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Relative Comparison of Benefits of Floor-Slab Insulation Methods, Using Polyiso and XPS Materials in South Africa, Subject to the New National Building Energy Efficiency Standards

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Abstract: This article aims to assess the benefits of floor-slab insulation measures using extruded polystyrene (XPS) and polyisocyanurate (polyiso) insulation materials at various levels of insulation thicknesses for a detached residential building. The EnergyPlus simulation analysis was carried out within the seven energy zones (represented by eight locations) of South Africa in accordance with the South African national code for building energy efficiency (SANS10400-XA). The energy savings and payback periods due to use of the insulation over a lifecycle period of 50 years were assessed. Cape Town (zone 4) behaved differently from other locations and hardly benefitted from the application of floor-slab insulation measures. Generally, polyiso insulation performed better than XPS, for vertical gap insulation. For vertical gap insulation, lower insulation thicknesses required higher insulation depths to maximize energy savings. Similarly, lower insulation thicknesses required higher perimeter insulation widths to maximize energy savings, for the horizontal perimeter insulation method. The locations that benefitted most from vertical gap floor-slab insulation were Pretoria (zone2), Kimberley (zone6), Nelspruit (zone3), Fraserburg (zone7), Welkom (zone1), Mthatha (zone5), Ixopo (zone5H) and Cape Town (zone4) in that order. This order was almost similar with those for the horizontal perimeter floor-slab insulation and horizontal full floor-slab insulation methods.

Keywords: energy efficiency; lifecycle analysis (LCA); embodied energy; source energy; site energy; energy savings; energy payback period

1. Introduction

1.1. Background

South Africa was the largest consumer of energy in Sub-Saharan Africa in 2021, followed by Nigeria and Algeria. The country has a large and intensive coal mining industry through which it meets most of its energy needs (United States Energy Information Administration, 2022). The number of households (in millions) globally that demand energy is projected to increase by 10.5% from 2208 million households (in 2022) to 2439 million households (in 2030), while the residential building expansion (in million square meter of floor area) is expected to be about 14.6% from 198090 million square meters in 2022 to 227039 million square meters in 2030 (International Energy Agency [IEA], 2023a). While IEA (2023b) indicates that residential buildings consumed about a fifth or 20.96% of global energy in 2022, the 2022-2030 energy demand trends indicate an expected growth in residential building energy consumption of at least 10% (between 2022 and 2030). Heat losses through floors in residential buildings are quite significant and can account for as much as 10 to 20% of total building heat losses (10% for slab on ground buildings). Majority of the floor slab-on –grade heat losses (about

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80%) occurred at the edges (perimeter) of the slab (EDF, 2023). In 2021, the most popular dwellings in South Africa (69.7%) were in form of either a house or brick/concrete block structure located on a separate stand or farm (Statistics South Africa [STATSA], 2021). Dwellings from traditional materials accounted for 4.2%, while flats or apartment accounted for only 3.6% of the total dwellings.

The use of the right technique of insulation and most suitable type of insulation material for residential building floors (slab-on-grade) may significantly reduce heat losses and therefore contribute to the reduction of both national and global building energy consumption.

This paper uses lifecycle cost analysis (LCA) and EnergyPlus simulations to comparatively evaluate the relative benefits of adding floor-slab insulation materials (XPS and polyisocyanurate or polyiso) in residential building floor-slabs, with respect to each of the seven SANS10400-XA energy zones in South Africa. The insulation material is applied at different levels of thickness and depths or widths from the slab edge, which influences the increase in embodied energy due to application of the floor insulation. The increase in embodied energy is then compared to the realized benefits in form of savings in operational energy, to evaluate the payback periods and net energy savings after 50 years. The clay brick cavity wall (with a minimum of 50mm air gap) was used as basis of the analysis subject to the SANS10400-XA building energy efficiency criteria.

The paper adds value to previous research by providing detailed insight into the Energy zones that benefit most from the vertical perimeter insulation methods, and the optimum thicknesses and depths that would maximize net energy savings based on the new SANS10400-XA building energy efficiency regulations. Just like wall insulation analysis, this would directly contribute towards the goal of implementing net-zero energy efficient buildings based on the national energy efficiency standards. It is important to note that the thermal conductivity of materials varies with changes in temperatures and moisture content. Therefore there are limitations to the results of the research, because point estimates of thermal conductivity for the floor insulation materials were used (Tariku, Shang, and Molleti, 2023).

This paper is divided into five sections. The latter part of section i) reviews previous studies and other relevant literature on the subject. Section ii) deals with the methodology. Section iii) presents the analysed results. In section iv), the results are discussed. In Section vi), both the summary, new contributions and the proposed further areas for research are presented.1.2. Literature review

1.2. Literature review

1.2.1. Factors that influence heat losses from ground floors

Several factors influence ground temperature. These include soil volumetric heat capacity, thermal conductivity, latent heat, changes in ambient temperatures, and the characteristics of the ground surface, such as vegetation and slope (Pokorska-Silva, Kadela, Orlik-Kozdon and Fedorowicz, 2022). The amplitude of daily average solar radiation flux (amount of solar power radiated through a given area in form of photons or other particles) affects the total amount of heat transferred between the environment and the sub-soil where the building is located (Larwa, 2019). The temperature of the ground surface is affected by several factors, including energy loss by evaporation, heat transfer between the ground surface and deeper layers, convection, and radiation both in the immediate and farther surroundings. However, the temperature of the ground at any given point (on surface or beneath) depends also on the depth of the point beneath the ground surface, which yields surface temperatures (for points on or immediately beneath the surface), subsurface temperatures (for points beneath the surface, but in the shallow zone), and deep surface temperatures, for points beneath the surface but in the deep zone (Pokorska-Silva et al, 2022). Tsilingiridis and Papakostas (2014) show that the factors influencing temperatures for surface, sub-surface, and deep surface zones significantly differ. For example points near the surface have their temperatures predominantly influenced by daily changes in the surface ground temperature, which in turn is influenced by weather conditions, including wind and rain. However, sub-surface (shallow zone) points have their temperature predominantly influenced by seasonal variations, and closely correspond to the average annual air temperature in the vicinity. On the other hand, deep zone points have their temperatures

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constant but also very slowly increasing with depth beneath the ground, with the rate of temperature increase with depth being dependent upon the local geothermal gradient. Geothermal gradient is an amount at any place that the earth's temperature increases with depth. The geothermal gradient varies with location as indicated by Dhansay, Musekiwa, Ntholi, ChevallierI, ColeI, and de Wit (2017). The geothermal gradient is high in places like Cape Town (Western Cape), Cradock (Eastern Cape), and Mbabane (Swaziland).

For single-family residential buildings (characterized by shallow foundations less than 1m deep), the area of heat losses though the floor slab mainly consists of the central floor zone (that is not influenced by changes in external temperatures), and the external zone along the perimeter or area around the external walls, having a width of about 0.75m, and in which the heat loss fluctuations are severely influenced by fluctuations in external temperatures (Pokorska-Silva et al, 2021). At these perimeter or near-perimeter areas, it is necessary to minimize heat losses in places where the vertical wall envelope meets the floor. Vertical perimeter insulation and a combination of vertical (along the slab edge) and horizontal (immediately beneath the slab) insulation methods along the slab edges serve to address these kinds of heat losses.

1.2.2. Factors that influence savings in embodied and operational energy due to application of floor slab insulation measures

The increments in embodied energy due to application of the floor-slab insulation measures are influenced by several factors. An increase in embodied energy due to application of floor-slab insulation may be followed by a larger or smaller reduction or increase in operational energy at the operational phase and vice versa. Some major factors are discussed below.

Analysis period and system boundaries: The LCA analysis period influences the amount of computed embodied quantities. It is important to maintain the analysis period constant when making relative comparisons. This period may determine the number of replacements of any particular material based on its useful life relative to the analysis period. Most studies recommend LCA analysis period of 50 years (Abouhamad and Abu-hamd, 2021). In addition, the system boundaries also influence the embodied quantity computations, and must be maintained constant when making relative comparisons. Figure 1 shows that it is possible to have system boundaries 1 up to 5 (S.B.1 to S.B.5) that involve production (A1-A3), construction(A4-A5), use (B1-B7) and end of life (C1-C4). The Boundaries may be extended to include benefits beyond end of life (such as recycling benefits: D1-D4). A combination of several studies indicates that the building operational phase (B6 and B7) tends to account for 38% to 49% of total energy depending on the building technology used and other factors (Abouhamad and Abu-hamd, 2021; Zhang, Liu and Zhang, 2020; Chastas, Theodosiou, Kontoleon and Bikas, 2018). This means the embodied energy may range from 51% to 62%.

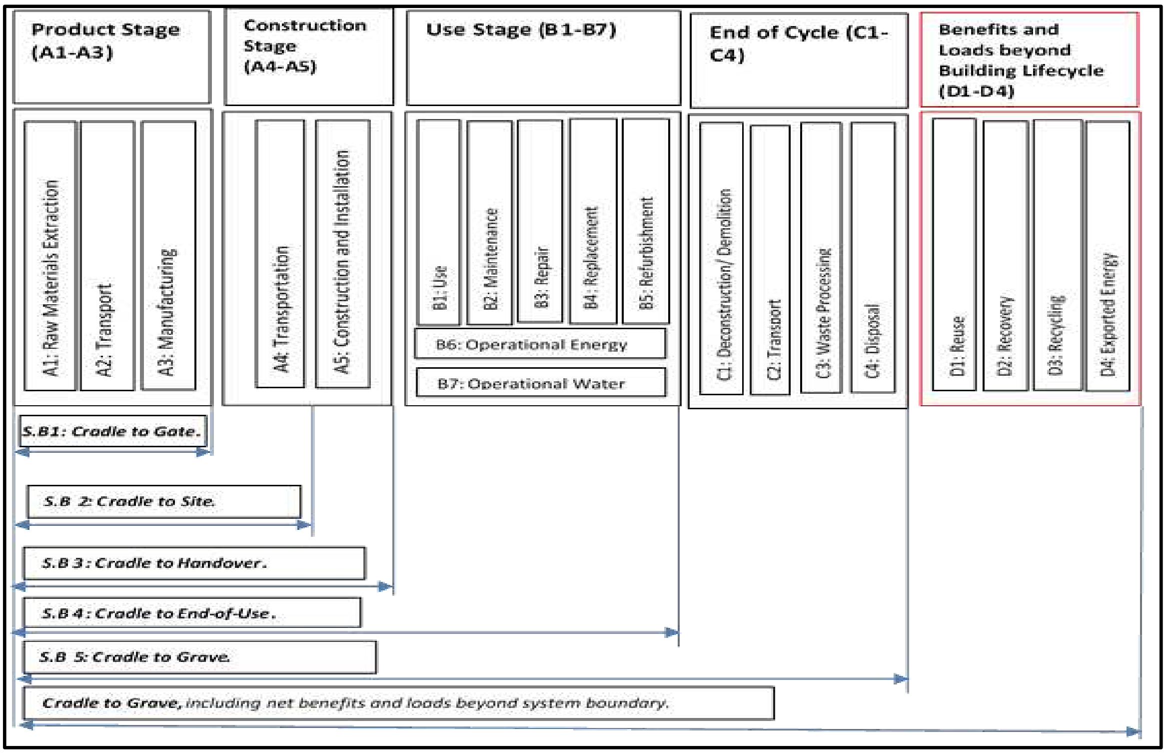

Figure 1. Building Life cycle Stages (Royal Institute of Chattered Surveyors[RICS], 2017).

This study will be based on system boundaries A1-C4, but excluding phases of B1-B3 and B5-B7. Only the replacement process will be modelled under the use stage.

Building typology: The building typology can influence the embodied energy. Building facades have differing thermal and solar performance (depending on the materials used, the front, left, right and back window-to-wall ratios, and the materials used in the windows), thus significantly influencing operational energy. Glass material has a high embodied carbon content, only second to aluminium, however the embodied energy of aluminium (211MJ/Kg) is more than seven (7) times that of glass, which is at 28.5MJ/Kg (ARUP, 2022). On the other hand, the embodied energy of steel (0.0227MJ/Kg) is less than ten times that of glass. According to the study by the Carbon Leadership Forum (2017), the embodied carbon per square meter (and therefore, embodied energy per square meter) significantly varies on basis of building typology (Commercial office, Commercial mixed use, commercial other, Residential multi-family and residential single family). Elongated building forms tended to be more suitable than compact ones in central Europe in regard to minimizing energy consumption for heating and cooling, because they allowed larger window areas (larger window-to-wall ratios) during winter and thus more efficient solar energy harvesting. However, proper shading needed to be applied during the summer cooling season (Kosil, Gostisa and Kristl, 2017). Therefore, a proper study of pure effect of floor-slab insulation should preferably be made using similar building typologies, unless the study aims to understand the influence of differences in typology.

Floor area and method of applying floor-slab insulation: Closely related to typology, is the square floor area of the building. A larger floor area will yield larger incremental embodied energy and emissions due to insulation measure application (unless the insulation material sequestrates carbon). Similarly, the embodied energy and emissions increments will be higher for a larger floor area when floor slab the insulation thickness or insulation depth is increased. However any gains in terms of energy savings due to greater efficiency are not necessarily directly dependent on floor area, but also more importantly on building form as seen from the study by Kosil et al (2017). The insulation method will also influence the incremental embodied energy and emissions, based on standard formula for computation of areas, volume, mass and eventually the embodied energy and emissions. However, different insulation methods may have differing effects on operational energy, operational emissions, and their corresponding net saved quantities per square meter of floor area, across the different energy zones or locations. Gap vertical insulation and external vertical insulation tend to be laid around the perimeter of the floor at selected insulation levels. Their depth going vertically downwards is also variable. While gap insulation is inserted between the slab and the foundation wall, exterior vertical insulation is inserted on the exterior side of the foundation wall. The factors influencing temperatures at different ground depths (near surface, sub-surface or shallow surface, and deep surface) differ from one another. The rate of change of temperatures with depth (geothermal gradient) are influenced by the ground depth (Pokorska-Silva et al, 2022; Tsilingiridis and Papakostas, 2014). They are also influenced by the location (Dhansay et al, 2017). In the case of horizontal floor-slab insulation, insight into its effects on energy savings for residential buildings can be derived from the research by Pokorska-Silva et al (2021), who showed that the central floor zone of the floor slab is hardly affected by changes in external temperatures, unlike the external wall perimeter-based zone of about 0.75m width.

Cox-Smith (2016) studied the practicalities and effectiveness of using concrete slab-floor perimeter insulation in residential houses in New Zealand. The results showed that the R-Values of the floor slab increased with area-to-perimeter ratios for the floor, using any of the insulation techniques. Square floor shaped buildings have greater area-to-floor ratios and therefore better thermal performance from a floor-slab insulation perspective. However, from a building envelope wall perspective, work done by Kosil et al (2017) shows that elongated building forms (lower area-to-perimeter ratios) were more suitable than compact ones in minimizing energy consumption for heating and cooling (for example, by allowing better cross ventilation). This apparent conflict in the effect of area to perimeter ratios requires balancing based on evaluating if the relative energy saving benefits due to cross ventilation (with an elongated building) are greater than those due to floor insulation (with an almost square floor shape building). Horizontal insulation (with vertical slab edge gap insulation) performed best followed by the vertical perimeter insulation and the horizontal floor slab insulation (without vertically insulating the slab edges). The results of the study also showed that at a given level of insulation thickness (for any insulation method involving gap vertical insulation) the R-values increased with floor area. For the same floor area, the R-values generally increased with insulation thickness (the maximum thickness was 100mm).

The ratios of the R-Value of insulated floor slab to the R-value of uninsulated floor slab, as the floor insulation depth increased were higher for smaller floor areas (such as 50 square meters) compared to higher floor areas (such as 200 square meters). However, for a given floor area, these R-values increased with insulation depth, but the rate of increase decreased with depth (Cox-Smith, 2016).

Local climatic conditions where the building is located: The local climatic conditions also influence the degree of increments or decrements in embodied and operational energy and emissions due to application of insulation measures. The region in Japan with highest cooling degree days and lowest heating degree days (hottest climatic zone) did not experience any tangible benefits of using insulation (Dong et al, 2023). It was also observed in South America that use of insulation in hot climates tended to increase (rather than reduce) the thermal load, reducing the possibility of any energy savings (Melo, Lamberts, Versage, and Zhang, 2015). Therefore, while some locations in these two studies experienced reductions in energy consumption due to application of insulation measures, other locations never benefitted.

National energy efficiency standards: The South African national building energy efficiency standards (SANS 10400-XA) will also impact upon the computed embodied and operational carbon and emissions, and their increments when there are changes in floor-slab insulation thickness and depth. Generally, the national energy efficiency standards affect the extent and proper way of applying building measures. For residential buildings with a floor area greater than or equal to 80 square meters, the SANS10400-XA regulations stipulate the minimum standards for wall envelopes to be either cavity walls (with minimum air gap of 50mm) or collar joint walls, depending on the energy zone or location (SANS10400-XA, 2022). Cavity walls have superior thermal insulating properties compared to single-leaf wall envelopes. Therefore the net and incremental net energy savings per square meter of nett floor area for residential buildings less than 80 square meters may be quite different than similar buildings that are greater or equal to 80 square meters in floor space. The relative impact of the cavity wall envelope design will also vary depending upon the energy zone or location.

The SANS10400-XA regulations also stipulate the minimum shading constants that should be applied, which are latitude-dependent. The net and increments of net energy savings per square meter of nett floor area for residential buildings will also vary significantly based upon the shading constants selected. Utilizing a shading constant which is SANS10400-XA compliant for all locations under consideration may not necessarily maximize energy savings for each of the locations. It is therefore important to use location-specific shading constants that maximize net energy savings per square meter of nett floor area for each location.

The SANS10400-XA regulations also recommend the preferable orientation of buildings for energy efficiency purposes. Orientations should preferably be in the North direction in all the energy zones, except for zone 5H, which is flexible (SANS10400-XA, 2022). While orientation will not affect the embodied energy and emissions, it will affect the operational energy, operational emissions, their corresponding net saved quantities, and possibly the patterns of increments in net saved quantities that arise due to variations in floor-slab insulation thicknesses and depths or widths.

The building orientation, shading, and wall envelope construction standards are just some examples of how the regulations impact on the building measures. Other measure controls include the occupancy schedules, acceptable indoor thermal comfort temperature ranges (19-25^{o}C), and minimum R (thermal resistance) and CR (multiple of thermal resistance and thermal capacitance) values for walls, roofs and floors as outlined in the SANS10400-XA (2022) regulations. The minimum R and CR values will directly affect the minimum thickness of the building technology materials used for walls, roofs and floors. The thickness will depend on the properties of the building technology material. The thickness will in turn have an impact upon the embodied energy, embodied emissions, and their corresponding operational quantities (by influencing the R-Values). According to Gervasio, Dimova and Pinto (2018), the embodied carbon contribution among non-residential buildings by steel ranged from 241-354 Kg CO_2/m^2, while reinforced concrete ranged from 332-433 Kg CO_2/m^2. On the other hand the contribution by wood (including residential buildings) was 108-288 Kg CO_2/m^2. If, therefore, the goal of the research is to investigate the impact of floor insulation measures on energy consumption and CO_2 emissions of residential buildings, then the rest of the measures must always be maintained within acceptable SANS10400-XA (2022) limits (as constants or variables), while the insulation measures are applied incrementally.

Energy and CO_2 emissions coefficient database accuracy: The embodied emissions and energy coefficients used can influence the quality of the energy and emissions lifecycle computations. Therefore, the accuracy of the database from which the coefficients are derived is very important, more so that increments in such embodied quantities will be compared against increments or decrements in operational energy and emissions. The operational energy and emissions are derived, not based on an energy and emissions coefficient database, but using the local country's energy mix proportions. Various databases, such as the inventory of carbon and energy (ICE) database, are available worldwide and can be used to compute relative energy consumption and emissions in South Africa (Circular ecology, 2023).

Other factors: Other factors which may affect the embodied and operational energy and emissions, but whose effects can be controlled during the study by maintaining them constant include the computational method for embodied quantities, and the major building component for which the quantities are evaluated. The two (2) computational methods usually used are the input-output method and the LCA method (Hasegawa et al., 2015; IEA, 2016; Zhang et al., 2020). The outputs for these methods may differ significantly. It is best to stick to only one of the methods throughout the study, unless if the aim of the study is to make relative comparisons between the computation methods.

Regarding the influence of building component on the embodied quantities computation, previous studies have shown generally that substructures of residential buildings generally accounted for 22%-45% of embodied emissions and 18% - 37% of the embodied energy (Abouhamad and Abu-hamd, 2021; Gervasio et al., 2018). However, since this research required the whole building as basis for the energy model, the entire building unit will be used consistently throughout the study rather than its major sub-components.

1.2.3. The floor-slab insulation materials

The floor-slab insulation materials which were used included polyisocyanurate (polyiso) and extruded polystyrene (XPS).

Polyisocyanurate (polyiso): Like polyurethane, polyiso is a thermosetting plastic, that consists of a closed-cell foam structure which contains a low-conductivity, hydrochlorofluorocarbon-free gas in its cells (US Department of energy, 2023). Polysio tends to suffer from thermal drift, which leads to its R-value dropping, especially in the first two years of its application. However, the use of plastic facings or foil can help to slow the thermal drift process. It contains recycled materials, is eco-friendly, is a good vapour barrier and contains a less toxic flame retardant. It has a higher flammability performance compared to polyurethane but has low cost (however it is more costly than XPS or EPS) and has outstanding thermal insulation properties due to thermal resistance of gases in its cells. The use of agricultural waste additives in polysio has great potential of providing new polysio composites with better properties (Lazo, Puga, Macías, Barragan, Manzano, Rivas, and Rigail-Cedeno, 2023).

Extruded polystyrene (XPS): Polystyrene is a colourless, transparent thermoplastic that is commonly used to make foam board or beadboard insulation, concrete block insulation, and loose-fill insulation consisting of small beads of polystyrene (US Department of Energy, 2023). The material is recyclable according to research (Netsch, Simons, Feil, Leibold, Richter, Slama, Yogish, Greiff, and Stapf, 2022; Reynoso, Romero, Viegas, and San Juan, 2021). Polystyrene can be installed as loose fill, as foam board, or as bead insulation. Extruded polystyrene (XPS) is installed usually as foam board, while expanded polystyrene (EPS) is installed as bead insulation (US Department of Energy, 2023). XPS is not as environmentally friendly when compared to polysio (Füchsl, Rheude, and Roder, 2022). It uses Hydrofluoro carbons during its production, which deplete the ozone layer. However XPS has a slightly higher R value than EPS and is more resistant to moisture.

2. Materials and methods

2.1. Overview of the methodology used

Figure 2 briefly summarizes the methodology followed by the research.

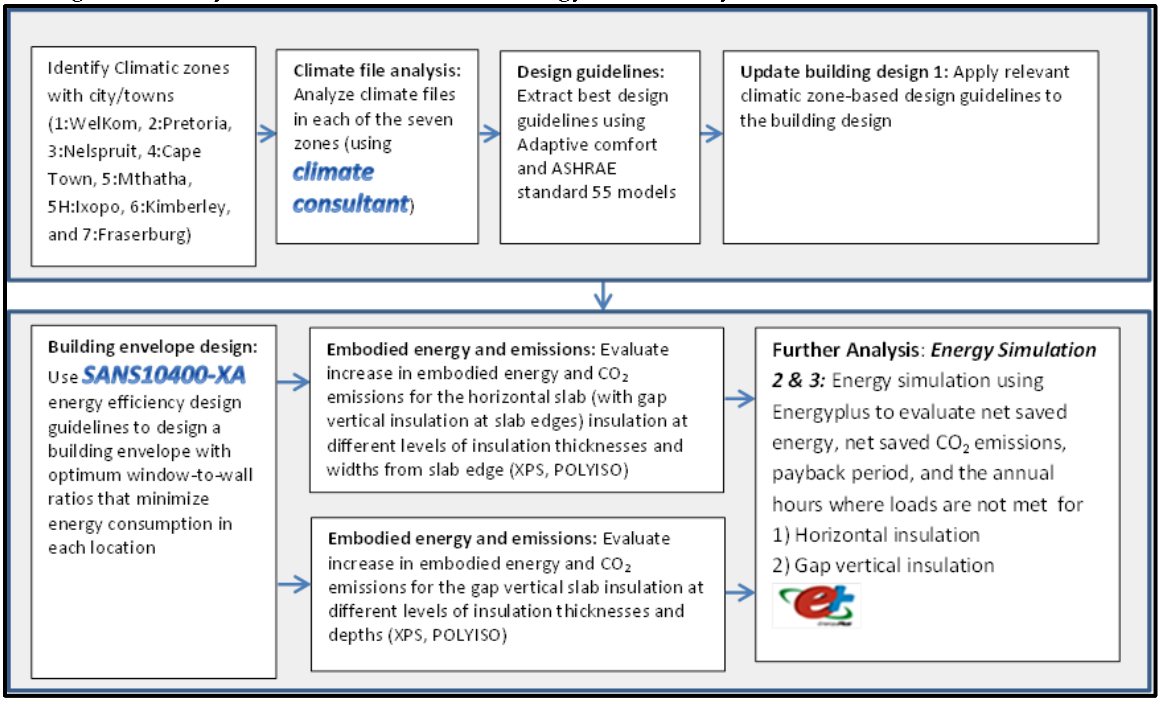

Figure 2. Diagrammatic overview of the methodology used (Source: Authors).

The methodology consisted of first using climate consultant (Society of Building Science Educators, 2023) and weather data to obtain the best building design strategies for each of the climatic zones in South Africa based on the adaptive comfort model and ASHRAE 55 model. The nature of the design will affect the computed embodied energy and emissions. Therefore, the energy efficiency standards and passive design strategies were used as a standard against which the design would be based. The second stage involved obtaining the optimum window to wall ratios (WWRs) through performance of relative energy simulations, regression modelling and optimization based on the evolutionary algorithm. The WWRs will affect the net wall area (excluding window area and door area) and hence the embodied carbon emissions and energy of the walls. On the other hand, WWRs contribute greatly to passive strategies of achieving thermal comfort, leading to operational energy savings. The third step involved updating of the building design using the optimum WWRs and SANS10400 energy efficiency guidelines, the computation of increase in embodied energy (due to application of floor-slab insulation), and the performance of energy simulations to evaluate the annual energy savings that arise due to the use of the insulation materials. The payback periods and net energy savings for a 50-year period were evaluated.

2.2. Data

Part of the data used consisted of weather files data (Climate.OneBuilding.Org, 2023) and secondary data from energy and emissions coefficient databases such as the ICE database (Circular Ecology, 2023). The other data was directly generated from the design specifications and material quantities corresponding to the building design and materials used. The material quantities were influenced by the SANS 10400 energy efficiency guidelines (SANS10400-XA, 2022), the nett floor area and the wall heights.

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2.3. Architectural design and bills of material

Climate consultant (Society of Building Science Educators, 2023) was used to obtain some of the basic energy efficiency, thermally comfortable design recommendations for the 105.4 m^2 nett floor area design of the residential unit.

Some of the quantities computed for the wall envelope, to ensure compliance, included the thermal resistance (R-Value), the thermal capacitance and the CR-Value. The CR value of the wall is the product of thermal resistance and thermal capacitance (SANS10400-XA, 2022). Wall assembly materials and their thicknesses affect the R and CR-Values of the assembly, based on their properties. The guidelines on methodology of computing the R, CR, fenestration-specific heat gain coefficients and U-Values, are outlined in the SANS 10400-XA document. Bills of materials for the walls were generated from the building designs with the help of Microsoft excel. The ICE database was used as basis for embodied computations. Its coefficients corresponded to system boundaries A1-A3. Missing coefficients were obtained from available environmental product declarations (EPD's). Emissions based on later system boundaries were obtained through further mathematical modelling. Figure 3 illustrates the model.

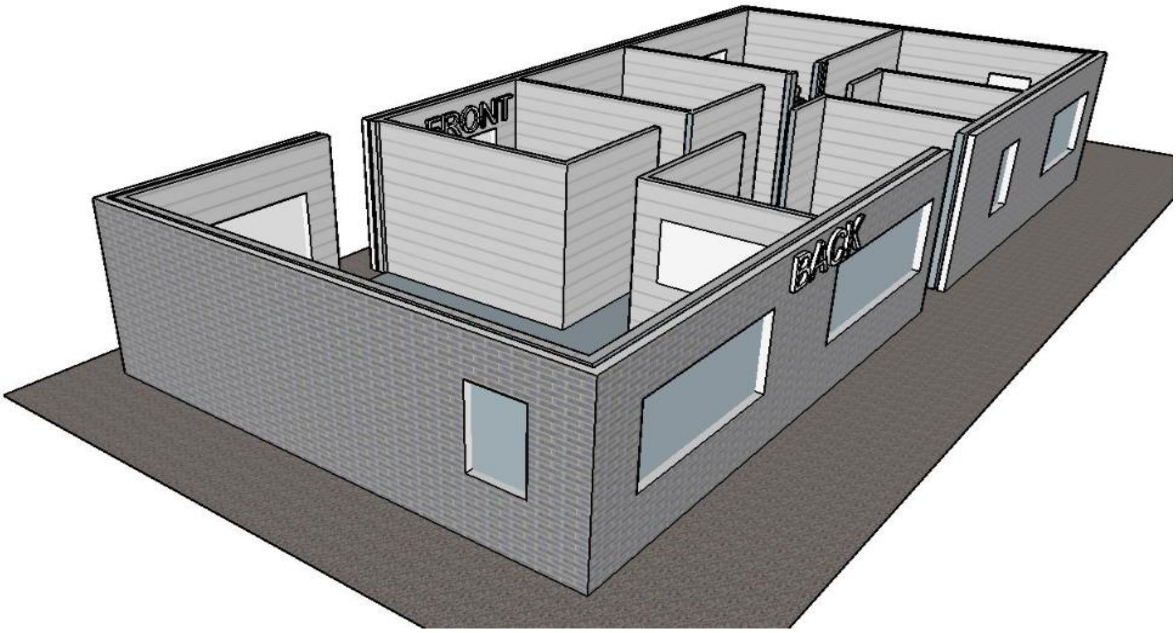

Figure 3. Diagrammatic representation of the building model (the wall envelope and inner partitions) **Source:** Author.

The window-to-wall ratios were carefully selected to ensure energy efficiency of the model in its passive form. Further design guidelines that influenced the model design are provided later using results from climate consultant.

2.3.1. Properties of building materials

The relevant properties of materials were obtained from the ICE database, Thermtest Instruments (2023), and the Intelligent Communities Lifecycle (2023). The properties were the thermal conductivity, specific heat, density, embodied carbon coefficients, and embodied energy coefficients.

2.3.2. South African Energy efficiency standards for wall envelopes and the surface density

The South African National Standard on energy efficiency of buildings (SANS10400-XA, 2022) recommends buildings in all seven energy zones (except zone 5H) to face northwards. Most of the window area should be in the north-facing and south facing walls in that order. Buildings that have greater length than width will therefore allow more cross ventilation as a form of passive cooling during summer.

Walls: Buildings with a floor area less or equal to 80 square meters are classified as "category 1" buildings according to SANS 10400-XA (2022). The minimum masonry wall requirements of "category 1" buildings are a single leaf masonry wall of a minimum thickness of 140mm. When the floor area is greater than 80 square meters (non-category 1 buildings) then the masonry wall system must either be collar joint (energy zones 3, 5 and 5H) or a cavity wall with minimum air gap thickness of 50mm (energy zones 1, 2, 4, 6, and 7). Based on the South African energy efficiency standards, the floor area can affect the nature of wall construction, which in turn affects the embodied carbon and energy footprint (by influencing thicknesses of walls), and the annual operational carbon and energy footprint of a building (by influencing minimum R-Values of walls).

According to the energy efficiency standards in South Africa, the minimum nominal R-Value for the collar joint wall assembly is 0.4 m^2.K/W if the surface density is greater or equal to 270 Kg/m^2. The minimum nominal R-Value for a cavity wall is 0.6 m^2.K/W if the surface density is greater or equal to 270 Kg/m^2. If the surface density is less than 270 Kg/m^2, then the minimum R-Value for both collar joint and cavity walls in energy zones 1, 2, 6, and 7 is 2.2 m^2.K/W; the minimum R-value in energy zones 3, 4, 5 and 5H is 1.9 m^2.K/W (SANS10400-XA, 2022). Therefore, the energy efficiency standards influence the nature of wall construction, the minimum R-Values and hence the minimum energy and carbon footprints of buildings per square meter of nett floor area, based on the energy zones in South Africa. Similarly, the minimum CR values would need to be 80 or 100 Hours depending on the energy zone where the analysis is being done.

Shading constants: The SANS10400-XA standard specifies the minimum shading constants to use, which are dependent upon the latitude of the location. The values are 0.33 for latitudes less of equal to 22 degrees; 0.36 for latitudes above 22 degrees and up to 24 degrees; 0.40 for latitudes above 24 degrees and up to 26 degrees; 0.42 for latitudes above 26 degrees and up to 28 degrees; 0.46 for latitudes above 28 degrees and up to 30 degrees; 0.50 for latitudes above 30 degrees and up to 32 degrees, and 0.54 for latitudes above 32 degrees (SANS10400-XA, 2022). The minimum length by which the shading device extends beyond the window width on either side is equal to the shading depth according to the SANS10400-XA standards. The shading depths were evaluated by multiplying the relevant shading constant by the vertical distance between the base of the glazing element and the shadow-creating edge of the window overhang.

2.3.3. Optimum window to wall ratios

Since front, back, left and right window-to-wall ratios affect both the embodied carbon emissions and operational energy (and hence operational carbon emissions), the research used separate energy simulations, regression methods, with F tests and evolutionary algorithm optimization techniques to derive optimum window-to-wall ratios that minimized operational energy consumption subject to SANS10400 (2022) standards and the climate consultant analysis results. The F and T tests passed and the R square values indicated that the window-to-wall ratios in each of the 4 directions (left, right, front and back) served to explain at least 90% of the variation in energy consumption. The analysis was done with respect to each zone. Although the detailed results of the analysis are not presented in this study, the final window-to wall ratios that were obtained were used by the research.

2.3.4. Optimum floor-slab insulation thickness, and the insulation depth or insulation width

According to SANS10400-XA regulations, the minimum required R-Value for non-heated floors is 0.0 W/ m^2.K, and for heated floors is 1.0 W/m^2.K. The floor in the model was considered non-heated. However, insulating floors may still improve upon the energy efficiency of the building. There are several techniques of insulating floor-slabs. The first is the vertical gap insulation that involves inserting insulation between the floor slab and the foundation wall and then extending it vertically downwards to varying levels of depths. The second involves the vertical gap insulation around edges of the floor slab (between floor slab and foundation wall) and partial horizontal insulation around the perimeter of the slab at varying insulation widths. The third is the full horizontal insulation of the entire slab area (beneath the slab), with gap insulation still being applied at the slab edges. This research deals with all the three insulation techniques. As a result, the insulation thickness and insulation depth (or widths) were of concern as a basis for analysis. Extruded polystyrene (XPS) and Polyisocyanurate (polyiso) insulations were used for the analysis. The research employed a 100mm thick concrete floor slab, and various levels of insulation thickness (25mm, 50mm, 100mm, 150mm, 200mm) and insulation depths or widths (200, 400, 600, 800, 1000, 1200, 1400, 1600, 1800, 2000mm) in all the energy zones. The minimum R values, where applicable, had to be met before any energy simulations or embodied energy computations were done (SANS 10400-XA, 2022). An evaluation of how the energy payback periods and net saved energy after 50 years both vary with the floor-slab insulation material thickness and depth was then done. The research also evaluated the optimum insulation material depth and thicknesses that maximized net energy savings per square meter floor area in each energy zone.

2.4. Estimation of IBT embodied energy and emissions

Equation 1 was used to estimate the embodied energy of the building models.

$$T = \sum_{i=1}^{k} C_{kgi}\{q_{bi} + n_i.q_{bi}\}(1+w) + f_k E_{kg}.\frac{q_{bi}}{Q_{bi}}\{(2d_{bi}(1+n_i)) + 60.v + (2d_{wi}(1+w+w.n_i)+v)\} \quad (1)$$

Equation 1 shows the estimated embodied energy for a residential building consisting of k building materials. While the emissions and energy coefficients correspond to the cradle-to gate (A1-A3) system boundaries, equation1 illustrates their use for evaluation of cradle to end-of-life (A1-C4 excluding B1, B6-B7) embodied energy.

The term (n_i) refers to the number of times any building material (i) will be replaced due to repair and maintenance during the analysis period. The term C_{kgi} refers the *cradle to gate* embodied energy coefficient of building material (i). The quantity q_{bi} refers to the initial quantity of building material *(i)* that was used in constructing the building. The term w is a percentage, expressing the amount of material wasted. The term f_k represents the fuel in kilograms that is burnt per kilometre. This term varies depending on the type of vehicle used to transport the materials and the fuel type used by the vehicle (petrol, diesel, electric vehicle, and others). The term E_{kg} represents the energy produced by this fuel in KWh per Kg of fuel. The term d_{bi} is the average distance from the factory gate to the building site for this material, and d_{wi} is the average distance from the building site to the dumping site for this material. The term T is the total embodied energy for the building. The term "v" is the rate of energy consumption per square meter of nett floor area being deconstructed or demolished. The term Q_{bi} refers to the maximum legal weight that can be carried by the vehicle which will be used to transport building materials to the site of to the landfill (Liu, Li, Sun, Wang, and Zhao, 2020; IEA, 2016). The embodied energy due to the use of floor slab insulation material at certain level of thickness would then be the difference between the embodied energy of the building when the floor slab insulation was applied and embodied energy of the building when the floor slab insulation was not applied.

2.5. Cradle to gate approximate embodied quantities due to insulation measures

2.5.1. Vertical Gap insulation only. The cradle-to-gate embodied energy due to the floor-slab insulation measure is given by equations 2

$$EE_{ins} = \{(L_{fs}+2T_{ins}).(W_{fs}+2T_{ins}).d_{ins} - L_{fs}W_{fs}d_{ins}\}D_{ins}C_{kge} \quad (2)$$

The terms L_{fs}, W_{fs}, T_{ins} , d_{ins}, and D_{ins} are the length of the floor slab, width of the floor slab, thickness of the insulation, depth of the insulation and density of the insulation , respectively. If EE_{ins} are the embodied energy due to the applied floor slab insulation measure, then C_{kge} is the cradle to gate embodied energy coefficient.

3.5.2. Horizontal insulation (with vertical gap insulation along the slab edges. The cradle-to-gate embodied energy due to the floor-slab insulation measure is given by equations 3 to 5.

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$$EE_{ins\_gap} = \{(L_{fs}+2T_{ins}).(W_{fs}+2T_{ins}).T_{fs} - L_{fs}W_{fs}T_{fs}\}D_{ins}C_{kge} \quad (3)$$

$$EE_{ins\_hrz} = \{L_{fs}W_{fs}T_{ins} - (L_{fs}-2W_{ins}).(W_{fs}-2W_{ins}).T_{ins}\}D_{ins}C_{kge} \quad (4)$$

$$EE_{ins\_htotal} = EE_{ins\_hrz} + EE_{ins\_gap} \quad (5)$$

The terms T_{fs}, and W_{ins}, are the thickness of the floor slab and the width of the insulation from the edge of the floor slab (in the horizontal direction). If EE_{ins_gap} are the embodied energy due to the applied gap floor slab insulation measure along edges of the floor slab, then C_{kge} is the cradle to gate embodied energy coefficient. If EE_{ins_hrz} are the embodied energy due to the applied horizontal floor slab insulation measure beneath the floor slab, then C_{kge} is also the cradle to gate embodied energy coefficient. The total embodied energy due to horizontal insulation is given by EE_{ins_htotal}.

2.6. Saved energy and energy payback periods

The system boundaries over which embodied energy was evaluated are A1-A5, B4 and C1-C4. The period of analysis was 50 years. The difference in embodied energy of the building due to application of insulation at various levels of thicknesses was evaluated. Using the building model at the different levels of floor slab insulation thicknesses and depths (vertical insulation) or widths (horizontal insulation), annual energy consumption was evaluated for each of the scenarios. The differences between annual building energy consumption when insulation was used and annual building energy consumption without insulation being used were evaluated. They represented the possible annual operational site energy savings at the given level of insulation thickness.

2.6.1. Saved energy after 50 years

The saved energy after 50 years (period for evaluating embodied energy) is given by equation 6:

$$ES_n = \frac{\{\sum_{t=1}^{t=n} OE_S\} - EE_n}{A_F} \quad (6)$$

The terms EE_n and CE_n respectively refer to the estimated increase in embodied energy of the building due to application of the floor slab insulation measure at a certain level of thickness (over a lifecycle period of 50 years). The terms OE_S and OC_S respectively refer to the estimated annual savings in operational site energy due to the application of floor-slab insulation at a certain level of thickness and depth (for vertical insulation) or width (for horizontal insulation). The terms ES_n and CS_n respectively refer to the estimated net saved energy per square meter of nett floor area (A_F) that are accumulated over a period of n years (50 years in this case) due to the application of the floor slab insulation at a certain level of thickness and depth (vertical) or width (horizontal). Larger values of ES_n and CS_n at certain level of floor slab insulation thickness and depth (vertical insulation) or width (horizontal insulation) indicate higher benefits are accrued due to application of the floor slab insulation.

2.6.2. Energy payback periods

The payback periods due to increase in operational energy and increase in embodied energy (over 50 years) because of the application of the floor slab insulation were also evaluated at different levels of floor slab insulation thicknesses and depths (vertical insulation) or width (horizontal insulation). The annual operational source energy savings corresponding to the use of the floor slab insulation at the same level of thickness that resulted in the increase in embodied energy were first evaluated. Equation 7 shows how the energy payback period (PB_E) was evaluated.

$$PB_E = \frac{EE_n}{OE_S} \quad (7)$$

2.6.3. Validation of the building energy model

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The SANS10400-XA (2022) validation standards were used as basis for validating the energy models. These standards state the maximum allowable annual energy consumption per square meter of nett floor area for residential buildings (classified as H3 and H4) in each of the seven South African energy zones. The occupancy and utilization rate schedules recommended by SANS 10400-XA are all greater than zero over the 24 hours of each day in a given week. The implication is that a residential building is assumed to be partly occupied at any time of the day, throughout the week. Therefore, when the simulations are run, 95% of the 8760 annual hours must be between temperatures of 19°C and 25°C inclusive (SANS10400-XA, 2022). Prior to running the simulations, the heating and cooling set point schedules were aligned with the recommended indoor comfort temperatures. After the simulations, the annual cooling and heating loads not met (in form of hours outside the comfort range) were obtained and compared to the maximum 5% allowed by SANS10400-XA standards.

While site energy corresponds to the amount of energy consumed by the building as reflected on the utility bills, source energy, refers to the energy consumed by utilities and other entities in order to supply the energy consumed by the building. EnergyPlus computes both site energy and source energy. The South African standards stipulate that the annual energy consumption per nett floor area of the building is based on the sum of the monthly consumption of 12 consecutive months (SANS10400-XA, 2022). The nett floor area, according to SANS10400-XA, 2022, is the floor area within a building envelope including area occupied by vertical elements such as internal walls, lift wells, enclosed stairs, storage areas and rooms. Since the model only used electricity from the grid, annual energy consumption directly corresponds to the building's site energy (as reflected on the electricity utility bill) rather than source energy. Site energy was used as basis for model validation and for evaluating the impact of the floor-slab XPS and polyiso insulation measures.

3. Results

3.1. Climatic recommendations and SANS 10400-XA Test results

Climate consultant results

Table 1 shows the results based on the adaptive comfort model and ASHRAE standard 55 model. The details of the best ten design guidelines extracted are summarized in the table in order of importance (highest number of comfortable hours added)

Table 1. Further details of the design guidelines that ensure 100% thermal comfort.

Guideline	Design Guideline	Zone1	Zone2	Zone3	Zone4	Zone5	Zone 5H	Zone6	Zone7
11	Heat gain from lights, people, and equipment greatly reduces heating needs so keep home tight, well insulated (to lower Balance Point temperature)	5	4	4	1	1	1	7	2
58	Shade to prevent over-heating, open house to breezes in summer and use passive solar gain in winter.	1	2	1	2	3	8	3	7
62	Use light-weight construction, with slab on grade, operable walls and shaded outdoor spaces	2	1	2	3	2	3	2	4
35	Good natural ventilation: use shaded windows that are oriented to prevailing breezes.	3	3	3	4	4	5	1	5
56	Screened porches and patios can provide passive comfort cooling by ventilation in warm weather and can prevent insect problems.	9	6	5	5	10		9	

63	In overcast cool climates, use low mass tightly sealed well insulated construction to provide rapid heat build-up in morning.				6		6		
55	Use low-pitched roofs with wide overhangs	8	7	7	7	9	11	8	10
19	For passive solar heating, face most of the glass area north to maximize winter sun exposure, but overhangs should be designed to fully shade in summer.	4	8	8	8	5	2	4	1
10	Glazing should minimize conductance loss and gain because undesired solar radiation gain has less impact on the temperate climate in Port Elizabeth				9		4		
33	Long narrow building floor plan helps to maximize cross-ventilation in this temperate, hot humid climate.	7	5	6	10	6	10	6	9
20	Provide double pane high performance glazing (Low-E) on west, south, and east, but clear on north for maximum passive solar gain	6	9	10		7		5	3
3	For heating and cooling, lower the indoor comfort temperature at night to reduce energy consumption (**At home:** 6pm to midnight=70-80°F; Midnight to 6am =55-78°F; 6am to 8am=70-80°F; **Not at home (work, school)**:8am to 6pm=65-85°F)		10		12	8	7		6
31	Organize floorplan so winter sun penetrates into daytime use spaces with specific functions that coincide with solar orientation	10							
36	To facilitate cross ventilation, locate door and window openings on opposite sides of building with larger openings facing up-wind if possible			9					
37	Window overhangs (designed for this latitude) or operable sunshades (awnings that extend in summer) can reduce or eliminate air conditioning							10	
8	Sunny wind-protected outdoor spaces can extend living areas in cool weather (seasonal sun rooms, enclosed patios, courtyards, or verandahs)						9		
1	Tiles or slate (even on wood floors) or a stone-faced fireplace provides enough surface mass to store winter daytime solar gain and summer nighttime 'coolth'								8

Source: Author.

The most important passive strategies, for all six thermal zones on average were 62, 11, 58, and 35. These strategies are the use of light-weight construction, with slab on grade, operable walls and shaded outdoor spaces; Use of internal Heat gains; Use of shade to prevent over-heating, opening the house to breezes in summer and use of passive solar gain in winter; Use of Good natural ventilation by using shaded windows that are oriented to prevailing breezes. A rectangular building floor plan would benefit all zones (Zone2, followed by zones 6 and 7 get highest benefits). Similarly, heat gain from lights, from people, and from equipment, facing the house North, and use of low pitched roof with wide overhangs benefit all zones. The design guideline 3 was overridden by SANS10400-XA recommended indoor temperature comfort range values of 19 to 25°C. Furthermore 69.7% of dwellings in South Africa utilize the brick or concrete block as the building element for the wall envelope (STATSA, 2021). Although mostly these materials are not light weights, thy are representative of the South African household dwelling preferences.

Therefore, most windows should be facing North and South directions for cross-ventilation and solar gain purposes in all zones. The inside floor and walls can be covered with high mass materials to store heat during the day and release it later at night.

Table 2 shows some of the design parameters of the building model.

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Table 2. Other details from the design.

Item	**Details**
Energy Zones:	Energy zones 1, 2, 3, 4, 5, 5H, 6 and 7
Location:	Welkom=zone1; Pretoria=zone2; Nespruit=zone3; Cape Town=zone4; Mthatha=zone5; Ixopo=zone5H; Kimberley=zone6; Fraserburg=zone7;
Shading depths (m)	Welkom =0.62; Pretoria=0.54; Nelspruit=0.54; Cape Town=0.73; Mthatha=0.68; Ixopo=0.68; Kimberley=0.57; Fraserburg=0.68.
Orientation of Building	Front wall faces North; Back wall faces South; Right wall faces East; Left wall faces West
Inside Length of the floor (m): runs East-West direction	15.5m
Inside Width of the floor (m): runs North-South direction	6.8m
Nett floor area (m²)	105.40 m²
Wall height (m)	2.7m
Inner wall thickness (m)	0.90m
Net Inner wall area (m²)	89.06m²
***Cavity wall thickness*: Gypsum plaster, Clay brick leaf1, Air Gap, Clay brick leaf 2, Gypsum plaster (units: m)**	0.010m, 0.110m, 0.050m, 0.110m, 0.010m
***Cavity wall*: Surface Density; R-Value; U-Value; [SANS10400-XA Reference R-Values]**	431.08 Kg/m² ; 0.68 m²K/W; 1.46 W/m²K; [Ref R: 0.4 & 0.6 m²K/W]
***Roof*: materials**	Lightweight metal Material; Gypsum plasterboard ceiling; OSB decking/sheathing, Insulation
***Roof*: R-Value; U-Value; [SANS10400-XA Reference R-Value]**	3.8 m²K/W; 0.46 W/m²K; [3.7 m²K/W]
Fenestration	
Fenestration to Nett floor area ; total fenestration area (m²)	0.228 m² ; 11.886 m²
U-Value; [SANS10400-XA U-Value reference upper limit]	2.258; [5.20 W/m²K]
SHGC ; [SANS10400-XA reference upper limit]	0.571; [0.66]
Window to wall ratios (WWRs)	
Front; Back; Left; Right WWRs [Overall WWR]	0.277; 0.240; 0.05; 0.05 [0.20]
Window to floor area	0.22
Cavity wall materials	***Values*** *(Density; Specific heat; conductivity; Embodied energy coefficient; Embodied CO_2 coefficient)**: SI units***
1.Clay brick (Service life=150 years or more)	1826Kgm⁻³; 0.835KJ/Kg.K; 0.820W/m.K; 3.20MJ/Kg; 0.240KgCO_2/Kg
Floor	
Floor slab thickness (m)	0.100
XPS vertical insulation (service life=100 years)	32 Kgm⁻³; 1.50 KJ/Kg.K; 0.028 W/m.K; 89.5 MJ/Kg; 2.80 (-1.41) KgCO_2/Kg
Polyiso vertical insulation (service life=120 years)	35 Kgm⁻³; 0.80 KJ/Kg.K; 0.025 W/m.K; 72 MJ/Kg; 3.9695 KgCO_2/Kg
Insulation depths analysed (m)	0.20 to 2.0 m an intervals of o,20m
Insulation thicknesses analysed (mm)	25, 50, 100, 150, 200mm
Foundation thickness (m): Strip Foundation (Stones used)	0.220m
WWR computation	Source energy was used as basis. (The only source of energy was electricity)
Model validation	Site energy was compared to standards (The only source of energy was electricity)

Model's determination of impact of insulation measures	Energy savings were based on site energy(The only source of energy was electricity)
Schedules: Cooling set point; Heating set point; Relative Humidity (weekdays and weekend)	25°C ; 19°C ; 60%

Source: Author.

For embodied energy computations, the period of analysis was 50 years, the average distance from factory to site was taken to be 220km, the average distance from site to landfill was 70km, and the fraction of material that is wasted was 2.5%. The energy to carbon conversion factor used was 1.131Kg/KWh, while the average cargo mass for transportation truck used was 18 tonnes.

3.2. Optimum Window to wall ratios

The optimum WWRs used were based on an earlier study. The detailed results of the analysis are not presented here, but the final WWRs are indicated in Table 2. The steps involved the simulation of annual energy consumption using EnergyPlus, regressing annual energy consumption over the WWRs, and optimization using the regression models and the Ms Excel-based evolutionary algorithm. The stargazer package in R was used to generate the regression models (Hlavac, 2022).

3.3. Energy Savings Model Validation for vertical gap insulation

Using the adopted WWRs, (Table 2) and recommended SANS 10400-XA load schedules, modifications were made in the building design and energy model before running the energy simulations to determine impact of the floor-slab insulation measures. The model validation consisted of two components. The first consisted of the evaluation and comparison of site energy consumption per square meter of nett floor area with the maximum allowable according to SANS10400-XA. The second consisted of the evaluation of unmet heating and cooling loads annually and comparing them to the maximum allowable SANS10400-XA of 5%.

3.3.1. Site energy consumption per square meter floor area (vertical gap insulation).

Table 3 shows the summarized site energy (and source energy in brackets) consumption statistics (according to energy zones) per nett floor area and the corresponding SANS10400-XA maximum site energy limits.

Table 3. Maximum, minimum and mean annual site energy consumption per nett floor area and loads not met (hours).

	Zone1	**Zone2**	**Zone3**	**Zone4**	**Zone5**	**Zone5 H**	**Zone6**	**Zone7**
Site Energy (Source Energy)								
Maximum (KWh/m²)	24.61 (77.7)	25.61 (80.79)	25.72 (81.23)	24.11 (76.14)	23.08 (72.69)	24.5 (77.36)	27.09 (85.35)	28.06 (88.29)
Minimum (KWh/m²)	20.83 (65.82)	20.69 (65.27)	21.47 (67.63)	23.39 (73.72)	21.19 (66.88)	21.91 (69.16)	22.61 (71.3)	23.8 (75.14)
Mean (KWh/m²)	22.22 (70.09)	22.49 (70.94)	23.13 (72.94)	23.75 (74.94)	21.82 (68.85)	22.82 (71.97)	24.22 (76.36)	25.43 (80.21)
SD (KWh/m²)	1.005 (3.164)	1.341 (4.231)	1.197 (3.797)	0.182 (0.566)	0.5 (1.576)	0.71 (2.24)	1.156 (3.653)	1.043 (3.284)
SANS10400-XA Reference (KWh/m²)	**90**	**100**	**50**	**80**	**85**	**60**	**110**	**110**

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Annual heating and cooling load not met								
Maximum (% hours)	0%	2%	1%	0%	2%	1%	1%	0%
Minimum (% hours)	0%	0%	0%	0%	1%	0%	0%	0%
Mean (% hours)	0%	1%	0%	0%	1%	0%	0%	0%
SD (% hours)	0.00%	0.61%	0.20%	0.00%	0.23%	0.26%	0.08%	0.00%
SANS 10400-XA Reference (% hours)	**5%**	**5%**	**5%**	**5%**	**5%**	**5%**	**5%**	**5%**

Source: Author.

The results show that the models used across all the energy zones were within the acceptable SANS10400-XA site energy limits per square meter of nett floor area.

The results also show that all the loads (sum of heating and cooling loads) which were not met annually were all less than 5%. The highest loads not met appeared to occur in energy zone 2, while the least occurred in energy zones 1 and 7. Therefore all the models used fulfilled the requirements of the SANS10400-XA standards.

3.3.2. Embodied energy of the building.

The evaluated embodied energy of the building (for 50 years) without using insulation in the wall envelope was 439556.8 MJ or 4170.4 MJ/m^2 (of nett floor area)**.** The embodied energy due to the floor was 99289.7MJ or 942.03MJ/m^2 (of nett floor area). The results are comparable to research done in other countries like Australia. Crawford (2019) used the input-output analysis method for evaluation of embodied quantities. While Crawford (2019) uses a 110mm thick concrete slab (leading to a 1053MJ/m^2 evaluation), this research uses a 100mm thick concrete slab.

3.4. Energy payback periods for vertical gap insulation depths greater or equal to 0.4m

The energy payback periods were evaluated using equation 7. Figures 4–7 illustrate the results:

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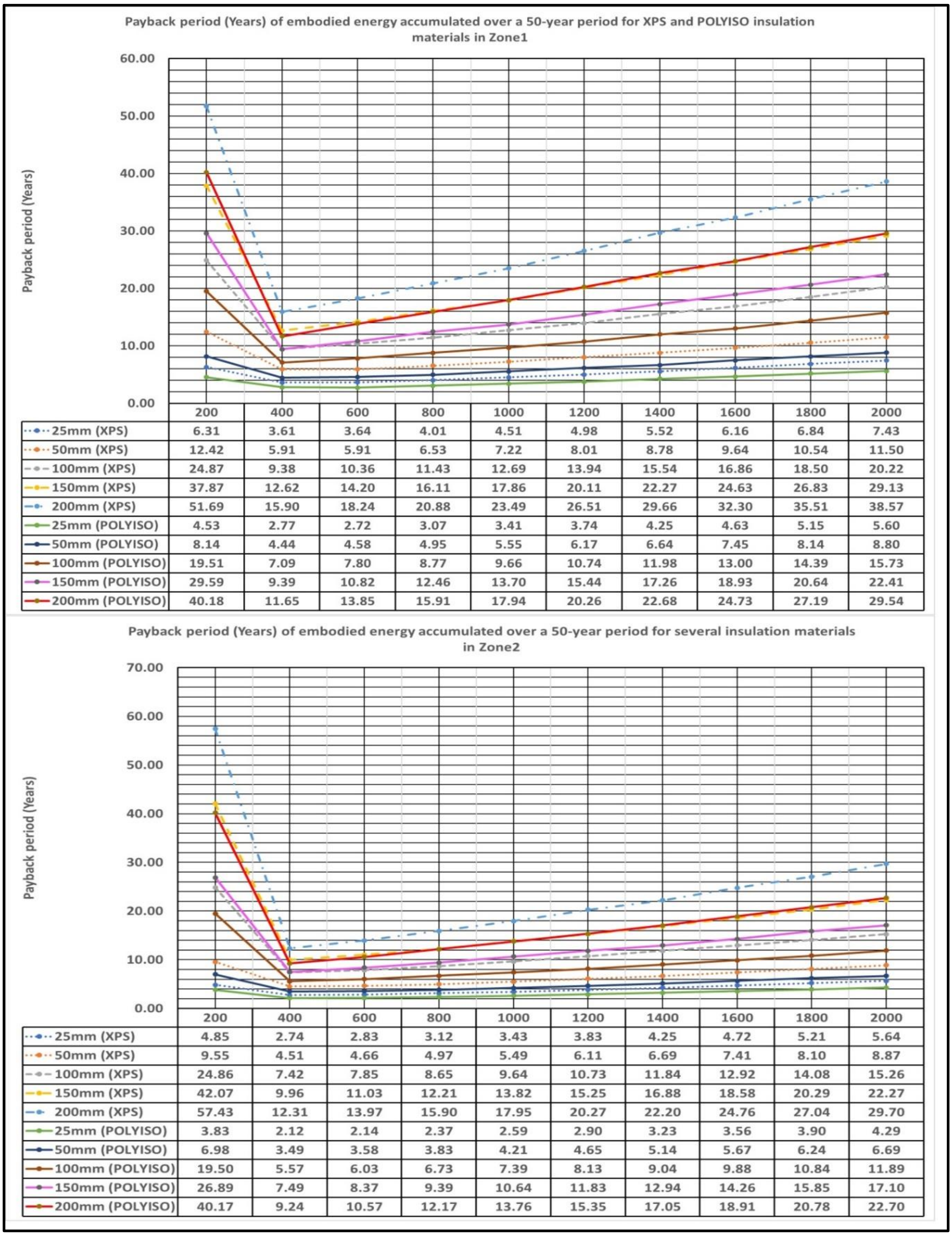

	200	400	600	800	1000	1200	1400	1600	1800	2000
25mm (XPS)	6.31	3.61	3.64	4.01	4.51	4.98	5.52	6.16	6.84	7.43
50mm (XPS)	12.42	5.91	5.91	6.53	7.22	8.01	8.78	9.64	10.54	11.50
100mm (XPS)	24.87	9.38	10.36	11.43	12.69	13.94	15.54	16.86	18.50	20.22
150mm (XPS)	37.87	12.62	14.20	16.11	17.86	20.11	22.27	24.63	26.83	29.13
200mm (XPS)	51.69	15.90	18.24	20.88	23.49	26.51	29.66	32.30	35.51	38.57
25mm (POLYISO)	4.53	2.77	2.72	3.07	3.41	3.74	4.25	4.63	5.15	5.60
50mm (POLYISO)	8.14	4.44	4.58	4.95	5.55	6.17	6.64	7.45	8.14	8.80
100mm (POLYISO)	19.51	7.09	7.80	8.77	9.66	10.74	11.98	13.00	14.39	15.73
150mm (POLYISO)	29.59	9.39	10.82	12.46	13.70	15.44	17.26	18.93	20.64	22.41
200mm (POLYISO)	40.18	11.65	13.85	15.91	17.94	20.26	22.68	24.73	27.19	29.54

	200	400	600	800	1000	1200	1400	1600	1800	2000
25mm (XPS)	4.85	2.74	2.83	3.12	3.43	3.83	4.25	4.72	5.21	5.64
50mm (XPS)	9.55	4.51	4.66	4.97	5.49	6.11	6.69	7.41	8.10	8.87
100mm (XPS)	24.86	7.42	7.85	8.65	9.64	10.73	11.84	12.92	14.08	15.26
150mm (XPS)	42.07	9.96	11.03	12.21	13.82	15.25	16.88	18.58	20.29	22.27
200mm (XPS)	57.43	12.31	13.97	15.90	17.95	20.27	22.20	24.76	27.04	29.70
25mm (POLYISO)	3.83	2.12	2.14	2.37	2.59	2.90	3.23	3.56	3.90	4.29
50mm (POLYISO)	6.98	3.49	3.58	3.83	4.21	4.65	5.14	5.67	6.24	6.69
100mm (POLYISO)	19.50	5.57	6.03	6.73	7.39	8.13	9.04	9.88	10.84	11.89
150mm (POLYISO)	26.89	7.49	8.37	9.39	10.64	11.83	12.94	14.26	15.85	17.10
200mm (POLYISO)	40.17	9.24	10.57	12.17	13.76	15.35	17.05	18.91	20.78	22.70

Figure 4. Energy payback period for zone 1 and zone 2, at different levels of slab insulation depth (200 to 2000mm) and insulation thickness (25 to 200mm). Source: Author.

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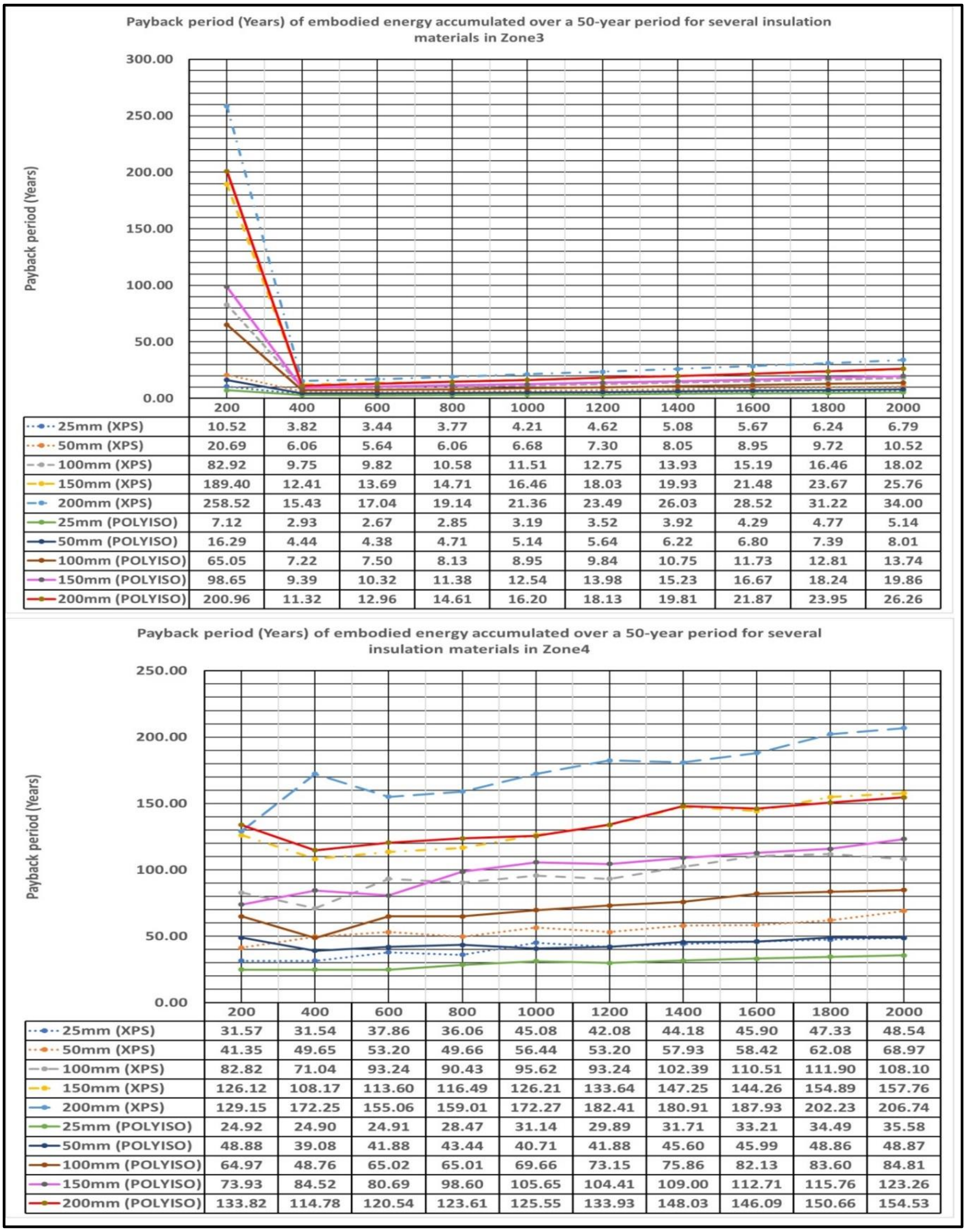
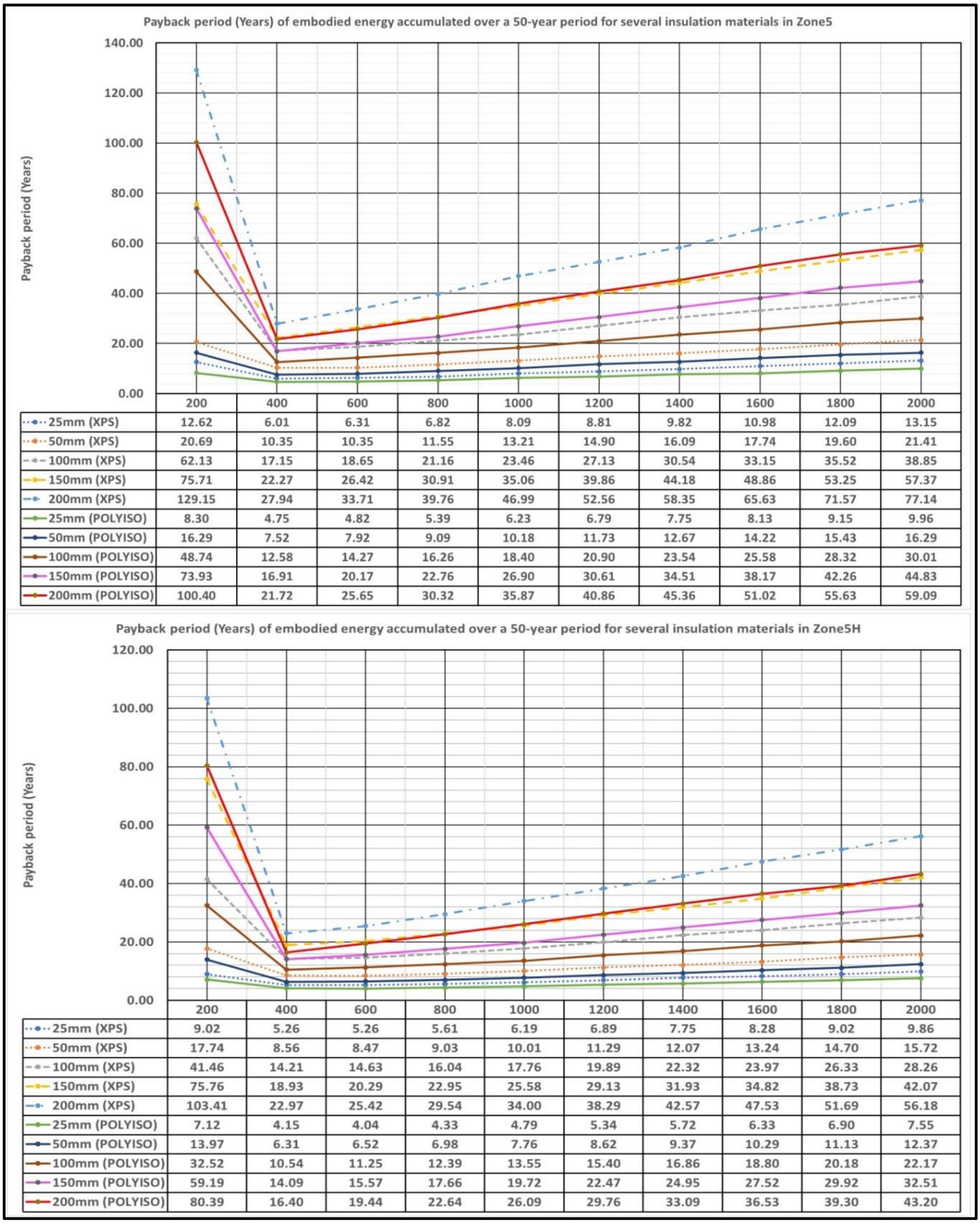


	200	400	600	800	1000	1200	1400	1600	1800	2000
25mm (XPS)	10.52	3.82	3.44	3.77	4.21	4.62	5.08	5.67	6.24	6.79
50mm (XPS)	20.69	6.06	5.64	6.06	6.68	7.30	8.05	8.95	9.72	10.52
100mm (XPS)	82.92	9.75	9.82	10.58	11.51	12.75	13.93	15.19	16.46	18.02
150mm (XPS)	189.40	12.41	13.69	14.71	16.46	18.03	19.93	21.48	23.67	25.76
200mm (XPS)	258.52	15.43	17.04	19.14	21.36	23.49	26.03	28.52	31.22	34.00
25mm (POLYISO)	7.12	2.93	2.67	2.85	3.19	3.52	3.92	4.29	4.77	5.14
50mm (POLYISO)	16.29	4.44	4.38	4.71	5.14	5.64	6.22	6.80	7.39	8.01
100mm (POLYISO)	65.05	7.22	7.50	8.13	8.95	9.84	10.75	11.73	12.81	13.74
150mm (POLYISO)	98.65	9.39	10.32	11.38	12.54	13.98	15.23	16.67	18.24	19.86
200mm (POLYISO)	200.96	11.32	12.96	14.61	16.20	18.13	19.81	21.87	23.95	26.26

	200	400	600	800	1000	1200	1400	1600	1800	2000
25mm (XPS)	31.57	31.54	37.86	36.06	45.08	42.08	44.18	45.90	47.33	48.54
50mm (XPS)	41.35	49.65	53.20	49.66	56.44	53.20	57.93	58.42	62.08	68.97
100mm (XPS)	82.82	71.04	93.24	90.43	95.62	93.24	102.39	110.51	111.90	108.10
150mm (XPS)	126.12	108.17	113.60	116.49	126.21	133.64	147.25	144.26	154.89	157.76
200mm (XPS)	129.15	172.25	155.06	159.01	172.27	182.41	180.91	187.93	202.23	206.74
25mm (POLYISO)	24.92	24.90	24.91	28.47	31.14	29.89	31.71	33.21	34.49	35.58
50mm (POLYISO)	48.88	39.08	41.88	43.44	40.71	41.88	45.60	45.99	48.86	48.87
100mm (POLYISO)	64.97	48.76	65.02	65.01	69.66	73.15	75.86	82.13	83.60	84.81
150mm (POLYISO)	73.93	84.52	80.69	98.60	105.65	104.41	109.00	112.71	115.76	123.26
200mm (POLYISO)	133.82	114.78	120.54	123.61	125.55	133.93	148.03	146.09	150.66	154.53

Figure 5. Energy payback period for zone 3 and zone 4 at different levels of slab insulation depth (200 to 2000mm) and insulation thickness (25 to 200mm). Source: Author.



	200	400	600	800	1000	1200	1400	1600	1800	2000
25mm (XPS)	12.62	6.01	6.31	6.82	8.09	8.81	9.82	10.98	12.09	13.15
50mm (XPS)	20.69	10.35	10.35	11.55	13.21	14.90	16.09	17.74	19.60	21.41
100mm (XPS)	62.13	17.15	18.65	21.16	23.46	27.13	30.54	33.15	35.52	38.85
150mm (XPS)	75.71	22.27	26.42	30.91	35.06	39.86	44.18	48.86	53.25	57.37
200mm (XPS)	129.15	27.94	33.71	39.76	46.99	52.56	58.35	65.63	71.57	77.14
25mm (POLYISO)	8.30	4.75	4.82	5.39	6.23	6.79	7.75	8.13	9.15	9.96
50mm (POLYISO)	16.29	7.52	7.92	9.09	10.18	11.73	12.67	14.22	15.43	16.29
100mm (POLYISO)	48.74	12.58	14.27	16.26	18.40	20.90	23.54	25.58	28.32	30.01
150mm (POLYISO)	73.93	16.91	20.17	22.76	26.90	30.61	34.51	38.17	42.26	44.83
200mm (POLYISO)	100.40	21.72	25.65	30.32	35.87	40.86	45.36	51.02	55.63	59.09

	200	400	600	800	1000	1200	1400	1600	1800	2000
25mm (XPS)	9.02	5.26	5.26	5.61	6.19	6.89	7.75	8.28	9.02	9.86
50mm (XPS)	17.74	8.56	8.47	9.03	10.01	11.29	12.07	13.24	14.70	15.72
100mm (XPS)	41.46	14.21	14.63	16.04	17.76	19.89	22.32	23.97	26.33	28.26
150mm (XPS)	75.76	18.93	20.29	22.95	25.58	29.13	31.93	34.82	38.73	42.07
200mm (XPS)	103.41	22.97	25.42	29.54	34.00	38.29	42.57	47.53	51.69	56.18
25mm (POLYISO)	7.12	4.15	4.04	4.33	4.79	5.34	5.72	6.33	6.90	7.55
50mm (POLYISO)	13.97	6.31	6.52	6.98	7.76	8.62	9.37	10.29	11.13	12.37
100mm (POLYISO)	32.52	10.54	11.25	12.39	13.55	15.40	16.86	18.80	20.18	22.17
150mm (POLYISO)	59.19	14.09	15.57	17.66	19.72	22.47	24.95	27.52	29.92	32.51
200mm (POLYISO)	80.39	16.40	19.44	22.64	26.09	29.76	33.09	36.53	39.30	43.20

Figure 6. Energy payback periods for zone 5 and zone 5H at different levels of slab insulation depth (200 to 2000mm) and insulation thickness (25 to 200mm). Source: Author.

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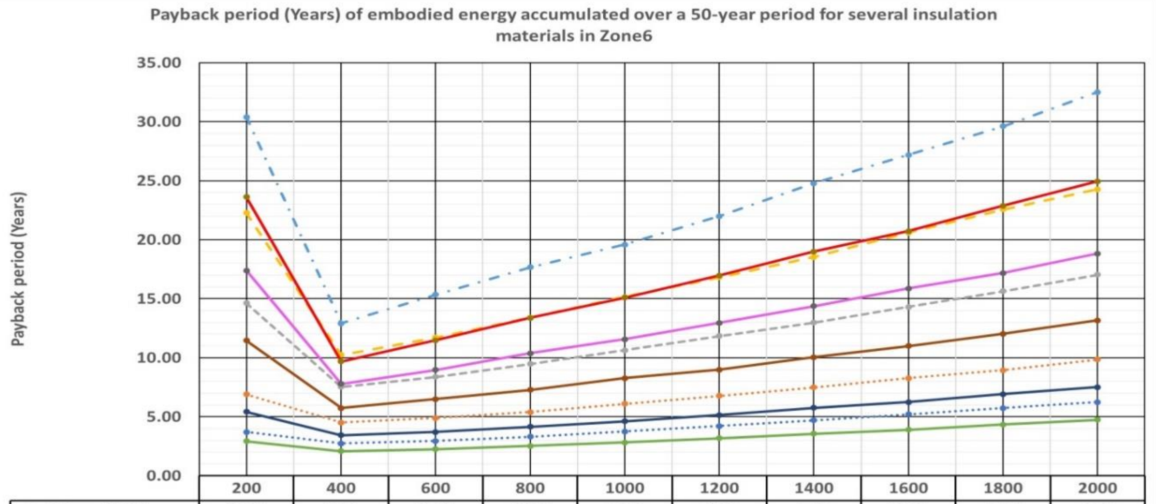
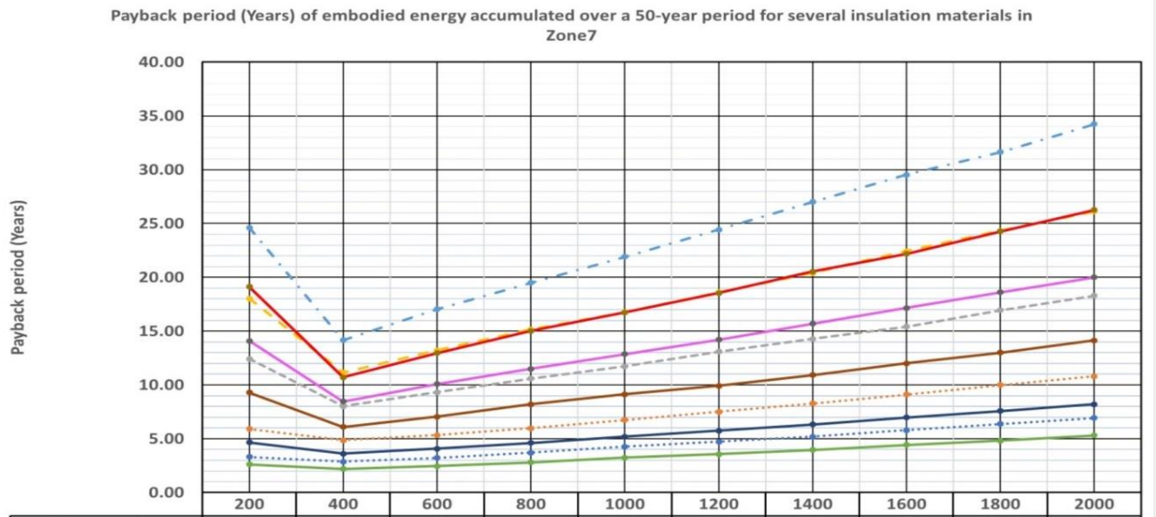


	200	400	600	800	1000	1200	1400	1600	1800	2000
25mm (XPS)	3.71	2.74	2.96	3.32	3.76	4.21	4.70	5.21	5.74	6.25
50mm (XPS)	6.90	4.51	4.90	5.40	6.09	6.77	7.49	8.28	8.94	9.85
100mm (XPS)	14.63	7.54	8.38	9.47	10.63	11.84	12.99	14.31	15.65	17.03
150mm (XPS)	22.27	10.23	11.71	13.40	15.15	16.83	18.54	20.61	22.57	24.27
200mm (XPS)	30.40	12.92	15.35	17.67	19.58	21.99	24.78	27.20	29.63	32.51
25mm (POLYISO)	2.93	2.08	2.26	2.52	2.83	3.18	3.56	3.91	4.35	4.74
50mm (POLYISO)	5.43	3.43	3.71	4.16	4.61	5.14	5.75	6.25	6.93	7.52
100mm (POLYISO)	11.47	5.74	6.50	7.29	8.27	9.00	10.04	10.99	12.02	13.18
150mm (POLYISO)	17.40	7.79	8.97	10.38	11.56	12.96	14.38	15.88	17.18	18.84
200mm (POLYISO)	23.63	9.68	11.48	13.39	15.10	16.98	19.00	20.74	22.89	24.96



	200	400	600	800	1000	1200	1400	1600	1800	2000
25mm (XPS)	3.32	2.87	3.21	3.71	4.26	4.73	5.20	5.80	6.38	6.94
50mm (XPS)	5.91	4.87	5.32	5.98	6.75	7.52	8.28	9.11	9.98	10.80
100mm (XPS)	12.43	8.02	9.32	10.58	11.73	13.09	14.27	15.42	16.95	18.28
150mm (XPS)	18.03	11.14	13.21	15.15	16.75	18.62	20.39	22.44	24.34	26.11
200mm (XPS)	24.61	14.16	17.04	19.50	21.90	24.42	27.00	29.53	31.64	34.23
25mm (POLYISO)	2.62	2.21	2.45	2.81	3.24	3.56	3.96	4.43	4.82	5.30
50mm (POLYISO)	4.65	3.62	4.07	4.60	5.20	5.75	6.33	6.98	7.58	8.21
100mm (POLYISO)	9.29	6.10	7.05	8.21	9.12	9.92	10.92	12.00	13.00	14.14
150mm (POLYISO)	14.09	8.45	10.09	11.49	12.86	14.20	15.69	17.15	18.62	19.99
200mm (POLYISO)	19.13	10.71	12.96	15.02	16.74	18.54	20.53	22.17	24.27	26.26

Figure 7. Energy payback periods for zone 6, and zone 7 at different levels of slab insulation depth (200 to 2000mm) and insulation thickness (25 to 200mm). Source: Author.

Figures 4 to 7 show that using at the same floor insulation thickness levels, XPS leads to higher payback periods compared to polyiso insulation for all energy zones. The Figures also indicate that higher insulation thicknesses for XPS and polyiso lead to higher payback periods. Therefore 25mm thick polyiso would yield the lowest payback periods followed by 25mm thick XPS.

Except for zone 4, the payback periods tend to reduce as the insulation depth is increased up to 400mm, and thereafter, they increase with increases in insulation depth. Except for zone 4, it appears

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that the insulation depths corresponding to lowest payback periods occur somewhere between 200mm and 400mm for both XPS and polyiso with respect to all levels of thickness (25mm to 200mm). Therefore, low insulation depth does not necessarily lead to energy savings, for insulation depth below 400mm. For insulation depths of 400mm and above, the highest payback periods occur in zone 4, followed by zone 5 and zone 5H. The lowest payback periods occur in zone 2, followed by zone 6, zone 3 and zone 7. Therefore, it is inadvisable to use vertical perimeter floor slab insulation in zone 4 using XPS or polyiso.

Using these results, it is therefore apparent that 25mm thick polyiso at insulation depth of 400mm would generally yield the lowest payback periods in energy zones 1, 2, 3, 5, 5H, 6 and 7. It was followed by 25mm thick XPS at insulation depth of 400mm. For insulation depths greater or equal to 400mm, Zone 2, zone 6, zone 3 and zone 7 had the lowest energy payback periods in that order. For insulation depths greater or equal to 400mm, Zone 4, zone 5, zone 5H and zone 1 had the highest energy payback periods in that order. The highest energy payback periods for XPS and polyiso in the energy zones were respectively 38.6 and 29.5 years in zone 1; 29.7 and 22.7 years in zone 2; 34.0 and 26.3 in zone 3; 206.7 and 154.5 in zone 4; 77.1 and 59.1 in zone 5; 56.2 and 46.2 in zone 5H; 32.5 and 25.0 in zone 6; 34.2 and 26.3 in zone 7.

3.5. Net saved energy for vertical gap insulation after 50 years

Equation 6 was used to evaluate the net saved energy after 50 years. Only the results for maximum and minimum net energy savings are presented in Table 6.

3.5.1. Minimum and maximum values per energy zone

Table 4 below shows the minimum and maximum net energy saving per square meter of nett floor area after 50 years, for the insulation materials and the energy zones.

Table 4. Minimum and maximum net energy savings per square meter of nett floor area (KWh/m^2) after 50 years.

	Zone1 (min ; max)	Zone2 (min ; max)	Zone3 (min ; max)	Zone4 (min ; max)	Zone5 (min ; max)	Zone5H (min ; max)	Zone6 (min ; max)	Zone7 (min ; max)
XPS (25mm)	12.1 ; 100.6	16.3 ; 138.2	6.6 ; 111.8	0.5 ; 2.7	5.2 ; 50.3	8 ; 71.8	21.9 ; 122.9	24.7 ; 109
XPS (50mm)	10.5 ; 116.3	14.6 ; 160.8	4.9 ; 129.5	-9.5 ; 0.7	4.9 ; 50.9	6.3 ; 76.7	21.6 ; 142.7	25.7 ; 125.4
XPS (100mm)	7 ; 108.8	7 ; 158.8	-2.7 ; 126.9	-37.2 ; -2.7	-1.4 ; 39.1	1.4 ; 62.8	16.7 ; 138	20.9 ; 124
XPS (150mm)	3.4 ; 94.7	2 ; 144.6	-7.8 ; 112	-71.9 ; -6.4	-13.5 ; 28.2	-3.6 ; 50.2	13.1 ; 125.1	18.7 ; 107
XPS (200mm)	-0.5 ; 81.1	-1.9 ; 128.4	-11.6 ; 97.3	-109 ; -8.8	-50.6 ; 22.7	-15.8 ; 41.7	9.3 ; 111.7	14.8 ; 92.2
Polyiso (25mm)	13.9 ; 109.9	16.7 ; 147.4	8.3 ; 121	1.4 ; 5.6	7 ; 57	8.3 ; 77.9	22.3 ; 132.1	25 ; 116.8
Polyiso (50mm)	14 ; 127.2	16.8 ; 175.8	5.6 ; 142.5	0.1 ; 3.2	5.6 ; 56.3	7 ; 85.4	22.3 ; 153.6	26.5 ; 138.3
Polyiso (100mm)	8.5 ; 123.5	8.5 ; 176.4	-1.3 ; 143.2	-22.3 ; 0.3	0.1 ; 46.6	2.9 ; 74.7	18.2 ; 154.2	23.8 ; 138.9
Polyiso (150mm)	5.7 ; 110.5	7.1 ; 165	-4.1 ; 131.6	-48.9 ; -2.7	-2.7 ; 39.4	-1.3 ; 63.1	15.4 ; 142.6	21 ; 126.1
Polyiso (200mm)	2.7 ; 99.9	2.7 ; 151.3	-8.4 ; 119.2	-75.6 ; -7	-17.2 ; 31.8	-4.2 ; 54	12.5 ; 130.4	18 ; 113.7

Source: Author.

The results indicate that the maximum net energy savings are not necessarily achieved at the highest insulation thickness levels and appear to be influenced by the insulation type, insulation thickness and the location or the energy zones.

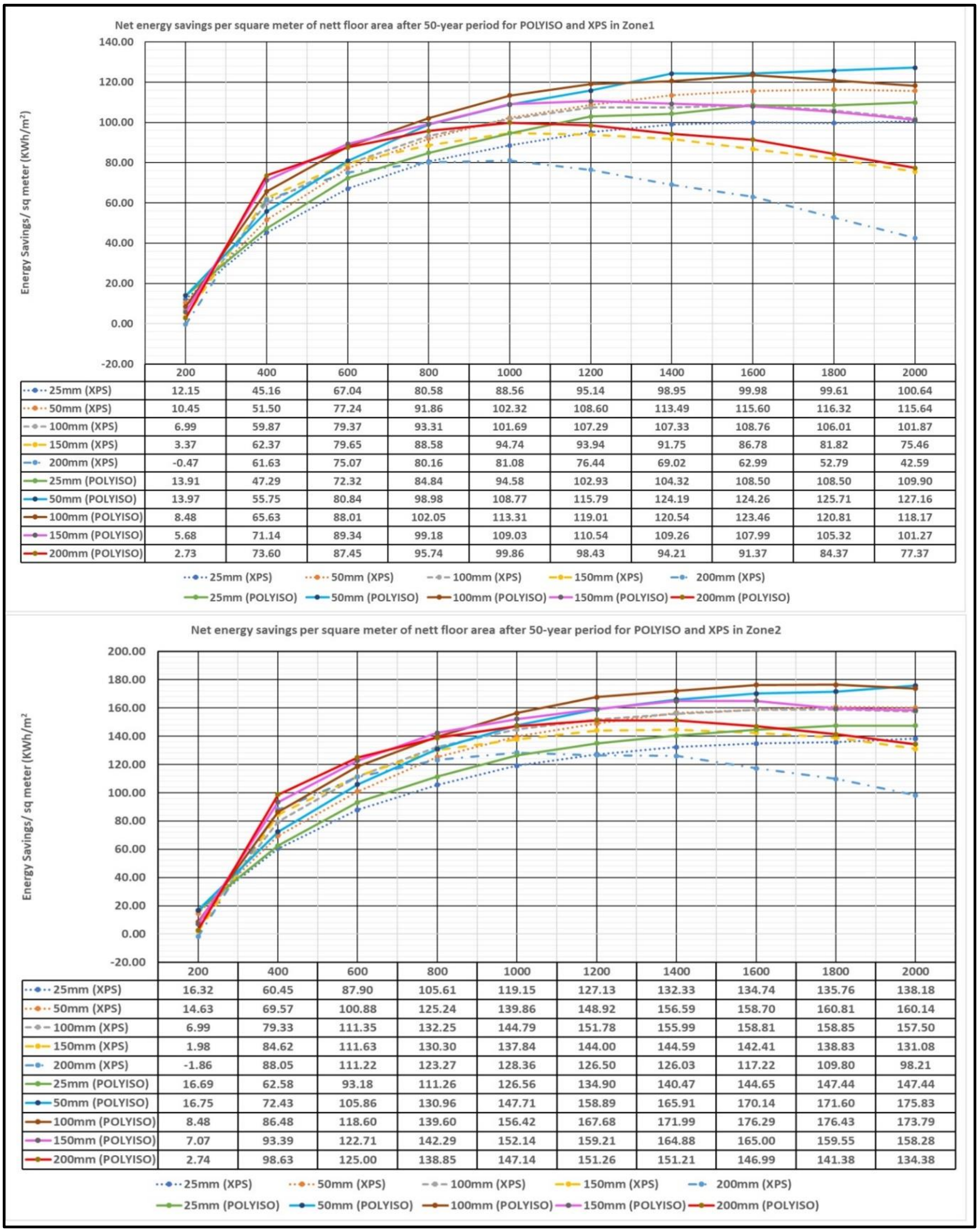
XPS: The maximum energy savings in zone 1, zone 2, zone 3, Zone 5, zone 5H, zone 6 and zone 7 occurred at floor-slab insulation thickness of 50mm. The maximum energy savings in zone 4 occurred at floor-slab insulation thickness of 25mm.

Polyiso: The maximum energy savings in zone 1, and zone 5H occurred at floor-slab insulation thickness of 50mm. The maximum energy savings in zone 2, zone 3, zone 6 and zone 7 all occurred at floor-slab insulation thickness of 100mm. However, the maximum energy savings in zone 4, and zone 5 occurred at floor-slab insulation thickness level of 25mm.

Therefore, based on net energy savings after 50 years, it is best to use Polyiso at insulation thicknesses of 25mm, 50mm or 100mm (depending on the energy zone) and to use XPS at insulation thicknesses of 25mm (zone 4) or 50mm (rest of the energy zones).

3.5.2. General results for net saved energy after 50 years based on zones.

Figures 8–11 represent data for net saved energy per nett floor area after 50 years for the 7 energy zones of South Africa due to use of XPS and polyiso for the floor-slab insulation in the model. The results show that the choice of the best insulation material based on the highest net saved energy per square meter after 50 years may keep changing due to differences in location (zones), the insulation thickness levels, and the insulation depth levels.



	200	400	600	800	1000	1200	1400	1600	1800	2000
25mm (XPS)	12.15	45.16	67.04	80.58	88.56	95.14	98.95	99.98	99.61	100.64
50mm (XPS)	10.45	51.50	77.24	91.86	102.32	108.60	113.49	115.60	116.32	115.64
100mm (XPS)	6.99	59.87	79.37	93.31	101.69	107.29	107.33	108.76	106.01	101.87
150mm (XPS)	3.37	62.37	79.65	88.58	94.74	93.94	91.75	86.78	81.82	75.46
200mm (XPS)	-0.47	61.63	75.07	80.16	81.08	76.44	69.02	62.99	52.79	42.59
25mm (POLYISO)	13.91	47.29	72.32	84.84	94.58	102.93	104.32	108.50	108.50	109.90
50mm (POLYISO)	13.97	55.75	80.84	98.98	108.77	115.79	124.19	124.26	125.71	127.16
100mm (POLYISO)	8.48	65.63	88.01	102.05	113.31	119.01	120.54	123.46	120.81	118.17
150mm (POLYISO)	5.68	71.14	89.34	99.18	109.03	110.54	109.26	107.99	105.32	101.27
200mm (POLYISO)	2.73	73.60	87.45	95.74	99.86	98.43	94.21	91.37	84.37	77.37

	200	400	600	800	1000	1200	1400	1600	1800	2000
25mm (XPS)	16.32	60.45	87.90	105.61	119.15	127.13	132.33	134.74	135.76	138.18
50mm (XPS)	14.63	69.57	100.88	125.24	139.86	148.92	156.59	158.70	160.81	160.14
100mm (XPS)	6.99	79.33	111.35	132.25	144.79	151.78	155.99	158.81	158.85	157.50
150mm (XPS)	1.98	84.62	111.63	130.30	137.84	144.00	144.59	142.41	138.83	131.08
200mm (XPS)	-1.86	88.05	111.22	123.27	128.36	126.50	126.03	117.22	109.80	98.21
25mm (POLYISO)	16.69	62.58	93.18	111.26	126.56	134.90	140.47	144.65	147.44	147.44
50mm (POLYISO)	16.75	72.43	105.86	130.96	147.71	158.89	165.91	170.14	171.60	175.83
100mm (POLYISO)	8.48	86.48	118.60	139.60	156.42	167.68	171.99	176.29	176.43	173.79
150mm (POLYISO)	7.07	93.39	122.71	142.29	152.14	159.21	164.88	165.00	159.55	158.28
200mm (POLYISO)	2.74	98.63	125.00	138.85	147.14	151.26	151.21	146.99	141.38	134.38

Figure 8. Net saved energy after 50 years under zone1 and zone2 at different levels of slab insulation depth (200 to 2000mm) and insulation thickness (25 to 200mm). Source: Author.

Zone1: In zone 1, under XPS insulation, the best insulation thickness at insulation depth from 400mm to 600mm (0.4-0.6m) was 150mm XPS. At 800mm (0.8m) depth, the best XPS insulation thickness was 100mm. At 1000mm to 2000mm (1.0-2.0m) depth, the best XPS insulation thickness was 50mm.

When polyiso was used, the best insulation thickness at 400mm (0.4m) insulation depth, was 200mm thick polyiso. At 600mm (0.6m) depth the best thickness was 150mm. From 800mm to

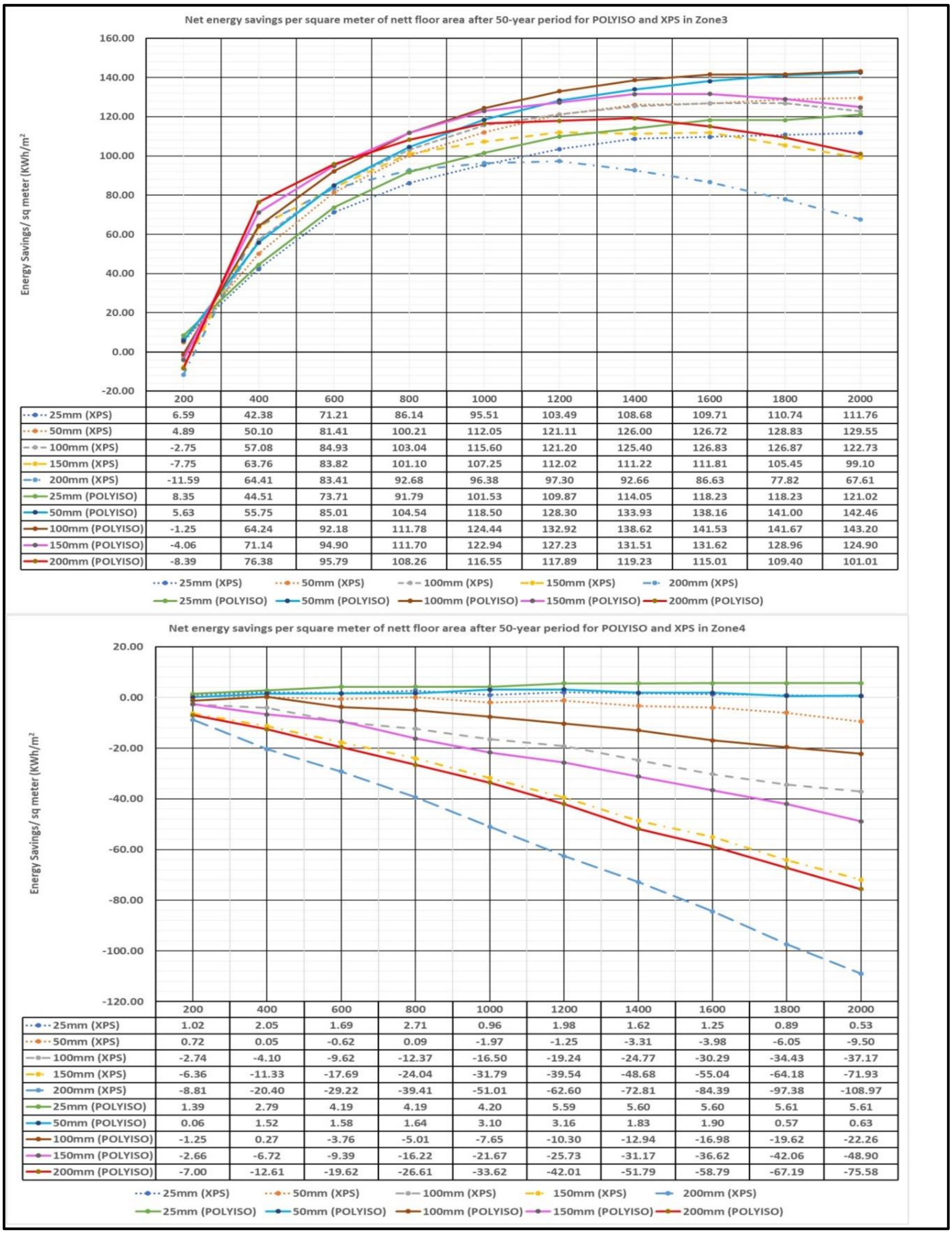
1200mm (0.8-1.2m) depth, the best insulation thickness was 100mm thick polyiso. From 1.4-2.0m depth (1400mm-2000mm), the best insulation thickness was 50mm thick polyiso.

Zone2: In zone 2, under XPS insulation, the best insulation thickness at insulation depth from 400mm (0.4m) upwards, but less than 600mm (0.6m) was 200mm XPS. At 600mm (0.6m) depth, the best XPS insulation thickness was 150mm. At 800mm to 1200mm (0.8-1.2m) depth, the best XPS insulation thickness was 100mm. From 1400 to 2000mm (1.4-2.0m) depth, the best insulation thickness was generally 50mm.

When polyiso was used, the best insulation thickness from 400mm to 600mm (0.4-0.6m) insulation depth, was 200mm thick polyiso. At 800mm (0.8m) depth the best thickness was 150mm. From 1000mm to 1800mm (1.0-1.8m) depth, the best insulation thickness was 100mm thick polyiso. At 2.0m depth (2000mm), the best insulation thickness was 50mm thick polyiso.

These results show that when the insulation depth level is increased, then the optimum thickness that maximizes net energy savings after 50 years reduces. Generally, zone 2 experiences greater energy savings than zone1 for the same insulation thickness levels and insulation depths

Optimal points: Since the maximum energy payback periods for zone 1 and zone 2 for both insulations was less than 50 years, the highest maximum energy savings in zone 1 that also allow a payback period less than 50 years correspond to the use of Polyiso at 50mm thickness and a depth of 2000mm (2.0m). Its payback period is 8.80 years. It corresponds to net energy savings of 127.16KWh/m^2. The highest maximum energy savings in zone 2 that also allow a payback period less than 50 years correspond to the use of Polyiso at 100mm thickness and a depth of 1800mm (1.8m). Its payback period is 10.84 years, It corresponds to net energy savings of 176.14KWh/m^2.



	200	400	600	800	1000	1200	1400	1600	1800	2000
25mm (XPS)	6.59	42.38	71.21	86.14	95.51	103.49	108.68	109.71	110.74	111.76
50mm (XPS)	4.89	50.10	81.41	100.21	112.05	121.11	126.00	126.72	128.83	129.55
100mm (XPS)	-2.75	57.08	84.93	103.04	115.60	121.20	125.40	126.83	126.87	122.73
150mm (XPS)	-7.75	63.76	83.82	101.10	107.25	112.02	111.22	111.81	105.45	99.10
200mm (XPS)	-11.59	64.41	83.41	92.68	96.38	97.30	92.66	86.63	77.82	67.61
25mm (POLYISO)	8.35	44.51	73.71	91.79	101.53	109.87	114.05	118.23	118.23	121.02
50mm (POLYISO)	5.63	55.75	85.01	104.54	118.50	128.30	133.93	138.16	141.00	142.46
100mm (POLYISO)	-1.25	64.24	92.18	111.78	124.44	132.92	138.62	141.53	141.67	143.20
150mm (POLYISO)	-4.06	71.14	94.90	111.70	122.94	127.23	131.51	131.62	128.96	124.90
200mm (POLYISO)	-8.39	76.38	95.79	108.26	116.55	117.89	119.23	115.01	109.40	101.01

	200	400	600	800	1000	1200	1400	1600	1800	2000
25mm (XPS)	1.02	2.05	1.69	2.71	0.96	1.98	1.62	1.25	0.89	0.53
50mm (XPS)	0.72	0.05	-0.62	0.09	-1.97	-1.25	-3.31	-3.98	-6.05	-9.50
100mm (XPS)	-2.74	-4.10	-9.62	-12.37	-16.50	-19.24	-24.77	-30.29	-34.43	-37.17
150mm (XPS)	-6.36	-11.33	-17.69	-24.04	-31.79	-39.54	-48.68	-55.04	-64.18	-71.93
200mm (XPS)	-8.81	-20.40	-29.22	-39.41	-51.01	-62.60	-72.81	-84.39	-97.38	-108.97
25mm (POLYISO)	1.39	2.79	4.19	4.19	4.20	5.59	5.60	5.60	5.61	5.61
50mm (POLYISO)	0.06	1.52	1.58	1.64	3.10	3.16	1.83	1.90	0.57	0.63
100mm (POLYISO)	-1.25	0.27	-3.76	-5.01	-7.65	-10.30	-12.94	-16.98	-19.62	-22.26
150mm (POLYISO)	-2.66	-6.72	-9.39	-16.22	-21.67	-25.73	-31.17	-36.62	-42.06	-48.90
200mm (POLYISO)	-7.00	-12.61	-19.62	-26.61	-33.62	-42.01	-51.79	-58.79	-67.19	-75.58

Figure 9. Net saved energy after 50 years under zone3 and zone4 at different levels of slab insulation depth (200 to 2000mm) and insulation thickness (25 to 200mm). Source: Author.

Zone3: These results also show that when the insulation depth level is increased, then the optimum thickness that maximizes net energy savings after 50 years reduces. Generally, zone 2 experiences greater energy savings than zone1 for the same insulation thickness levels and insulation depths

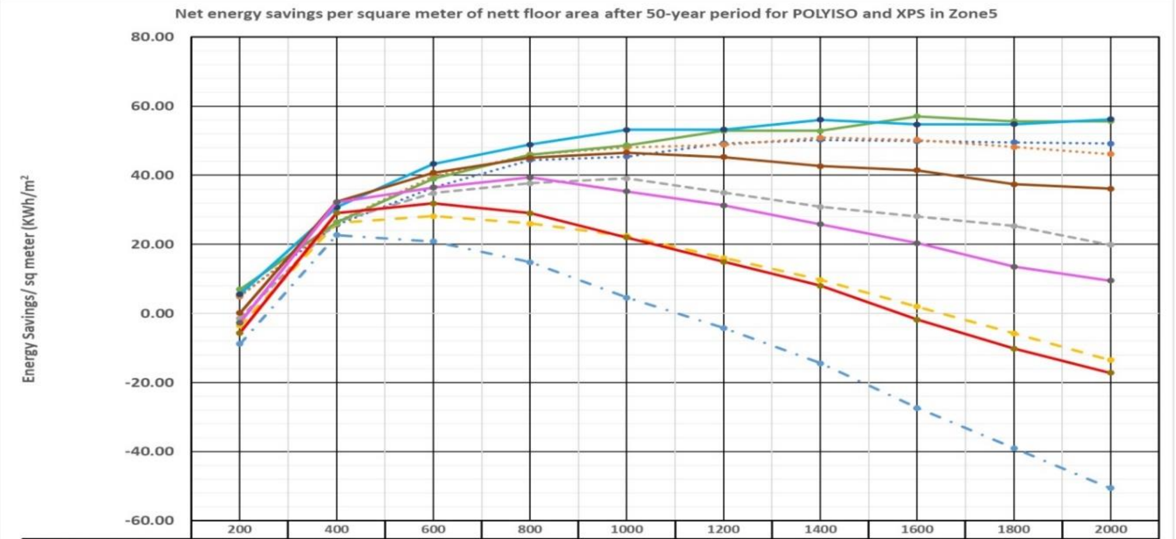
For example under XPS, the best insulation thickness at 400mm insulation depth was 200mm; From 600 to 1200mm insulation depth, the best insulation thickness was 100mm; from 1400 to 2000mm insulation depth, the best thickness was 50mm.

Under polyiso, the best insulation thickness for insulation depth from 400 to 600mm was 200mm; The best insulation thickness for insulation depths from 800 to 2000mm was 100mm.

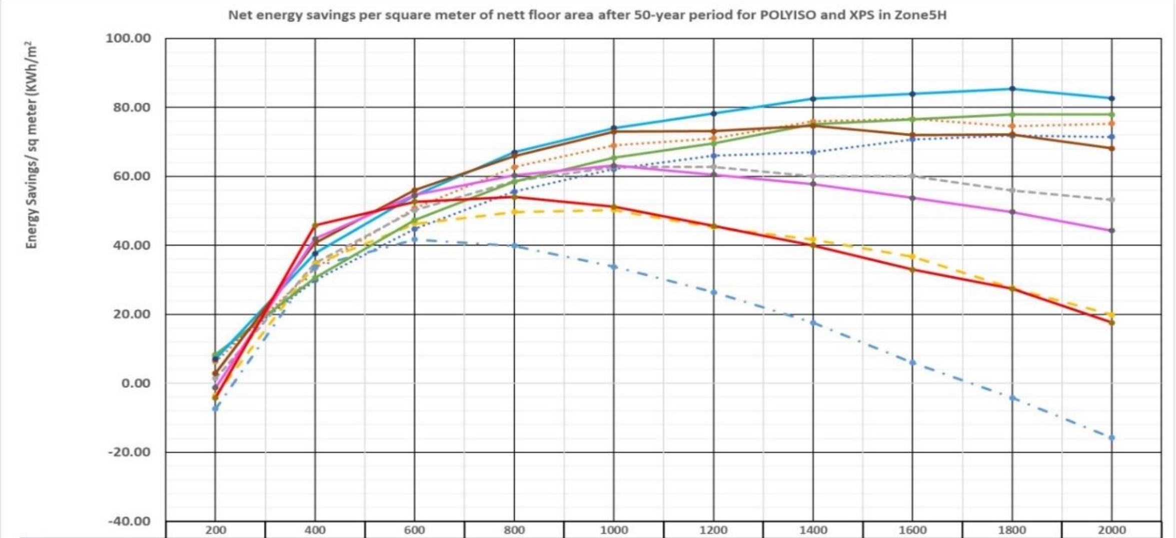
Zone4: Zone 4 had the lowest energy savings per square meter nett floor area. With the exception of XPS at 25mm thickness and polysio at 25 and 50mm thicknesses, the energy savings were generally negative for other levels of insulation thicknesses, and became more negative with the increase in insulation depth. Therefore, if vertical perimeter insulation is to be used in zone 4, it should be used at very low levels of insulation thicknesses for both XPS and polyiso.

Optimal points: Since the maximum energy payback periods for zone 3 for both insulations was less than 50 years, the highest maximum energy savings in zone 3 that also allow a payback period less than 50 years correspond to the use of Polyiso at 100mm thickness and a depth of 2000mm (2.0m). The payback period is 13.74 years. It corresponds to net energy savings of 143.20KWh/m^2. The maximum payback periods for polyiso at 25mm thickness in zone 4 is 35.58 years (less than 50 years). Therefore it is still possible to use 25mm thick polyiso at an insulation depth of 2.0m, leading to net energy savings of 5.61 KWh/m^2. However these net energy savings are quite low, rendering the application of the insulation almost

Figure 10 shows the net energy savings per square meter of nett area in zone5 and zone5H.



	200	400	600	800	1000	1200	1400	1600	1800	2000
25mm (XPS)	5.20	25.69	36.45	44.43	45.45	49.26	50.29	49.92	49.55	49.19
50mm (XPS)	4.89	26.47	39.70	45.98	48.09	48.81	50.92	50.24	48.18	46.12
100mm (XPS)	-1.35	26.49	34.87	37.69	39.12	34.99	30.85	28.11	25.36	19.84
150mm (XPS)	-3.58	26.22	28.20	26.01	22.44	16.08	9.72	1.97	-5.78	-13.53
200mm (XPS)	-8.81	22.70	20.84	14.81	4.61	-4.20	-14.40	-27.39	-38.98	-50.57
25mm (POLYISO)	6.96	26.43	38.95	45.90	48.69	52.87	52.87	57.05	55.66	55.67
50mm (POLYISO)	5.63	30.72	43.29	48.92	53.15	53.22	56.06	54.73	54.79	56.25
100mm (POLYISO)	0.14	32.26	40.74	45.04	46.57	45.32	42.67	41.42	37.39	36.13
150mm (POLYISO)	-2.66	32.21	36.50	39.40	35.34	31.28	25.84	20.39	13.55	9.50
200mm (POLYISO)	-5.61	29.10	31.83	29.00	22.00	15.00	8.00	-1.79	-10.18	-17.18



	200	400	600	800	1000	1200	1400	1600	1800	2000
25mm (XPS)	7.97	29.86	44.79	55.55	62.14	65.94	66.97	70.77	71.80	71.44
50mm (XPS)	6.28	33.42	50.82	62.66	68.94	71.05	75.94	76.66	74.60	75.32
100mm (XPS)	1.42	34.83	50.17	58.54	62.75	62.79	60.05	60.09	55.95	53.21
150mm (XPS)	-3.58	34.56	46.28	49.65	50.24	45.27	41.70	36.73	27.59	19.84
200mm (XPS)	-7.42	33.82	41.69	39.84	33.81	26.38	17.57	5.98	-4.22	-15.81
25mm (POLYISO)	8.34	30.60	47.29	58.42	65.37	69.55	75.12	76.51	77.91	77.91
50mm (POLYISO)	7.01	37.67	54.42	66.99	74.01	78.24	82.48	83.93	85.38	82.67
100mm (POLYISO)	2.91	40.60	56.03	65.90	72.99	73.13	74.65	72.01	72.15	68.11
150mm (POLYISO)	-1.28	41.94	54.57	60.25	63.15	60.48	57.82	53.76	49.70	44.25
200mm (POLYISO)	-4.22	45.78	52.69	54.03	51.20	45.58	39.98	32.97	27.36	17.58

Figure 10. Net saved energy after 50 years under zone5, and zone5H. Source: Author.

Zone5: The zone 5, results also show that when the insulation depth level was increased, then the optimum thickness that maximized the net energy savings after 50 years reduced.

Under XPS, the best insulation thickness at 400mm insulation depth was 100mm; From 600 to 1600mm insulation depth, the best insulation thickness was 50mm; from 1800 to 2000mm insulation depth, the best thickness was 25mm.

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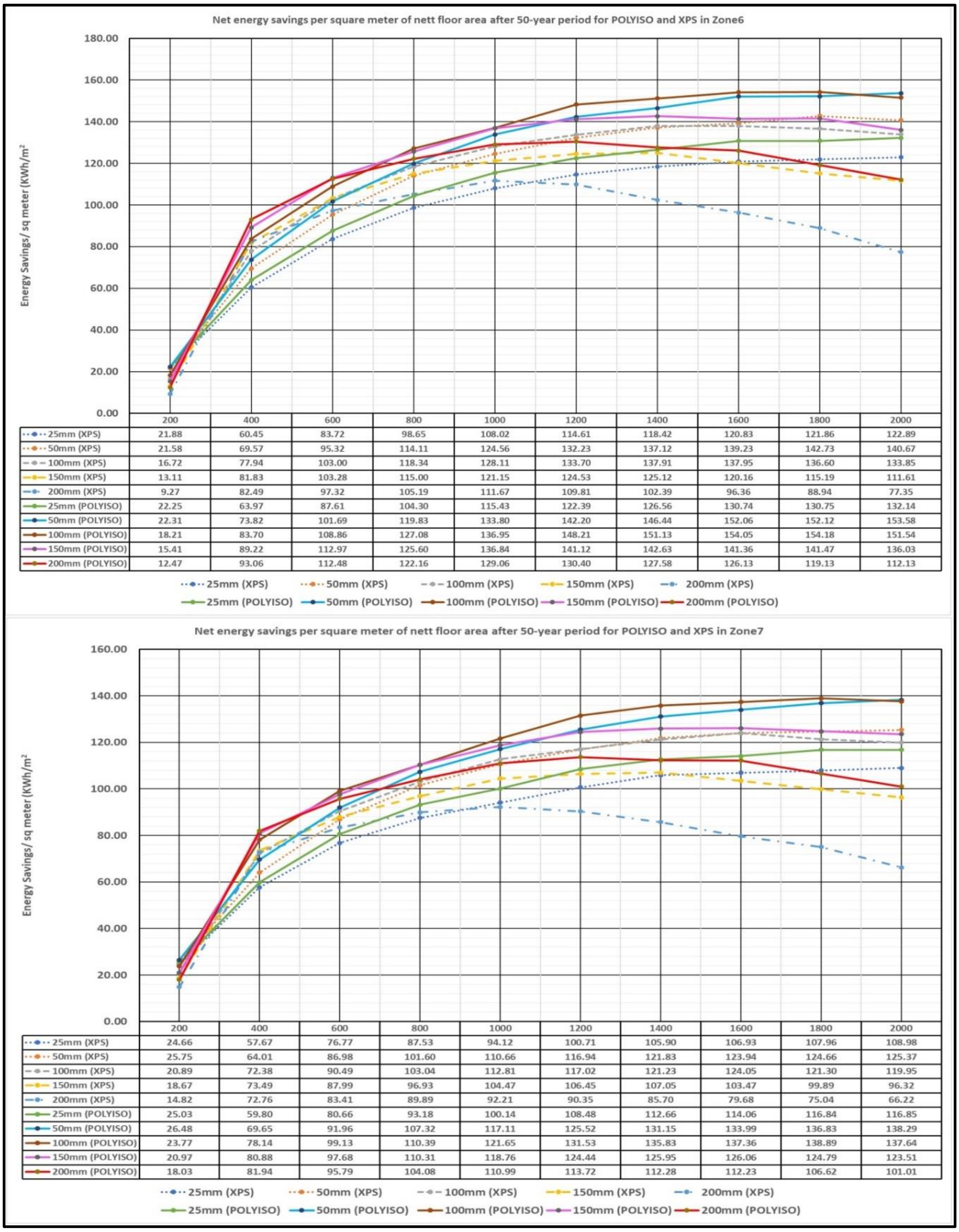
Under polyiso, the best insulation thickness for insulation depth from 400mm was 100mm. For insulation thickness depths of 600 to 1400mm, the best insulation thickness was 50mm. The best insulation thickness for insulation depths from 1600 to 2000mm was 25mm.

Zone 5H: In zone 5H, under XPS, the best insulation thickness at 400mm insulation depth was 100mm; From 600 to 2000mm insulation depth, the best insulation thickness was 50mm.

Under polyiso, the best insulation thickness for insulation depth from 400mm was 200mm. For insulation thickness depths of 600mm, the best insulation thickness was 100mm. The best insulation thickness for insulation depths from 800 to 2000mm was 50mm.

Optimal points: Since the maximum energy payback periods for zone 5 and zone 5H for 25mm and 50mm thick polyiso was less than 50 years, the highest maximum energy savings in zone 5 that also allow a payback period less than 50 years correspond to the use of Polyiso at 25mm thickness and a depth of 1600mm (1.6m). The payback period is 8.13 years. It corresponds to net energy savings of 57.05KWh/m^2. The highest maximum energy savings in zone 5H that also allow a payback period less than 50 years correspond to the use of Polyiso at 50mm thickness and a depth of 1800mm (1.8m). The payback period is 11.13 years. It corresponds to net energy savings of 85.38KWh/m^2.



	200	400	600	800	1000	1200	1400	1600	1800	2000
25mm (XPS)	21.88	60.45	83.72	98.65	108.02	114.61	118.42	120.83	121.86	122.89
50mm (XPS)	21.58	69.57	95.32	114.11	124.56	132.23	137.12	139.23	142.73	140.67
100mm (XPS)	16.72	77.94	103.00	118.34	128.11	133.70	137.91	137.95	136.60	133.85
150mm (XPS)	13.11	81.83	103.28	115.00	121.15	124.53	125.12	120.16	115.19	111.61
200mm (XPS)	9.27	82.49	97.32	105.19	111.67	109.81	102.39	96.36	88.94	77.35
25mm (POLYISO)	22.25	63.97	87.61	104.30	115.43	122.39	126.56	130.74	130.75	132.14
50mm (POLYISO)	22.31	73.82	101.69	119.83	133.80	142.20	146.44	152.06	152.12	153.58
100mm (POLYISO)	18.21	83.70	108.86	127.08	136.95	148.21	151.13	154.05	154.18	151.54
150mm (POLYISO)	15.41	89.22	112.97	125.60	136.84	141.12	142.63	141.36	141.47	136.03
200mm (POLYISO)	12.47	93.06	112.48	122.16	129.06	130.40	127.58	126.13	119.13	112.13

	200	400	600	800	1000	1200	1400	1600	1800	2000
25mm (XPS)	24.66	57.67	76.77	87.53	94.12	100.71	105.90	106.93	107.96	108.98
50mm (XPS)	25.75	64.01	86.98	101.60	110.66	116.94	121.83	123.94	124.66	125.37
100mm (XPS)	20.89	72.38	90.49	103.04	112.81	117.02	121.23	124.05	121.30	119.95
150mm (XPS)	18.67	73.49	87.99	96.93	104.47	106.45	107.05	103.47	99.89	96.32
200mm (XPS)	14.82	72.76	83.41	89.89	92.21	90.35	85.70	79.68	75.04	66.22
25mm (POLYISO)	25.03	59.80	80.66	93.18	100.14	108.48	112.66	114.06	116.84	116.85
50mm (POLYISO)	26.48	69.65	91.96	107.32	117.11	125.52	131.15	133.99	136.83	138.29
100mm (POLYISO)	23.77	78.14	99.13	110.39	121.65	131.53	135.83	137.36	138.89	137.64
150mm (POLYISO)	20.97	80.88	97.68	110.31	118.76	124.44	125.95	126.06	124.79	123.51
200mm (POLYISO)	18.03	81.94	95.79	104.08	110.99	113.72	112.28	112.23	106.62	101.01

Figure 11. Net saved energy after 50 years under zone6, and zone7. Source: Author.

The zone 6 and zone 7 results also show that when the insulation depth level was increased, then the optimum thickness that maximized the net energy savings (per square meter of nett floor area) after 50 years reduced.

Zone6: Under XPS, the best insulation thickness at 400mm insulation depth was 200mm. The best insulation thickness from 600mm to 800mm insulation depth was 150mm; From 1000 to 1400mm insulation depth, the best insulation thickness was 100mm; from 1600 to 2000mm insulation depth, the best thickness was 50mm.

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Under polyiso, the best insulation thickness for insulation depth of 400mm was 200mm. For insulation thickness depths of 600mm, the best insulation thickness was 150mm. The best insulation thickness for insulation depths from 800 to 1800mm was 100mm. The best insulation thickness for insulation depths of 2000mm was 50mm.

Zone7: Under polyiso, the best insulation thickness at 400mm insulation depth was 200mm. Generally, the best insulation thickness from 600mm to 1600mm insulation depth was 100mm. From 1800 to 2000mm insulation depth, the best insulation thickness was 50mm.

Under polyiso, the best insulation thickness for insulation depth of 400mm was 200mm. For insulation thickness depths of 600mm to 1800mm, the best insulation thickness was 100mm. The best insulation thickness for insulation depths from 800 to 1800mm was 100mm. The best insulation thickness for insulation depths of 2000mm was 50mm.

Optimal points: Since the maximum energy payback periods for zone 6 and zone 7 for both insulations was less than 50 years, the highest maximum energy savings in zone 6 that also allow a payback period less than 50 years correspond to the use of Polyiso at 100mm thickness and a depth of 1800mm (1.8m). The payback period is 12.02 years. It corresponds to net energy savings of 154.18KWh/m^2. The highest maximum energy savings in zone 7 that also allow a payback period less than 50 years correspond to the use of Polyiso at 100mm thickness and a depth of 1800mm (1.8m). The payback period is 13.0 years. It corresponds to net energy savings of 138.89KWh/m^2.

General patterns: Generally zone2, zone 6, zone 3. And zone 7 corresponded to the highest net energy savings per square meter of nett floor area after 50 years, in that order. Zone 4, zone 5, zone 5H and zone1 corresponded to the lowest net energy savings per square meter of nett floor area after 50 years, in that order. For zones 1, 2, 3, 5, 5H, 6, and 7, the net saved energy after 50 years also tended to initially increase with the level of insulation depth up to a maximum and then decreased at later values of insulation depths. This phenomenon was especially more pronounced at higher levels of insulation thicknesses. At lower levels of insulation thicknesses there was a general increase in net energy savings with insulation depth, although the rate of increase decreased as the insulation depth increased. Therefore increase in insulation depths produced higher marginal benefits (in form of net energy savings per square meter of nett floor area) at lower levels of insulation depth. The increase in net energy savings with lower values of insulation thickness is in general agreement with the work done by Cox-Smith (2016) in New Zealand, which showed that the R-values generally reduced with increase in insulation thickness.

3.6. Horizontal perimeter insulation (with vertical gap insulation along floor slab edges)

The method of insulation was changed to horizontal insulation (with gap insulation along the floor-slab edges). Only polyiso results were presented for some selected scenarios.

3.6.1. Site energy consumption per square meter floor area (horizontal insulation in general)

Table 5 shows the summarized site energy (and source energy in brackets) consumption statistics per nett floor area for the building energy models used and the corresponding SANS10400-XA maximum site energy limits. The tables apply both for horizontal perimeter floor-slab insulation and horizontal full floor-slab insulation.

Table 5. Maximum, minimum and mean annual site energy consumption per nett floor area and loads not met (hours) for horizontal insulation.

	Zone1	Zone2	Zone3	Zone4	Zone5	Zone5H	Zone6	Zone7
Site Energy (Source Energy)								
Maximum (KWh/m^2)	24.61 (77.7)	25.61 (80.79)	25.72 (81.23)	24.11 (76.14)	23.08 (72.69)	24.5 (77.36)	27.09 (85.35)	28.06 (88.29)
Minimum (KWh/m^2)	21.86 (68.86)	21.89 (69.02)	22.64 (71.41)	23.03 (72.64)	21.47 (67.69)	22.28 (70.36)	23.78 (74.97)	24.83 (78.45)

Mean (KWh/m²)	22.17 (69.91)	22.38 (70.6)	23.04 (72.69)	23.48 (74.06)	21.66 (68.33)	22.58 (71.2)	24.18 (76.22)	25.25 (79.65)
SD (KWh/m²)	0.426 (1.363)	0.584 (1.852)	0.49 (1.555)	0.205 (0.677)	0.228 (0.713)	0.338 (1.083)	0.514 (1.608)	0.514 (1.604)
SANS10400-XA Reference (KWh/m²)	**90**	**100**	**50**	**80**	**85**	**60**	**110**	**110**
Annual heating and cooling load not met								
Maximum (% hours)	0%	2%	1%	0%	2%	1%	0%	0%
Minimum (% hours)	0%	1%	0%	0%	1%	0%	0%	0%
Mean (% hours)	0%	1%	0%	0%	2%	0%	0%	0%
SD (% hours)	0.00%	0.24%	0.04%	0.00%	0.06%	0.13%	0.07%	0.00%
SANS 10400-XA Reference (% hours)	**5%**	**5%**	**5%**	**5%**	**5%**	**5%**	**5%**	**5%**

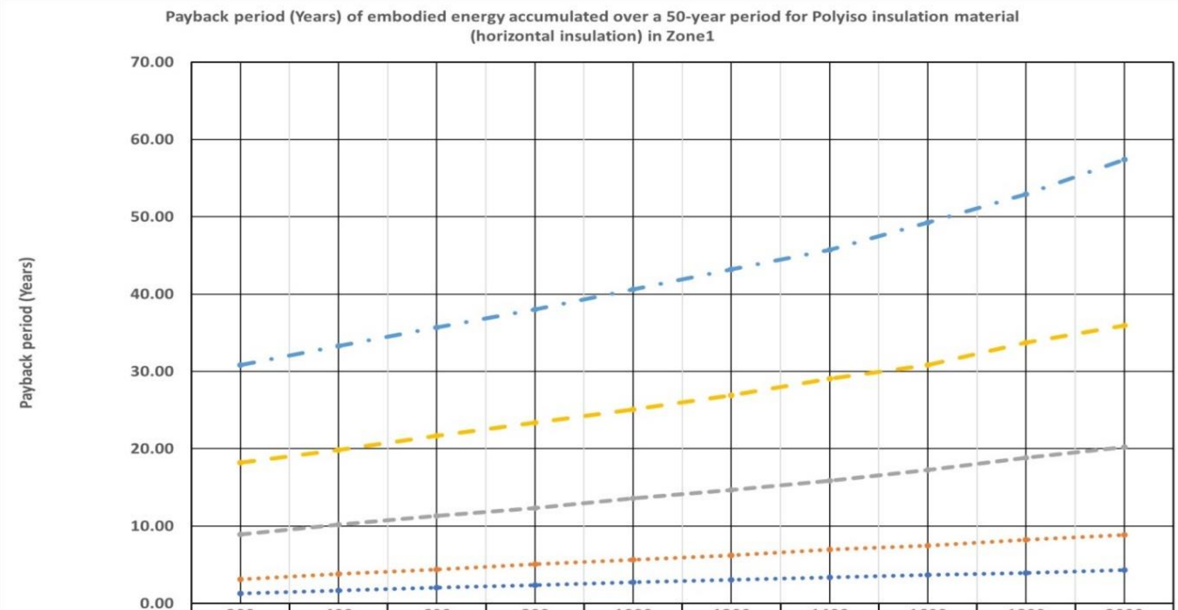
Source: Author.

Just like the results for vertical gap insulation, the results for all the energy models used for horizontal floor-slab insulation were within the acceptable SANS10400-XA site energy limits per square meter of nett floor area.

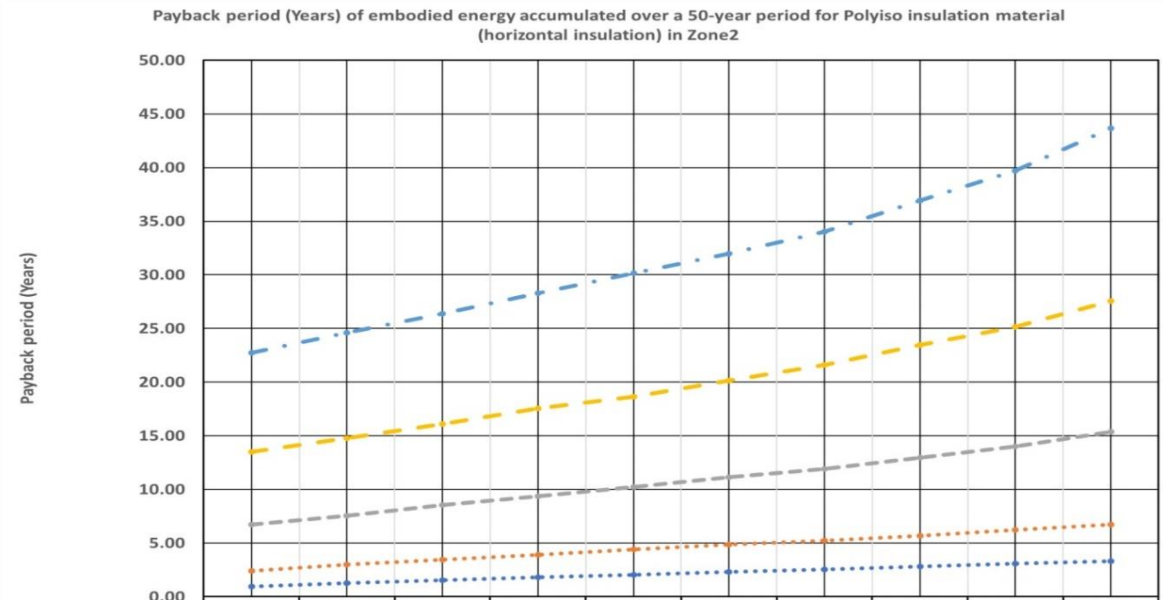
Furthermore, all the loads (sum of heating and cooling loads) that were not met annually were less than 5%. The highest loads not met again appeared to occur in energy zone 2, while the least again occurred in energy zones 1 and 7. Therefore all the models used for horizontal floor slab insulation measure analysis fulfilled the requirements of the SANS10400-XA standards.

3.6.2. Payback periods (horizontal perimeter insulation).

The energy payback periods due to application of horizontal insulation were evaluated, across the different locations (energy zones). Figures 12–15 represent the results.



	200	400	600	800	1000	1200	1400	1600	1800	2000
25mm (Polyiso)	1.29	1.65	2.03	2.35	2.71	3.05	3.38	3.70	3.94	4.28
50mm (Polyiso)	3.14	3.80	4.39	5.05	5.61	6.21	6.94	7.49	8.21	8.83
100mm (Polyiso)	8.89	10.17	11.29	12.34	13.60	14.68	15.88	17.23	18.80	20.19
150mm (Polyiso)	18.17	19.86	21.66	23.39	25.05	26.91	29.04	30.85	33.70	35.91
200mm (Polyiso)	30.79	33.29	35.69	38.00	40.62	43.20	45.74	49.27	52.93	57.39



	200	400	600	800	1000	1200	1400	1600	1800	2000
25mm (Polyiso)	0.97	1.27	1.55	1.80	2.06	2.30	2.55	2.81	3.07	3.32
50mm (Polyiso)	2.42	2.99	3.44	3.92	4.41	4.88	5.23	5.70	6.21	6.72
100mm (Polyiso)	6.72	7.57	8.56	9.38	10.23	11.13	11.91	12.96	14.02	15.36
150mm (Polyiso)	13.49	14.78	16.12	17.54	18.65	20.13	21.61	23.45	25.14	27.55
200mm (Polyiso)	22.75	24.60	26.37	28.29	30.16	31.99	34.04	36.95	39.70	43.68

Figure 12. Energy payback periods for zone 1 and zone 2, at different levels of slab horizontal insulation width from the slab edges (200 to 2000mm) and insulation thickness (25 to 200mm). Source: Author.

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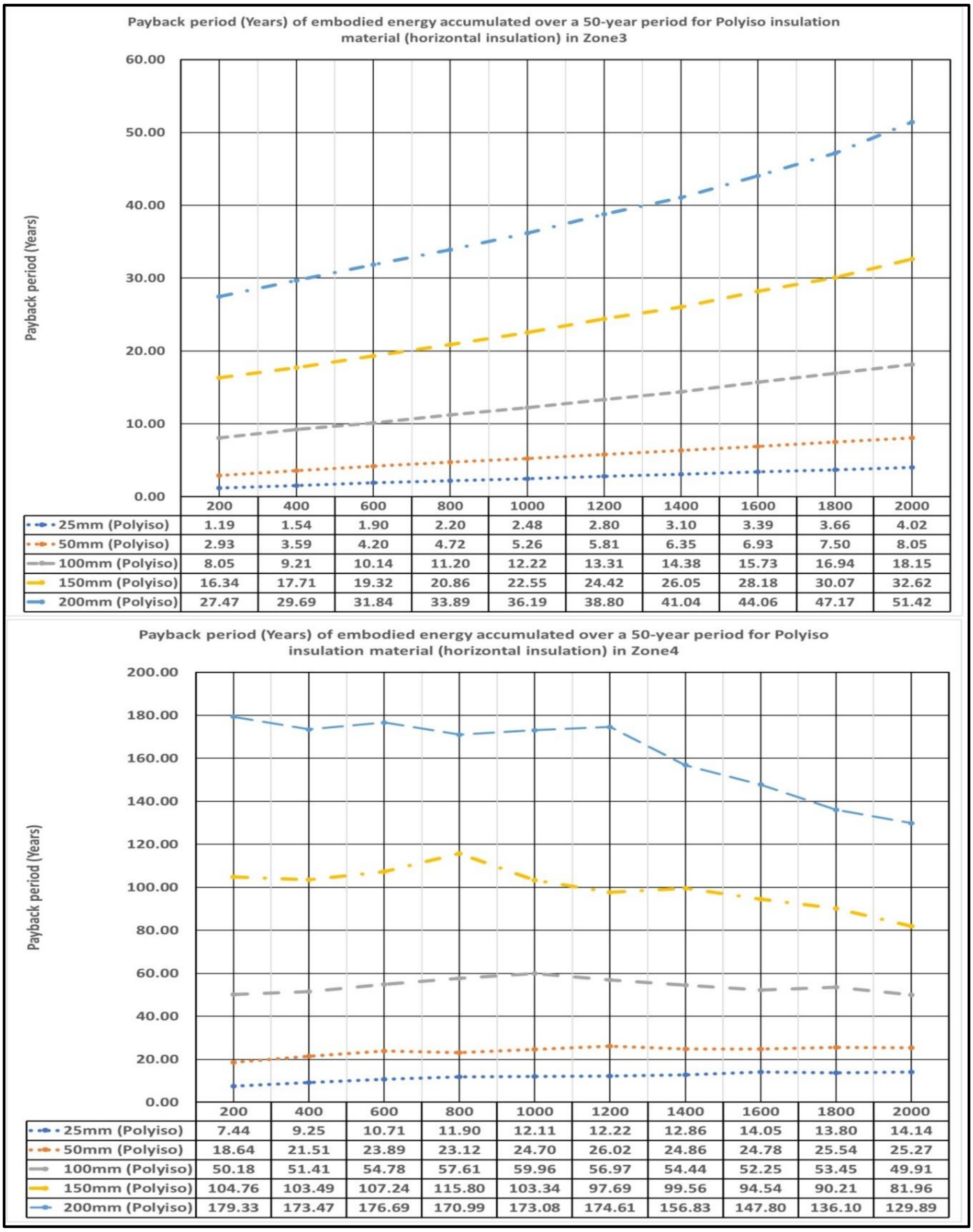

	200	400	600	800	1000	1200	1400	1600	1800	2000
25mm (Polyiso)	1.19	1.54	1.90	2.20	2.48	2.80	3.10	3.39	3.66	4.02
50mm (Polyiso)	2.93	3.59	4.20	4.72	5.26	5.81	6.35	6.93	7.50	8.05
100mm (Polyiso)	8.05	9.21	10.14	11.20	12.22	13.31	14.38	15.73	16.94	18.15
150mm (Polyiso)	16.34	17.71	19.32	20.86	22.55	24.42	26.05	28.18	30.07	32.62
200mm (Polyiso)	27.47	29.69	31.84	33.89	36.19	38.80	41.04	44.06	47.17	51.42

	200	400	600	800	1000	1200	1400	1600	1800	2000
25mm (Polyiso)	7.44	9.25	10.71	11.90	12.11	12.22	12.86	14.05	13.80	14.14
50mm (Polyiso)	18.64	21.51	23.89	23.12	24.70	26.02	24.86	24.78	25.54	25.27
100mm (Polyiso)	50.18	51.41	54.78	57.61	59.96	56.97	54.44	52.25	53.45	49.91
150mm (Polyiso)	104.76	103.49	107.24	115.80	103.34	97.69	99.56	94.54	90.21	81.96
200mm (Polyiso)	179.33	173.47	176.69	170.99	173.08	174.61	156.83	147.80	136.10	129.89

Figure 13. Energy payback periods for zone 3 and zone 4, at different levels of slab horizontal insulation width from the slab edges (200 to 2000mm) and insulation thickness (25 to 200mm). Source: Author.

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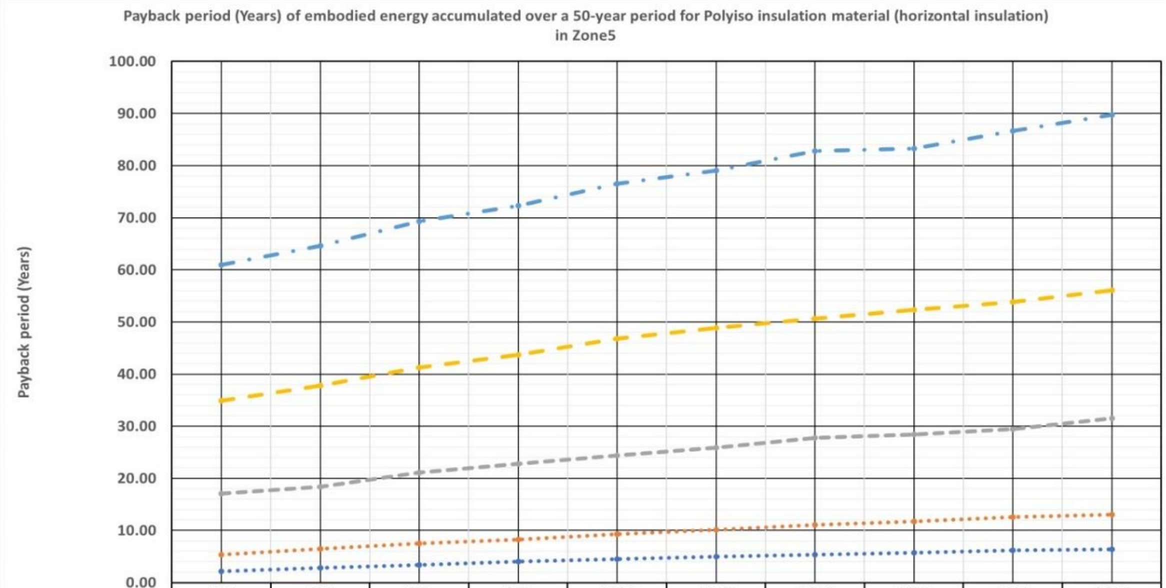
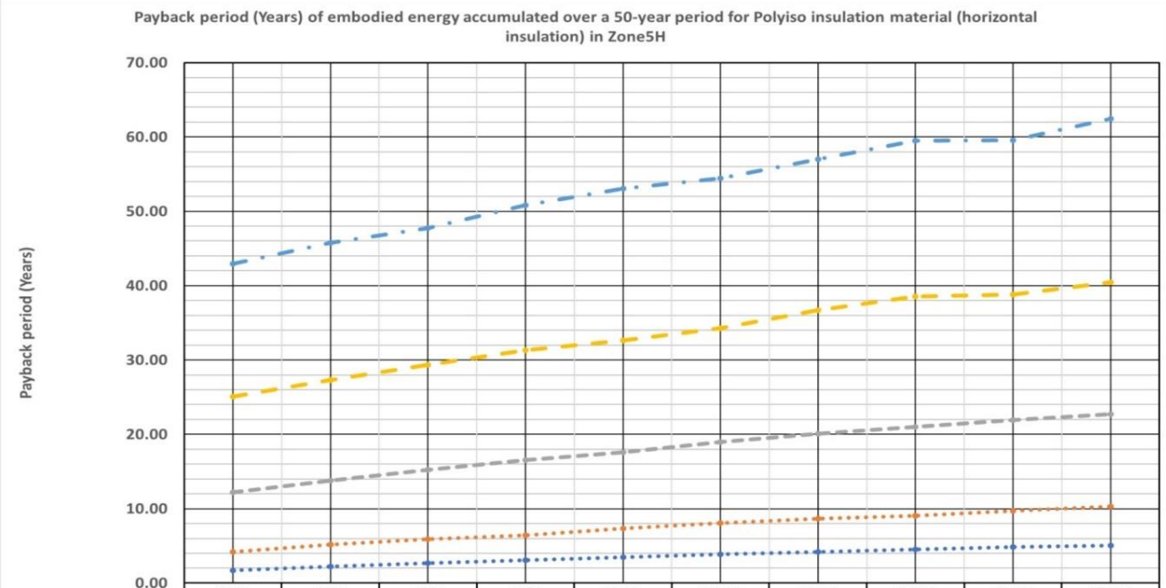


	200	400	600	800	1000	1200	1400	1600	1800	2000
25mm (Polyiso)	2.18	2.80	3.41	4.06	4.48	4.94	5.36	5.74	6.20	6.38
50mm (Polyiso)	5.33	6.45	7.49	8.29	9.32	10.12	11.05	11.71	12.54	13.08
100mm (Polyiso)	17.06	18.43	21.07	22.83	24.43	25.89	27.72	28.42	29.49	31.52
150mm (Polyiso)	34.92	37.81	41.24	43.70	46.80	48.84	50.69	52.34	53.81	56.08
200mm (Polyiso)	60.97	64.62	69.29	72.35	76.56	79.07	82.85	83.31	86.61	89.74



	200	400	600	800	1000	1200	1400	1600	1800	2000
25mm (Polyiso)	1.69	2.23	2.68	3.08	3.49	3.87	4.22	4.53	4.82	5.08
50mm (Polyiso)	4.21	5.21	5.88	6.46	7.37	8.04	8.65	9.07	9.71	10.32
100mm (Polyiso)	12.19	13.76	15.22	16.57	17.59	18.99	20.06	21.04	21.93	22.74
150mm (Polyiso)	25.08	27.31	29.38	31.30	32.64	34.25	36.68	38.57	38.83	40.46
200mm (Polyiso)	42.94	45.78	47.75	50.84	53.08	54.43	57.03	59.51	59.55	62.48

Figure 14. Energy payback periods for zone 5 and zone 5H, at different levels of slab horizontal insulation width from the slab edges (200 to 2000mm) and insulation thickness (25 to 200mm). Source: Author.

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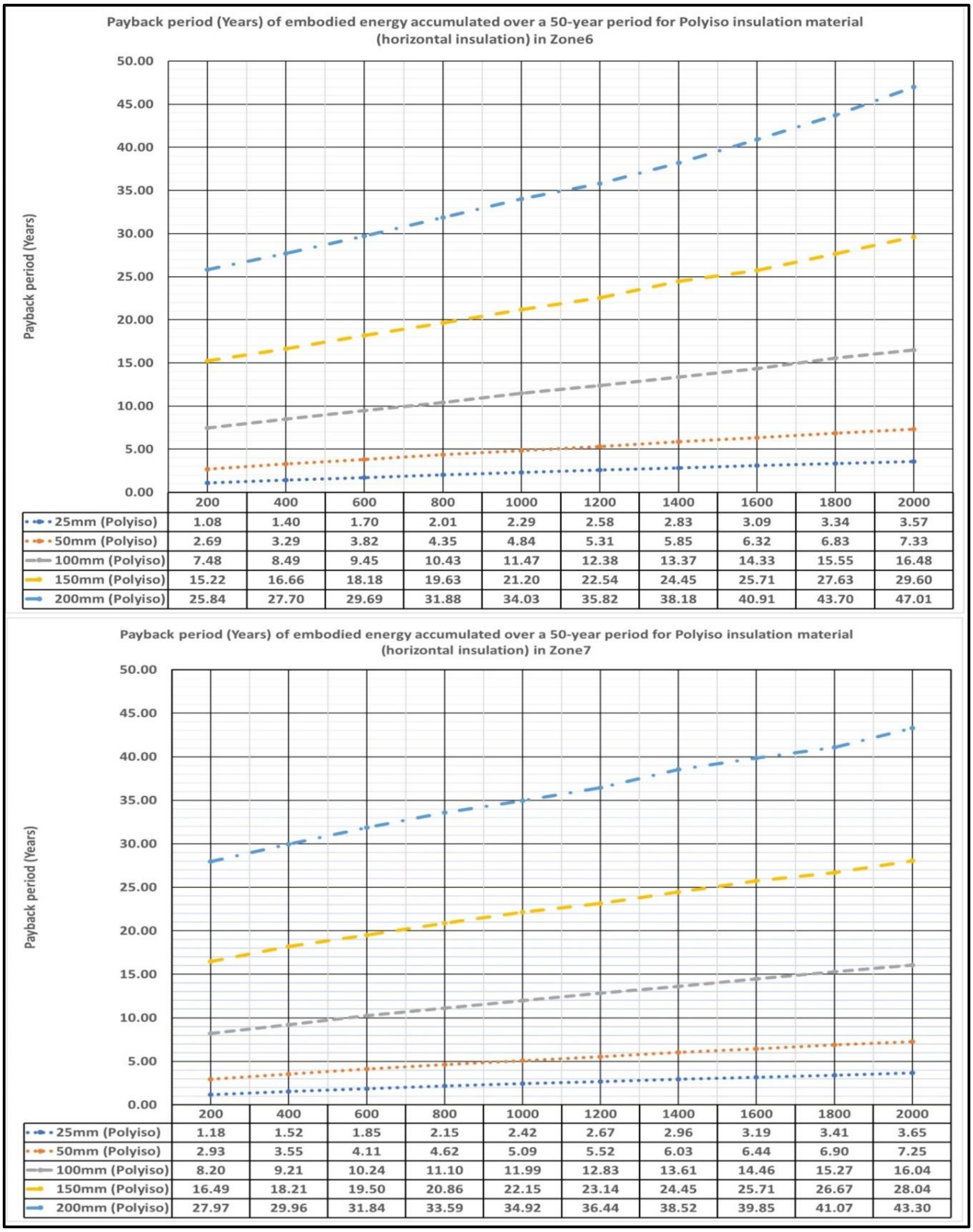

	200	400	600	800	1000	1200	1400	1600	1800	2000
25mm (Polyiso)	1.08	1.40	1.70	2.01	2.29	2.58	2.83	3.09	3.34	3.57
50mm (Polyiso)	2.69	3.29	3.82	4.35	4.84	5.31	5.85	6.32	6.83	7.33
100mm (Polyiso)	7.48	8.49	9.45	10.43	11.47	12.38	13.37	14.33	15.55	16.48
150mm (Polyiso)	15.22	16.66	18.18	19.63	21.20	22.54	24.45	25.71	27.63	29.60
200mm (Polyiso)	25.84	27.70	29.69	31.88	34.03	35.82	38.18	40.91	43.70	47.01

	200	400	600	800	1000	1200	1400	1600	1800	2000
25mm (Polyiso)	1.18	1.52	1.85	2.15	2.42	2.67	2.96	3.19	3.41	3.65
50mm (Polyiso)	2.93	3.55	4.11	4.62	5.09	5.52	6.03	6.44	6.90	7.25
100mm (Polyiso)	8.20	9.21	10.24	11.10	11.99	12.83	13.61	14.46	15.27	16.04
150mm (Polyiso)	16.49	18.21	19.50	20.86	22.15	23.14	24.45	25.71	26.67	28.04
200mm (Polyiso)	27.97	29.96	31.84	33.59	34.92	36.44	38.52	39.85	41.07	43.30

Figure 15. Energy payback periods for zone 6 and zone 7, at different levels of slab horizontal insulation width from the slab edges (200 to 2000mm) and insulation thickness (25 to 200mm). Source: Author.

According to Figures 12–15, the energy payback period increases with horizontal insulation thickness and width from the edges, except for zone 4. Although payback period increases with insulation thickness in zone 4, it tends to decrease with horizontal insulation width where the thickness is greater than or equal to 150mm. Therefore if the thickness is 150mm and above, it is better to use larger insulation widths (from the floor slab edges) in zone 4. Generally, the lowest payback

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periods for the horizontal floor slab insulation were experienced in zone2, zone 7, zone 6, zone 3, zone 1, zone 5H, zone 5 and zone 4 in that order. Zone 4 had the highest payback periods.

3.6.3. Minimum and maximum values of net energy savings after 50 years

Table 4 below shows the minimum and maximum net energy saving per square meter of nett floor area after 50 years, for the polyiso horizontal perimeter insulation and the energy zones.

Table 4. Minimum and maximum net energy savings per square meter of nett floor area (KWh/m^2) after 50 years.

	Zone1 (min ; max)	**Zone2 (min ; max)**	**Zone3 (min ; max)**	**Zone4 (min ; max)**	**Zone5 (min ; max)**	**Zone5H (min ; max)**	**Zone6 (min ; max)**	**Zone7 (min ; max)**
Polyiso: (25mm)	93.5 ; 100.7	125.4 ; 134	101.8 ; 109.7	14.2 ; 22.9	54.5 ; 61.9	71.2 ; 79.9	112.9 ; 119.4	103.2 ; 115.3
Polyiso: (50mm)	95 ; 110.3	131.2 ; 143.7	106.2 ; 117.1	11.6 ; 19.9	57.3 ; 61.5	77.2 ; 82.3	118.7 ; 128.4	116.5 ; 122.5
Polyiso: (100mm)	73.8 ; 109.8	112.7 ; 152.9	87.7 ; 123.7	-6.1 ; 0.1	29.3 ; 46.5	59.9 ; 73.6	101.6 ; 134.8	105.8 ; 120.9
Polyiso: (150mm)	34.9 ; 86.7	72.4 ; 134	47.4 ; 102	-38.6 ; -25.9	-9.6 ; 21.4	21 ; 49.2	61.3 ; 113.2	69.6 ; 100.6
Polyiso: (200mm)	-17.7 ; 52.9	19.9 ; 101.5	-3.8 ; 69.6	-84.4 ; -61.1	-60.8 ; -15.3	-27.4 ; 13.9	8.7 ; 79.3	21.2 ; 66.8

Source: Author.

The results also indicate that the maximum net energy savings are not necessarily achieved at the highest insulation thickness levels and also appear to be influenced by the insulation thickness and the location or the energy zones.

The maximum energy savings for polyiso in zone 1, zone 5H, and zone 7 occurred at floor-slab insulation thickness of 50mm. The maximum energy savings for polyiso in zone 2, zone 3, and zone 6 occurred at floor-slab insulation thickness of 100mm. The maximum energy savings in zone 4, and zone 5 occurred at floor-slab insulation thickness of 25mm. Zone 4 had the lowest net energy savings, followed by zone 5, zone 5H, zone 1, and zone 3 in that order. The greatest beneficiaries from the net energy savings after 50 years due to horizontal floor slab insulation were zone 2, zone 6, zone 7, zone 3, zone 1, zone 5H, zone 5 and zone 4 in that order.

3.6.4. Net saved energy for horizontal perimeter insulation after 50 years.

The energy payback periods due to application of horizontal insulation were evaluated, across the different locations (energy zones). Figures 16–19 represent the results.

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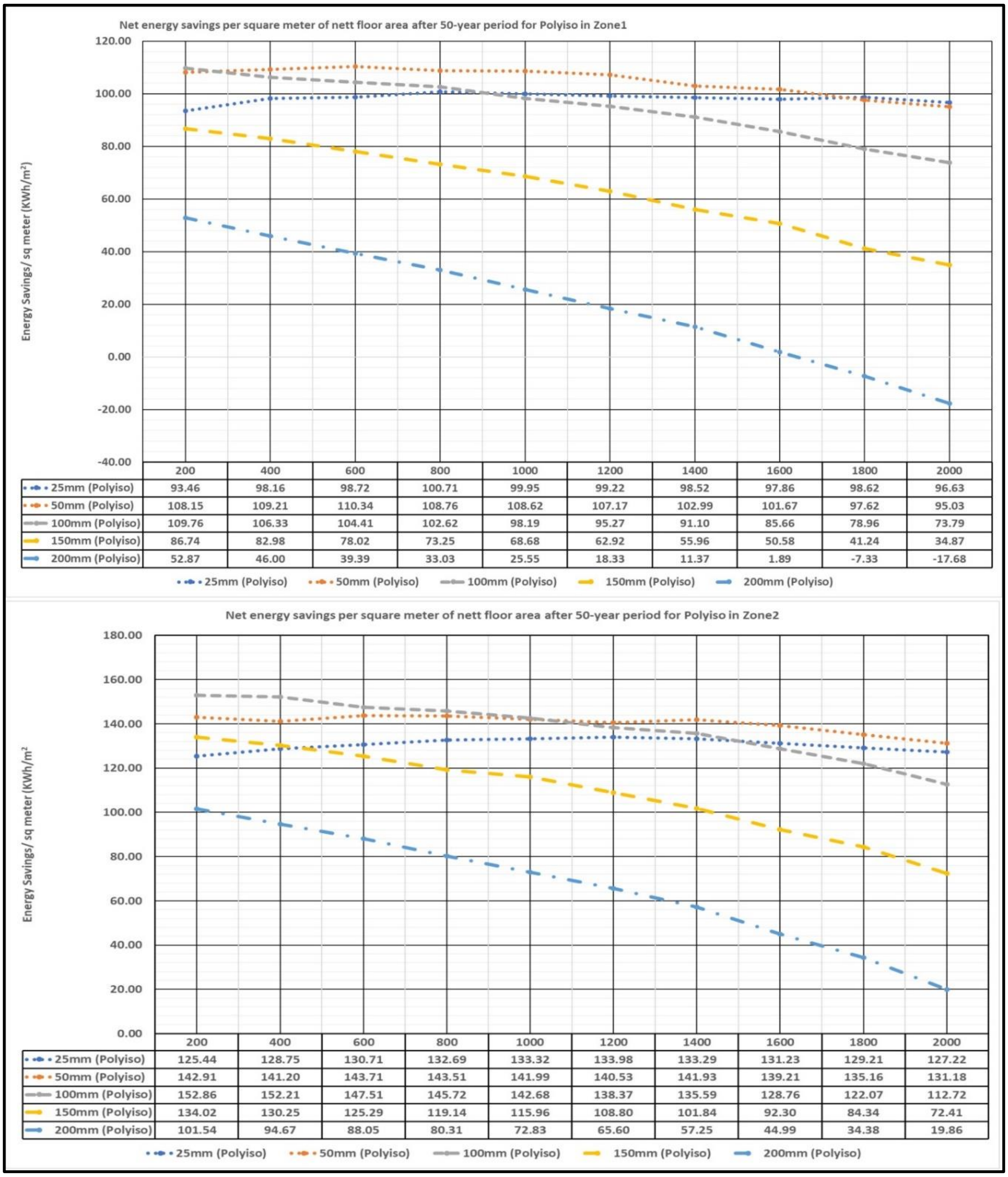

	200	400	600	800	1000	1200	1400	1600	1800	2000
25mm (Polyiso)	93.46	98.16	98.72	100.71	99.95	99.22	98.52	97.86	98.62	96.63
50mm (Polyiso)	108.15	109.21	110.34	108.76	108.62	107.17	102.99	101.67	97.62	95.03
100mm (Polyiso)	109.76	106.33	104.41	102.62	98.19	95.27	91.10	85.66	78.96	73.79
150mm (Polyiso)	86.74	82.98	78.02	73.25	68.68	62.92	55.96	50.58	41.24	34.87
200mm (Polyiso)	52.87	46.00	39.39	33.03	25.55	18.33	11.37	1.89	-7.33	-17.68

	200	400	600	800	1000	1200	1400	1600	1800	2000
25mm (Polyiso)	125.44	128.75	130.71	132.69	133.32	133.98	133.29	131.23	129.21	127.22
50mm (Polyiso)	142.91	141.20	143.71	143.51	141.99	140.53	141.93	139.21	135.16	131.18
100mm (Polyiso)	152.86	152.21	147.51	145.72	142.68	138.37	135.59	128.76	122.07	112.72
150mm (Polyiso)	134.02	130.25	125.29	119.14	115.96	108.80	101.84	92.30	84.34	72.41
200mm (Polyiso)	101.54	94.67	88.05	80.31	72.83	65.60	57.25	44.99	34.38	19.86

Figure 16. Net energy savings after 50 years for zone 1 and zone 2, at different levels of slab horizontal insulation width from the slab edges (200 to 2000mm) and insulation thickness (25 to 200mm). Source: Author.

Generally the highest energy payback periods in zone1 and zone 2 occur at insulation thicknesses of 100mm or less. Higher insulation widths tend to require lower insulation thicknesses in order to maximize net energy savings per square meter of nett floor area.

Zone1: For insulation width of 200mm or less, it is better to use insulation thickness of 100mm. For insulation widths from 400mm to 1600mm, it is better to use insulation thicknesses of 50mm in order to maximize energy savings in zone 1. For insulation widths of 1800mm and above it is better to use insulation thickness of 25mm.

Zone2: Insulation widths up to 1000mm would require 100mm insulation thickness to maximize net energy savings. Beyond 1000mm of insulation widths, insulation thickness of 50mm would be suitable.

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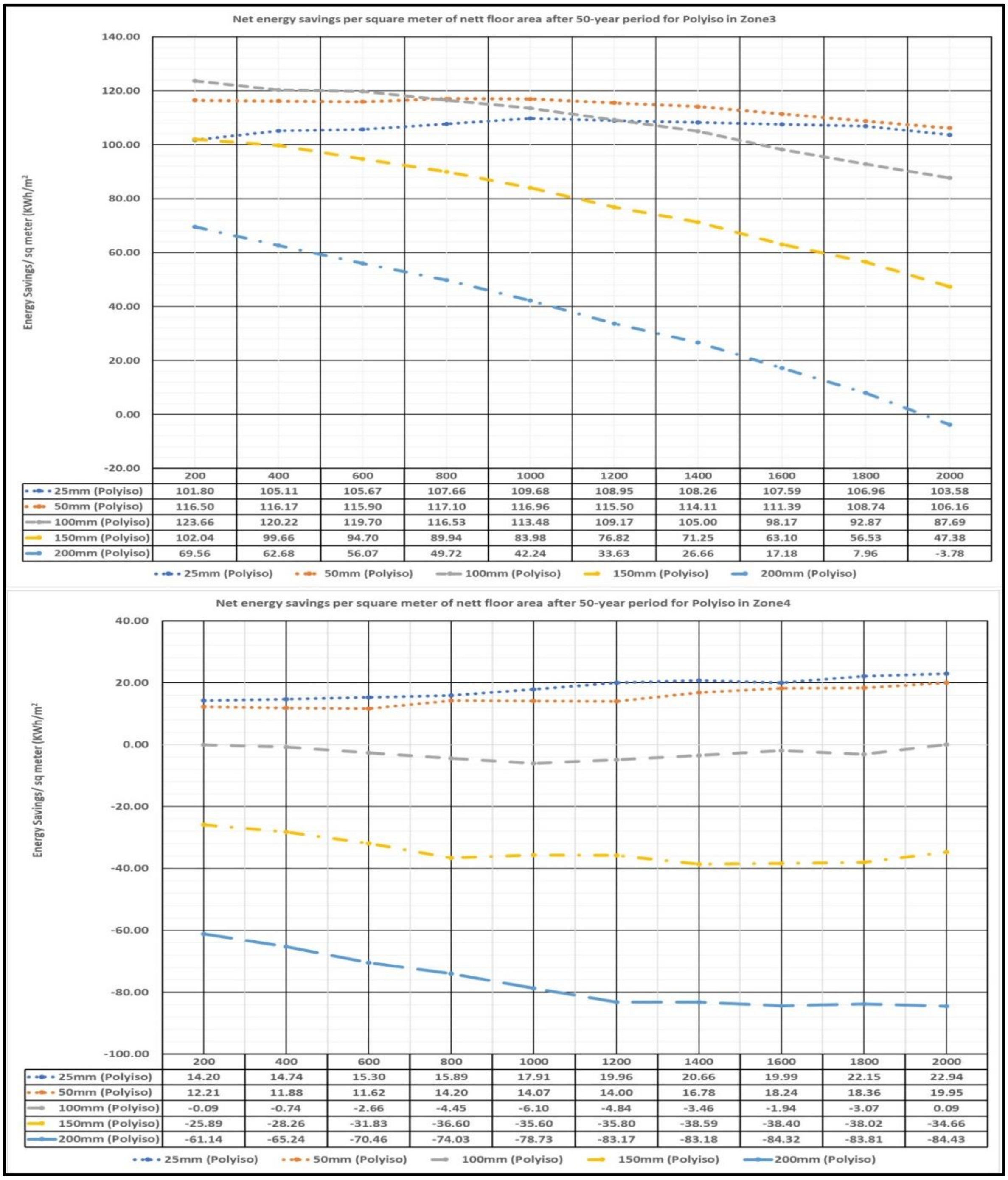

	200	400	600	800	1000	1200	1400	1600	1800	2000
25mm (Polyiso)	101.80	105.11	105.67	107.66	109.68	108.95	108.26	107.59	106.96	103.58
50mm (Polyiso)	116.50	116.17	115.90	117.10	116.96	115.50	114.11	111.39	108.74	106.16
100mm (Polyiso)	123.66	120.22	119.70	116.53	113.48	109.17	105.00	98.17	92.87	87.69
150mm (Polyiso)	102.04	99.66	94.70	89.94	83.98	76.82	71.25	63.10	56.53	47.38
200mm (Polyiso)	69.56	62.68	56.07	49.72	42.24	33.63	26.66	17.18	7.96	-3.78

	200	400	600	800	1000	1200	1400	1600	1800	2000
25mm (Polyiso)	14.20	14.74	15.30	15.89	17.91	19.96	20.66	19.99	22.15	22.94
50mm (Polyiso)	12.21	11.88	11.62	14.20	14.07	14.00	16.78	18.24	18.36	19.95
100mm (Polyiso)	-0.09	-0.74	-2.66	-4.45	-6.10	-4.84	-3.46	-1.94	-3.07	0.09
150mm (Polyiso)	-25.89	-28.26	-31.83	-36.60	-35.60	-35.80	-38.59	-38.40	-38.02	-34.66
200mm (Polyiso)	-61.14	-65.24	-70.46	-74.03	-78.73	-83.17	-83.18	-84.32	-83.81	-84.43

Figure 17. Net energy savings after 50 years for zone 3 and zone 4, at different levels of slab horizontal insulation width from the slab edges (200 to 2000mm) and insulation thickness (25 to 200mm). Source: Author.

Zone3: Insulation widths up to 600mm would require 100mm insulation thickness to maximize net energy savings. Beyond 600mm of insulation widths, insulation thickness of 50mm would be suitable.

Zone4: To maximize net energy savings, insulation thickness of 25mm would generally be required for use throughout. Only insulation thicknesses of up to 50mm would yield positive net energy savings. Thicknesses 100mm and above would not yield positive net energy savings.

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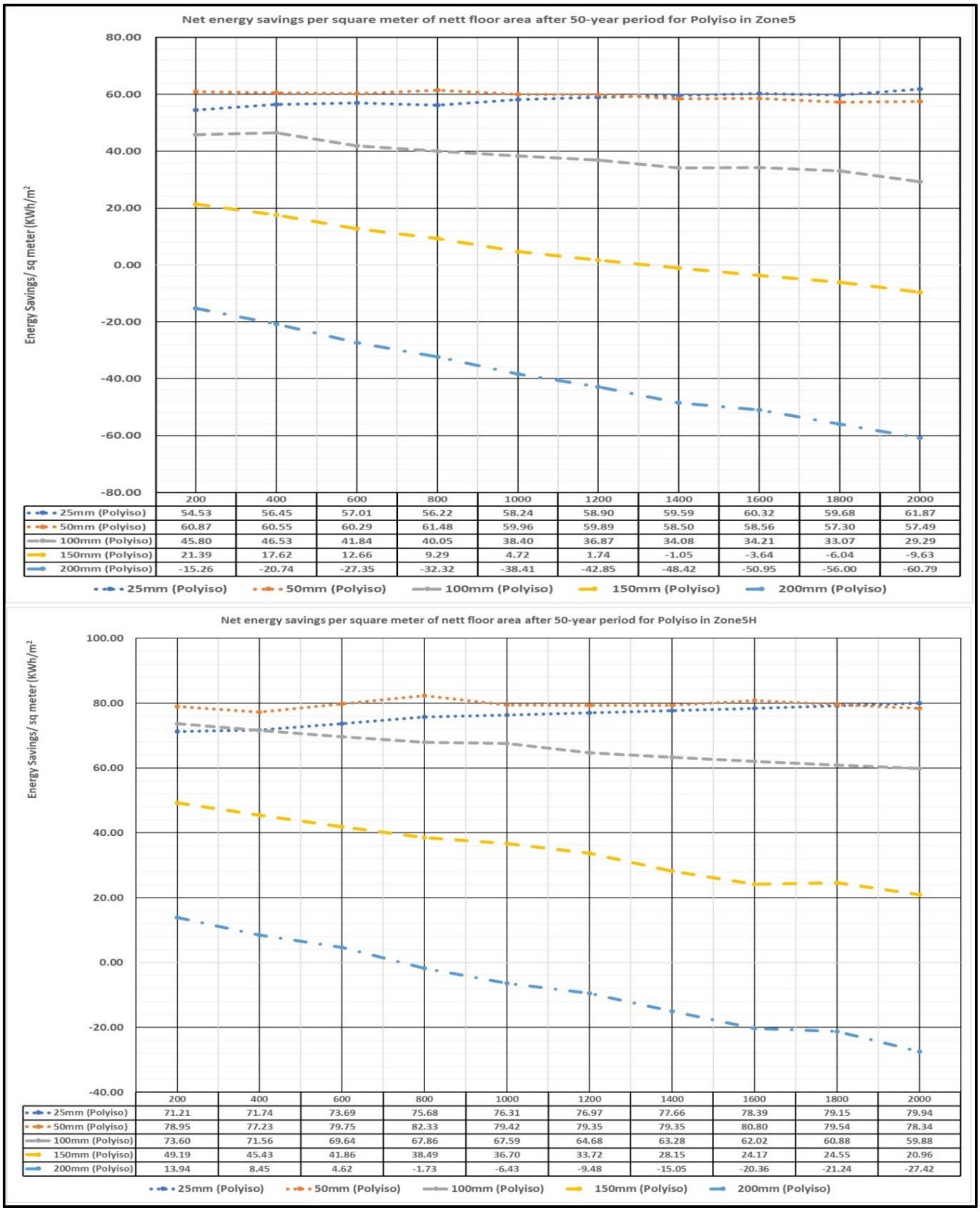


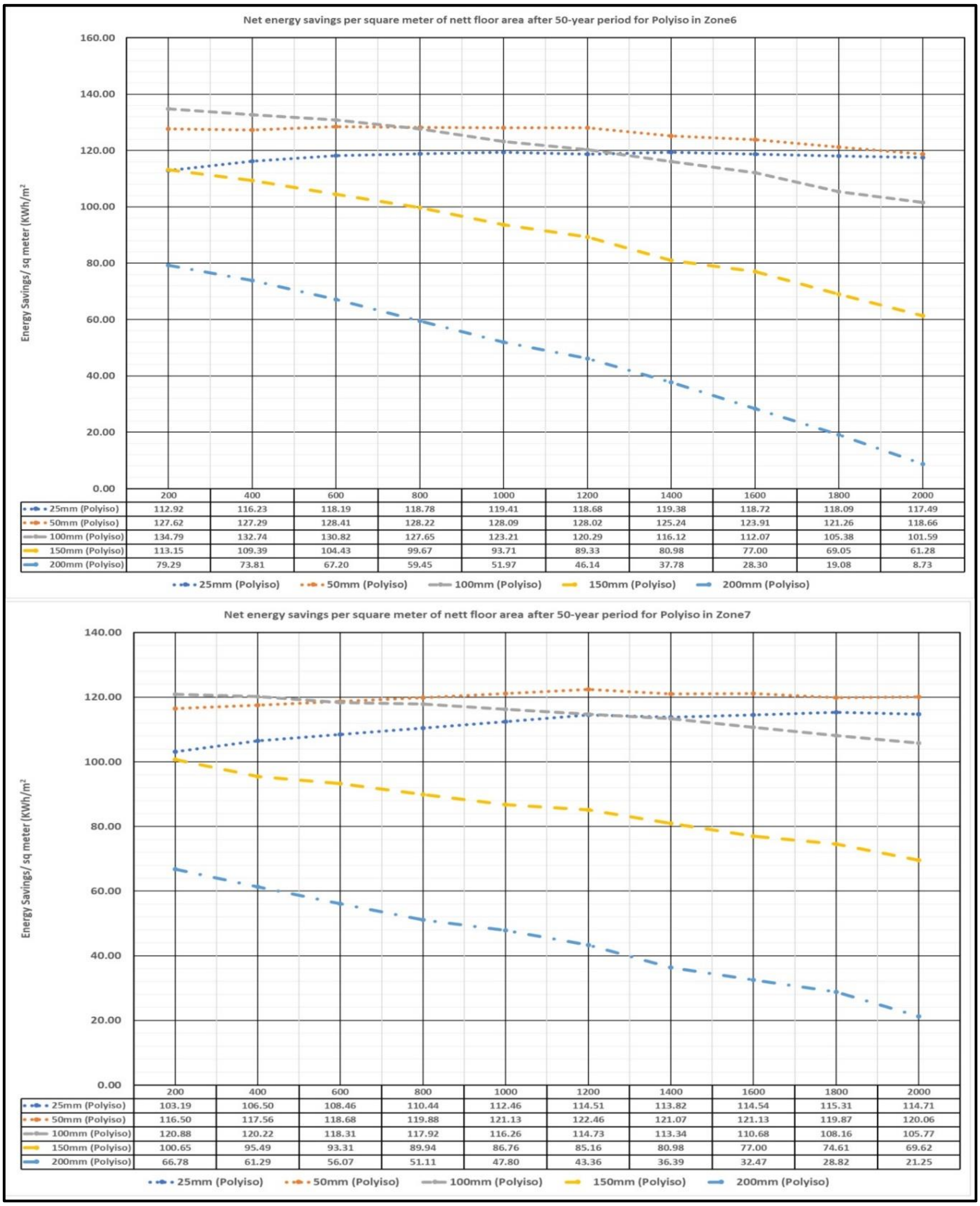
	200	400	600	800	1000	1200	1400	1600	1800	2000
25mm (Polyiso)	54.53	56.45	57.01	56.22	58.24	58.90	59.59	60.32	59.68	61.87
50mm (Polyiso)	60.87	60.55	60.29	61.48	59.96	59.89	58.50	58.56	57.30	57.49
100mm (Polyiso)	45.80	46.53	41.84	40.05	38.40	36.87	34.08	34.21	33.07	29.29
150mm (Polyiso)	21.39	17.62	12.66	9.29	4.72	1.74	-1.05	-3.64	-6.04	-9.63
200mm (Polyiso)	-15.26	-20.74	-27.35	-32.32	-38.41	-42.85	-48.42	-50.95	-56.00	-60.79

	200	400	600	800	1000	1200	1400	1600	1800	2000
25mm (Polyiso)	71.21	71.74	73.69	75.68	76.31	76.97	77.66	78.39	79.15	79.94
50mm (Polyiso)	78.95	77.23	79.75	82.33	79.42	79.35	79.35	80.80	79.54	78.34
100mm (Polyiso)	73.60	71.56	69.64	67.86	67.59	64.68	63.28	62.02	60.88	59.88
150mm (Polyiso)	49.19	45.43	41.86	38.49	36.70	33.72	28.15	24.17	24.55	20.96
200mm (Polyiso)	13.94	8.45	4.62	-1.73	-6.43	-9.48	-15.05	-20.36	-21.24	-27.42

Figure 18. Net energy savings after 50 years for zone 5 and zone 5H, at different levels of slab horizontal insulation width from the slab edges (200 to 2000mm) and insulation thickness (25 to 200mm). Source: Author.

Zone5: Insulation widths up to 1200mm would require 50mm insulation thickness to maximize net energy savings. Beyond 1200mm of insulation widths, insulation thickness of 25mm would be suitable. Only insulation thicknesses of up to 100mm would yield positive net energy savings at all the levels of insulation width. Thicknesses 200mm and above would not yield positive net energy savings. 150mm thick insulation would yield positive net energy savings only for insulation width less than or equal to 1200mm.

Zone5H: Insulation widths up to 1800mm would require 50mm insulation thickness to maximize net energy savings. Beyond 1800mm of insulation widths, insulation thickness of 25mm would be suitable. Only insulation thicknesses of up to 150mm would yield positive net energy savings at all the levels of insulation width. 200mm thick insulation would yield positive net energy savings for insulation width less than or equal to 600mm.



	200	400	600	800	1000	1200	1400	1600	1800	2000
25mm (Polyiso)	112.92	116.23	118.19	118.78	119.41	118.68	119.38	118.72	118.09	117.49
50mm (Polyiso)	127.62	127.29	128.41	128.22	128.09	128.02	125.24	123.91	121.26	118.66
100mm (Polyiso)	134.79	132.74	130.82	127.65	123.21	120.29	116.12	112.07	105.38	101.59
150mm (Polyiso)	113.15	109.39	104.43	99.67	93.71	89.33	80.98	77.00	69.05	61.28
200mm (Polyiso)	79.29	73.81	67.20	59.45	51.97	46.14	37.78	28.30	19.08	8.73

	200	400	600	800	1000	1200	1400	1600	1800	2000
25mm (Polyiso)	103.19	106.50	108.46	110.44	112.46	114.51	113.82	114.54	115.31	114.71
50mm (Polyiso)	116.50	117.56	118.68	119.88	121.13	122.46	121.07	121.13	119.87	120.06
100mm (Polyiso)	120.88	120.22	118.31	117.92	116.26	114.73	113.34	110.68	108.16	105.77
150mm (Polyiso)	100.65	95.49	93.31	89.94	86.76	85.16	80.98	77.00	74.61	69.62
200mm (Polyiso)	66.78	61.29	56.07	51.11	47.80	43.36	36.39	32.47	28.82	21.25

Figure 19. Net energy savings after 50 years for zone 6 and zone 7, at different levels of slab horizontal insulation width from the slab edges (200 to 2000mm) and insulation thickness (25 to 200mm). Source: Author.

Zone6: Insulation widths up to 600mm would require 100mm insulation thickness to maximize net energy savings. Beyond 600mm of insulation widths, insulation thickness of 50mm would be suitable.

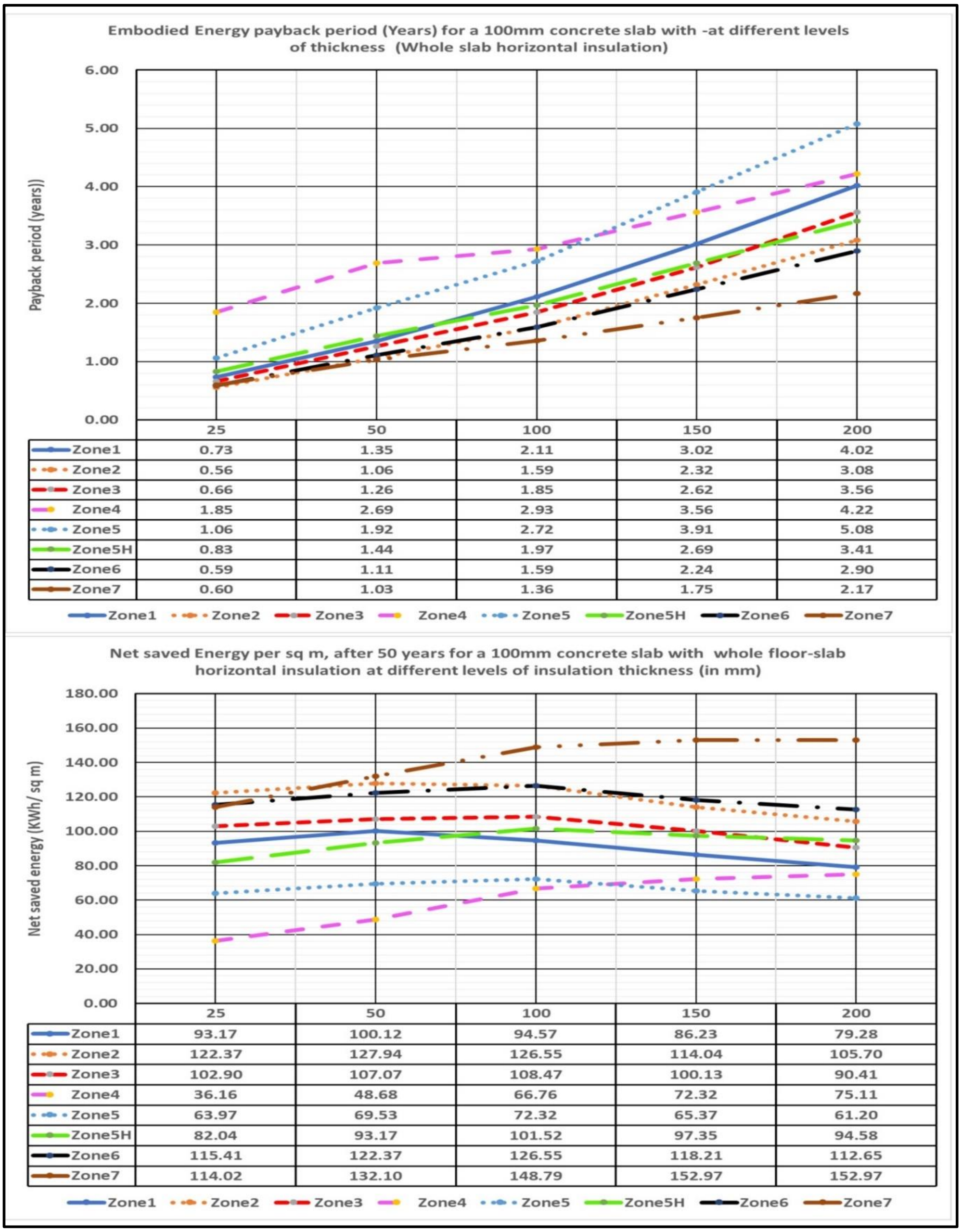
Zone7: Insulation widths up to 400mm would require 100mm insulation thickness to maximize net energy savings. Beyond 400mm of insulation widths, insulation thickness of 50mm would be suitable.

Overall general trends: Generally smaller insulation thicknesses of 50mm or less tended to slightly increase, remain constant or slightly reduce with changes in insulation width. Except for zone 4, larger insulation thicknesses of 100mm and above generally decreased significantly with increase in insulation width. Operating at lower horizontal insulation thicknesses and lower horizontal insulation width would tend almost to maximize net energy savings after 50 years, yield lower payback periods and also lead to lower costs being spent on insulation materials.

This is in sharp contrast to the vertical gap insulation method where maximum net energy savings were generally achieved at lower levels of insulation thickness, but at higher levels of insulation depths. This means more insulation material (to increase insulation depth) would be required for gap vertical insulation in order to maximize net energy savings after 50 years.

3.7. Energy payback periods and net saved energy for horizontal full floor slab insulation after 50 years

Energy payback periods and net saved energy were evaluated at various levels of insulation thickness, when the whole floor slab was insulated. Table 5 still applies to the energy models used for full floor-slab horizontal insulation. Figure 20 shows the results.



	25	50	100	150	200
Zone1	0.73	1.35	2.11	3.02	4.02
Zone2	0.56	1.06	1.59	2.32	3.08
Zone3	0.66	1.26	1.85	2.62	3.56
Zone4	1.85	2.69	2.93	3.56	4.22
Zone5	1.06	1.92	2.72	3.91	5.08
Zone5H	0.83	1.44	1.97	2.69	3.41
Zone6	0.59	1.11	1.59	2.24	2.90
Zone7	0.60	1.03	1.36	1.75	2.17

	25	50	100	150	200
Zone1	93.17	100.12	94.57	86.23	79.28
Zone2	122.37	127.94	126.55	114.04	105.70
Zone3	102.90	107.07	108.47	100.13	90.41
Zone4	36.16	48.68	66.76	72.32	75.11
Zone5	63.97	69.53	72.32	65.37	61.20
Zone5H	82.04	93.17	101.52	97.35	94.58
Zone6	115.41	122.37	126.55	118.21	112.65
Zone7	114.02	132.10	148.79	152.97	152.97

Figure 20. Energy payback periods and net energy savings (after 50 years) for full floor-slab horizontal polyiso insulation, at different levels of insulation thickness (25 to 200mm). Source: Author.

Payback periods: Small payback periods were associated with lowest levels of insulation thickness and vice versa. The energy zones with lowest payback periods were zone7 or zone 6 or zone 2, depending on the thickness level. Zone 4 had the highest payback periods for thicknesses of 100mm or less. For thicknesses greater than 100mm, zone 5 had the highest payback periods.

Net energy savings: For thicknesses 25mm or less, zone 2 had the highest net energy savings per square meter of nett floor area. For insulation thicknesses greater than 50mm, zone 7 had the highest

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net energy savings, followed by either zone 6 or zone 2 and then zone3. Net energy savings per square meter for zone 7 and zone 4, generally increased with increase in insulation thickness. Therefore, operating at insulation thicknesses of 200mm or more would ensure maximization of net energy savings in these 2 zones, but would come at an added monetary cost due to the extra insulation material required to meet the insulation thickness. This trend is similar to the results due to the work done by Cox-Smith (2016) in Australia, where the thermal performance increased with perimeter insulation thickness. However, this trend does not apply for all energy zones in this research, because the maximization of net energy savings in zone 5, zone 5H, zone 3 and zone 6 would be best at around 100mm, where the respective graphs peak. Maximization of net energy savings in zone 2, and zone 1 would be best at around 50mm, where these two graphs peak. For thicknesses less than 100mm, zone 4 had the lowest net energy savings. However for thicknesses greater than 100mm, zone 5 had the lowest net energy savings.

Unlike vertical gap insulation or horizontal perimeter insulation, the full floor-slab horizontal insulation method could be applied at all levels of thickness in zone 4 and still yield positive (but relatively low) net energy savings.

4. Discussions

The study considered whether it was beneficial to use floor-slab insulation materials for a 50mm air-gap cavity wall made of clay-brick masonry for a residential building whose nett floor area was 105.4 m^2, within several locations located in the seven energy zones for South Africa. Three methods of insulation were analysed, using polyiso, and in some cases XPS insulation. These were the gap vertical insulation, the horizontal perimeter floor slab insulation, and the full horizontal floor slab insulation methods. The study first implemented an energy efficient design using the passive design strategy recommendations from climate consultant and the SANS10400-XA building energy efficiency standards, before evaluating the embodied and operational site energy. 8 locations representing the seven energy zones were used for the analysis. These were Welkom (zone1), Pretoria (zone2), Nelspruit (zone3), Cape Town (zone4), Mthatha (zone5), Ixopo (zone5H), Kimberley (zone6), Fraserburg (zone7). The SANS 10400-XA shading multipliers were applied to obtain minimum applicable shading depths of 0.62 (Welkom); 0.68 (Fraserburg, Mthatha and Ixopo); 0.54 (Pretoria and Nelspruit); 0.73 (Cape Town) and 0.57 (Kimberley). Addition of floor-slab vertical gap insulation material as a measure hardly yielded any operational site energy savings in Cape Town (zone 4). This indicates that thermal vertical gap insulation is not necessarily beneficial for certain building typologies in zones such as zone 4 (Cape Town). Previous research done in South America and Japan also showed that the use of thermal insulation does not necessarily lead to a reduction in annual energy consumption (Melo, Lamberts, Versage, and Zhang, 2015; Dong et al, 2023). In case of horizontal perimeter insulation, application of the insulation measures in zone 4 (Cape Town) was only beneficial at lower levels of insulation thickness (50mm and below). Horizontal full floor-slab insulation was beneficial for all levels of insulation thickness in zone 4, but the benefits were relatively the lowest compared to other zones at most of the insulation thickness levels. Generally zone 4 (Cape Town) had the lowest benefits from the application of insulation measures using any of the three methods.

Greater net energy savings per square meter were experienced at lower floor-slab insulation thickness levels for the vertical gap and horizontal perimeter methods of floor-slab insulation, although other factors also influenced the savings. This is in agreement with the work done by Cox-Smith (2016) in New Zealand, where R-Values (thermal performance) tended to decrease with increase in vertical insulation thickness. In the case of full horizontal floor-slab insulation method, the insulation thickness levels corresponding to the peak values of net saved energy did not necessarily correspond to lowest values of thickness, and varied with respect to the energy zone.

With the exception of zone 4 (Cape Town), the net energy savings per square meter (for vertical gap insulation) also initially tended to increase with insulation depth (but the rate of increase reduced with depth), peaked in some instances, and started decreasing with the insulation depth (up to a maximum depth of 2000mm or 2.0m). The same trends are confirmed by Cox-Smith (2016) where the R-Values were shown to increase with insulation height, but the rate of increase reduced with insulation height (up to a maximum height of 1.0m). Since research by Cox-Smith (2016) used depths only up to 1.0m, and never considered locations in different energy zones, it may serve to explain why the peak points were never reached in his research.

The energy zones with low energy payback periods generally corresponded to high net energy savings after 50 years. In the case of vertical gap insulation, polyiso generally yielded lower payback periods compared to XPS under similar conditions.

Analysis based on energy payback periods showed that the lowest payback periods occurred at lowest insulation thicknesses (for all three insulation methods), at lowest insulation depths that were greater than 0.4m (for gap vertical insulation) and lowest insulation widths (for perimeter horizontal insulation).

However the gap vertical insulation analysis for net saved energy after 50 years showed that the maximum net energy savings never corresponded to lowest thickness level or lowest insulation depth (for depths greater than 0.4m), but varied with the insulation type, insulation thickness level, insulation depth and energy zone. The maximum energy payback periods for all cases of the optimum energy payback scenarios were all less than 50 years (the analysis period) for both XPS and polyiso insulation thickness levels and insulation depths. They ranged from 8.80 years to 13.74 years, if zone 4 (Cape Town) was excluded. If zone 4 (Cape Town) was included then they ranged from 8.80years to 35.58 years. All optimal points (for maximum net energy savings per square meter of nett floor area) corresponded to polyiso floor-slab insulation (for vertical gap insulation method).

The zones that benefitted most from the gap vertical floor-slab insulation were (from highest to lowest beneficiary) zone2 (Pretoria), zone 6 (Kimberley), zone 3 (Nelspruit), zone 7 (Fraserburg), zone 1 (Welkom), zone 5 (Mthatha), zone 5H (Ixopo) and zone 4 (Cape Town) in that order. This was almost the same order for horizontal perimeter insulation and horizontal full floor-slab insulation, with some slight modifications or departures. Zone 4 was the least beneficiary from floor slab insulation using any of the three methods.

Apart from its good thermal properties, polyiso is also a good fire retardant and moisture barrier. However it tends to be more costly than XPS, and suffers from thermal drift. It is recommended that polyiso be used with plastic facings or aluminium foil in order to slow down the thermal drift. The addition of selected agricultural waste has also been reported to improve its properties (Lazo et al, 2023). XPS on the other hand, though less costly, is significantly less environmentally friendly compared to polyiso (Füchsl et al, 2022).

5. Conclusion

Floor-slab XPS and polyiso insulation materials display similarity performance patterns within the energy zones 1, 2, 3, 5, 5H, 6 and 7 with respect to payback period trends and net energy savings after 50 years. The behavioural patterns, however, are different in zone 4 (Cape Town). Zone 4 hardly benefits from the application of vertical, gap floor-slab insulation, and corresponds to comparatively higher energy payback periods. Zone 4, however had some small benefits for horizontal perimeter insulation for thicknesses of 50mm and below, and for horizontal full floor-slab insulation. Polyiso tended to perform better than XPS, other factors remaining constant. Insulation depths of 200mm and below are not recommended for gap vertical insulation in energy zones 1, 2, 3, 5, 5H, 6 and 7. Insulation depths from 400mm and above were beneficial to apply in these zones. Given that the thermal conductivity of materials changes with temperatures and moisture content, there are limitations to the results of this research (Tariku, Shang, and Molleti, 2023). The results are also limited to residential buildings with cavity wall envelopes and the derived window-to-wall ratios for the front (0.277), back (0.240), left (0.05) and right (0.05) envelope wall facades. They apply only to the 8 locations (Welkom, Pretoria, Nelspruit, Cape Town, Mthatha, Ixopo, Kimberley, and Fraserburg) in each of the 7 energy zones of South Africa (1, 2, 3. 4. 5. 5H, 6, and 7 respectively) and their minimum derived shading depths according to the SANS10400-XA standard. Further research can consider the application of other suitable floor-slab insulation materials, or even application of polyiso with agricultural additives within the confines of SANS10400-XA standards.

Supplementary Materials: The following supporting information can be downloaded at: www.mdpi.com/xxx/s1, Table S1: Output simulation Results for vertical gap insulation; Table S2: Output simulation results for horizontal insulation.

Author Contributions: Conceptualization, Emmanuel Kabundu, Sijekula Mbanga and Brink Botha.; methodology, Emmanuel Kabundu, Sijekula Mbanga, Brink Botha.; software, Emmanuel Kabundu.; validation, Emmanuel Kabundu.; formal analysis, Emmanuel Kabundu.; investigation, Emmanuel Kabundu, Emma Ayesu-Koranteng.; resources, Emma Ayesu-Koranteng.; data curation, Emmanuel Kabundu, Emma Ayesu-Koranteng.; writing—original draft preparation, Emmanuel Kabundu, Emma Ayesu-Koranteng, Sijekula Mbanga, Brink Botha.; writing—review and editing, Emmanuel Kabundu, Emma Ayesu-Koranteng, Sijekula Mbanga, Brink Botha.; visualization, Emmanuel Kabundu,.; supervision, Emma Ayesu-Koranteng, Sijekula Mbanga.; project administration, Emma Ayesu-Koranteng, Sijekula Mbanga.; funding acquisition, Emmanuel Kabundu, Emma Ayesu-Koranteng, Sijekula Mbanga, Brink Botha. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

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