PIR at 0.33 years, Cellulose and PUR both at 0.48 years, XPS at 0.74 years, PF at 1.13 years, MW at 1.2 years, and finally aerogel with the longest CPBT at 2.31 years.

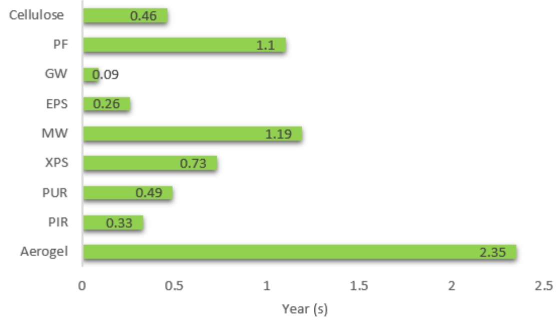
Papers with the same way to find CPBT is not found in order to compare the results, but some related studies have investigated environmental payback time with different wall and roof layers and different climate zone which all effects the thickness of thermal insulations. A study of the airport terminal building calculated 50 mm of thermal insulation thickness for the wall with 4.09 years CPBT and 70 mm for the roof with 2.09 years CPBT in a warm humid climate (56). Danelle Densley et al. in another cradle-to-gate study found the CPBT of 0.36-0.56 years for MW and 0.32-0.5 years for EPS (57). For the other climate zones, a paper covered the countries, Poland, Germany, Czech Republic,(58), and Finland. The CPBT depends on the country, 0.5-1.2 for GW, 0.6-1.1 for EPS, 1.1-3.9 for XPS, 1.2-2.1 for PUR, and for Cellulose, 0.1-0.3 years are calculated (58).

Table.3 Comparison of GWP of different insulation in FCO

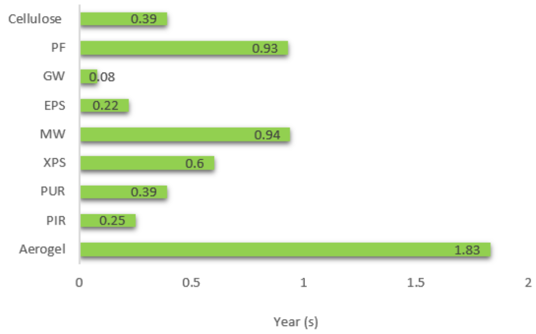
	Thermal insulation	Optimum thickness (mm)	Mass of insulation in the unit area (kg/m^2)	GWP of insulation (kgCO_2e/Kg) (1)	GWP saving for cooling (kgCO_2e/kWh)	GWP saving for heating (kgCO_2e/kWh)	Carbon payback time (year)
North Orientation	Aerogel	10	1.22	13976	507	5448	2.35
	PIR	13	0. 377	1938	508	5344	0.33
	PUR	16	0.48	2857	508	5371	0.49
	XPS	17	0.595	4331	508	5351	0.73
	MW	22	3.08	6884	507	5274	1.19
	EPS	22	0.33	1517	507	5275	0.26
	GW	22	0.264	498	504	5274	0.09
	PF	22	0.66	6474	508	5388	1.1
	Cellulose	22	1.056	295	508	5389	0.46
West Orientation	Aerogel	6	0.732	8385	371	4204	1.83
	PIR	8	0.232	1193	369	4352	0.25
	PUR	10	0.3	1785	370	4231	0.39
	XPS	11	0.385	2802	371	4296	0.6
	MW	15	2.1	4694	371	4310	1
	EPS	15	0.225	1034	371	4350	0.22
	GW	15	0.18	339	371	4350	0.08

	PF	15	0.45	4414	371	4351	0.93
	Cellulose	15	0.72	1842	371	4351	0.39
South Orientation	Aerogel	9	1.098	12578	486	5142	2.23
	PIR	12	0.348	1789	487	5102	0.32
	PUR	14	0.42	2499	488	4993	0.45
	XPS	15	0.525	3821	487	4994	0.7
	MW	20	2.8	6258	488	4996	1.14
	EPS	20	0.3	1379	488	4993	0.25
	GW	20	0.24	453	487	4993	0.08
	PF	20	0.6	5885	487	4994	1.07
	Cellulose	20	0.96	2456	487	4994	0.49
East Orientation	Aerogel	14	1.708	19566	627	6261	2.84
	PIR	19	0.551	2833	627	6266	0.41
	PUR	23	0.69	4106	627	6252	0.6
	XPS	25	0.875	6369	626	6238	0.93
	MW	33	4.62	10327	627	6238	1.5
	EPS	33	0.495	2275	627	6262	0.33
	GW	33	0.396	747	627	6262	0.11
	PF	33	0.99	9710	627	6263	1.41
	Cellulose	33	1.584	4052	627	6265	0.59

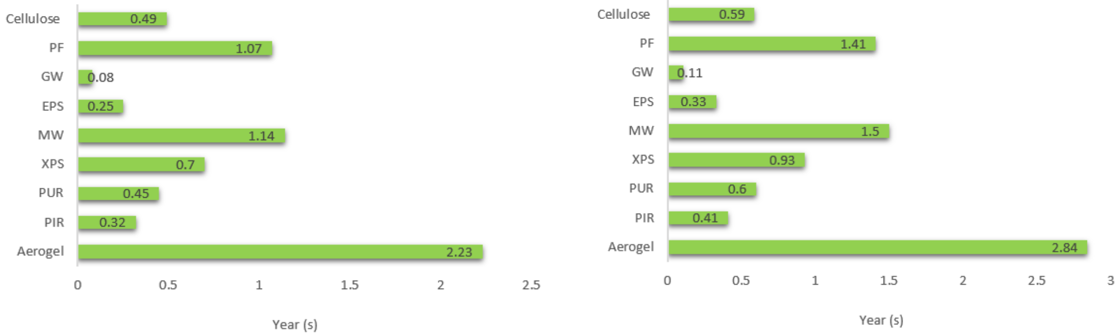
(1) GWP of the total building require insulation



North



West



South West

Fig.10. CPBT of FCO

5. Conclusion

The current study focused on evaluating the performance of various thermal insulation materials commonly available in the market. Through simulations conducted without insulation, it was observed that energy consumption varied based on building orientation, with the order of lowest to highest energy consumption being north, west, east, and south.In this research, nine conventional thermal insulation types were analyzed to determine OIT for each of the FCO. The results revealed that the OIT depended on the cooling and heating energy requirements, as well as the λ of the insulation. The OIT was determined by achieving the same EC benchmark, which served as a reference for determining the optimal thickness across all insulation types and orientations. Notably, the thickest OIT was found for the east orientation, followed by north, south, and west, respectively.

Considering the climate zone of the case study, characterized by hot summers and mild winters necessitating less cooling energy, the optimal thickness was not substantial, leading to a shorter CPBT. LCA was employed to calculate the CPBT, with GWP serving as a primary environmental impact indicator. The insulation materials with the highest GWP were identified as Aerogel, PF, XPS, PUR, PIR, EPS, cellulose fiber, MW, and GW, respectively.Furthermore, after determining the optimal thickness, it was observed that aerogel had the longest CPBT, followed by MW, PF, XPS, PUR, cellulose fiber, PIR, EPS, and GW. This order remained consistent across different climate zones and building studies, although CPBT may vary in colder or other climate zones.

These findings provide valuable insights into the CPBT of different insulation materials, highlighting the significance of factors such as insulation thickness, density, and GWP. The study underscores the importance of considering both energy savings and environmental impact when assessing the overall sustainability of insulation choices. The results can aid in decision-making processes for architects, engineers, and policymakers, facilitating the selection of appropriate insulation materials based on their environmental payback time.

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