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Abstract: The potential savings in space heating energy from the installation of Fumed Silica (FS) and Glass Fibre (GF) Vacuum Insulation Panels (VIPs) were compared to conventional expanded polystyrene (EPS) insulation for three different non-domestic buildings situated in London (UK). A discounted payback period analysis was used to determine the time taken for the capital cost of installing the insulation to be recovered. VIP materials were ranked using cost and density indexes. The methodology of the Payback analysis carried out considered the time dependency of VIP thermal performance, fuel prices and rental income from buildings. These calculations show that VIP insulation reduced the annual space heating energy demand and carbon dioxide (CO2) emissions by approximately 10.2%, 41.3% and 26.7% for a six storey office building, a two floor retail unit building and a four storey office building respectively. FS VIPs had the shortest payback period among the insulation materials studied, ranging from 2.5 years to 17 years, depending upon the rental income of the building. For GF VIPs the calculated payback period was considerably longer and in the case of the typical 4 storey office building studied its cost could not be recovered over the life time of the building. For EPS insulation the calculated payback period was longer than its useful life time for all three buildings. FS VIPs were found to be economically viable for installation onto non-domestic buildings in high rental value locations assuming a lifespan of up to 60 years.

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Editor-in-Chief
Applied Energy journal.

Dear Professor Yan

We would like to thank the reviewers and the concerned editor for their time and efforts expended on assessing the quality of our paper (APEN-D-16-06879) titled "*Energy and economic analysis of Vacuum insulation panels (VIPs) used in non-domestic buildings***"**.

We have included the reviewer's comments and suggestions in the revised manuscript, which is being resubmitted. Also attached is our detailed response to the reviewers and editor's comments.

We hope that the revised paper with enhanced information and improved format will be acceptable for publication.

I look forward to hearing from you.

Yours Sincerely,

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Detailed Response to Reviewers

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Reviewer 1: *This paper reported the payback period and space heating energy saving analysis of fumed silica (FS) and Glass fibre (GF) Vacuum Insulation Panels (VIPs). It presented an interesting area, is novel and is also well written. It is suitable for publish, if some more review of the state of the art of VIPs or similar materials e.g. Transparent Insulation Materials (including their performances) that could be demonstrated in the introduction section. In addition, some more review of evaluation the payback period of similar systems and relevant methods should be demonstrated.*

Suggested articles as below:
Experimental and numerical investigation of the thermal performance of a protected vacuum-insulation system applied to a concrete wall, applied energy,Volume 83,Pages 841-855 Effect of nano vacuum insulation panel and nanogel glazing on the energy performance of office building, applied energy, Volume 173,Pages 141-151 Thermal evaluation of a double glazing façade system with integrated Parallel Slat Transparent Insulation Material (PS-TIM), Building and Environment, Volume 105, Pages 69-81 Experimental measurement and numerical simulation of the thermal performance of a double glazing system with an interstitial Venetian blind, Building and Environment, Pages 111-122

Response: We thank the reviewer for appreciating the main intent of our article and for his advice to broaden its scope.

In the section 1, Introduction, more up to date review of the VIP research has been added covering the energy saving potential and economics of VIPs in buildings. Recently published research reporting core materials for opaque VIP insulation and transparent insulation material has also been included. Newly added sources of information are:

Mujeebu M.A., Ashraf N., Alsuwayigh H.A. (2016a). Effect of nano vacuum insulation panel and nanogel glazing on the energy performance of office building. Applied energy,173,141-151.

Nussbaumer T., Wakili K.G.,Tanner Ch. (2006). Experimental and numerical investigation of the thermal performance of a protected vacuum-insulation system applied to a concrete wall. Applied energy, 83, 841-855

Kucukpinara E., Miesbauera O., Carmib Y., Frickec M., Gullbergd L., Erkeye C., Caps R., Rochefortg M., Morenoh A.G., Delgadoi C., Koehlj M., Holdsworthk P., Klaus Nollera K. (2015). Development of transparent and opaque vacuum insulation panels for energy efficient buildings. Energy Procedia, 78,412 – 417.

Sun Y., Wu Y, Wilson R., Sun S. (2016). Thermal evaluation of a double glazing façade system with integrated Parallel Slat Transparent Insulation Material (PS-TIM). Building and Environment, 105, 69 - 81.

Li C.D., Saeed M.U., Pan N., Chen Z.F., Xu T.Z. (2016). Fabrication and characterization of low-cost and green vacuum insulation panels with fumed silica/rice husk ash hybrid core material. Materials and Design, 107, 440-449.

Mujeebu M.A., Ashraf N., Alsuwayigh H.A. (2016b). Energy performance and economic viability of nano aerogel glazing and nano vacuum insulation panel in multi-story office building. Energy, 113, 949-956.

Dylewski R., Adamczyk J. (2012). Economic and ecological indicators for thermal insulating building investments. Energy and Buildings, 54,88–95.

Reviewer 2:

Comment 1. *Line 70-71 should be rewritten as: feasible in existing and new buildings, or advanced insulation such as Vacuum Insulation Panels (VIPs) are needed.*

Response: Line 72-73 (previously line 70-71) has been rewritten. It now reads as: "may not be feasible in existing or even new buildings. Alternatively, thinner layers of advanced insulation products, such as VIPs, could be used due to their thermal …."

Comment 2. *Line 116: correct spelling from 'birding' to bridging.*

Response: Line 139 (previously line 116) – spelling of 'bridging' has been corrected.

Comment 3. *Line 196: Delete 'Heating degree' and the 'brackets around HDD'.*

Response: Line 219 (previously line 196), Heating degree and brackets around HDD have been deleted. It now reads as: "The HDD data used to determine energy consumption for space heating was the 5 ……"

Comment 4. *Line 198: Provide a reference for the rate of decrease of thermal efficiency of gas condensing boiler*

Response: Line 222 (previously line 198), Rate of decrease of thermal efficiency of gas condensing boiler has been taken as 0.5% per annum. This rate of decrease of thermal efficiency has been calculated based on the assumption that initial efficiency of a new installed gas condensing boiler is 90% and over its service life it efficiency decreases to 80%.

Comment 5. *Line 271: it should be rewritten as: Phenolic foam has been assumed to have*-------------

Response: Line 291-292 (previously line 271) has been rewritten. It now reads as: "The thermal conductivity of the Phenolic foam used was assumed as of 0.020 $Wm^{-1}K^{-1}$.

Comment 6. *Line 279: replace 'has' with 'have' and 'was' with 'were'*

Response: Line 297-298 (previously line 279) has been rewritten. It now reads as: "…..emission from using VIP insulation in all three types of buildings (described in table 4) were calculated. The annual space heating energy saving (E_A) for any year (n) …."

Comment 7. *Symbols used in eq (11) have been described under eq (3); hence some of the description can be deleted.*

Response: Repetition of symbols description under equation 7 (previously equation 11) has been deleted.

Comment 8. *Line 308: delete 'the'*

Response: Line 318 (previously line 308) has been rewritten. It now read as: "Using the parameters outlined previously in table 4 over the assumed building life…"

Comment 9. *Line 320: 'feature' should be replaced with 'features'*

Response: Line 334 (previously line 320) 'feature' has been replaced with 'features'. It now read as: "Geometric and thermal features of the buildings studied are shown in table 5."

Comment 10. *Line 397: add full stop after 4*

Response: Line 406-407 (previously line 397) has been rewritten. It now reads as "Geometric and thermal features of the six storey office are detailed in table 4 and table 5."

Editor's comments:

Comment 1: *An updated and complete literature review should be conducted. The relevance to Applied Energy should be enhanced with the considerations of scope and readership of the Journal*.

Response: In the Introduction section, further review of the relevant latest research on VIPs has been included showing the energy saving potential of VIPs in buildings. Outcomes of newly published research into core materials for opaque and transparent vacuum insulation panel has also been included. Newly added sources of information are:

Mujeebu M.A., Ashraf N., Alsuwayigh H.A. (2016a). Effect of nano vacuum insulation panel and nanogel glazing on the energy performance of office building. Applied energy,173,141-151.

Nussbaumer T., Wakili K.G.,Tanner Ch. (2006). Experimental and numerical investigation of the thermal performance of a protected vacuum-insulation system applied to a concrete wall. Applied energy, 83, 841-855

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Dylewski R., Adamczyk J. (2012). Economic and ecological indicators for thermal insulating building investments. Energy and Buildings, 54,88–95.

Comment 2: *A proof reading should be conducted to improve both language and organization quality.*

Response: Manuscript has been read and edited to correct English language and grammar mistakes by a native English speaker, Dr David Redpath, who is a co-author on the paper.

Comment 3: *The originality of the paper needs to be further clarified. The present form does not have sufficient results to justify the novelty of a high quality journal paper.*

Response: It is strongly believed that the paper contains original research. This is the first time ever that a consolidated equation for predicting realistic payback period of VIPs when used in buildings has been presented. Such an equation has been long sought after in research as well as industrial communities. A set of realistic values of all independent variables that are used to derive this equation is also presented. Calculation of payback period using this equation has been demonstrated in non-domestic buildings located in the UK. The procedure can be easily adapted globally for any building type.

Comment 4: *The results should be further elaborated to show how they could be used for the real applications.*

Response: We have used real non-domestic buildings situated in the UK in our analysis. The payback period equation and the procedure developed in this paper can be easily adapted globally for any other building type. The payback period formulation can be employed by architects, engineers, specifiers and researchers to predict and understand the economic feasibility of using VIPs in buildings and other application such as refrigerators, freezers and refrigerated vehicles.

***Highlights (for review)**

- A novel methodology for payback analysis of vacuum insulation panels was proposed
- The methodology considers the variation of techno-economic parameters with time
- Space heating energy and emission savings were calculated
- Longer lifespan vacuum insulation panel achieved a shorter payback period
- Fumed silica VIPs are economically viable for adoption into non-domestic buildings

*Revised Manuscript with No Changes Marked

Energy and economic analysis of Vacuum Insulation Panels (VIPs) used in non-domestic buildings

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Abstract

The potential savings in space heating energy from the installation of Fumed Silica (FS) and Glass Fibre (GF) Vacuum Insulation Panels (VIPs) were compared to conventional expanded polystyrene (EPS) insulation for three different non-domestic buildings situated in London (UK). A discounted payback period analysis was used to determine the time taken for the capital cost of installing the insulation to be recovered. VIP materials were ranked using cost and density indexes. The methodology of the Payback analysis carried out considered the time dependency of VIP thermal performance, fuel prices and rental income from buildings. These calculations show that VIP insulation reduced the annual space heating energy demand and carbon dioxide (CO_2) emissions by approximately 10.2%, 41.3% and 26.7% for a six storey office building, a two floor retail unit building and a four storey office building respectively. FS VIPs had the shortest payback period among the insulation materials studied, ranging from 2.5 years to 17 years, depending upon the rental income of the building. For GF VIPs the calculated payback period was considerably longer and in the case of the typical 4 storey office building studied its cost could not be recovered over the life time of the building. For EPS insulation the calculated payback period was longer than its useful life time for all three buildings. FS VIPs were found to be economically viable for installation onto non-domestic buildings in high rental value locations assuming a lifespan of up to 60 years.

Keywords: Payback period; Space heating energy savings; Vacuum Insulation Panel (VIP);Fumed Silica; Glass fibre; Non-domestic buildings.

Contents

1 Introduction

The combustion of fossil fuels to generate energy is recognised as the major cause of anthropogenic climate change. To mitigate this, the international community has agreed to collectively endeavour to limit global temperature rise to within 1.5°C above pre-industrial levels by reducing emissions of greenhouse gases through the use of cleaner energy sources and increased energy efficiency [1]. In 2013, emissions from space heating energy use in UK buildings accounted for 98 million tonnes of carbon dioxide (CO_2), constituting 17% of total UK greenhouse gas emissions [2]. Energy efficiency requirements for UK buildings are continuously improved through stricter stipulations in the building regulations. The aim is to reduce overall UK CO_2 emissions by at least 80% from the 1990 level by 2050 as set in the Climate Change Act 2008 [3]. With over 60% of the energy consumed in the buildings used for space heating [4], the development of building fabrics with substantially improved insulation properties are essential for the UK to achieve its long term carbon reduction goals.

To reduce heat losses from building fabric using conventional insulation products, such as Expanded Polystyrene (EPS), will require prohibitively thick layers, which may not be feasible in existing or even new buildings. Alternatively, thinner layers of advanced insulation products, such as VIPs, could be used due to their thermal resistivity being 5-8 times greater than conventional insulation [5,6,7,8,9].

A VIP is a composite rigid sheet comprising an evacuated (pressure ≤0.5 mbar) inner core board laminated inside an outer barrier envelope [10]. VIPs can be installed on opaque building surfaces (externally or internally) and on hot water storage cylinders to improve their thermal resistance. For façade applications, transparent insulation materials [11,12] are under development.
In 2014, only 10%of the VIPs production were used for insulating buildings, refrigeration and transportation industry were the main users of this technology consuming 30% and 60% of the annual production of VIPs respectively [13]. The uptake of VIPs for building applications has not achieved its full potential due to their high installed cost compared with other insulation products. Presently, VIP use can only be justified in a few construction scenarios; for example, heritage and narrow city centre buildings with unique architectural features or limited usable indoor space. The high cost of VIPs is due to the materials required for manufacturing, necessitating the development of lower cost core and envelope materials with similar or improved thermal insulation properties than those currently in use. Previous research on VIP core materials has focused mainly on Fumed Silica (FS) due to its excellent thermo-physical properties [14]. But, FS is expensive and several studies, as shown in table 1, have proposed alternative core materials.

Table 1. Core materials other than FS and glass fibre reported in previous studies

Core Material	Initial Centre of Panel Conductivity ($Wm^{-1}K^{-1}$)	Reference
Melamine-formaldehyde Fibre fleece	0.0023	[15]
Expanded perlite and fumed silica composite	0.0074	[16]
Open pore melamine formaldehyde foam	0.006	[17]
Granular Silica	0.014	[18]
Phenolic foam	0.005	[19]
Fumed silica/rice husk ash hybrid mixture	0.0055-0.0062	[20]

Published research on the materials listed in table 1 have primarily focused on the thermo-physical performance of VIPs neglecting the potential for energy savings and the associated economic analysis. Cho et al. [21], Alam et al. [10] and Tenpierik [22] published economic analysis of VIPs but only considered domestic building applications. Kucukpinar et al. [11] demonstrated that VIP insulation reduced annual energy consumption by 25% for two mock-up rooms situated in Poland and Spain. Mujeebu et al. [23] predicted using ECOTECT software that VIPs fixed to the roof and external walls would reduce annual energy consumption by 0.62% for a single office building and 0.79% for a multi-storey office building compared to EPS.

Clearly, the energy saving potential of VIPs is dependent on the type of building and its location (climatic and economic factors) thus further research to clarify the energy saving potential of VIPs is required. Mujeebu et al. [24] predicted the simple payback period of VIPs to be 5.3 times longer than that of EPS if installed in a multi-storey office building in Saudi Arabia. The, simple payback method used by Mujeebu et al. [24], did not consider the impact on energy savings from the deterioration of the VIP thermal performance with time, the economic value of space savings due to thinner section of VIPs and the varying time value of money. These factors significantly influence payback periods and must be considered to enable a more accurate calculation to be made of the cost effectiveness of VIPs compared to other insulation materials.

The objective of this paper is to calculate the payback period of VIPs through a discounted economic analysis whilst simultaneously accounting for the other identified factors which affect it. To investigate this, an energy saving and economic payback analysis of FS and GF VIPs installed on three representative non-domestic buildings situated in London (UK) was undertaken. A novel methodology which considered the change of VIP thermal performance over time, fuel price variability, heating system efficiency degradation with time and the economic value of space savings realised from using comparatively thinner VIPs was developed. No such information currently exists in the peer reviewed literature. Cost and density indices linked to the thermal conductivity of FS and GF VIPs were calculated. The discounted payback period for VIPs was then compared to that of conventional expanded polystyrene (EPS) insulation, to assess the cost effectiveness of each.

2 Cost and density indices for VIP types

VIPs are classified by the type of main core materials used in their manufacturing, which includes FS, expanded perlite (EP), FS and EP composites (FS+EP), glass fibre (GF) and polyurethane foam (PU) along with opacifiers, getters and desiccants. VIPs with diverse core materials have different expected life times, which determines their suitability for specific applications. The cost of VIP core materials can account for 45% of the total cost.

The price, initial (measured at the time of manufacturing) centre of panel thermal conductivity (λ) design thermal conductivity (thermal conductivity including the thermal bridging effect and ageing effect) and density of VIPs made with different core materials are shown in table 2.

Table 2. Cost and main physical properties of different types of VIPs

Type of VIP	Cost ($£m^{-3}$)	Initial centre of panel λ ($Wm^{-1}K^{-1}$)	Design λ ($Wm^{-1}K^{-1}$)	Density (kgm^{-3})	Service Life (years)
VIP Fumed silica (FS)	2365	0.0043[a]	0.008	180[a]	60[a]
VIP Fumed silica& Expanded perlite composite (FS+EP)	2152	0.0076[b]	0.0116	330[b]	30
VIP Expanded perlite (EP)	1809	0.013	0.017	290	20
VIP Polyurethane (PU)	2000	0.009[a]	0.013	65[a]	15[a]
VIP Glass fibre (GF)	1464	0.0028[c]	0.0068	200[c]	10[c]

[a] va-Q-tec AG (2016) [25]; [b] Alam et al.(2014) [16]; [c] Di et al.(2013) [26]

Cost and density indices for the materials shown in table 2 were derived. The cost index, was the product of cost and initial centre of panel thermal conductivity. The density index, was the product of density and the initial centre of panel thermal conductivity. VIPs with smaller values of these indices are more desirable. Figure 1 shows the calculated cost and density index of the materials listed in table 2.

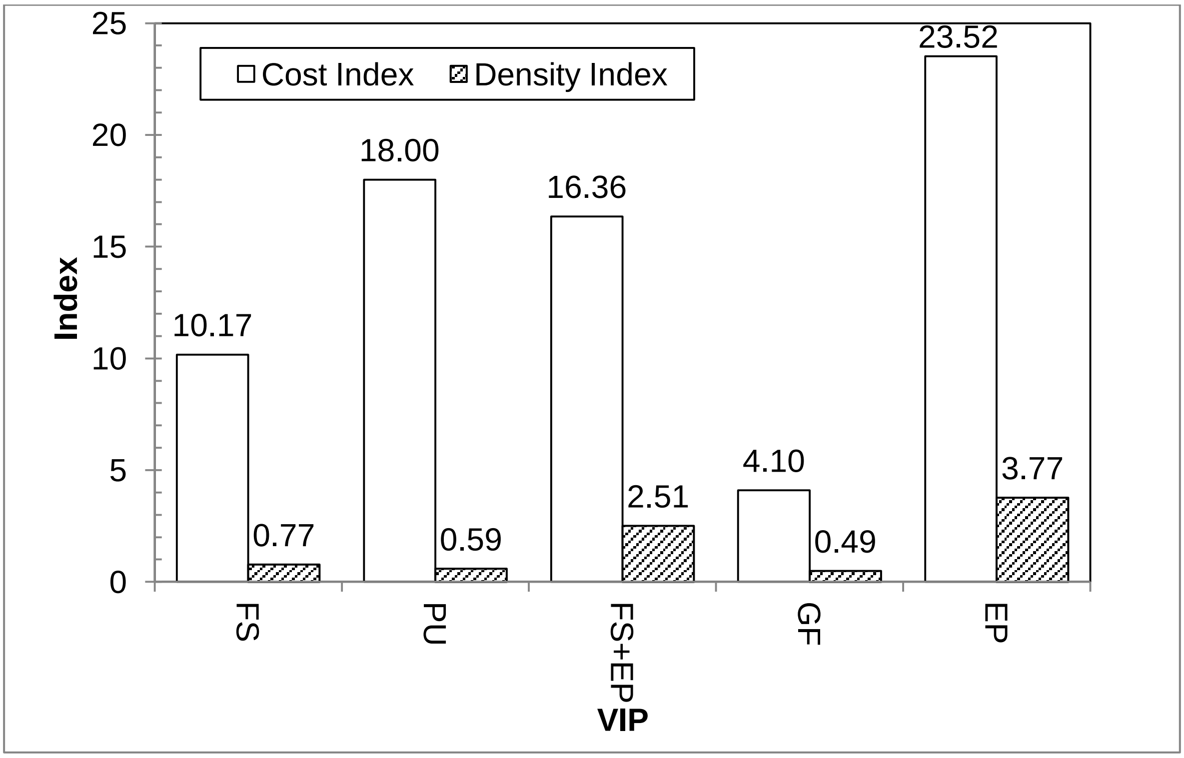

Figure 1. Cost and density index of different types of VIPs

Calculating the cost and density index of VIPs allows the relationship between cost and thermo-physical properties to be observed. From figure 1, GF VIP returned the smallest cost index of 4.10 (best performance) followed by FS, FS+EP composite, PU and EP in that order. Comparing the values of density index shown in figure 1, GF VIPs have the lowest calculated value of 0.49, whilst EP VIPs the highest value of 3.77. FS VIP, with a comparatively lower initial thermal conductivity and density, has 2.4X and 1.5X lower cost and density indices respectively than that of FS+EP composite VIP. FS VIP had a calculated cost and density index 2.48X and 1.57X greater respectively than GF VIPs. However, GF VIPs have a significantly shorter life time, of 10-12 years, compared to the lifetime of 50-60 years expected for FS VIPs.

3 Payback period calculation

The discounted payback period is the time taken for an investment, such as the installation of VIPs, to repay the initial capital through the realised savings taking into account fuel cost savings and other accrued benefits. It is a critical factor in the choice of the most cost effective insulation and was quantified by calculating the Profit on investment (POI) for each scenario investigated using equation (1). The POI accounts for present values of energy savings, space savings and present value of the capital costs. The payback year of any investment is reached when the POI equals zero for the very first time [27]. In case of commercial buildings, space savings due to thinner VIP sections would provide additional revenue for building owners, and is included in equation (1):

$$POI = \left[\frac{86400 \times HDD \times \Delta L \times C_F}{H_v \times \left(\frac{\eta_i - x \times n}{100}\right)} \times \frac{1}{(1+r)^n}\right] + \left[Y \times \Delta d \times 2\left\{(L_f + \Delta d) + (W_f + \Delta d)\right\} \times \frac{1}{(1+r)^n}\right] - [C_{Mt} + C_M + C_I] \qquad (1)$$

where

C_{Mt} is the material cost of VIP core and envelope (£)
C_M is the manufacturing cost of VIP (£)
C_I is the installation cost of VIP (£)
HDD is the heating degree days (°C days)
C_F is the cost of fuel (£m^{-3})
H_V is the calorific value of fuel (Jm^{-3})
η_i is the initial thermal efficiency of the heating system, boiler (%)
x is the annual rate of decrease of thermal efficiency of heating boiler (%)
ΔL is the difference of total building transmission heat loss coefficient (L) before and after applying insulation (WK^{-1})
n is the number of year
r is the annual discount rate (% fraction)
Y is the annual rental value (£m^{-2})

A_s the floor area saved (m^2)
F is the number of floors
$\triangle d$ is the difference in thickness of conventional insulation and VIP insulation (m)
L_f is the length of internal floor (m)
W_f is the width of the internal floor (m)

Total building transmission heat loss coefficient (L) is described as equation (2)

$$L = \sum_{i=1}^{i=N} U_i(t)\, A_i + \frac{I(\rho c_p)_{air} V}{3600} \quad (2)$$

where
A_i is the insulated area of the building element i (m^2)
U_i is the U-value of the building element i (Wm^{-2}K^{-1})
I is the air exchange rate per hour (ach^{-1})
V is the internal volume of the building (m^3)
$(\rho c_p)_{air}$ is the volumetric thermal capacity of air (Jm^{-3}K^{-1}) taken as 1200 Jm^{-3}K^{-1}. Hence, the equation (2) can be rewritten as

$$L = \sum_{i=1}^{i=N} U_i(t)\, A_i + \frac{IV}{3} \quad (3)$$

In equation (3), term $\frac{IV}{3}$ is the ventilation conductance (WK^{-1}) [28].

The different parameters used for calculating the discounted payback period analysis presented in this study are detailed in table 3. The long term price forecast reported by the UK Department of Energy and Climate Change [29] for natural gas which is shown in figure 2 and extrapolated for the assumed life time of the buildings under investigation was used to calculate space heating energy savings
The HDD data used to determine energy consumption for space heating was the 5 year average (2011 to 2015) for a base temperature of 15.5 °C for St. James Park London [30]. Gas condensing boilers are assumed to suffer from an annual fall in their thermal efficiency by 0.5% with a useful lifespan of 20 years. The installation cost was assumed to be the same for all VIP types investigated so was not included in the calculations.

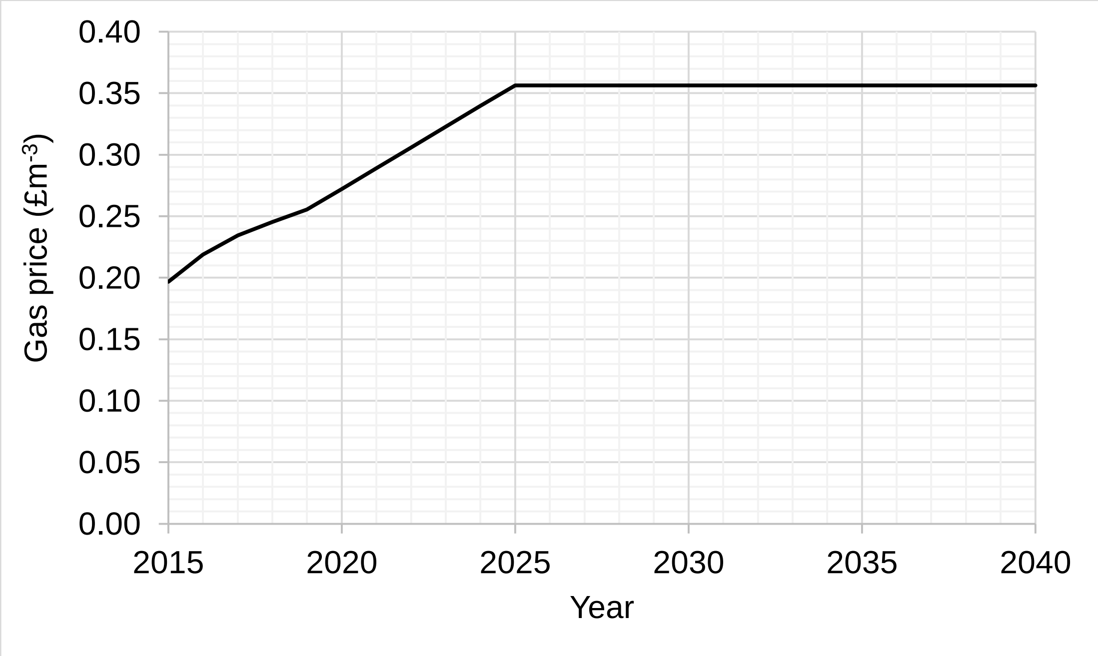

Figure 2. Gas price forecast [29]

Table 3. Parameters used for payback period calculation

Parameters	**Description/Value**
Fuel	Natural gas
HDD (°Cdays) [26]	1624
Fuel cost , $C_{F,}$ (£m^{-3}) [25]	0.196
Heating value, H_V, (MJm^{-3})	39.5
Initial heating system efficiency, η_i, (%)	90
Annual discount rate, r, (%)	4

The U-value of building elements was determined by calculating the thermal resistances of the constituent material layers and adjacent air layers as shown in equation (4) [28]. The thermal resistance of any building material layer is the ratio of its thickness to thermal conductivity.

$$U = \frac{1}{R_{si} + (\sum R_e) + R_{sx}} \quad (4)$$

where
U is the thermal transmittance (Wm^{-2}K^{-1})
R_{si} is the internal surface resistance (m^{2}KW^{-1})
R_e is the thermal resistances of a material layer (m^{2}KW^{-1})

R_{sx} is the external surface resistance (m^2KW^{-1})

The thermal conductivity of a VIP decreases with time as pressure inside VIP increases due to outgassing, or via penetration to the interior by atmospheric air and moisture. Degradation in VIP performance was accounted for when calculating the U-value of the building elements insulated with VIPs, by modifying equation (4) as shown in equation (5).

$$U\,(t) = \frac{1}{R_{si} + (\sum R_e) + R_{vip}(t) + R_{sx}} \tag{5}$$

where

$R_{vip}(t)$ is the time dependent thermal resistivity of the VIP layer in a building element and calculated using equation (6):

$$R_{vip}(t) = \frac{d_{vip}}{\lambda_{vip}(t)} \tag{6}$$

where d_{vip} is the thickness and $\lambda_{vip}(t)$ the time dependent thermal conductivity of VIP.

For the U-value calculations used by this research, design thermal conductivity values of 0.008 $Wm^{-1}K^{-1}$, 0.007 $Wm^{-1}K^{-1}$ and 0.035 $Wm^{-1}K^{-1}$ were used for FS VIP, GF VIP and EPS respectively. For FS VIPs and GF VIPs the annual increase in thermal conductivity was assumed as 0.0001 $Wm^{-1}K^{-1}a^{-1}$ [31] and 0.0018 $Wm^{-1}K^{-1}a^{-1}$ respectively [26].

4 Details of the non-domestic buildings investigated

The opaque elements (i.e. walls, floor and roof) of three different types of commercial (non-domestic) buildings situated in London (UK); a two floor retail unit, a four storey office and a six storey office were considered for retrofitting with VIPs or EPS.

The two floor retail unit building is representative of 10% of the current retail building stock in the UK by age of construction (1989-90) and 13% by floor area (250-500 m^2) [32]. The four storey office building type accounts for 9% of the office building stock in the UK by age of construction (1981-85) and 20% by floor area (2500-10,000m^2) [32]. The six storey office building accounts for 11% of the office building stock in the UK by age of construction (1986-90) and 20% by floor area (2500-10,000m^2) [32]. Table 4 shows the relevant details for each of the buildings investigated. Each building was assumed as refurbished to current building regulation standards by applying internal insulation on all opaque elements achieving U-values of 0.30 $Wm^{-2}K^{-1}$, 0.18 $Wm^{-2}K^{-1}$ and 0.25 $Wm^{-2}K^{-1}$ for wall, roof and floor respectively [33]. Table 4 shows U-values before and after applying insulation on all buildings considered in the study along with their thickness values. It was assumed that VIPs covered 95% of the opaque elements with phenolic foam insulation covering the remaining 5%. The thermal conductivity of the Phenolic foam used was assumed as of 0.020 $Wm^{-1}K^{-1}$.

Table 4. Details of buildings studied and U-values before and after the application of insulation

Building	Parameter	Wall	Floor	Roof
Retail Unit	Existing U-value ($Wm^{-2}K^{-1}$)	0.65	0.46	0.96
	U-value after applying insulation ($Wm^{-2}K^{-1}$)	0.30	0.25	0.18
	FS VIP Thickness (mm)	25	25	65
	GF VIP Thickness (mm)	40	40	110
	EPS Thickness (mm)	60	65	155
4 Storey Office	Existing U-value ($Wm^{-2}K^{-1}$)	0.65	0.30	0.87
	U-value after applying insulation ($Wm^{-2}K^{-1}$)	0.30	0.25	0.18
	FS VIP Thickness (mm)	30	10	65
	GF VIP Thickness (mm)	40	20	110
	EPS Thickness (mm)	74.5	20	155
6 Storey Office	Existing U-value ($Wm^{-2}K^{-1}$)	0.44	0.30	0.37
	U-value after applying insulation ($Wm^{-2}K^{-1}$)	0.30	0.25	0.18
	FS VIP Thickness (mm)	15	10	40
	GF VIP Thickness (mm)	25	20	65
	EPS Thickness (mm)	40	25	100

5 Space heating energy saving potential

The potential space heating energy savings and associated reduction in CO_2 emission from using VIP insulation in all three types of buildings (described in table 4) were calculated. The annual space heating energy saving (E_A) for any year (n) was calculated using equation (7).

$$E_A = \frac{86400 \times HDD \times \Delta L}{H_v \times \left(\frac{\eta_i - x \times n}{100}\right)} \quad (7)$$

The building transmission heat loss coefficient (L) incorporates the U-values of all building elements. In the case of applying VIP insulation the U-value varies with time and can be calculated using equations (5) and (6). The time dependent U-values of the wall, floor and roof of the retail unit building insulated with VIPs is shown in figure 3.

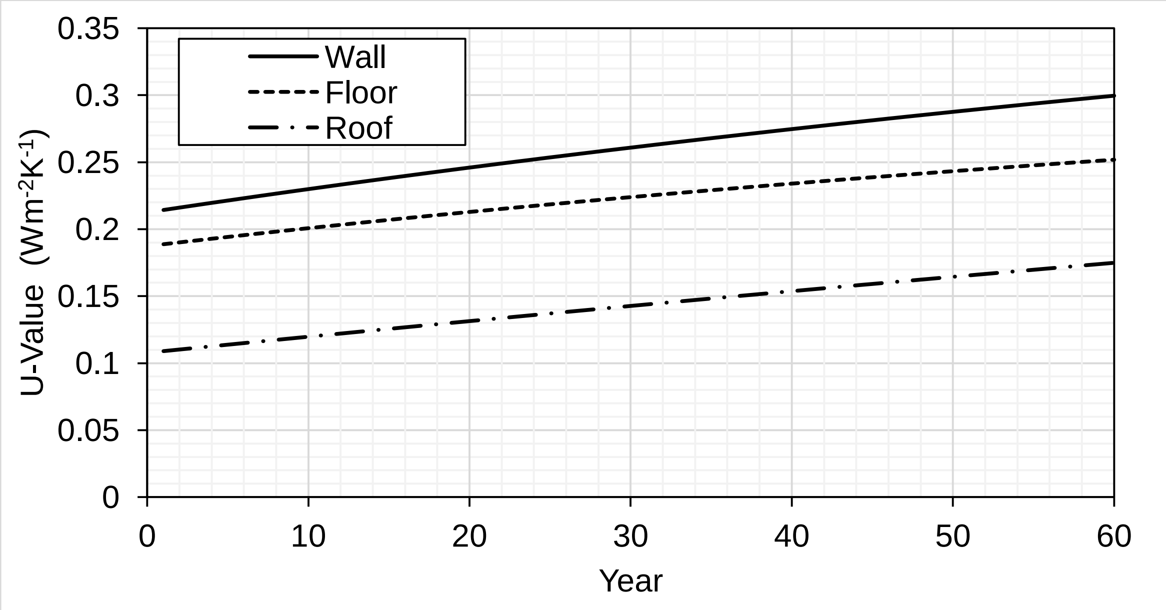

Figure 3. Time dependent U-values of VIP insulated wall, floor and roof of the two floor retail unit building studied

Applying VIP insulation reduced the U-value of building elements, as shown in table 4, saving space heating energy. The energy saved over the assumed 60 year life time of the three buildings considered is shown in figure 4.

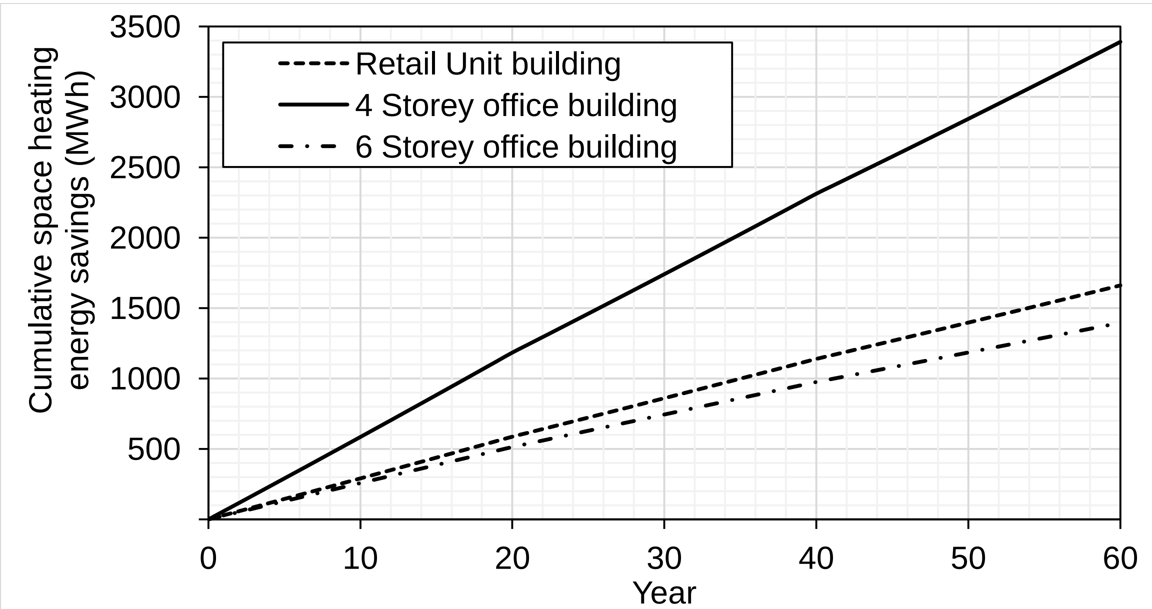

Figure 4. Cumulative space heating energy savings of the VIP insulated buildings studied

Using the parameters outlined previously in table 4 over the assumed building life span of 60 years, installing VIPs would reduce the energy used for space heating by 1395.3 MWh, 1661.2 MWh and 3391.6 MWh for the six storey office building, the retail unit building and the four storey office building respectively. The potential reduction in CO_2 emissions was calculated using a fuel emission factor of 0.18365 $kgCO_2/kWh$ [34] and shown in figure 5. Use of VIPs was calculated to potentially reduce CO_2 emissions by 10.2%, 41.3% and 26.7% respectively for six storey office building, retail unit building and four storey office building.

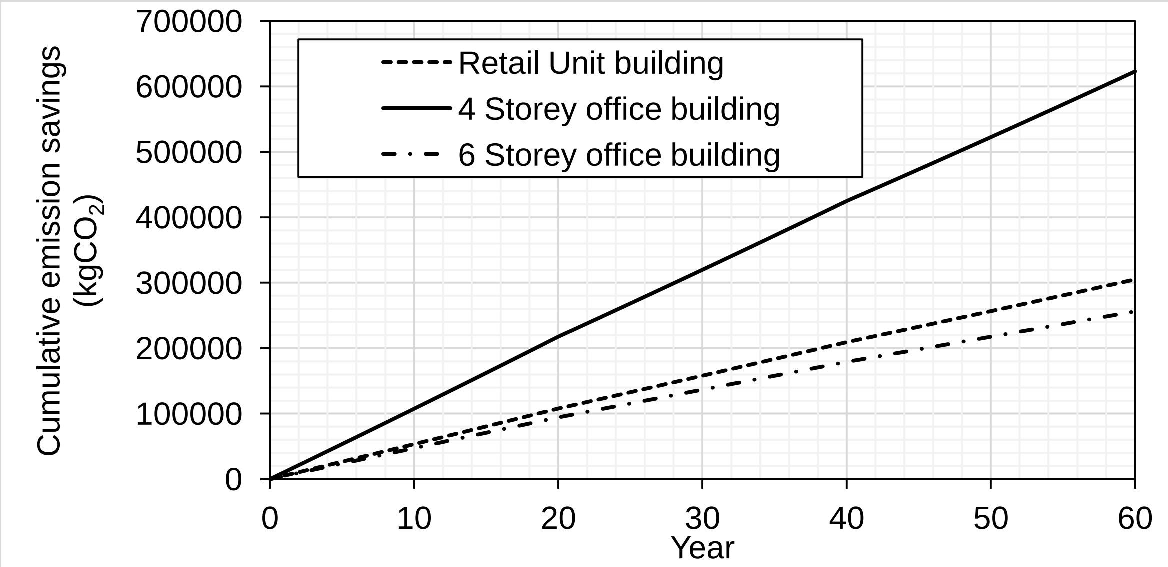

Figure 5. Reduction in CO_2 emissions for three buildings studied

6 Payback period results

A discounted Payback period analysis of FS VIPs, GF VIPs and EPS insulation applied in buildings described in table 4 was carried out using equation (1-6) and the results are presented in section 6.1, 6.2 and 6.3.

6.1 Two floor retail unit

Geometric and thermal features of the buildings studied are shown in table 5. The wall, floor and roof U-values are shown in table 4.
The cost of installing sufficient EPS for achieving current building insulation standards could not be recovered within its lifetime, see figure 6. For EPS, no space saving revenue is possible, which means that investments are solely recovered through fuel cost savings. Also, EPS due to a comparatively shorter service life of 20 years requires replacement three times over an assumed 60 year building life span leading to a higher insulation cost. A life span of 60 years for building was assumed to match the

Table 5. Geometric and thermal features of the buildings considered in this study

Parameter	Two-floor Retail Unit	Four Storey Office	Six Storey Office
Length (m)	15	40	60
Width (m)	15	15	15
Height of each storey (m)	4.5	3.7	3.7
Glazing Area (m^2)	81.0	769.6	1665.0
Glazing U-Value ($Wm^{-2}K^{-1}$)	5.38	2.75	1.9
Air infiltration rate (ach)	0.25	0.25	0.25

prescribed life span of VIPs used for buildings in the UK. In the case of VIPs, the additional benefit of commercial space saving can partially offset higher initial insulation costs. The Results of payback period analysis for two different types of VIPs (FS and GF) taking into account

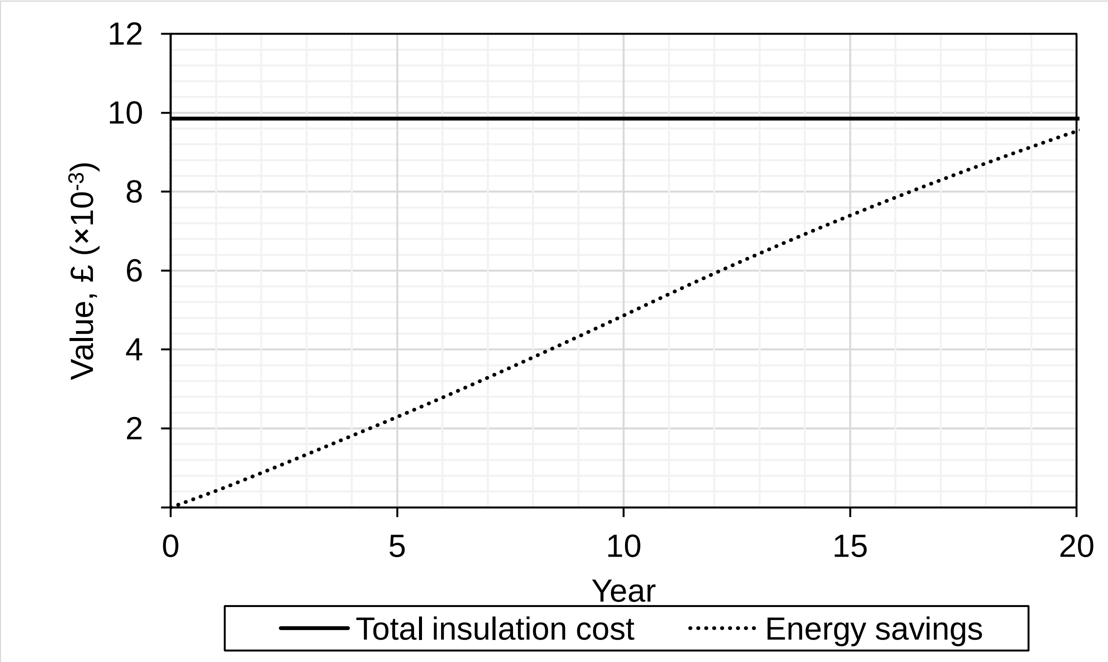

Figure 6. Cost and savings of applying EPS insulation in a retail unit building

the economic potential of space saving with average annual rental value in London (UK) ranging from £1000 m^{-2} to £4000 m^{-2} [35] is shown in figures 7 and 8 respectively. Figures 7 and 8 demonstrate that the cost of GF VIP insulation with a rental value of £1000 m^{-2} cannot be recovered over the life time of the building whereas FS VIP will take only 7 years to recover the investment. This finding can be explained as follows. GF VIP, though costing 1.6 times lesser than FS VIP, must be replaced six times over the life time of the building due to a shorter service life (10 years), compared to that of FS VIP (60 years). As expected, as the rental values increase the payback period for VIP insulation becomes shorter. For rental values of

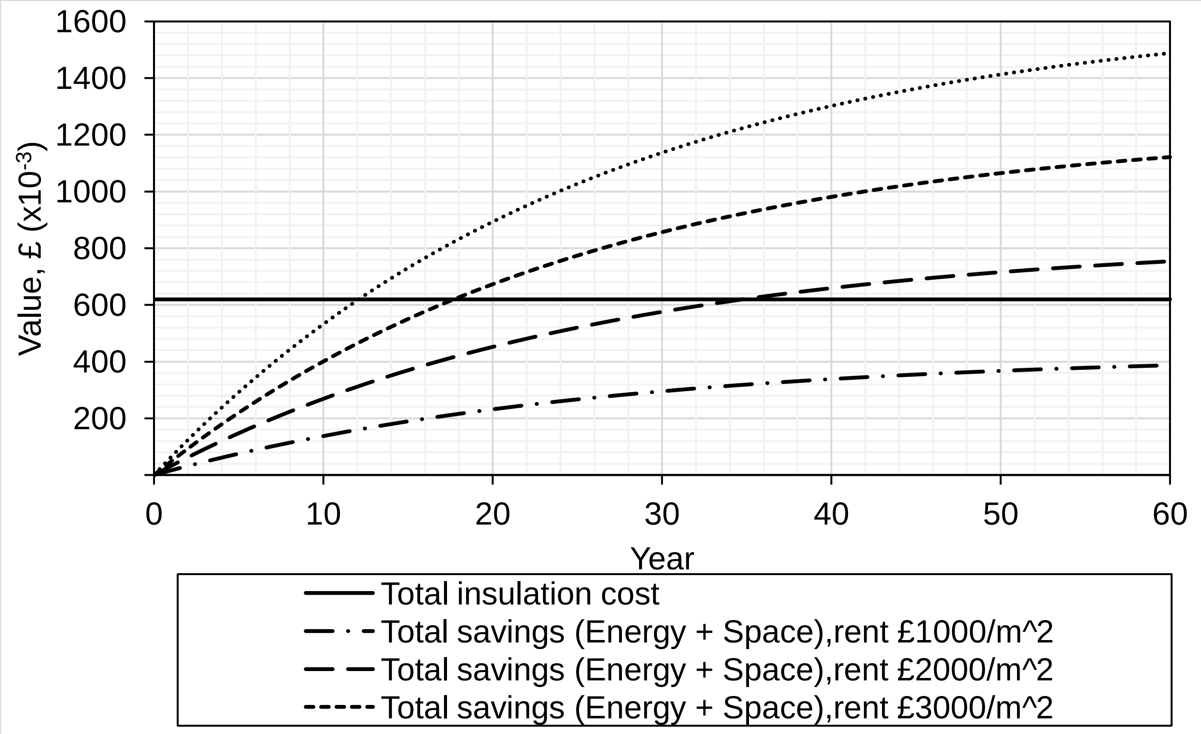

Figure 7. Cost and savings of applying GF VIP insulation in the retail unit building studied

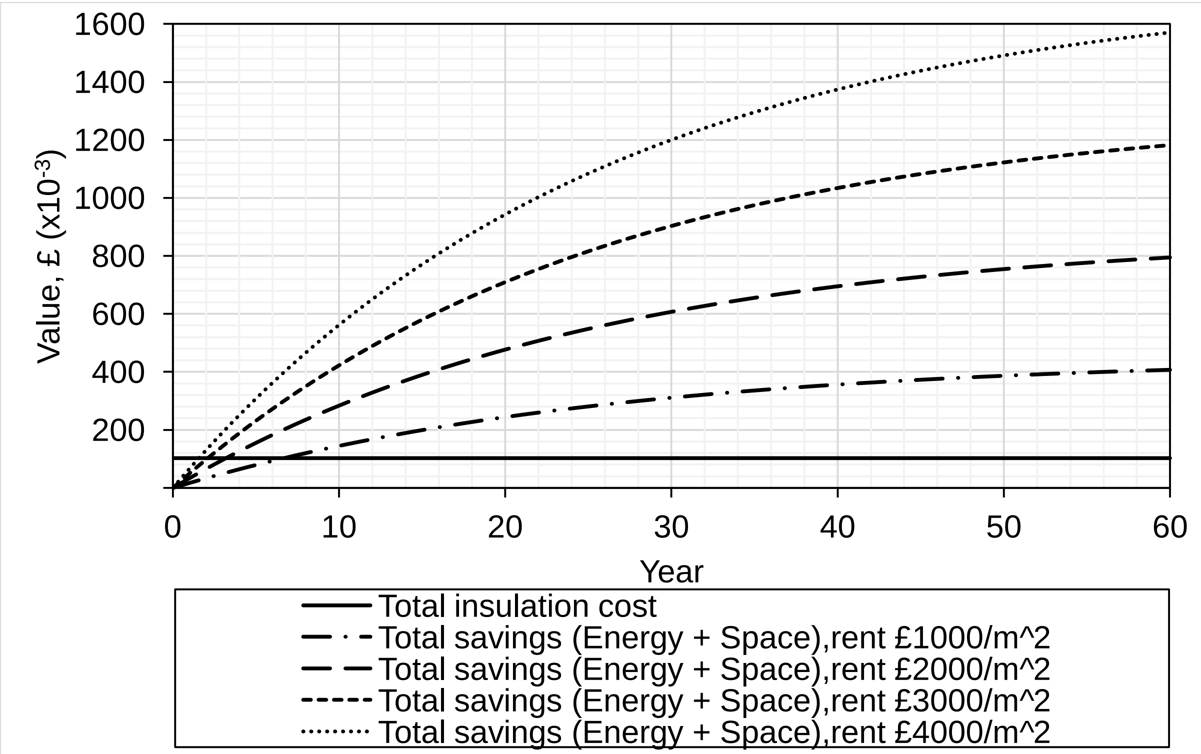

Figure 8. Cost and savings of applying FS VIP insulation in the retail unit building studied

£2000 m^{-2} and £3000 m^{-2} the discounted payback period was 35 years and 18 years respectively for GF VIP and 4 years and 3 years for FS VIP. For average rental value of £4000 m^{-2} payback period of FS VIP becomes approximately 2 years, whereas it is still prohibitively longer (12 years) for GF VIPs.

6.2 Four storey office

Geometric and thermal features of the four storey office are shown in table 4 and table 5. The discounted payback period analysis for the four storey office retrofitted to meet current building insulation standards using EPS insulation, GF VIPs and FS VIPs is presented in figures 9 to 11 respectively.

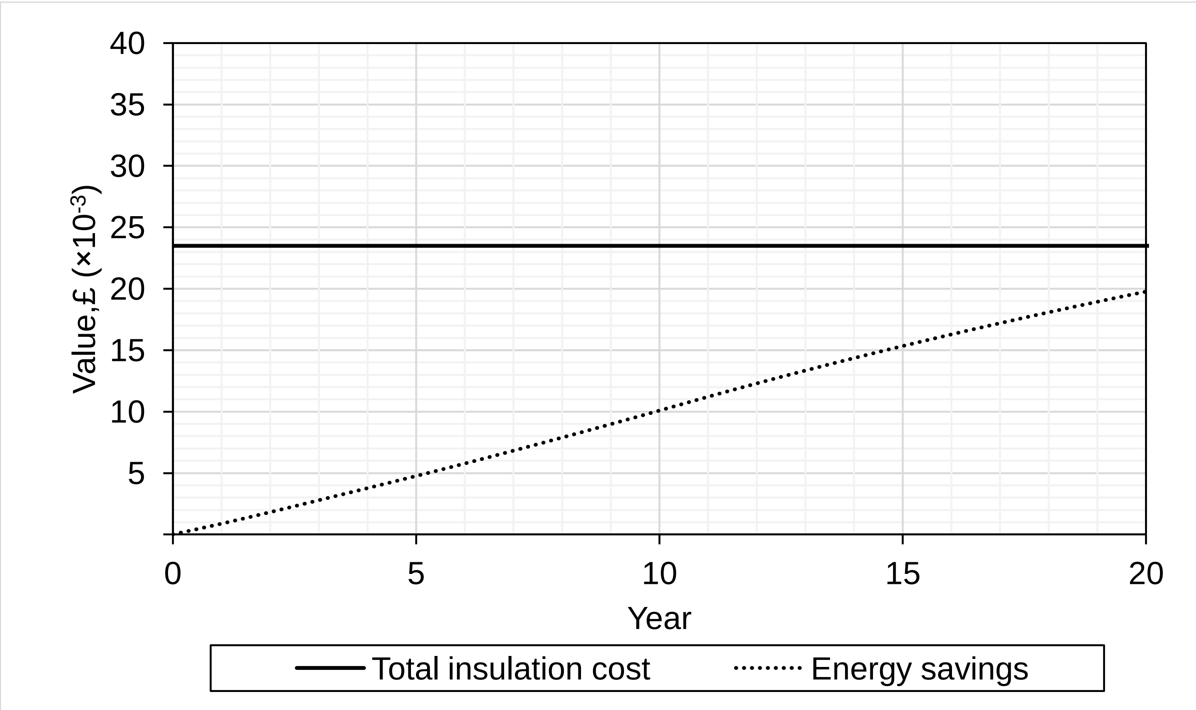

Figure 9. Cost and savings of applying EPS insulation in the 4 storey office building studied

Figure 9 demonstrates that EPS insulation cannot recover the initial capital cost over its life time of 20 years. For GF VIPs the cost of insulation cannot be recovered over the life time of building as shown in figure 10 even with the additional economic benefits from space saving with average annual floor rents ranging from £400 m^{-2} to £1000 m^{-2} [36]. As discussed in section 6.1, the reason for long payback period for GF VIPs is their short service life (10 years) requiring replacement six times during 60-year life time of the building.

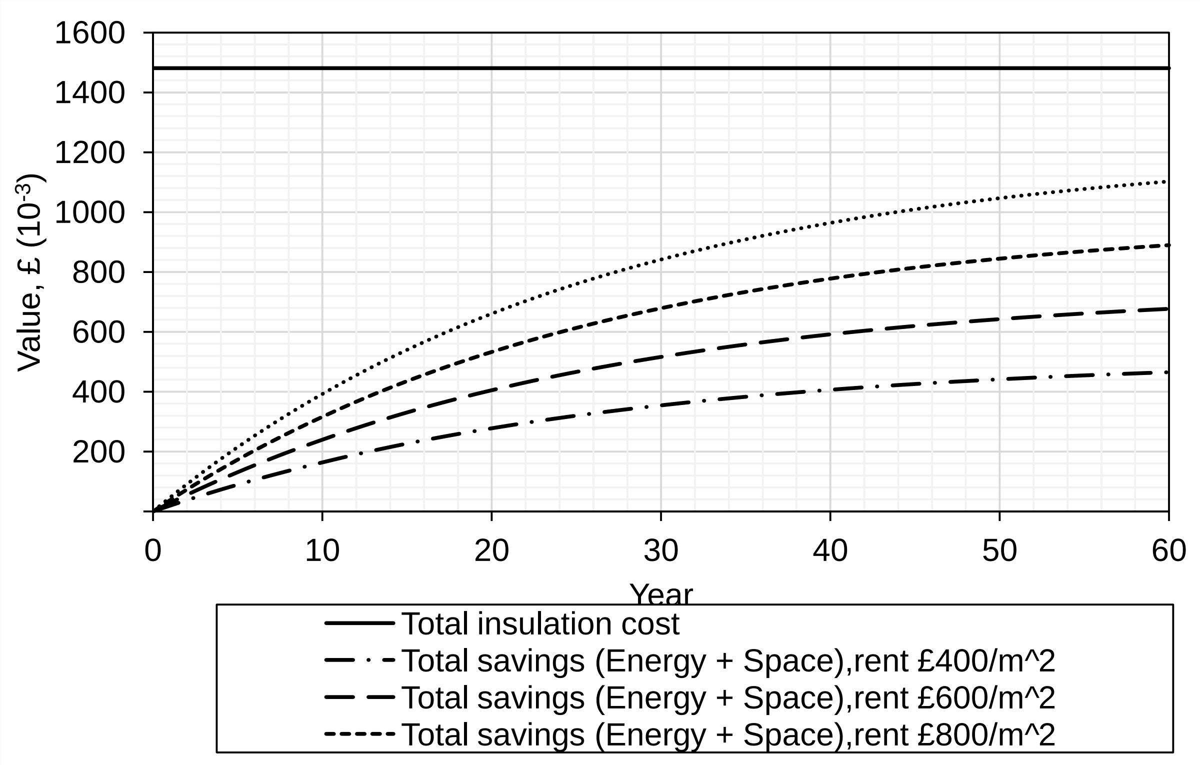

Figure 10. Cost and savings of applying GF VIP insulation in the 4 storey office building studied

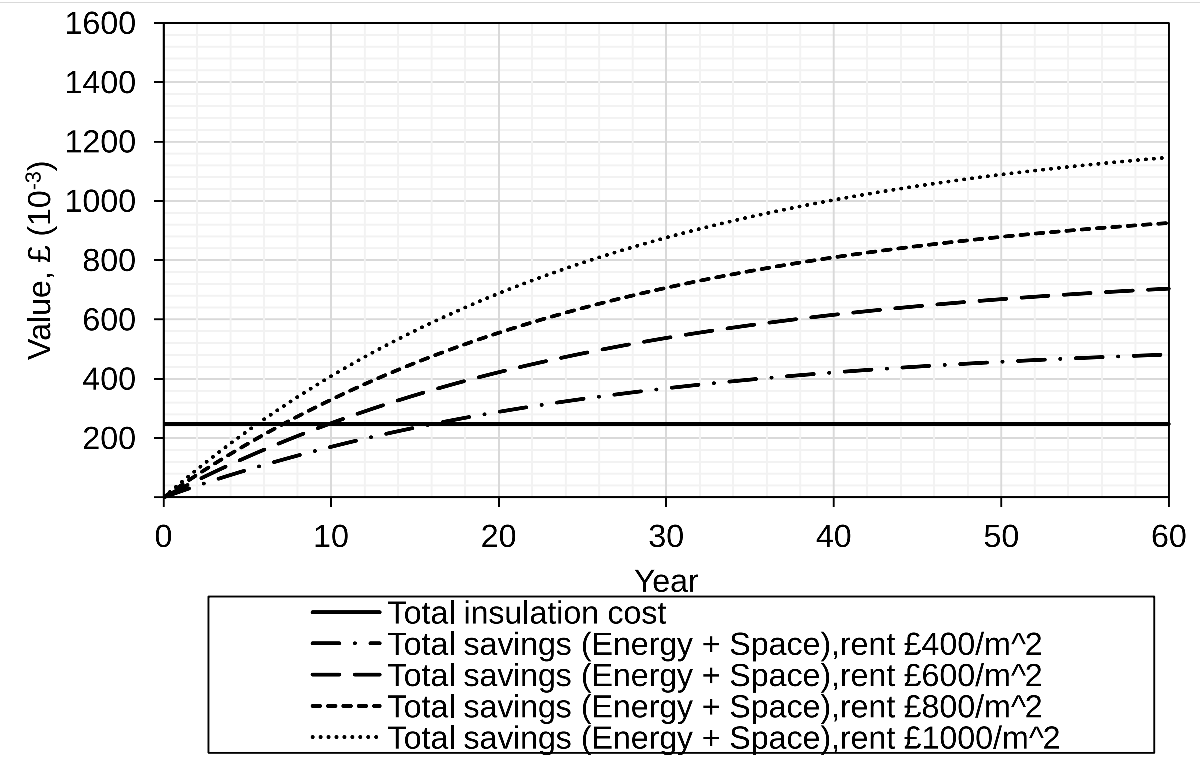

Figure 11. Cost and savings of applying FS VIP insulation in the 4 storey office building studied

From figure 11, it can be seen that upgrading the 4 storey office with FS VIP insulation to comply with current building regulations resulted in payback periods of 17 years, 10 years, 7 years and 6 years for rental values of £400 m^{-2}, £600 m^{-2}, £800 m^{-2} and £1000 m^{-2} respectively.

6.3 Six storey office

Geometric and thermal features of the six storey office are detailed in table 4 and table 5. Results of the discounted payback period analysis for the six storey office building are shown in figures 12 to 14.

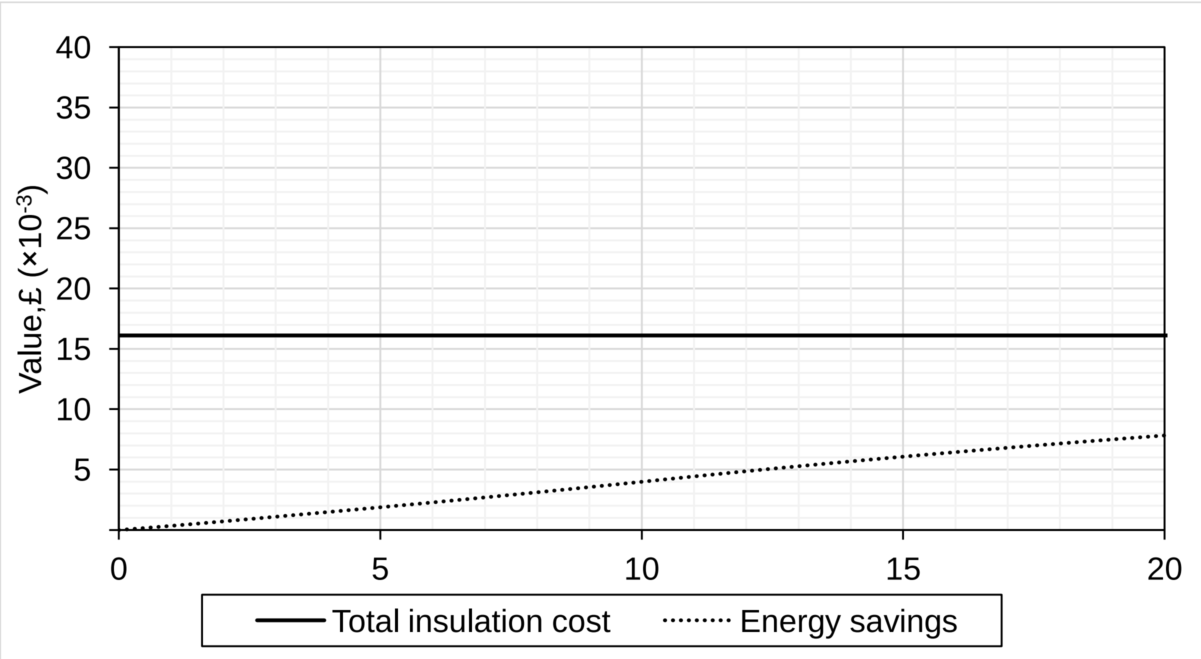

Figure 12. Cost and savings of applying EPS insulation in the 6 storey office building studied

Figure 12 shows that EPS insulation had a discounted payback period longer than its assumed life time of 20 years. It can be seen from figure 13 that in the case of GF VIP, the cost of insulation cannot be recovered with average annual rent of £400 m^{-2} and £600 m^{-2}. For higher annual rents of £800m^{-2} and £1000m^{-2} payback periods of respectively 39 years and 25 years are predicted. It is clearly observed, from figure 14, that FS VIPs had a shorter payback period than EPS or GF VIPs. FS VIP was found to have a payback period of 7 years, 5 years, 3 year and 2.5 years with rental values of £400 m^{-2}, £600 m^{-2}, £800 m^{-2} and £1000 m^{-2} respectively. These results clearly show that FS VIPs are economically viable to be used in high-rise office buildings despite their higher initial cost and decreasing thermal performance over service life.

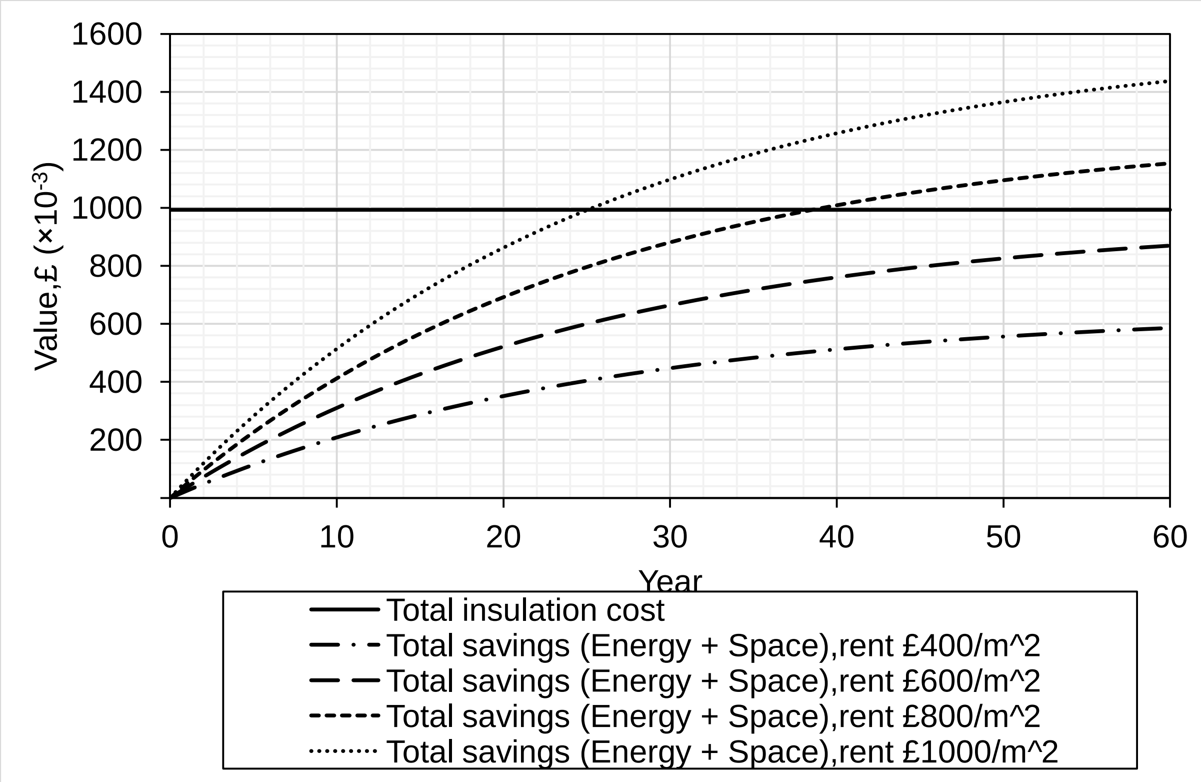

Figure 13. Cost and savings of applying GF VIP insulation in the 6 storey office building studied

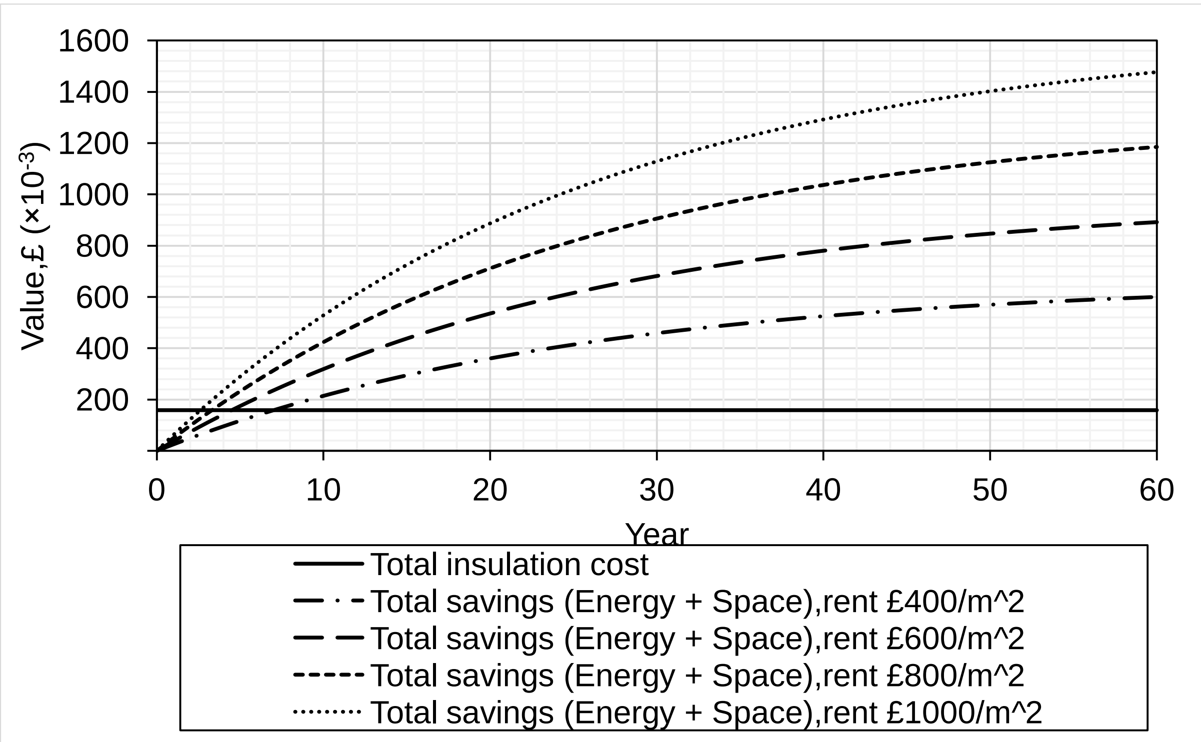

Figure 14. Cost and savings of applying FS VIP insulation in the 6 storey office building studied

7 Conclusions

In this study the energy savings and economic performance of Glass fibre (GF) and Fumed silica (FS) VIPs when used for retrofitting three non-domestic UK buildings to meet current building standards was evaluated and compared to that of conventional insulation, expanded polystyrene (EPS). Installing VIP insulation resulted in space heating energy savings of 1395.3 MWh,1661.2 MWh and 3391.6 MWh for a six storey office building, a two floor retail unit building and a four storey office building respectively over a life time of 60 years. GF VIP was found to have a higher total cost than FS VIP due to its shorter service life requiring more frequent replacement, once every 10 years. An interesting finding is that EPS insulation cannot even recover its cost over its useful lifetime for all three buildings. Similarly, GF VIPs could not recover their cost for the case of the 4 storey office building. FS VIPs in comparison with EPS insulation and GF VIPs had shorter payback periods due to their longer service life of 60 years. This is despite of FS VIPs being 1.6 times more expensive than GF VIPs. This is a remarkable result establishing the economic viability of using FS VIPs in non-domestic buildings located in high rental value locations around the world, such as London. Longevity has been found to be a critical factor in determining the economic viability of VIPs. It has been shown that despite a higher initial cost a longer lifespan VIP will achieve a shorter payback period. A methodology to predict the payback period for VIP insulation has been proposed. An all-inclusive equation capable of taking into account the change in VIP thermal conductivity with time, variable fuel costs and revenues generated from space savings to predict payback year of VIP insulation was presented. The equation can be easily solved on a spreadsheet to estimate the payback period for VIP insulation for any installation irrespective of application, buildings (domestic or non-domestic), refrigerators, freezers and refrigerated vans among many others.

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***Revised Manuscript with Changes Marked**

Energy and economic analysis of Vacuum Insulation Panels (VIPs) used in non-domestic buildings

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Abstract

~~Payback period and~~The potential savings in space heating energy ~~saving analysis~~ from the installation of ~~fumed silica~~Fumed Silica (FS) and Glass ~~fibre~~Fibre (GF) Vacuum Insulation Panels (VIPs) ~~when used in three distinct non-domestic buildings has been performed and results~~ were compared ~~with that of~~to conventional expanded polystyrene (EPS) insulation~~.~~ for three different non-domestic buildings situated in London (UK). A discounted payback period analysis was used to determine the time taken for the capital cost of installing the insulation to be recovered. VIP materials ~~have been~~were ranked ~~on the basis of~~using cost ~~index~~ and density ~~index. Payback period~~indexes. The methodology ~~developed is capable of taking into account~~of the Payback analysis carried out considered the time dependency of VIP thermal performance, fuel prices and rental income from buildings. ~~Calculations have shown~~These calculations show that VIP insulation ~~can reduce~~reduced the annual space heating energy demand and carbon dioxide (CO_2) emissions by approximately 10.2%, 41.3% and 26.7% ~~respectively~~ for a six storey office building, a two floor retail unit building and a four storey office building~~. Fumed silica~~ respectively. FS VIPs ~~were found to have~~had the shortest payback period among the insulation materials studied~~. It ranged~~, ranging from 2.5 years to 17 years, depending upon the rental income of the building. For GF VIPs the calculated payback period ~~is~~was considerably longer and in the case of ~~a~~the typical 4 storey office building studied its cost could not be recovered ~~at all~~ over the ~~whole~~ life time of the building. For EPS insulation the calculated payback period was longer than its useful life time for all three buildings. ~~It is concluded that the~~ FS VIPs ~~are~~were found to be economically viable for ~~implementation~~installation onto non-domestic buildings

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in high rental value locations ~~due to their better performance over a longer~~assuming a lifespan of up to 60 years.

Keywords: Payback period; Space heating energy savings; Vacuum Insulation Panel (VIP);Fumed Silica; Glass fibre; Non-domestic buildings.

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Contents

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1 Introduction

UseThe combustion of fossil fuels have beento generate energy is recognised as the major cause of the current trend ofanthropogenic climate change and. To mitigate this, the international community has recently agreed to collectively endeavour to limit global temperature rise to within 1.5°C above pre-industrial levels [1].by reducing emissions of greenhouse gases through the use of cleaner energy sources and increased energy efficiency [1]. In 2013, emissions from space heating energy use in UK buildings accounted for 98 million tonnes of carbon dioxide (CO_2), constituting 17% of total UK greenhouse gas emissions [2]. Energy efficiency requirements for UK buildings are being continuously improved through stricter stipulations in the building regulations. The aim is to assist in reducingreduce overall UK CO_2 emissions by at least 80% from the 1990 level by 2050 as set in the Climate Change Act 2008 [3]. With over 60% of the energy consumed in buildings used for space heating [4], building envelopes with the lowest U-value are critical for the UK to achieve its long term carbon reduction goals. However, to achieve the lowest U-value, either a prohibitively thick layers of conventional insulation, which may not be feasible in existing and new buildings, or advanced insulation material such as Vacuum Insulation Panel (VIP) are needed. VIPs offer thinner alternative due to their thermal resistance potentially being 5-8 times higher than the conventional insulation [5,6,7,8]. VIP is produced as a rigid panel made of evacuated inner core board laminated in an outer barrier envelope. VIPs can be applied in buildings on external or internal surfaces of walls, on ceiling or roof, ground floor, door and window frames and on hot water cylindersthe buildings used for space heating [4], the development of building fabrics with substantially improved insulation properties are essential for the UK to achieve its long term carbon reduction goals.

A meagre 10%To reduce heat losses from building fabric using conventional insulation products, such as Expanded Polystyrene (EPS), will require prohibitively thick layers, which may not be feasible in existing or even new buildings. Alternatively, thinner layers of advanced insulation products, such as VIPs, could be used due to their thermal resistivity being 5-8 times greater than conventional insulation [5,6,7,8,9].

A VIP is a composite rigid sheet comprising an evacuated (pressure ≤0.5 mbar) inner core board laminated inside an outer barrier envelope [10]. VIPs can be installed on opaque building surfaces (externally or internally) and on hot water storage cylinders to improve their thermal resistance. For façade applications, transparent insulation materials [11,12] are under development.

In 2014, only 10%of the VIPs currently produced areproduction were used infor insulating buildings with, refrigeration and transportation industry were the main users of this technology consuming 30% and 60% of the annual production of VIPs respectively 60% and 30% [9]. Uptake[13]. The uptake of VIPs in the buildingsfor building applications has not achieved its full potential due to their high installed cost. compared with other insulation products. Presently their, VIP use can only be justified in a few construction scenarios such as difficult to insulate buildings on account of their ; for example, heritage status and narrow city centre buildings with unique architectural features or limited usable indoor space. High

The high cost of VIPs is caused by the materials used in VIP production and it is of utmost importance to develop low cost due to the materials which can be used to produce in VIPs having equal or better thermal performance. Bulk of the required for manufacturing, necessitating the development of lower cost core and envelope materials with similar or improved thermal insulation properties than those currently in use. Previous research work considered expensive fumed silica as VIP core material for building applicationson VIP core materials has focused mainly on Fumed Silica (FS) due to its suitableexcellent thermo-physical properties, for example, Singh et al. (2015) [10]. Several studies have reported investigations into various core materials, such as Melamine-formaldehyde fibre fleece [11], expanded perlite and fumed silica composite [12], open pore melamine formaldehyde foam [13], granular silica [14], phenolic foam [15], achieving initial centre of panel thermal conductivity values of 0.0023 $Wm^{-1}K^{-1}$, 0.0074 $Wm^{-1}K^{-1}$, 0.006 $Wm^{-1}K^{-1}$, 0.014 $Wm^{-1}K^{-1}$ and 0.005 $Wm^{-1}K^{-1}$ respectively. However, these studies have restricted themselves to scientific investigations whilst [14]. But, FS is expensive and several studies, as shown in table 1, have proposed alternative core materials.

Table 1. Core materials other than FS and glass fibre reported in previous studies

Core Material	Initial Centre of Panel Conductivity ($Wm^{-1}K^{-1}$)	Reference
Melamine-formaldehyde Fibre fleece	0.0023	[15]
Expanded perlite and fumed silica composite	0.0074	[16]
Open pore melamine formaldehyde foam	0.006	[17]
Granular Silica	0.014	[18]
Phenolic foam	0.005	[19]
Fumed silica/rice husk ash hybrid mixture	0.0055-0.0062	[20]

Published research on the materials listed in table 1 have primarily focused on the thermo-physical performance of VIPs neglecting the potential for energy savings and the associated economic analysis~~ of VIPs has been largely overlooked with few exceptions such as~~. Cho et al. ~~(2014) [16~~[21], Alam et al. ~~(2011) [17~~[10] and Tenpierik ~~(2009) [18], though these three studies have only covered ~~[22] published economic analysis of VIPs but only considered domestic ~~buildings. ~~building applications. Kucukpinar et al. [11] demonstrated that VIP insulation reduced annual energy consumption by 25% for two mock-up rooms situated in Poland and Spain. ~~This paper reports the most comprehensive and realistic~~Mujeebu et al. [23] predicted using ECOTECT software that VIPs fixed to the roof and external walls would reduce annual energy consumption by 0.62% for a single office building and 0.79% for a multi-storey office building compared to EPS.

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Clearly, the energy saving ~~and economic ~~potential of VIPs is dependent on the type of building and its location (climatic and economic factors) thus further research to clarify the energy saving potential of VIPs is required. Mujeebu et al. [24] predicted the simple payback ~~analysis of VIPs when used in ~~period of VIPs to be 5.3 times longer than that of EPS if installed in a multi-storey office building in Saudi Arabia. The, simple payback method used by Mujeebu et al. [24], did not consider the impact on energy savings from the deterioration of the VIP thermal performance with time, the economic value of space savings due to thinner section of VIPs and the varying time value of money. These factors significantly influence payback periods and must be considered to enable a more accurate calculation to be made of the cost effectiveness of VIPs compared to other insulation materials.

The objective of this paper is to calculate the payback period of VIPs through a discounted economic analysis whilst simultaneously accounting for the other identified factors which affect it. To investigate this, an energy saving and economic payback analysis of FS and GF VIPs installed on three representative ~~nondomestic~~non-domestic buildings situated in London (UK~~).~~) was undertaken. A novel methodology ~~has been developed which is able to take into account~~which considered the change of VIP thermal performance ~~with~~over time, fuel price variability, heating system efficiency degradation with time ~~as well as~~and the ~~money~~economic value of space savings ~~resulting~~realised from using comparatively thinner VIPs~~.~~ was developed. No such information currently exists in the peer reviewed literature. ~~Realistic cost~~Cost and density indices linked ~~with~~to the thermal conductivity of FS and GF VIPs were calculated~~ and presented. Payback~~. The discounted payback period for VIPs ~~has been~~was then compared ~~with~~to that of conventional expanded polystyrene (EPS) insulation~~ in order~~, to assess ~~their comparative~~the cost effectiveness of each.

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2 Cost and density indices for VIP types

VIPs are ~~typically ~~classified ~~based on~~by the type of main core materials used ~~for~~in their manufacturing, which includes ~~fumed silica (~~FS~~),~~, expanded perlite (EP), FS and EP composites (FS+EP), glass fibre (GF) and polyurethane foam (PU) along with opacifiers, getters and desiccants. VIPs with ~~different~~diverse core materials have ~~varying~~different expected life ~~time~~times, which determines their suitability for ~~a~~ specific ~~application. Cost~~applications. The cost of VIP core materials can account for ~~up to 40-~~45% of the total ~~VIP cost. Table 1 shows the price, initial centre of panel thermal conductivity (λ) (thermal conductivity at the time of manufacturing at centre of panel), design thermal conductivity (thermal conductivity including the thermal birding effect and ageing effect) and density of VIPs made with different core materials~~cost.

~~Cost~~The price, initial (measured at the time of ~~VIPs can be linked with their main physical properties such as~~manufacturing) centre of panel thermal conductivity (λ) design thermal conductivity (thermal conductivity including the thermal bridging effect and ageing effect) and density ~~to compare performance~~ of VIPs made with different ~~types of VIPs. For this~~core materials are shown in table 2.

Table ~~1~~2. Cost and main physical properties of different types of VIPs

Type of VIP	Cost ($£m^{-3}$)	Initial centre of panel λ ($Wm^{-1}K^{-1}$)	Design λ ($Wm^{-1}K^{-1}$)	Density (kgm^{-3})	Service Life (years)
VIP Fumed silica (FS)	2365	0.0043[a]	0.008	180[a]	60[a]
VIP Fumed silica& Expanded perlite composite (FS+EP)	2152	0.0076[b]	0.0116	330[b]	30
VIP Expanded perlite (EP)	1809	0.013	0.017	290	20
VIP Polyurethane (PU)	2000	0.009[a]	0.013	65[a]	15[a]
VIP Glass fibre (GF)	1464	0.0028[c]	0.0068	200[c]	10[c]

[a] va-Q-tec AG (2016) [~~19~~25]; [b] Alam et al.(2014) [~~12~~16]; [c] Di et al.(2013) [~~20~~26]

~~purpose a~~Cost and density indices for the materials shown in table 2 were derived. The cost index, ~~defined as~~was the product of cost and initial centre of panel thermal conductivity~~ and~~. The density index, ~~defined as~~was the product of density and the

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initial centre of panel thermal conductivity~~, were calculated as shown in figure 1.~~. VIPs with smaller values of these indices are more desirable. Figure 1 shows the calculated cost and density index of the materials listed in table 2.

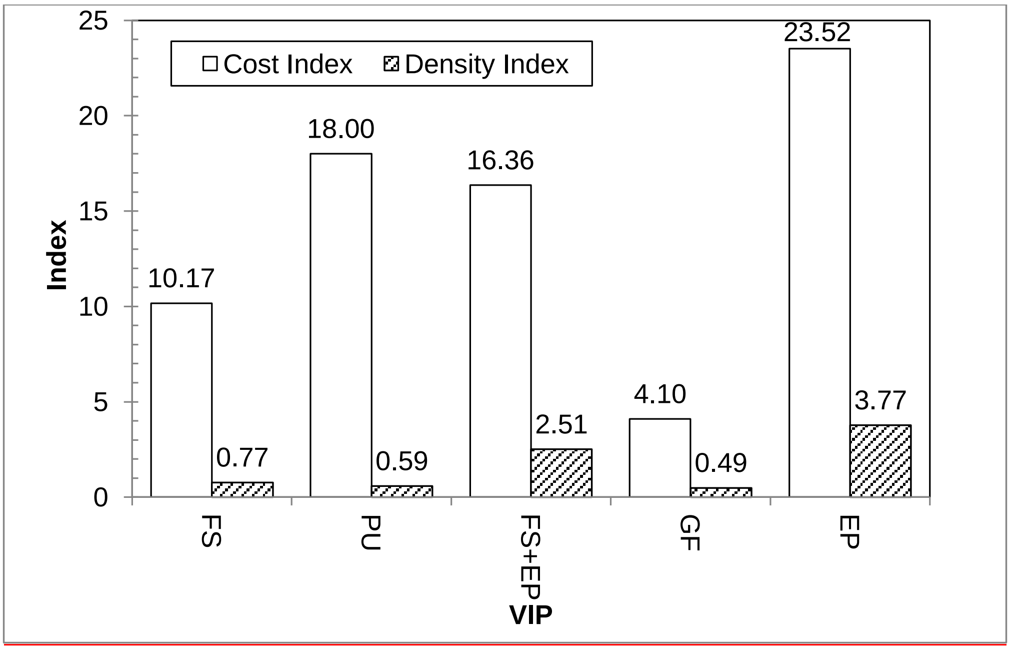

Figure 1. Cost and density index of different types of VIPs

~~desired compared to those having higher values.~~Calculating the cost and density index of VIPs allows the relationship between cost and thermo-physical properties to be observed. From figure 1, GF VIP returned the smallest cost index of 4.10 (best performance) followed by FS, FS+EP composite, PU and EP in that order. ~~With respect to~~Comparing the values of density index shown in figure 1, GF ~~VIP has~~VIPs have the ~~least~~lowest calculated value of 0.49, ~~again performing best,~~ whilst EP ~~VIP returned a~~ VIPs the highest value of 3.77. FS VIP, ~~due to its~~with a comparatively lower initial thermal conductivity and density, has 2.~~4 times~~4X and 1.~~5 times~~5X lower cost and density indices respectively than that of FS+EP composite VIP. ~~One interesting fact that came out of this analysis is that~~ FS VIP ~~has~~had a calculated cost ~~index 2.48 times~~ and density index 2.48X and 1.~~57 times higher~~57X greater respectively than ~~that of~~ GF ~~VIP~~VIPs. However, GF ~~VIP suffers from~~VIPs have a significantly shorter life time, ~~approximately~~of 10-12 years, compared to the lifetime of 50-60 years ~~of~~expected for FS ~~VIP~~VIPs.

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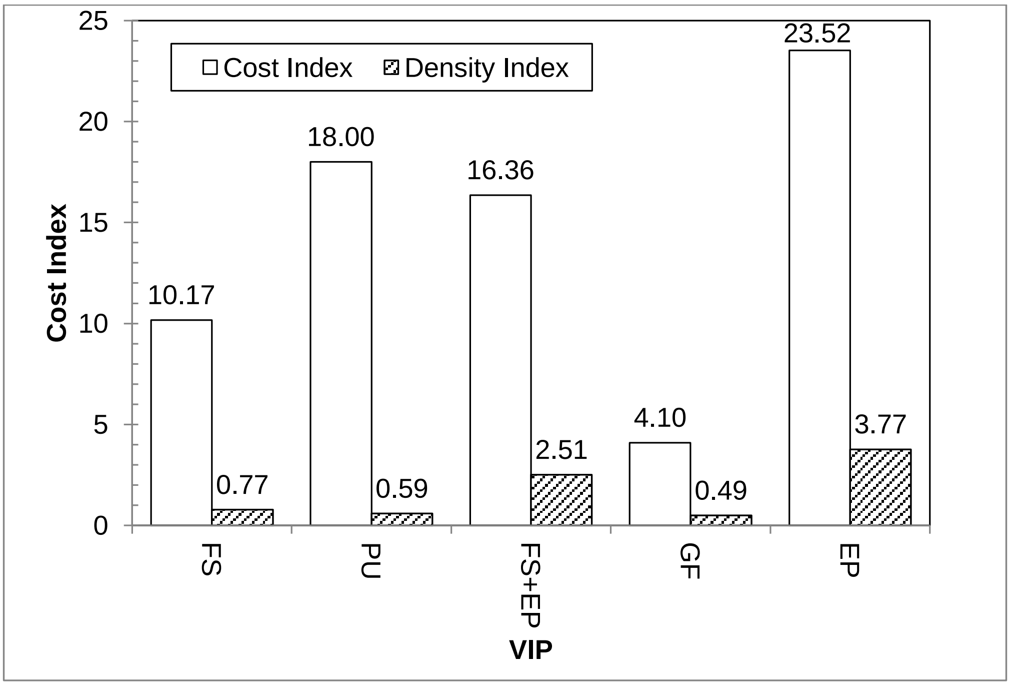

~~Figure 1. Cost and density index of different types of VIPs~~

3 Payback period calculation

~~Payback period, defined~~The discounted payback period is the time taken for an investment, such as the ~~least possible time insulation takes~~installation of VIPs, to ~~recover its installed cost~~repay the initial capital through the realised savings taking into account fuel cost savings and other accrued benefits~~,~~. It is a critical factor in the choice of ~~insulation. Net present value (NPV) which~~the most cost effective insulation and was quantified by calculating the Profit on investment (POI) for each scenario investigated using equation (1). The POI accounts for ~~the time value of money can be used to evaluate the payback period for VIPs;~~present values of energy savings, space savings and present value of the capital costs. The payback ~~period~~year of ~~an~~any investment is reached when ~~NPV~~the POI equals zero~~. NPV can be calculated using equation (1):~~

~~$NPV = -C_I + [C_E \times 1/(1+r)^n] + [C_S \times 1/(1+r)^n]$ (1)~~

~~where~~

~~C_I is the total insulation cost (£)~~

~~C_E is annual energy cost saving (£)~~

n ~~is the number of year~~

~~r is the annual discount rate~~

C_S is the annual for the very first time [27]. In case of commercial buildings, space savings due to thinner VIP sections would provide additional rental income due to space saving (£)revenue for building owners, and is included in equation (1):

C_T, C_E and C_S can be calculated using equations (2), (3) and (8) respectively.

$$C_T = C_{Mt} + C_M + C_I \qquad (2)$$

$$POI = \left[\frac{86400 \times HDD \times \Delta L \times C_F}{H_v \times \left(\frac{\eta_i - x \times n}{100}\right)} \times \frac{1}{(1+r)^n}\right] + \left[Y \times \Delta d \times 2\{(L_f + \Delta d) + (W_f + \Delta d)\} \times \frac{1}{(1+r)^n}\right] - [C_{Mt} + C_M + C_I] \qquad (1)$$

where

C_{Mt} is the material cost of VIP core and envelope (£)
C_M is the manufacturing cost of VIP (£)
C_I is the installation cost of VIP (£)

$$C_E = \frac{86400 \times HDD \times \Delta L \times C_F}{H_V \times \eta(1-x)} \qquad (3)$$

where
HDD is the heating degree days (°C days)
C_F is the cost of fuel (£m^{-3})
H_V is the calorific value of fuel (Jm^{-3})
$\eta\eta_i$ is the initial thermal efficiency of the heating system (, boiler) (%)
x is the annual rate of decrease of thermal efficiency of heating boiler (%)
ΔL is the difference of total building transmission heat loss coefficient (L) before and after applying insulation (WK^{-1})
n is the number of year
r is the annual discount rate (% fraction)
Y is the annual rental value (£m^{-2})
A_s the floor area saved (m^2)
F is the number of floors
Δd is the difference in thickness of conventional insulation and VIP insulation (m)
L_f is the length of internal floor (m)
W_f is the width of the internal floor (m)

Total building transmission heat loss coefficient (L) is described inas equation (42)

$$L = \sum_{i=1}^{i=N} U_i(t) A_i + \frac{I(\rho c_p)_{air} V}{3600} \qquad (4)$$

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$$L = \sum_{i=1}^{i=N} U_i(t)\, A_i + \frac{I(\rho c_p)_{air} V}{3600} \quad (2)$$

where

A_i is the insulated area of the building element i (m^2)

U_i is the U-value of the building element i ($Wm^{-2}K^{-1}$)

I is the air exchange rate per hour (ach^{-1})

V is the internal volume of the building (m^3)

$(\rho c_p)_{air}$ is the volumetric thermal capacity of air ($Jm^{-3}K^{-1}$) taken as 1200 $Jm^{-3}K^{-1}$.

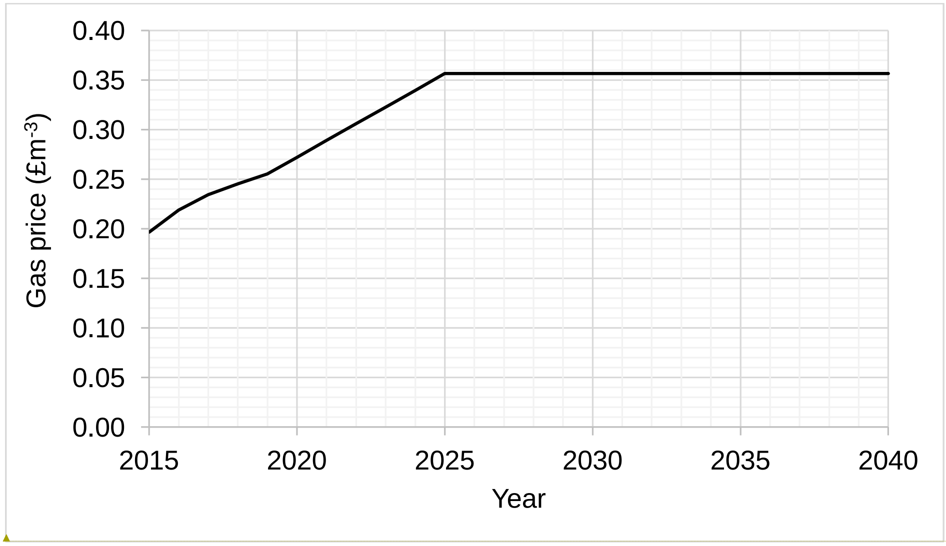
Hence, the equation (42) can be rewritten as

$$L = \sum_{i=1}^{i=N} U_i(t)\, A_i + \frac{IV}{3}$$

(53)

In equation (53), term $\frac{IV}{3}$ is the ventilation conductance (WK^{-1}) [2128].

DifferentThe different parameters used for calculating the discounted payback period analysis presented in this study are detailed in table 23. The annual discount rate was taken as 4%. Natural gaslong term price has been taken fromforecast reported by the UK Department of Energy and Climate Change long term price forecast [22], [29] for natural gas which is shown in figure 2, and extrapolated for the assumed life time of the building.buildings under investigation was used to calculate space heating energy savings



The Figure 2. Gas price forecast [22]

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~~Heating degree (~~HDD~~)~~ data ~~was~~used to determine energy consumption for space heating was the 5 year average (2011 to 2015) for a base temperature of 15.5 °C for St. James Park London [~~23]. The rate of decrease of~~30]. Gas condensing boilers are assumed to suffer from an annual fall in their thermal efficiency ~~of gas condensing boiler system has been taken as~~by 0.5 ~~% per annum. Installation~~% with a useful lifespan of 20 years. The installation cost ~~has been~~was assumed to be the same for all VIP types ~~and has~~investigated so was not ~~been~~ included in the calculations.

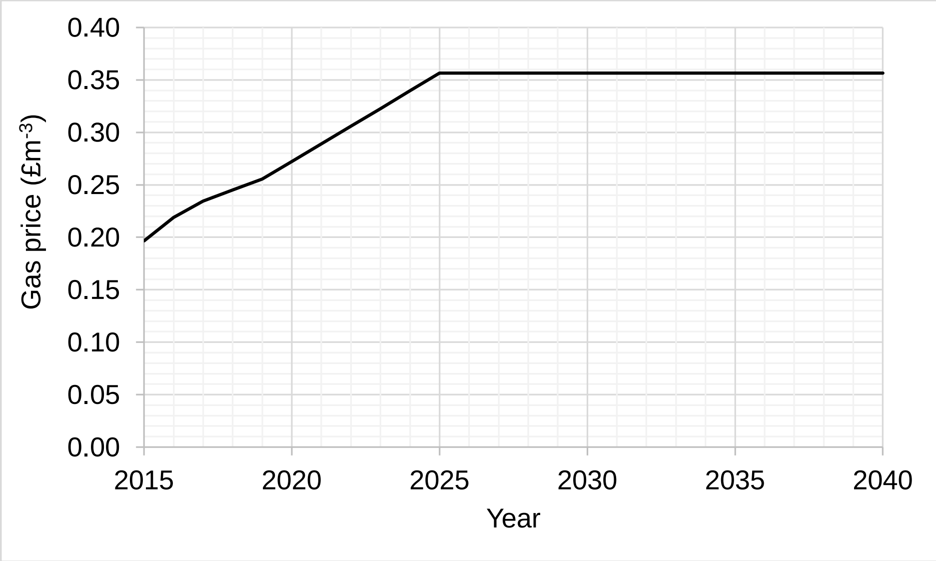

Figure 2. Gas price forecast [29]

Table ~~2~~3. Parameters used for payback period calculation

Parameters	Description/Value
Fuel	Natural gas
HDD (°Cdays) [26]	1624
Fuel cost , C_F, (£m^{-3}) [25]	0.196
Heating value, H_V, (MJm^{-3})	39.5
~~Heating~~Initial heating system efficiency, ~~η,~~ η_i, (%)	90
Annual discount rate, r, (%)	4

The U-value of ~~a~~ building ~~element~~elements was ~~obtained~~determined by calculating the thermal resistances of ~~its~~the constituent material layers and ~~the~~ adjacent air

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layers as shown in equation (6) and (7) [23]. Thermal 4) [28]. The thermal resistance of any building material layer is the ratio of its thickness to its thermal conductivity.

$$U = \frac{1}{R_{si} + (\sum R_e) + R_{sx}}$$

(64)

where

U is the thermal transmittance (Wm^{-2}K^{-1})

R_{si} is the internal surface resistance (m^{2}KW^{-1})

R_e is the thermal resistances of a material layer (m^{2}KW^{-1})

R_{sx} is the external surface resistance (m^{2}KW^{-1})

ThermalThe thermal conductivity of a VIP variesdecreases with time as the core pressure inside VIP increases due to outgassing from core and envelope and, or via penetration ofto the interior by atmospheric air and moisture to the interiors of VIP. This degradation. Degradation in VIP performance should bewas accounted for whilstwhen calculating the U-value of anythe building element containing VIP insulation. Thus,elements insulated with VIPs, by modifying equation (6) can be modified to arrive at4) as shown in equation (75).

$$U\,(t) = \frac{1}{R_{si} + (\sum R_e) + R_{vip}(t) + R_{sx}}$$

(75)

where

$R_{vip}(t)$ is the time dependent thermal resistanceresistivity of the VIP layer in a building element and can be described ascalculated using equation (86):

$$R_{vip}(t) = \frac{d_{vip}}{\lambda_{vip}(t)}$$

(86)

where d_{vip} is the thickness and $\lambda_{vip}(t)$ the time dependent thermal conductivity of VIP.

In this studyFor the U-value calculations used by this research, design thermal conductivity values of 0.008 Wm^{-1}K^{-1}, 0.007 Wm^{-1}K^{-1} and 0.035 Wm^{-1}K^{-1} were used for FS VIP, GF VIP and EPS respectively for U-value calculations.. For FS VIP rate ofVIPs and GF VIPs the annual increase in thermal conductivity rise ofwas assumed as 0.0001 Wm^{-1}K^{-1}a^{-1} [2431] and for GF VIP 0.0018 Wm^{-1}K^{-1}a^{-1} [20] has been adopted.respectively [26].

Use of VIPs can yield extra usable indoor space compared to conventional EPS insulation whilst achieving equal U-values. In case of commercial buildings, this

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valuable space can provide additional revenue for building owners, and has been included in NPV equation (1) as the annual savings (C_s) calculated using equation (9):

$$C_s = Y \times A_s \quad (9)$$

Where 4 Details of the non-domestic buildings investigated

The opaque elements (i.e. walls, floor and roof) of three different types of commercial (non-domestic) Y is the annual rental value (£m^{-2}) and A_s the floor area saved (m^2).

Floor area savings for buildings can be calculated using equation (10) [18]:

$$A_s = F \times \Delta d \times 2 \times [(L_f + \Delta d) + (W_f + \Delta d)] \quad (10)$$

where

F is the number of floors

Δd is the difference in thickness of conventional insulation and VIP insulation (m)

L_f is the length of internal floor (m)

W_f is the width of the internal floor (m)

4 Insulating non-domestic buildings

Threesituated in London based non-domestic buildings,(UK); a two floor retail unit, a four storey office and a six storey office, have been studied to have were considered for retrofitting with VIPs andor EPS insulation on all opaque elements (i.e. walls,. The two floor retail unit building is representative of 10% of the current retail building stock in the UK by age of construction (1989-90) and 13% by floor area (250-500 m^2) [32]. The four storey office building type accounts for 9% of the office building stock in the UK by age of construction (1981-85) and roof), see table 3 for 20% by floor area (2500-10,000m^2) [32]. The six storey office building accounts for 11% of the office building stock in the UK by age of construction (1986-90) and 20% by floor area (2500-10,000m^2) [32]. Table 4 shows the relevant details. for each of the buildings investigated. Each building has beenwas assumed to beas refurbished to current building regulation standards by applying internal insulation on all opaque elements achieving U-values of 0.30 Wm^{-2}K^{-1}, 0.18 Wm^{-2}K^{-1} and 0.25 Wm^{-2}K^{-1} for wall, roof and floor respectively [2533]. Table 34 shows U-values before and after applying insulation on all buildings considered in the study along with their thickness values. It has beenwas assumed that VIPs covercovered 95% of the all opaque elements whilstwith phenolic foam insulation covering the remaining 5%. The thermal conductivity of the Phenolic foam hasused was assumed to have a thermal conductivityas of 0.020 Wm^{-1}K^{-1}.

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Table 34. Details of buildings studied and U-values before and after the application of insulation

Building	Parameter	Wall	Floor	Roof
Retail Unit	Existing U-value ($Wm^{-2}K^{-1}$)	0.65	0.46	0.96
	U-value after applying insulation ($Wm^{-2}K^{-1}$)	0.30	0.25	0.18
	FS VIP Thickness (mm)	25	25	65
	GF VIP Thickness (mm)	40	40	110
	EPS Thickness (mm)	60	65	155
4 Storey Office	Existing U-value ($Wm^{-2}K^{-1}$)	0.65	0.30	0.87
	U-value after applying insulation ($Wm^{-2}K^{-1}$)	0.30	0.25	0.18
	FS VIP Thickness (mm)	30	10	65
	GF VIP Thickness (mm)	40	20	110
	EPS Thickness (mm)	74.5	20	155
6 Storey Office	Existing U-value ($Wm^{-2}K^{-1}$)	0.44	0.30	0.37
	U-value after applying insulation ($Wm^{-2}K^{-1}$)	0.30	0.25	0.18
	FS VIP Thickness (mm)	15	10	40
	GF VIP Thickness (mm)	25	20	65
	EPS Thickness (mm)	40	25	100

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5 Space heating energy saving potential

PotentialThe potential space heating energy savings and associated reduction in carbon dioxide (CO_2) emission from using VIP insulation in all three types of buildings (described in table 3) has been4) were calculated. AnnualThe annual space heating energy savingssaving (E_A) of buildingsfor any year (n) was calculated using equation (117).

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$$E_A = \frac{86400\times HDD\times \Delta L}{H_v\times\eta(1-x)}$$

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(11 $$\frac{86400\times HDD\times\Delta L}{H_v\times\left(\frac{\eta_i - x\times n}{100}\right)}$$ (7)

where
HDD is the heating degree days (°C days)
H_v is the calorific value of fuel (Jm^{-3})
η is the thermal efficiency of the heating system (boiler)
x is the annual rate of decrease of thermal efficiency of heating boiler
ΔL is the difference of total building transmission heat loss coefficient before and after applying insulation (WK^{-1}).

~~Total~~The building transmission heat loss coefficient (L) ~~takes into account~~incorporates the U-values of all building elements. In the case of applying VIP insulation the U-value varies with time and can be calculated using equations (~~7~~5) and (~~8). Time~~6). The time dependent U-values of the wall, floor and roof of the retail unit building insulated with VIPs is shown in figure 3.

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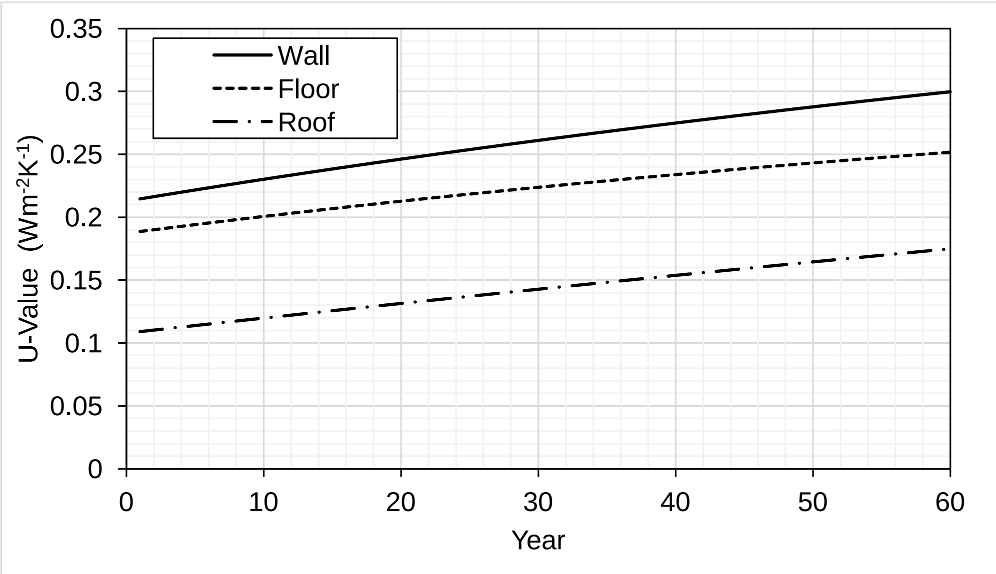

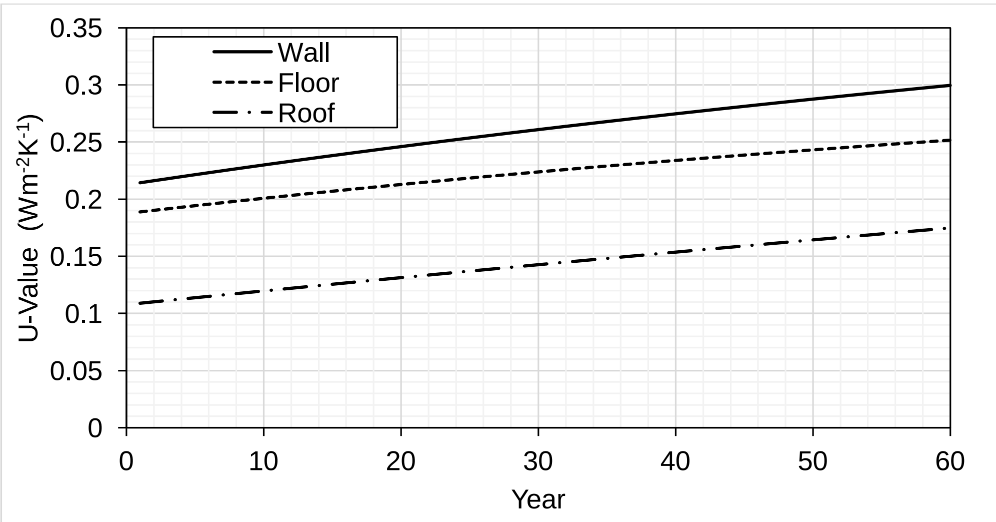

Figure 3. Time dependent U-values of VIP insulated wall, floor and roof of the two floor retail unit building studied

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Applying VIP insulation ~~reduces~~reduced the U-value of building elements, ~~see~~as shown in table ~~3, and results in~~4, saving space heating energy~~ savings~~. The energy saved over the assumed 60 year life time of the ~~building, assumed to be 60 years, for all~~three buildings considered is shown in figure 4.

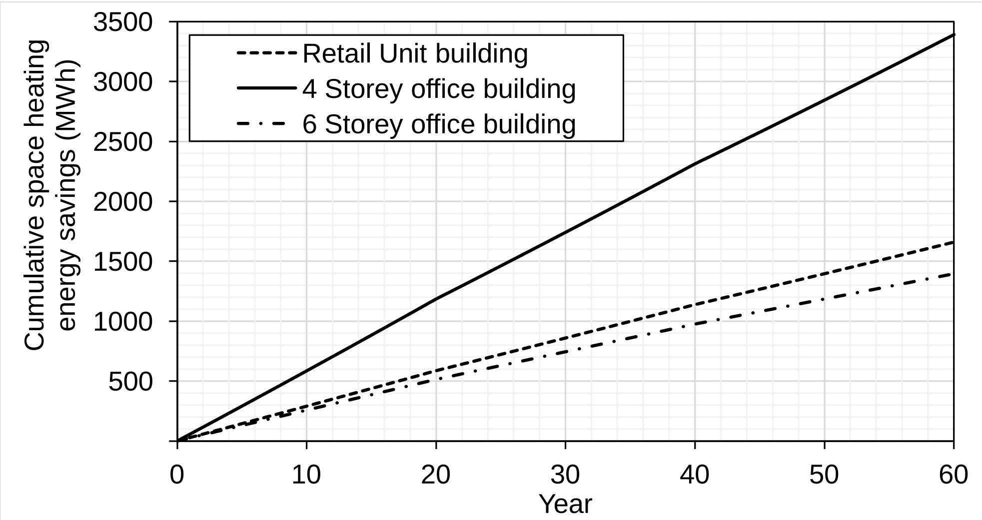

Figure 4. Cumulative space heating energy savings of the VIP insulated buildings studied

~~Over~~Using the ~~full~~parameters outlined previously in table 4 over the assumed building life ~~time,~~span of 60 years, installing VIPs ~~can save~~ would reduce the energy used for space heating ~~energy of~~by 1395.3 MWh, 1661.2 MWh and 3391.6 MWh for the six storey office building, the retail unit building and the four storey office building

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respectively. PotentialThe potential reduction in CO_2 emissions werewas calculated using a fuel emission factor of 0.18365 $kgCO_2/kWh$ [2634] and are shown in figure 5. Use of VIPs was calculated to potentially reduce CO_2 emissions by 10.2%, 41.3% and 26.7% respectively for six storey office building, retail unit building and four storey office building.

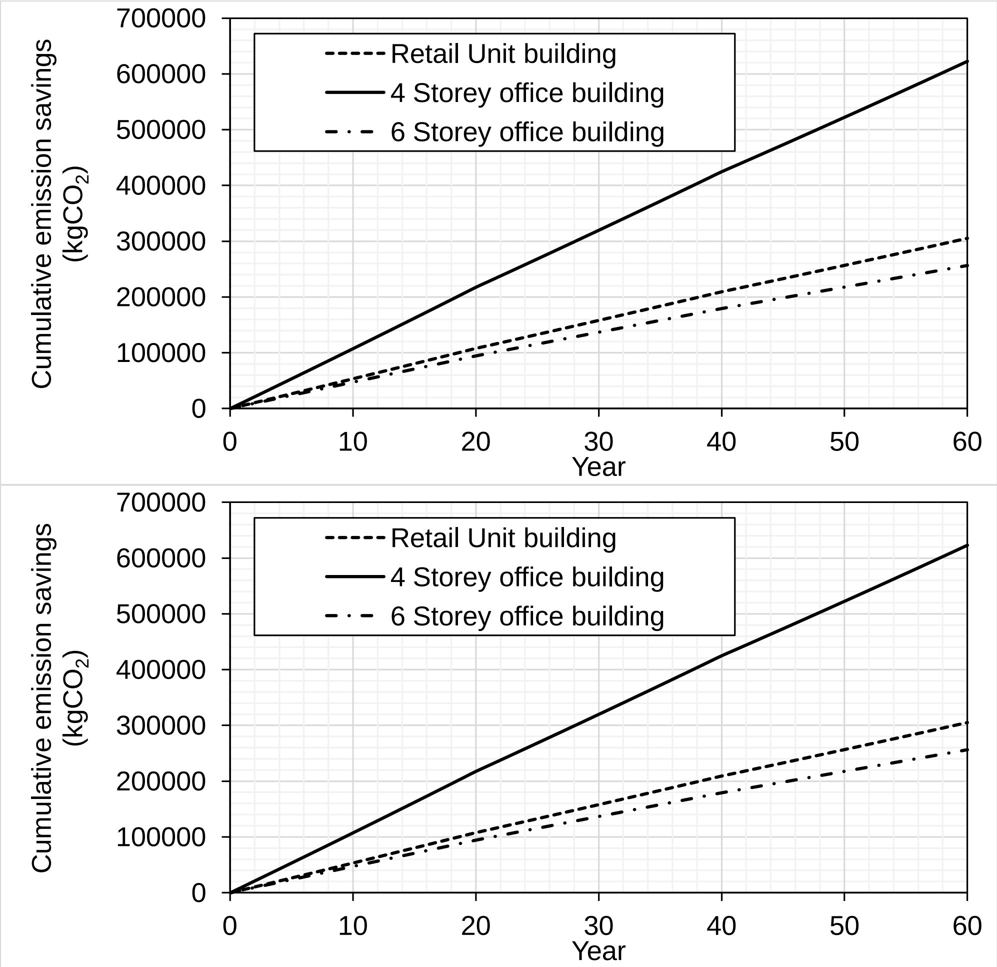

Figure 5. Reduction in CO_2 emissions for three buildings studied

6 Payback period results

A discounted Payback period analysis of FS VIPs, GF VIPs and EPS insulation applied in buildings described in table 4 was carried out using equation (1-6) and the results are presented in section 6.1, 6.2 and 6.3.

6.1 Two floor retail unit

The geometricGeometric and thermal featurefeatures of the buildingbuildings studied are shown in table 4. This type of buildings account for 10% of the retail building

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stock in the UK by age of construction (1989-90) and 13% by floor area (250-500 m^2) [27].5. The wall, floor and roof U-values are shown in table 4. Payback period analysis of FS VIPs and GF VIPs has been carried out employing equations (1-10) and compared with that of EPS insulation. EPS insulation was found to take longer than its life time to recover the The cost of insulationinstalling sufficient EPS for achieving current building insulation standards could not be recovered within its lifetime, see figure 6. For EPS, no space saving revenue is possible, which means that investments are solely recovered through fuel cost savings. Also, EPS due to a comparatively shorter service life of 20 years will require to be replacedrequires replacement three times over an assumed 60 year building life span of the building leading to a higher insulation cost. A life span of 60 years for building has beenwas assumed to match the

Table 45. Geometric and thermal features of the buildings considered in this study

Parameter	Two-floor Retail Unit	Four Storey Office	Six Storey Office
Length (m)	15	40	60
Width (m)	15	15	15
Height of each storey (m)	4.5	3.7	3.7
Glazing Area (m^2)	81.0	769.6	1665.0
Glazing U-Value (Wm^{-2}K^{-1})	5.38	2.75	1.9
Air infiltration rate (ach)	0.25	0.25	0.25

match the prescribed life span of VIPs used for buildings in the UK. In the case of VIPs, the additional benefit of commercial space saving can partially offset the higher initial insulation cost.costs. The Results of payback period analysis for two different types of VIPs (FS and GF) taking into account

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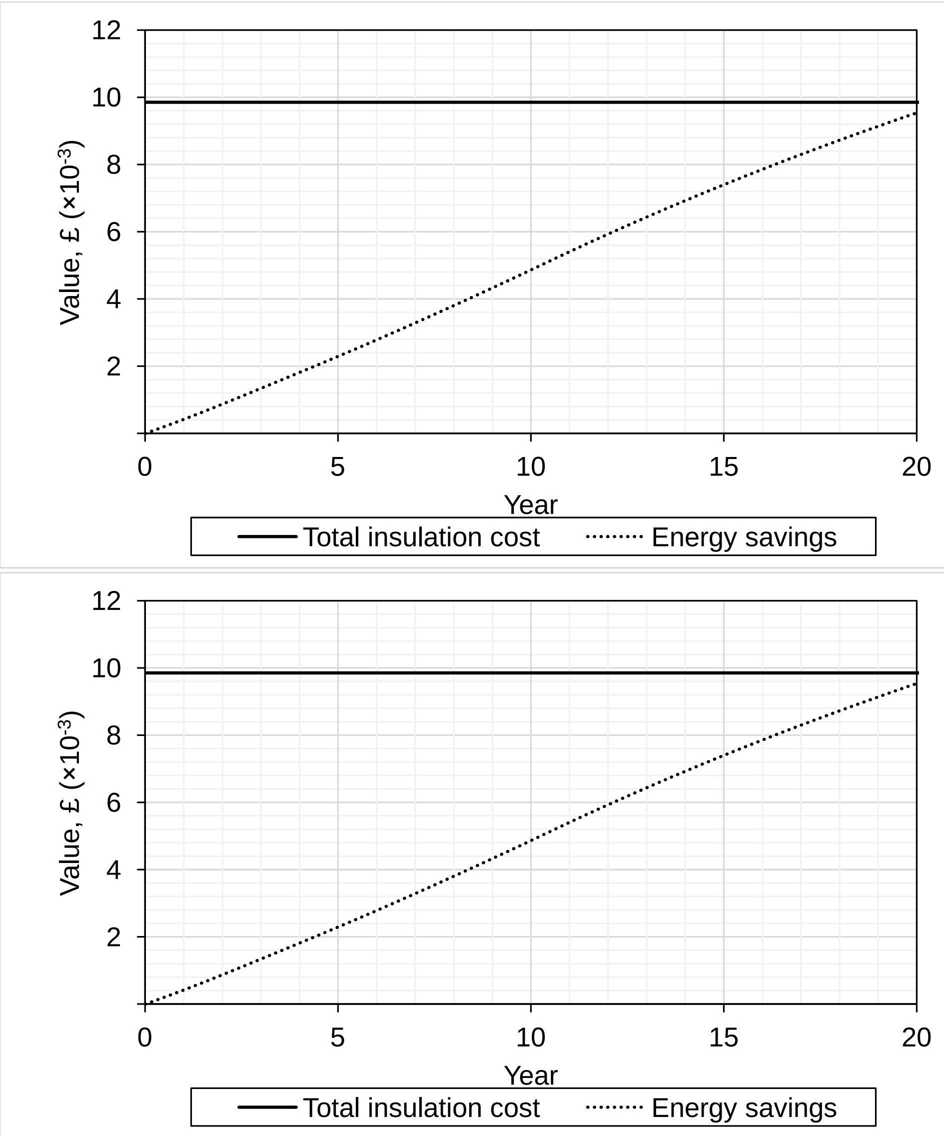

Figure 6. Cost and savings of applying EPS insulation in a retail unit building

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the economic potential of space saving with average annual rental value in London (UK) ranging from £1000 m^{-2} to £4000 m^{-2} [~~28] has been~~35] is shown in ~~figure~~figures 7 and 8 respectively. ~~Results show~~Figures 7 and 8 demonstrate that the cost of GF VIP insulation with a rental value of £1000 m^{-2} cannot be recovered over the life time of the ~~buildings~~building whereas FS VIP will take only 7 years to recover the investment. This finding can be explained as follows. GF VIP, though costing 1.6 times lesser than FS VIP, ~~will need to~~must be replaced six times over the life time of the building due to ~~their~~a shorter service life (10 years~~) as~~), compared to that of FS

VIP (60 years). As expected, as the rental values increase the payback period for VIP insulation becomes shorter. For rental ~~value~~values of

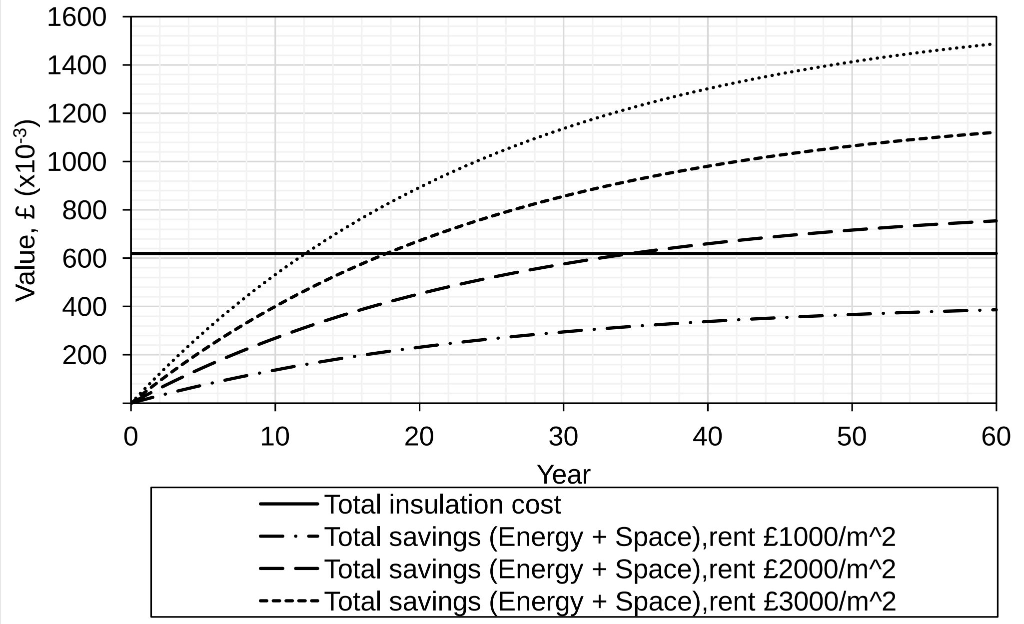

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Figure 7. Cost and savings of applying GF VIP insulation in the retail unit building studied

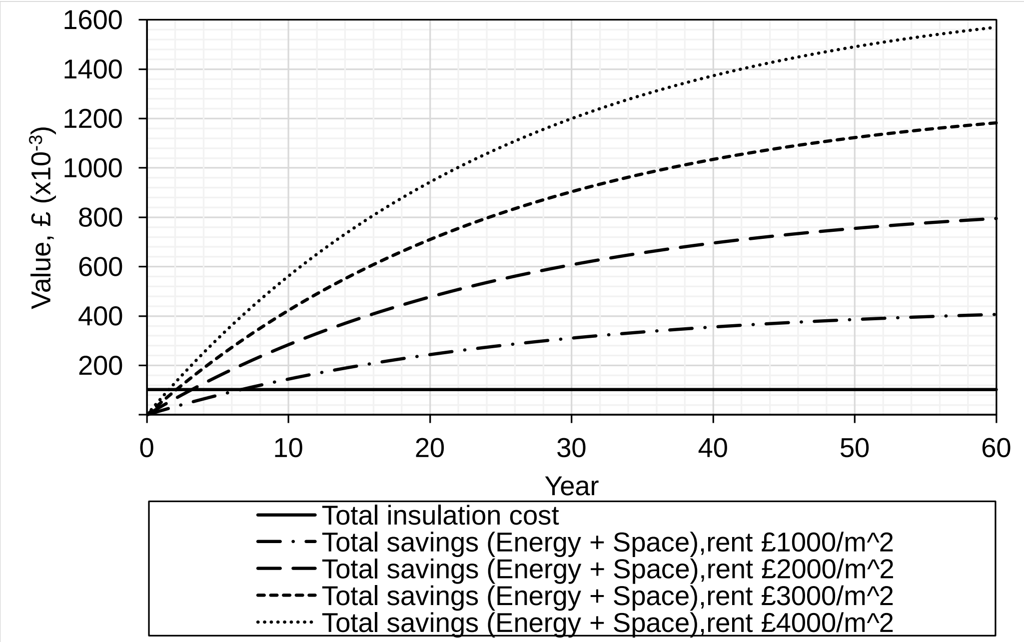

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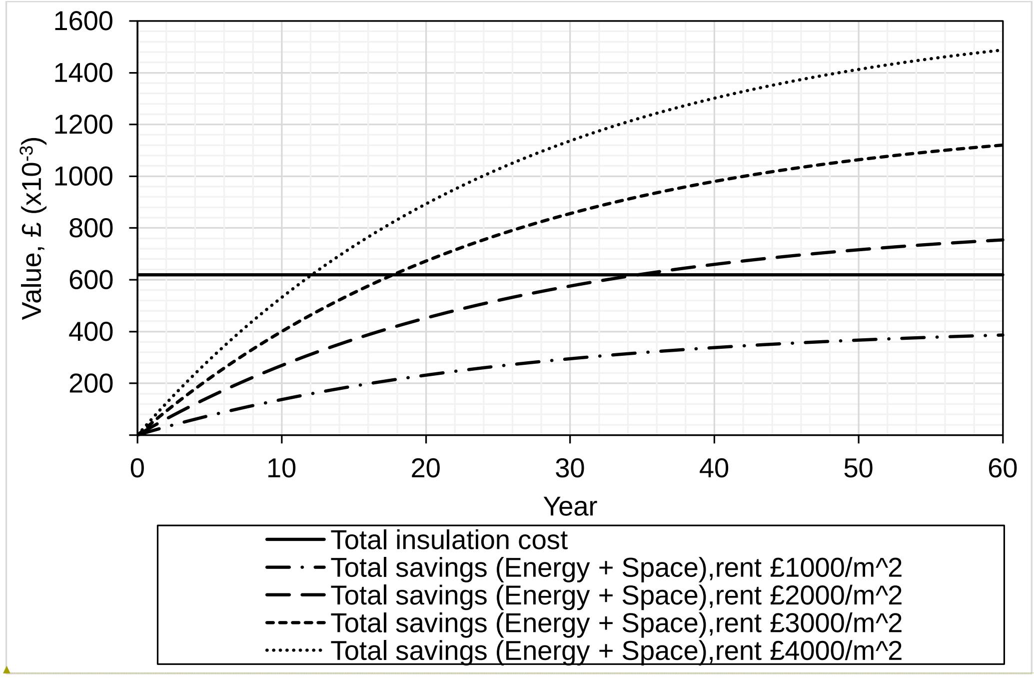
Figure 8. Cost and savings of applying FS VIP insulation in the retail unit building studied

£2000 m^{-2} and £3000 m^{-2} ~~it is~~the discounted payback period was 35 years and 18 years respectively for GF VIP and 4 years and 3 years for FS VIP. For average rental value of £4000 m^{-2} payback period of FS VIP becomes approximately 2 years, whereas it is still prohibitively longer (12 years) for GF VIPs.



~~Figure 7. Cost and savings of applying GF VIP insulation in the retail unit building studied~~

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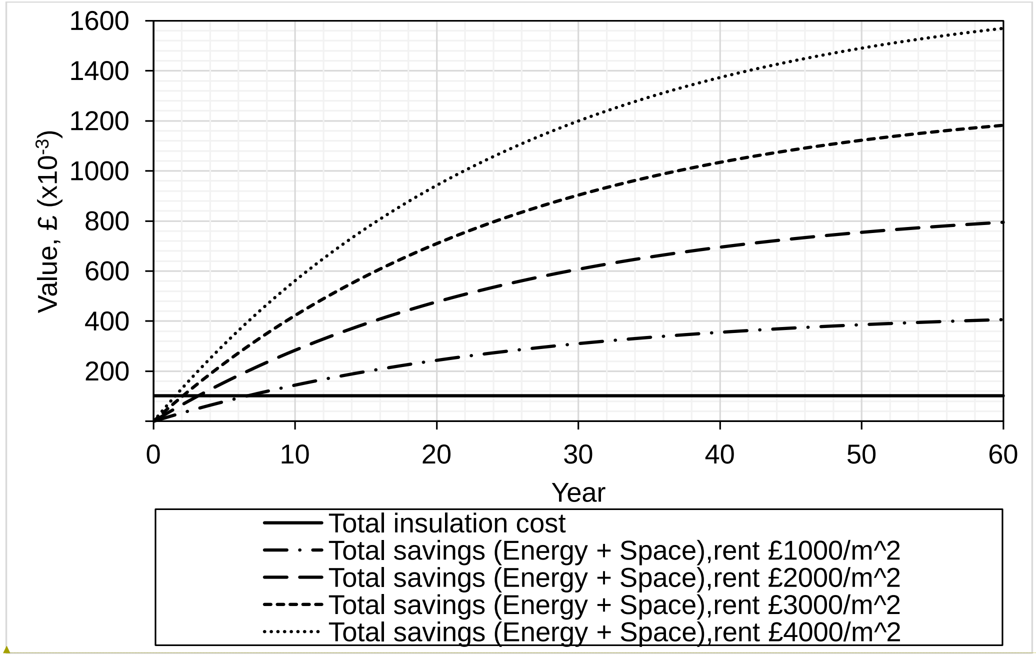

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Figure 8. Cost and savings of applying FS VIP insulation in the retail unit building studied

6.2 Four storey office

The geometricGeometric and thermal featurefeatures of the building studied four storey office are shown in table 4. This building type accounts for 9% of the office building stock in the UK by age of construction (1981-85) and 20% by floor area (2500-10,000m^2) [27]. The wall, floor and roof U-values are shown in table 3. Payback5. The discounted payback period analysis for the four storey office is presented in figure 9, 10 and 11 for achievingretrofitted to meet current building insulation standards withusing EPS insulation, GF VIP insulationVIPs and FS VIP insulation VIPs is presented in figures 9 to 11 respectively.

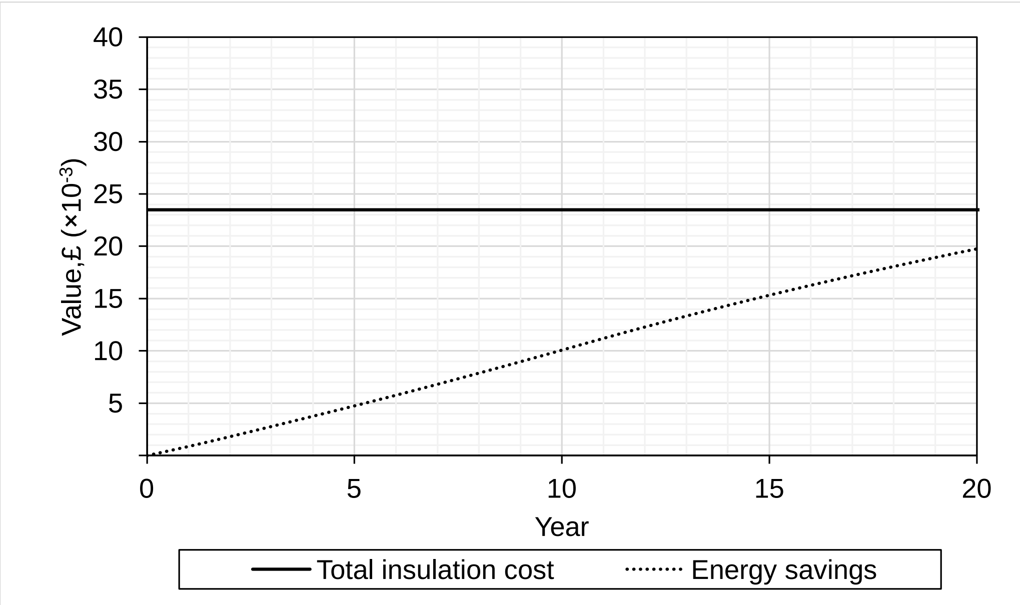

Figure 9. Cost and savings of applying EPS insulation in the 4 storey office building studied

Figure 9 ~~shows~~demonstrates that EPS insulation cannot recover the initial capital cost over its life time of 20 years. For GF ~~VIP even considering additional benefit of the economic potential of space saving with average annual rent ranging from £400 m^{-2} to £1000 m^{-2} [29]~~VIPs the cost of insulation cannot be recovered over the life time of building as shown in figure 10~~.~~ even with the additional economic benefits from space saving with average annual floor rents ranging from £400 m^{-2} to £1000 m^{-2} [36]. As ~~stated~~discussed in section 6.1, the reason for long payback period for GF VIPs is their short service life (10 years) requiring replacement six times during 60~~-~~-year life time of the building.

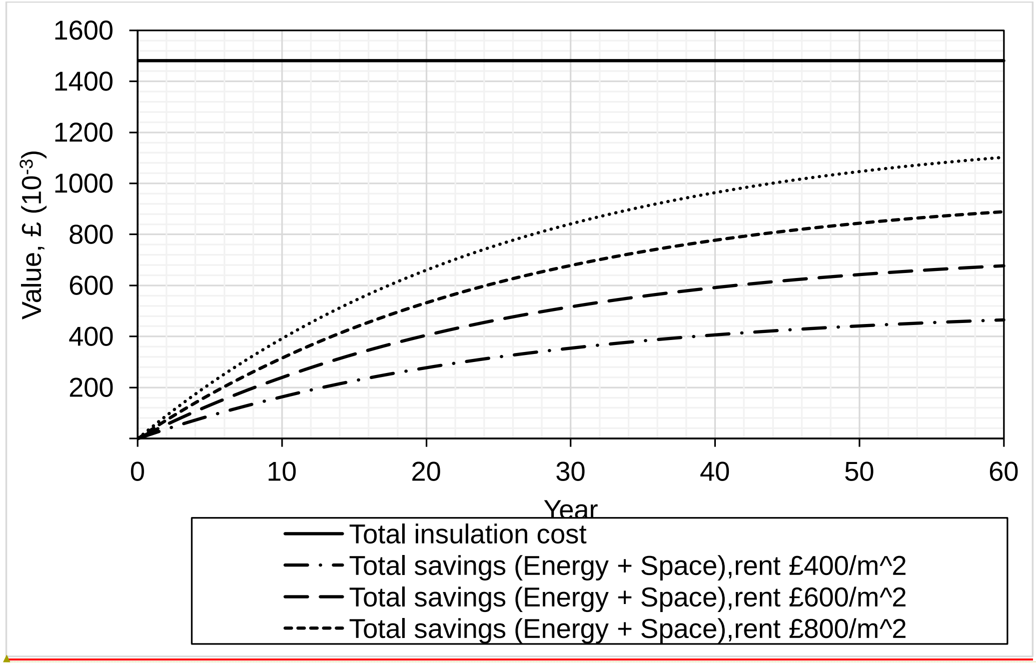

Figure 10. Cost and savings of applying GF VIP insulation in the 4 storey office building studied

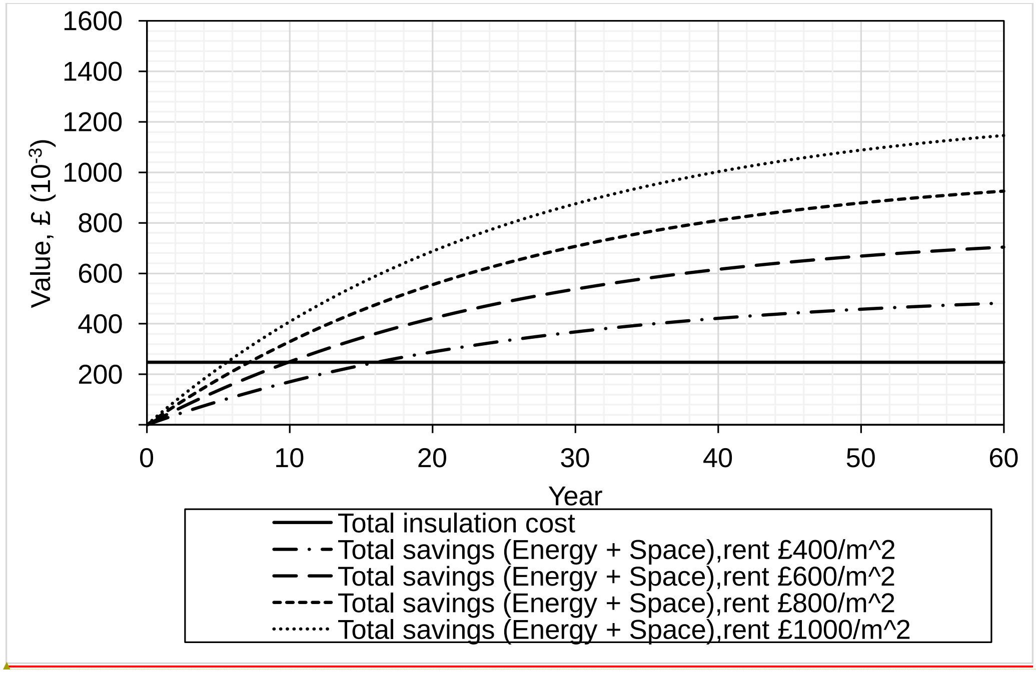

Figure 11. Cost and savings of applying FS VIP insulation ~~returned~~in the 4 storey office building studied

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From figure 11, it can be seen that upgrading the 4 storey office with FS VIP insulation to comply with current building regulations resulted in payback periods of 17 years, 10 years, 7 years and 6 years for rental values of £400 m^{-2}, £600 m^{-2}, £800 m^{-2} and £1000 m^{-2} respectively.

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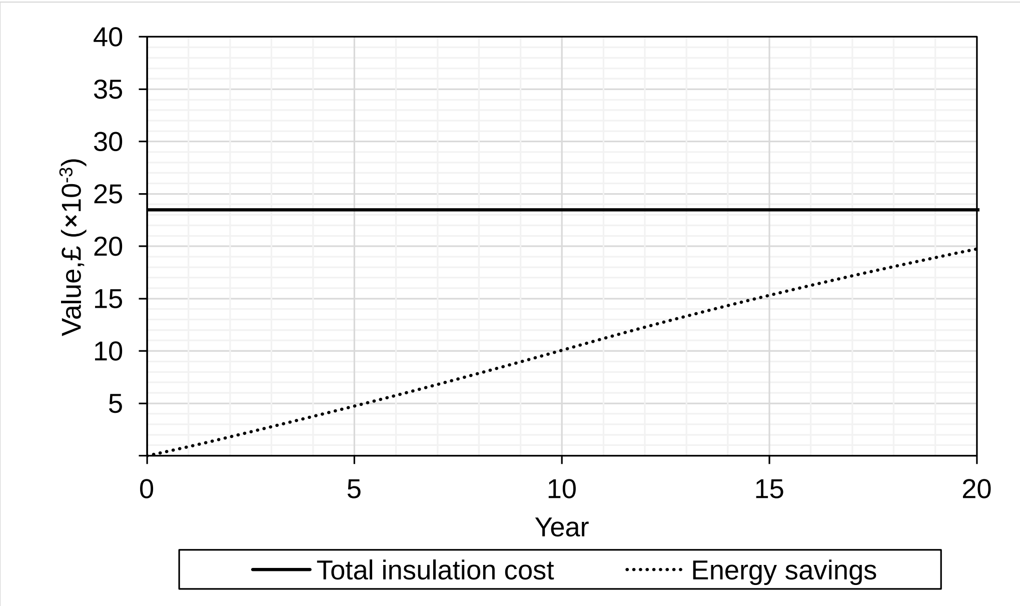

~~Figure 9. Cost and savings of applying EPS insulation in the 4 storey office building studied~~

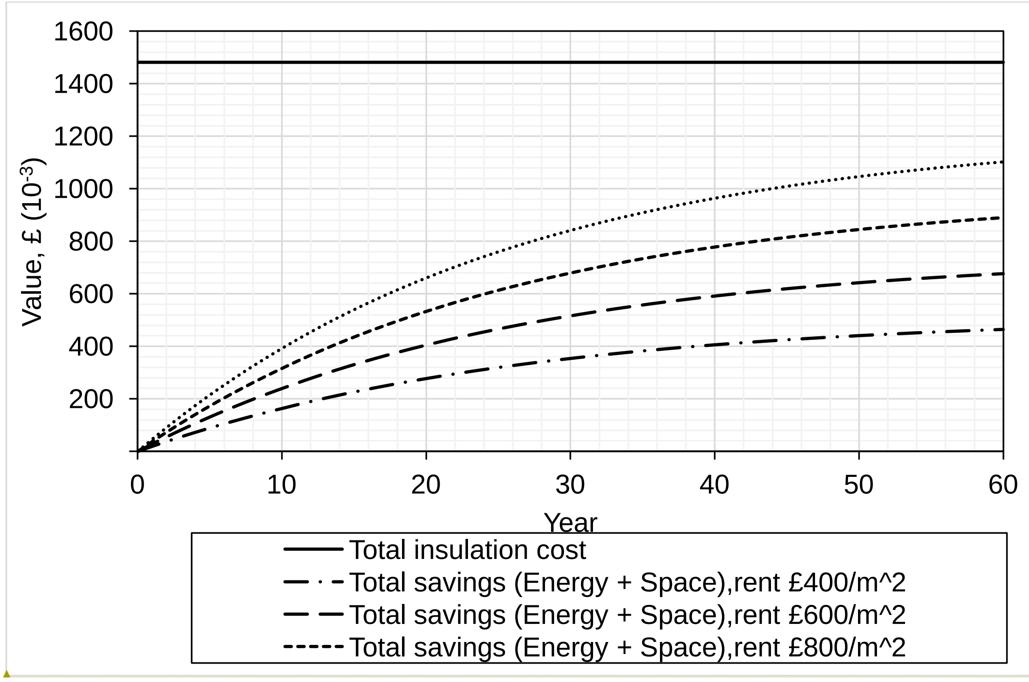

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Figure 10. Cost and savings of applying GF VIP insulation in the 4 storey office building studied

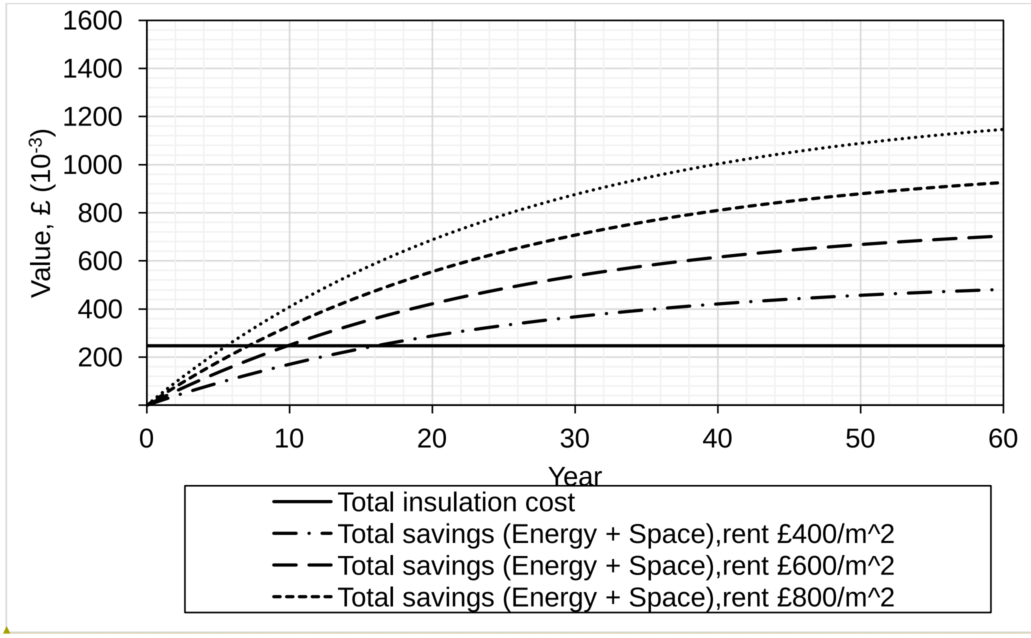

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Figure 11. Cost and savings of applying FS VIP insulation in the 4 storey office building studied

6.3 Six storey office

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~~The geometric~~Geometric and thermal ~~feature~~features of the ~~building studied~~ six storey office are detailed in table 4 ~~This building type accounts for 11% of the office building stock in the UK by age of construction (1986-90)~~ and ~~20% by floor area (2500-10,000m^2) [27].~~table 5. Results of the discounted payback period analysis for the six storey office building ~~is~~are shown in ~~figure~~figures 12~~, figure 13 and figure~~ to 14.

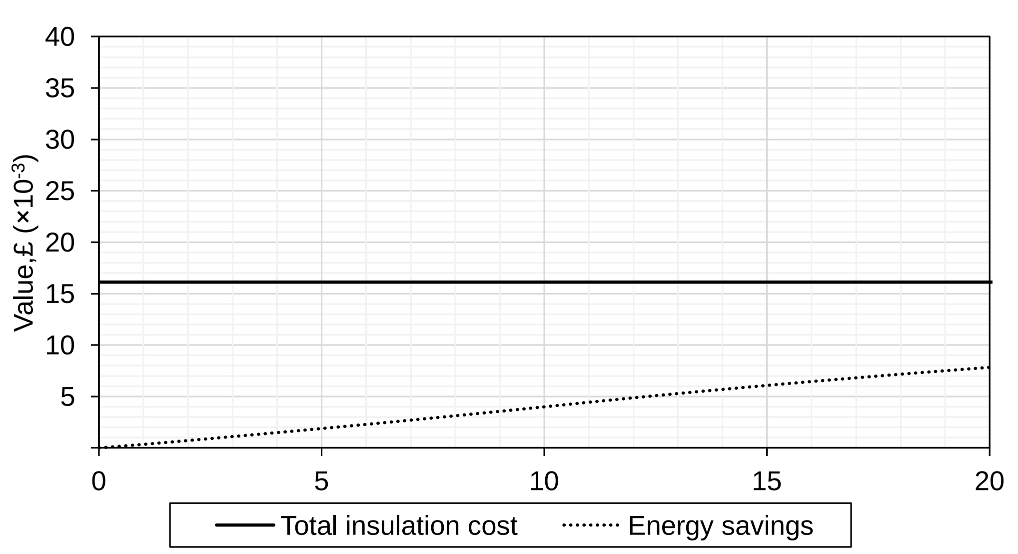

Figure 12. Cost and savings of applying EPS insulation in the 6 storey office building studied

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Figure 12 shows that EPS insulation ~~was found to have the~~had a discounted payback period longer than its assumed life time of 20 years. ~~In~~It can be seen from figure 13 that in the case of GF VIP, the cost of insulation cannot be recovered with average annual rent of £400 m^{-2} and £600 m^{-2} ~~as shown in figure 13.~~. For higher annual rents of £800m^{-2} and £1000m^{-2} payback periods of respectively 39 years and 25 years are predicted. ~~Interestingly, FS VIP achieves~~It is clearly observed, from figure 14, that FS VIPs had a shorter payback period than ~~both~~ EPS ~~and~~or GF ~~VIP~~VIPs. FS VIP ~~is shown~~was found to have a payback period of 7 years, 5 years, 3 year and 2.5 years with rental values of £400 m^{-2}, £600 m^{-2}, £800 m^{-2} and £1000 m^{-2} respectively~~, figure 14~~. These results clearly show that FS VIPs are economically viable to be used in high-rise office buildings despite their higher initial cost and decreasing thermal performance over service life.

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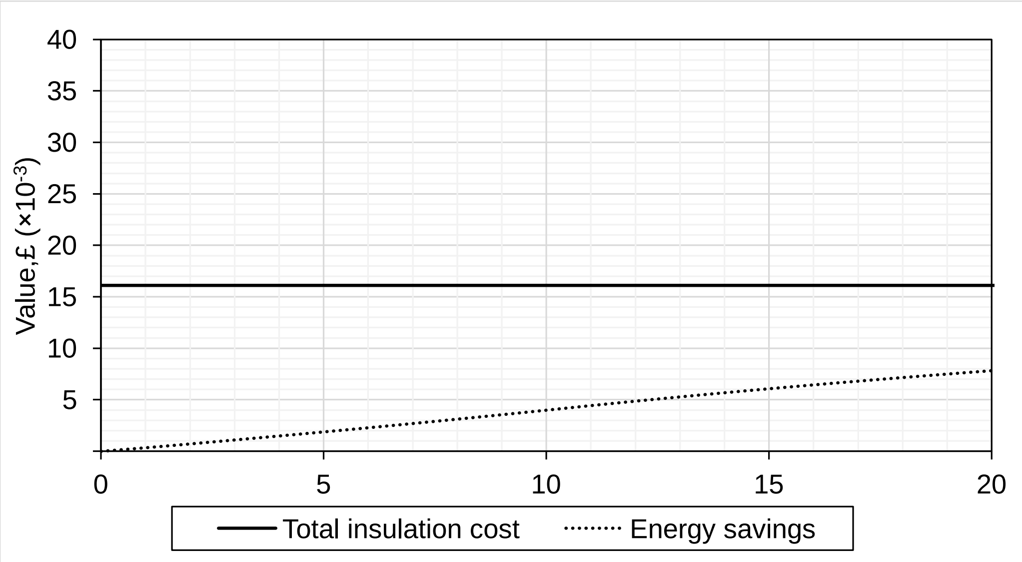
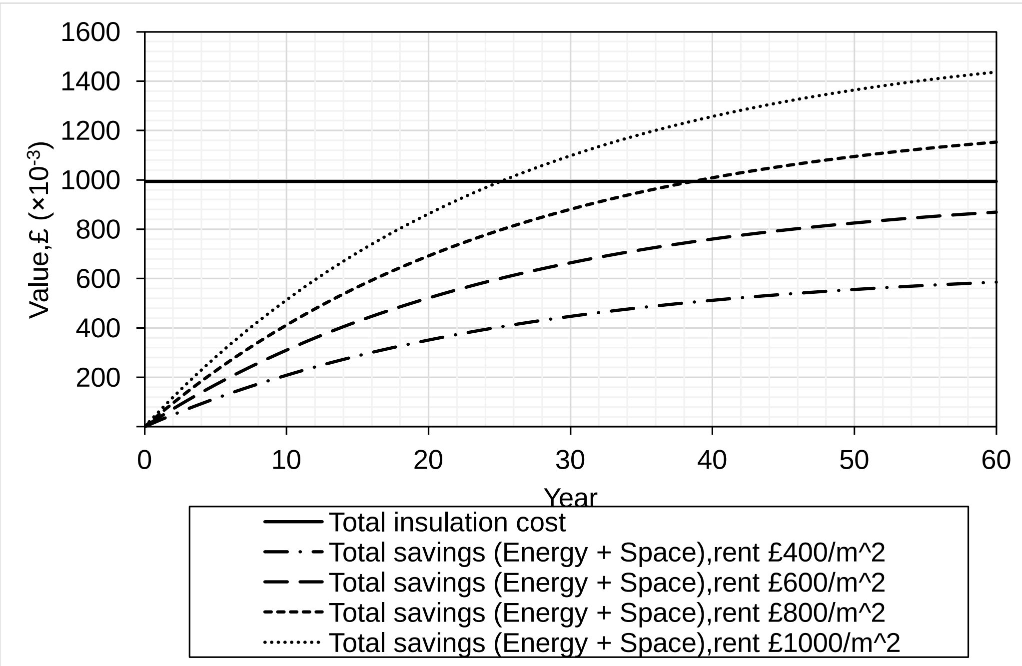
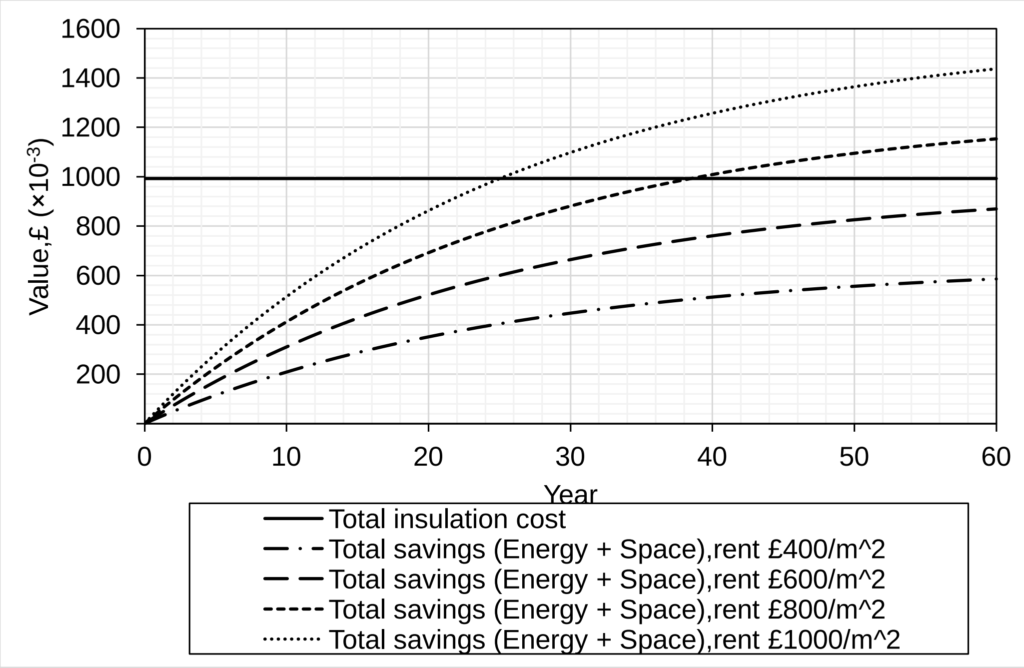


Figure 12. Cost and savings of applying EPS insulation in the 6 storey office building studied





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613 Figure 13. Cost and savings of applying GF VIP insulation in the 6 storey office
614 building studied
615

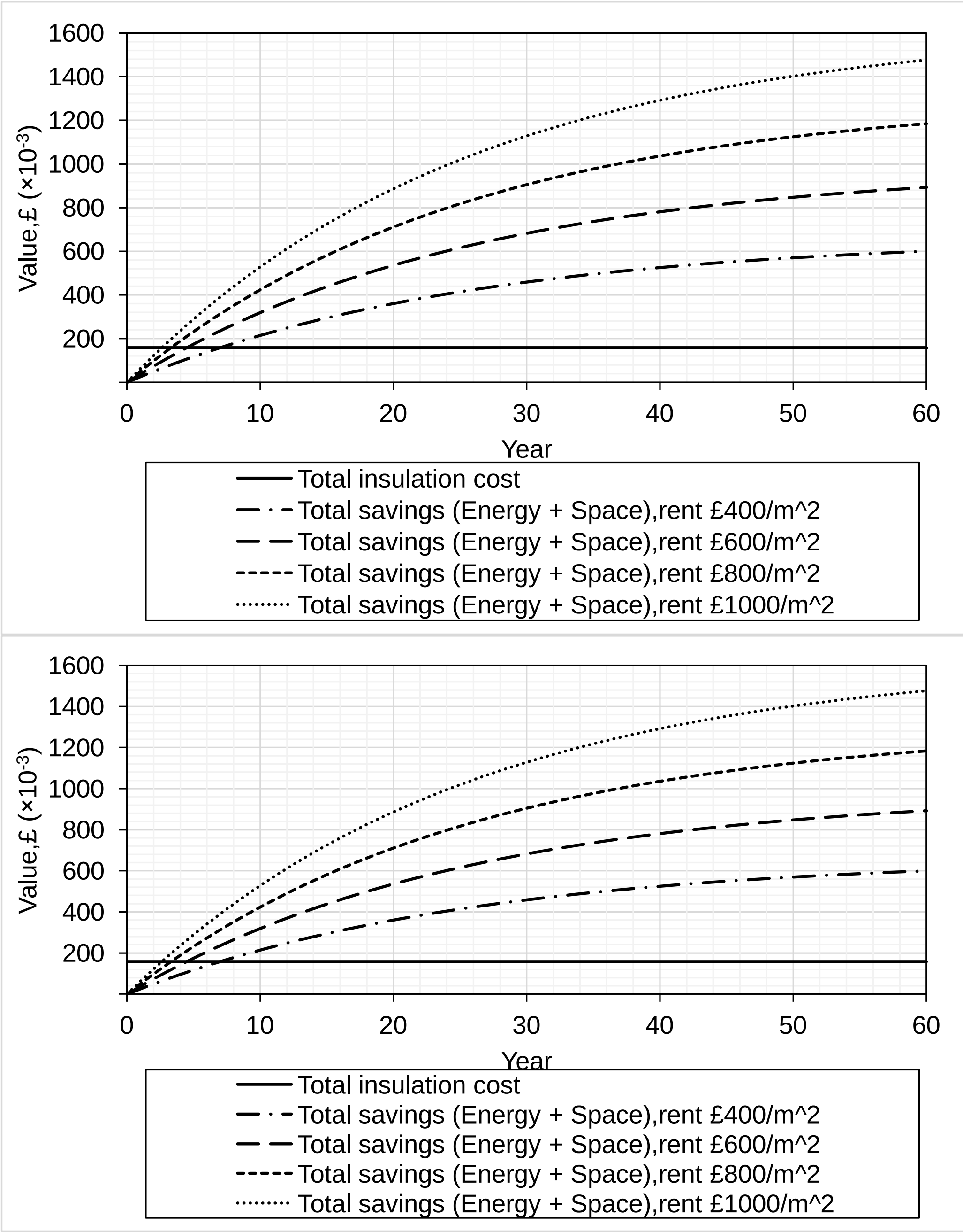

Figure 14. Cost and savings of applying FS VIP insulation in the 6 storey office building studied

7 Conclusions

In this study the energy savings and economic performance of Glass fibre (GF) and Fumed silica (FS) VIPs when used ~~in~~for retrofitting three non-domestic UK buildings ~~have been~~ to meet current building standards was evaluated and compared ~~with~~to that of conventional insulation, expanded polystyrene (EPS). Installing VIP insulation ~~have been shown to save~~ resulted in space heating energy savings of 1395.3 MWh,1661.2 MWh and 3391.6 MWh for a six storey office building, a two floor retail unit building and a four storey office building respectively over a life time of 60 years. ~~A methodology to predict the payback period for VIP insulation has been proposed as well. The proposed methodology is capable of taking into account the change in thermal conductivity of VIPs with time, variable fuel costs and revenues generated from space savings.~~ GF VIP was found to have a higher total cost than FS VIP due to its ~~short~~shorter service life requiring more frequent replacement, once every 10 years. An interesting finding is that EPS insulation cannot even recover its cost over its useful lifetime for all three buildings. Similarly, GF VIPs could not recover their cost ~~in~~for the case of the 4 storey office building. FS VIPs in comparison with EPS insulation and GF VIPs ~~are found to have~~had shorter payback periods due to their longer service life of 60 years. This is despite of FS VIPs being 1.6 times more expensive than GF VIPs. This is a remarkable result establishing the economic viability of using FS VIPs in non-domestic buildings located in high rental value locations around the world, such as London. Longevity has been found to be a critical factor in determining the economic viability of VIPs. It has been shown that despite a higher initial cost a longer lifespan VIP will achieve a shorter payback period. A methodology to predict the payback period for VIP insulation has been proposed. An all-inclusive equation capable of taking into account the change in VIP thermal conductivity with time, variable fuel costs and revenues generated from space savings to predict payback year of VIP insulation was presented. The equation can be easily solved on a spreadsheet to estimate the payback period for VIP insulation for any installation irrespective of application, buildings (domestic or non-domestic), refrigerators, freezers and refrigerated vans among many others.

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