# 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.

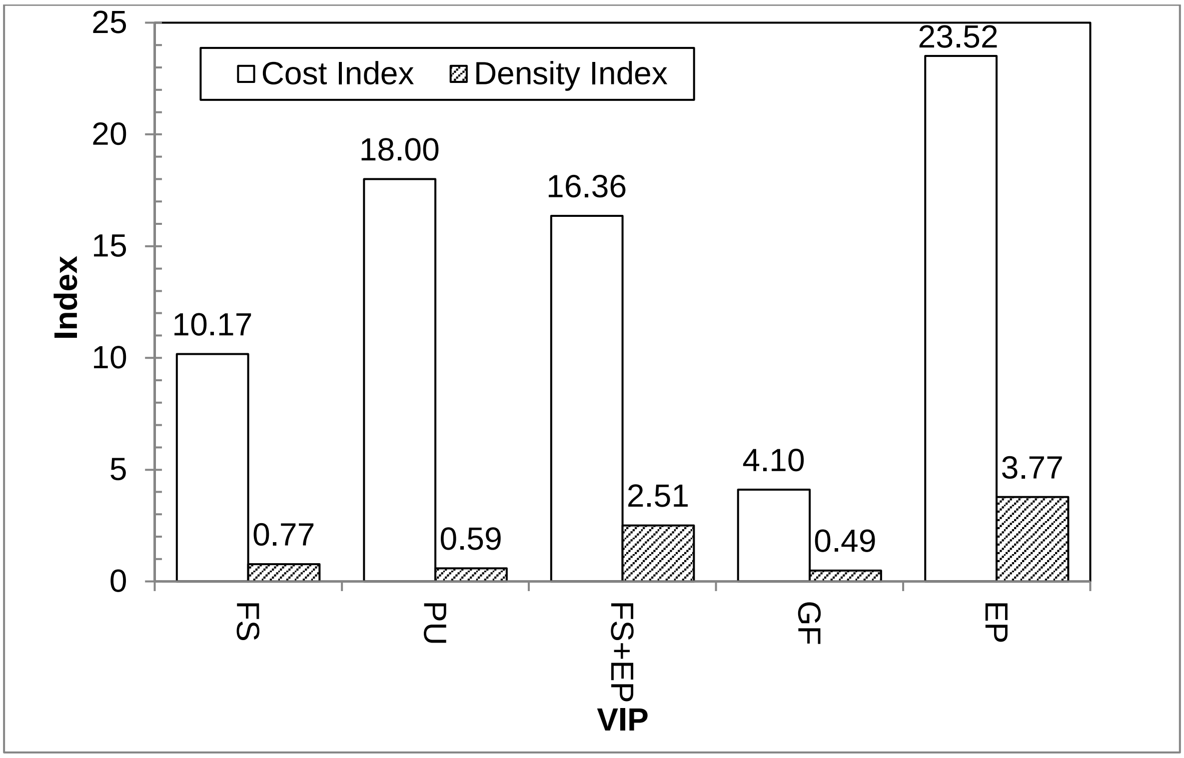


Figure 1. Cost and density index of different types of VIPs

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):

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

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$^{-3}$)
$\eta_i$ is the initial thermal efficiency of the heating system, boiler (%)
$x$ is the annual rate of decrease of thermal efficiency of heating boiler (%)
$\Delta L$ 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
$\Delta d$ 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)

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

where
$\mathrm{A}_i$ 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 ($m^3$)
$(\rho \mathrm{c_p})_{air}$ 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

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

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.

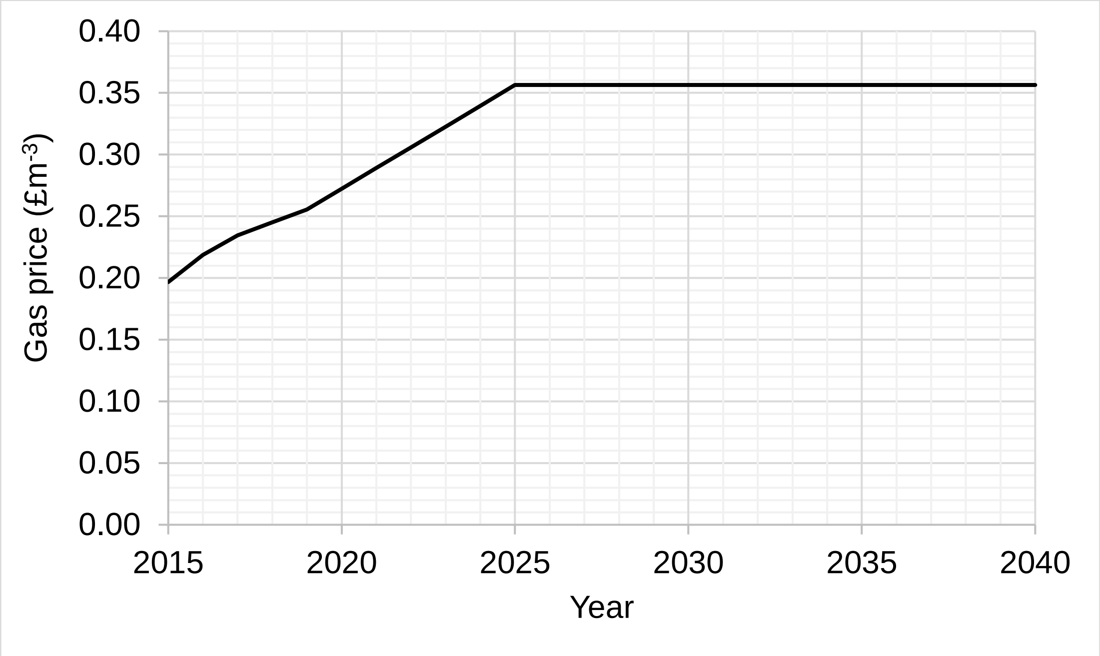


Figure 2. Gas price forecast [29]

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, $\eta_i$, (%) | 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.

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

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 (2500-10,000$m^2$) [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 (2500-10,000$m^2$) [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).

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

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.

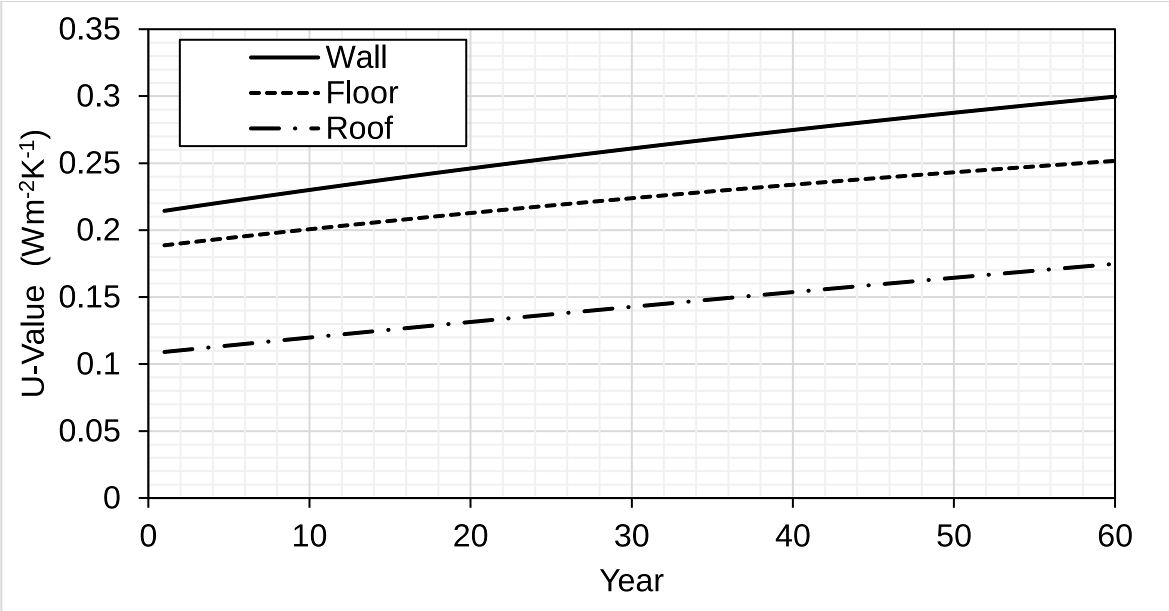


Figure 3. Time dependent U-values of VIP insulated wall, floor and roof of the two floor retail unit building studied

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.

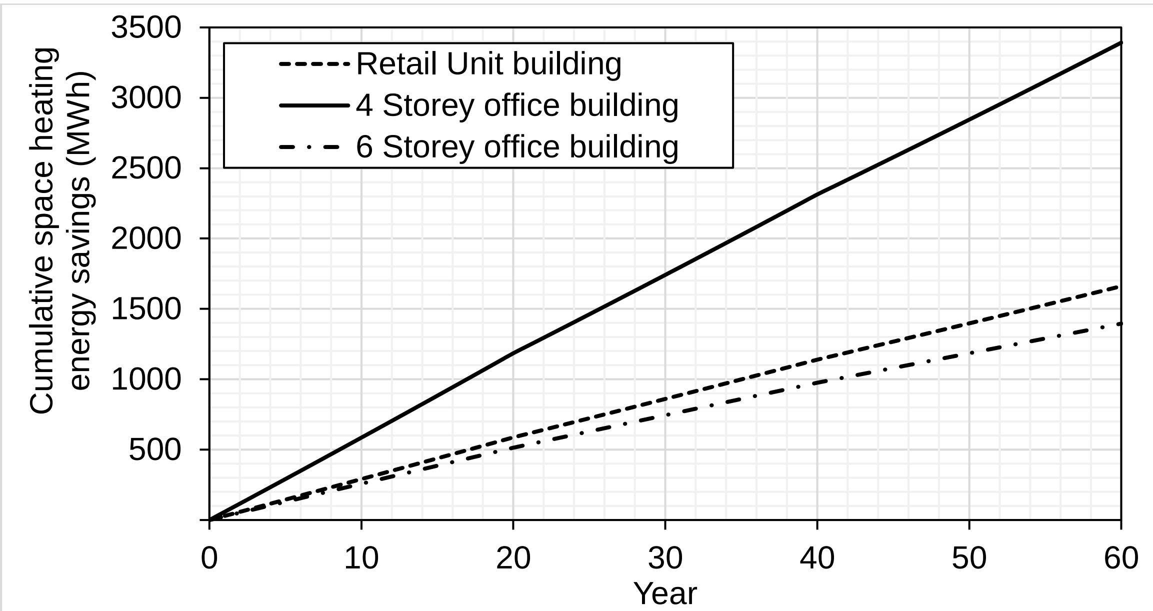


Figure 4. Cumulative space heating energy savings of the VIP insulated buildings studied

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.

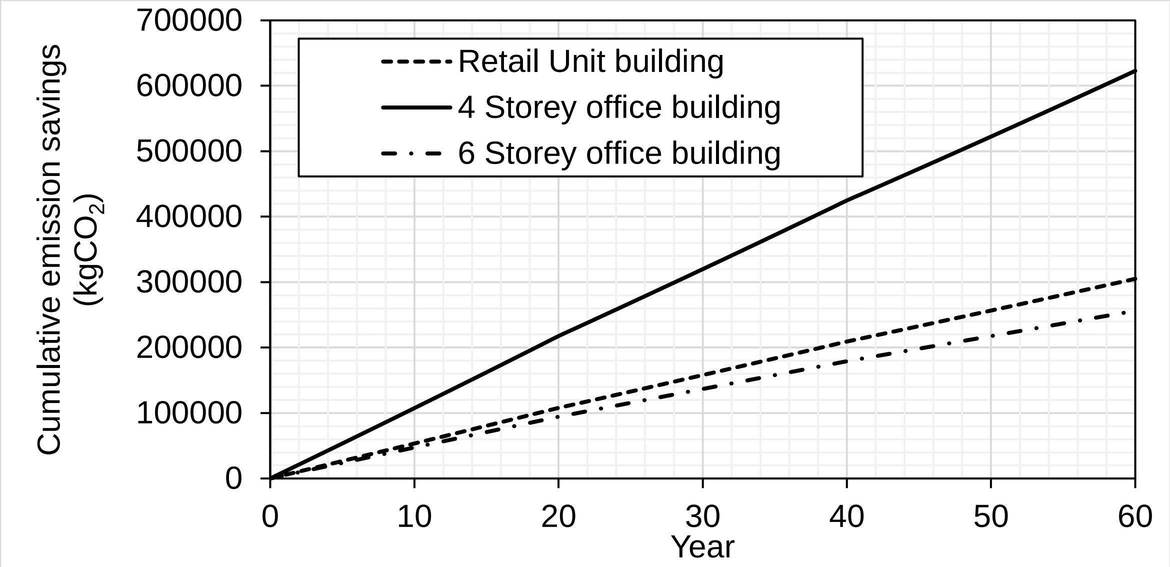


Figure 5. Reduction in $CO_2$ emissions for three buildings studied

**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

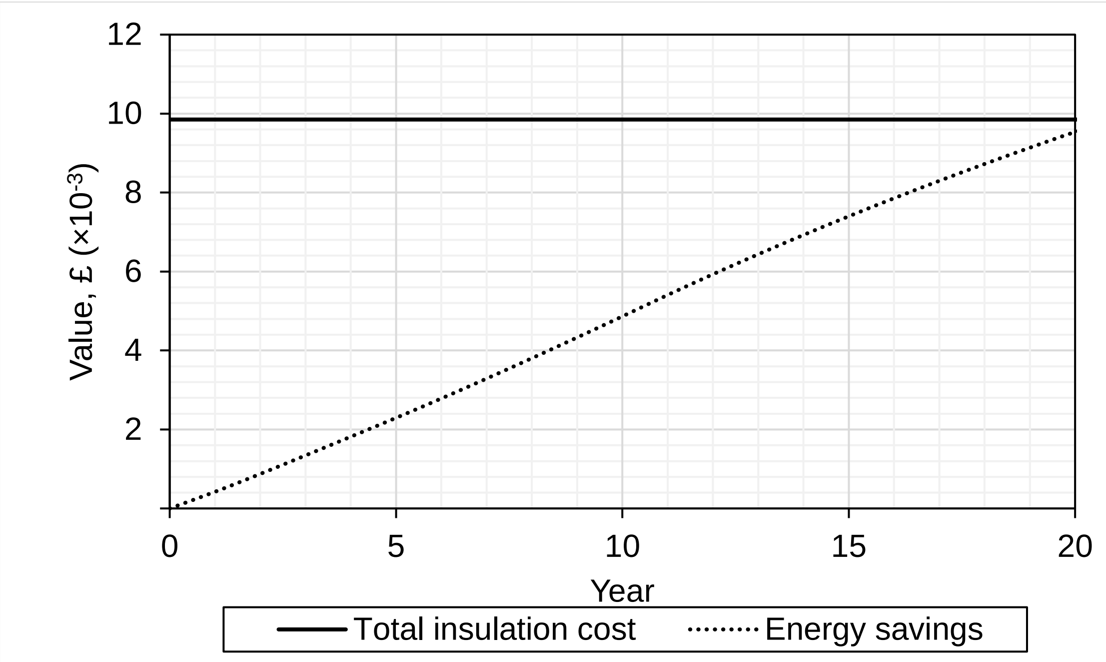


Figure 6. Cost and savings of applying EPS insulation in a retail unit building

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

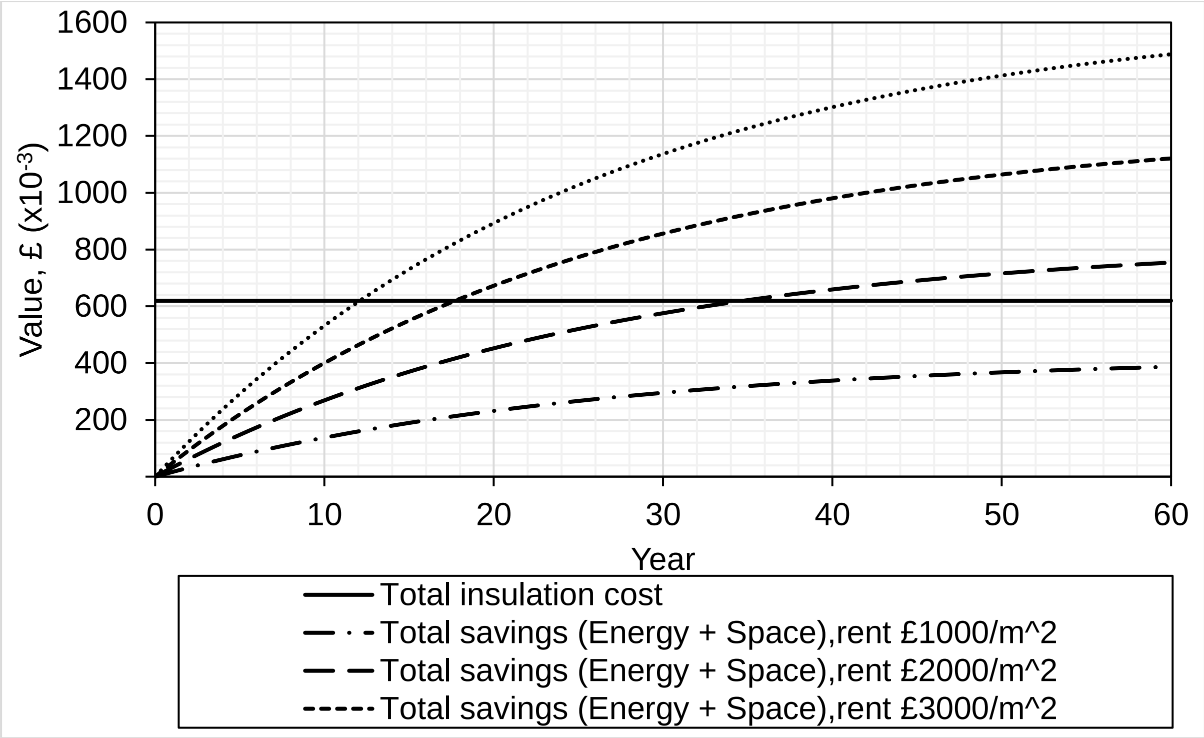


Figure 7. Cost and savings of applying GF VIP insulation in the retail unit building studied


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.

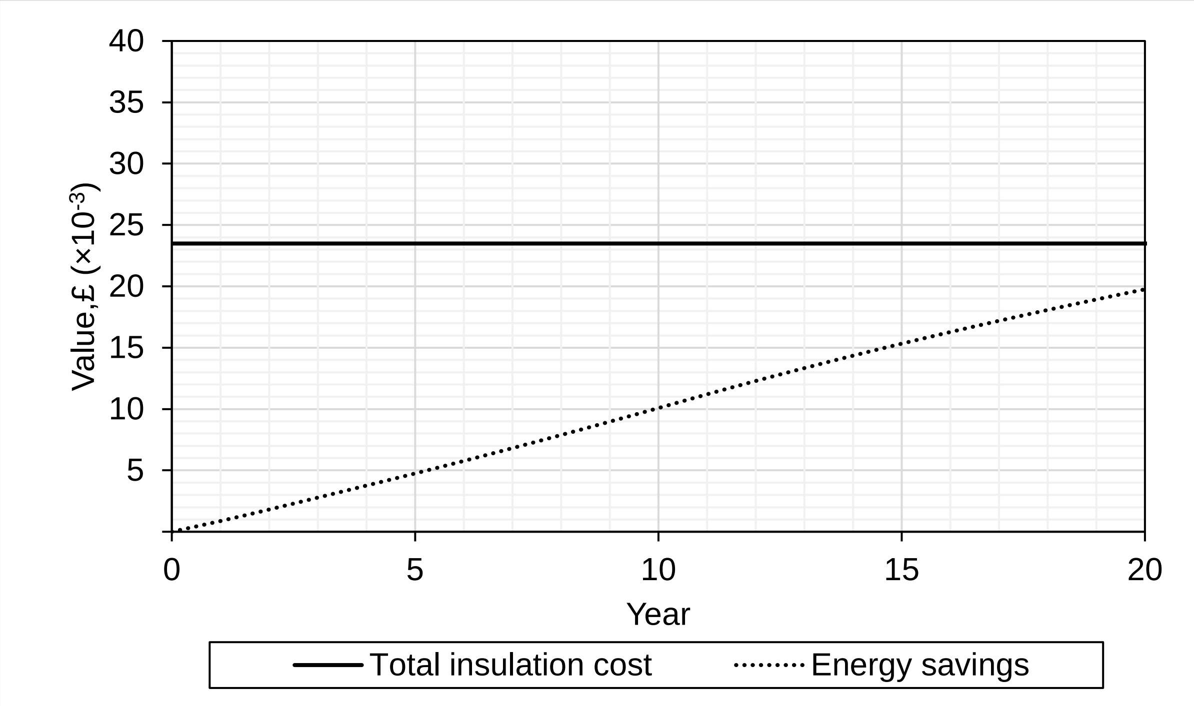


Figure 9. Cost and savings of applying EPS insulation in the 4 storey office building studied

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.

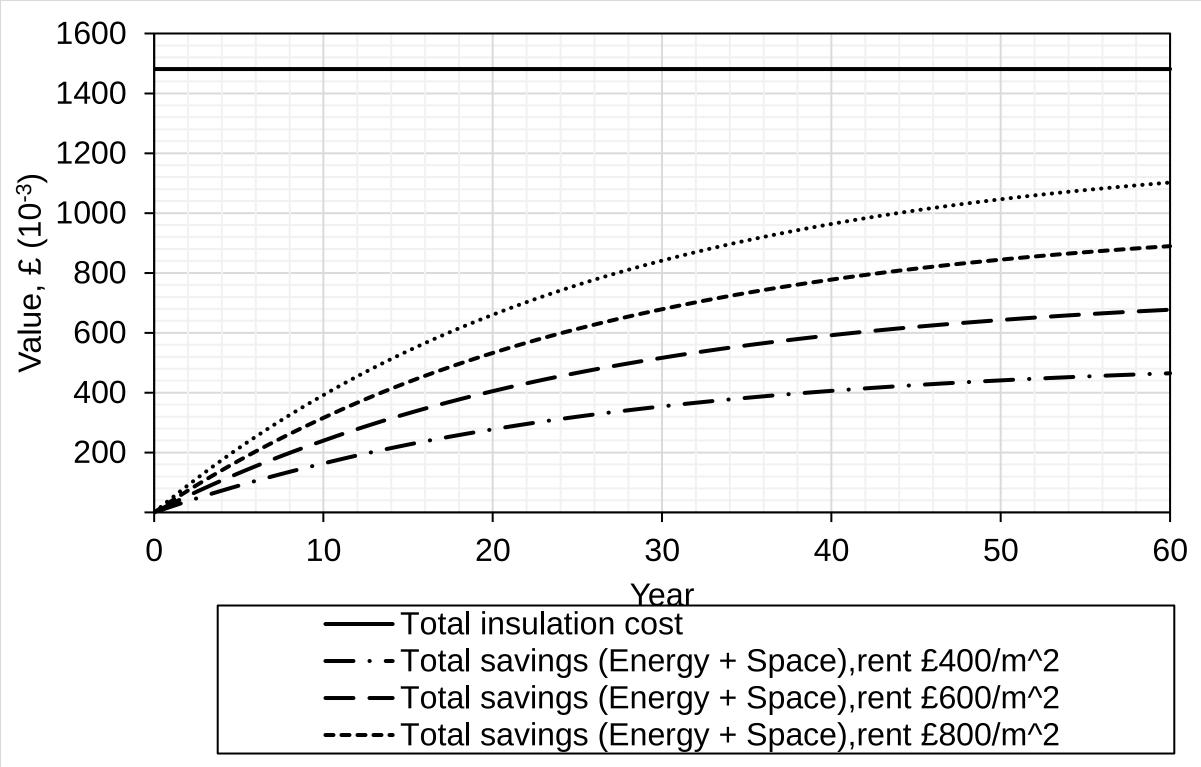


Figure 10. Cost and savings of applying GF VIP insulation in the 4 storey office building studied

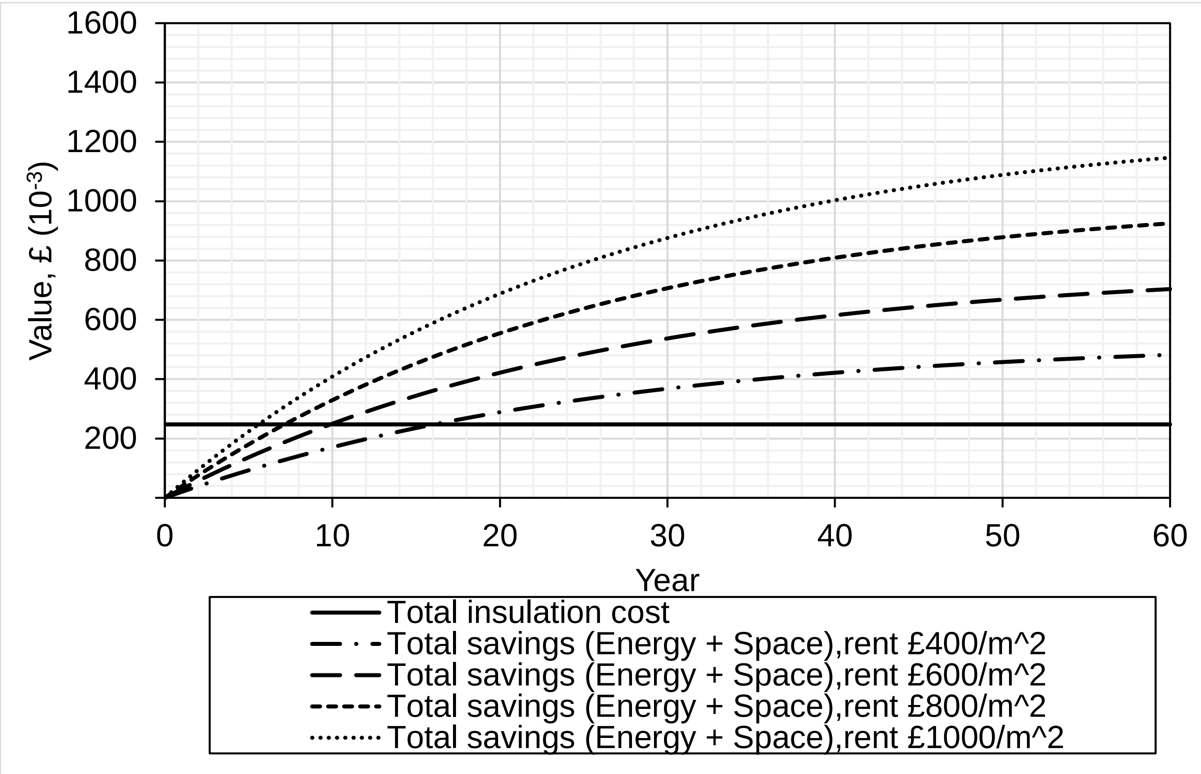


Figure 11. Cost and savings of applying FS VIP insulation in the 4 storey office building studied

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.

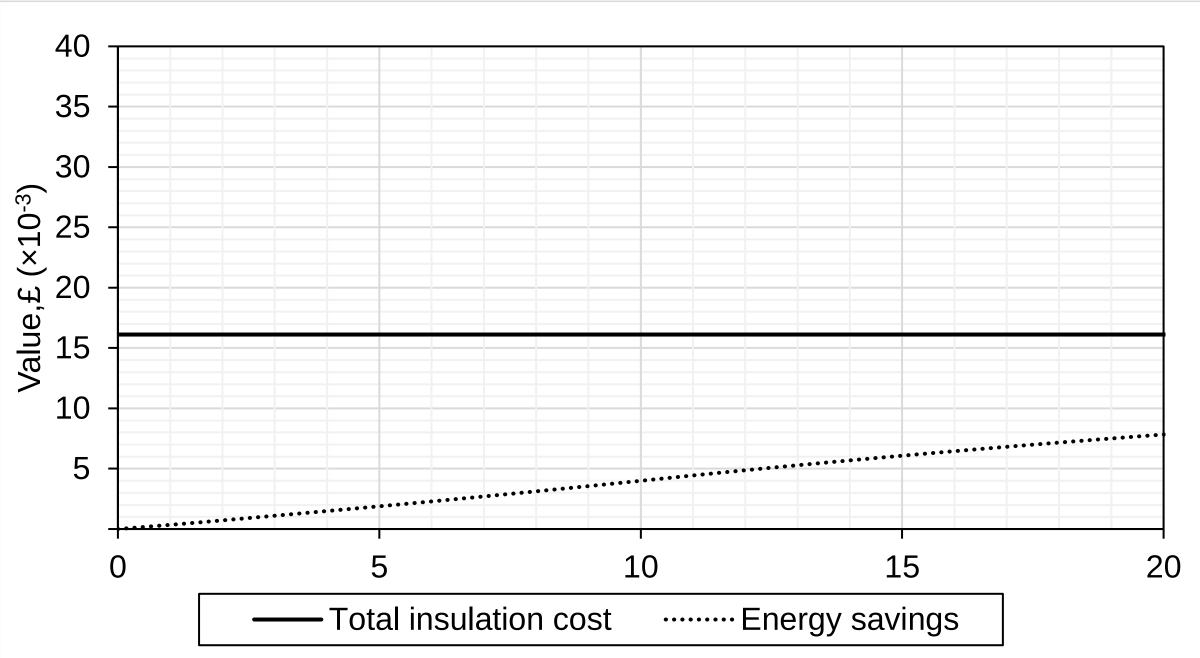


Figure 12. Cost and savings of applying EPS insulation in the 6 storey office building studied

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 £800$m^{-2}$ and £1000$m^{-2}$ 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.

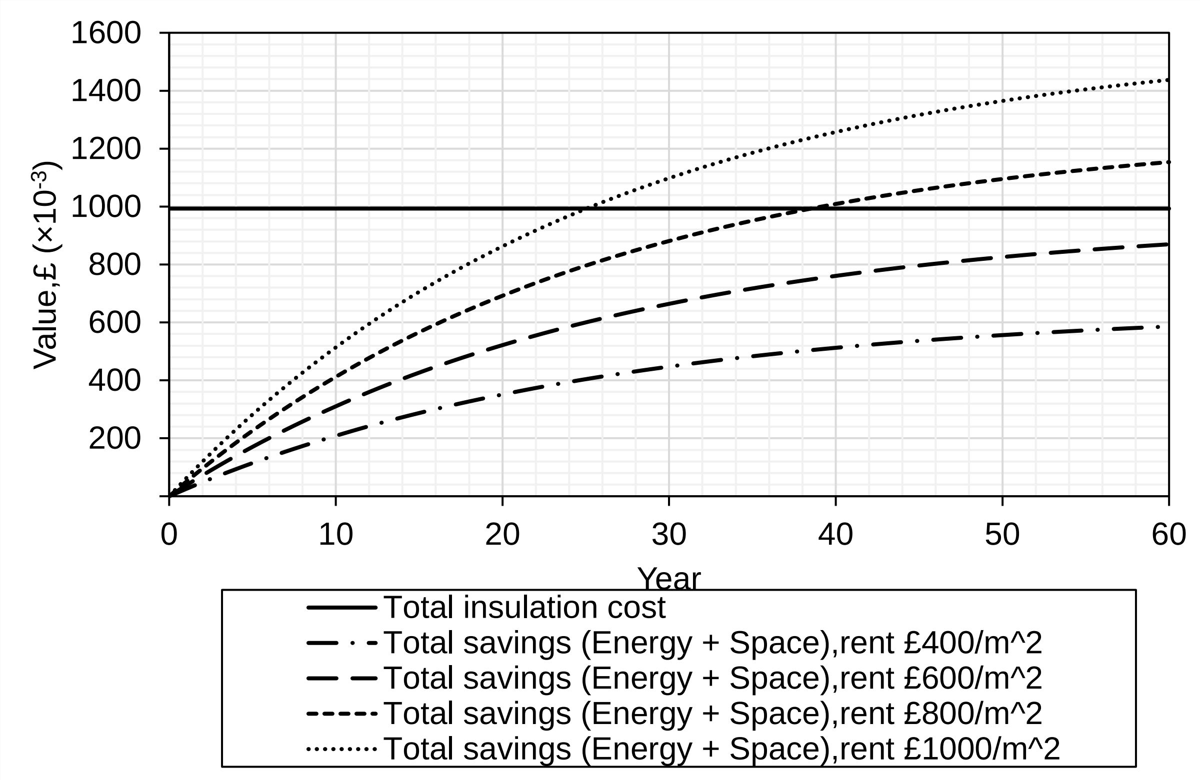


Figure 13. Cost and savings of applying GF VIP insulation in the 6 storey office building studied

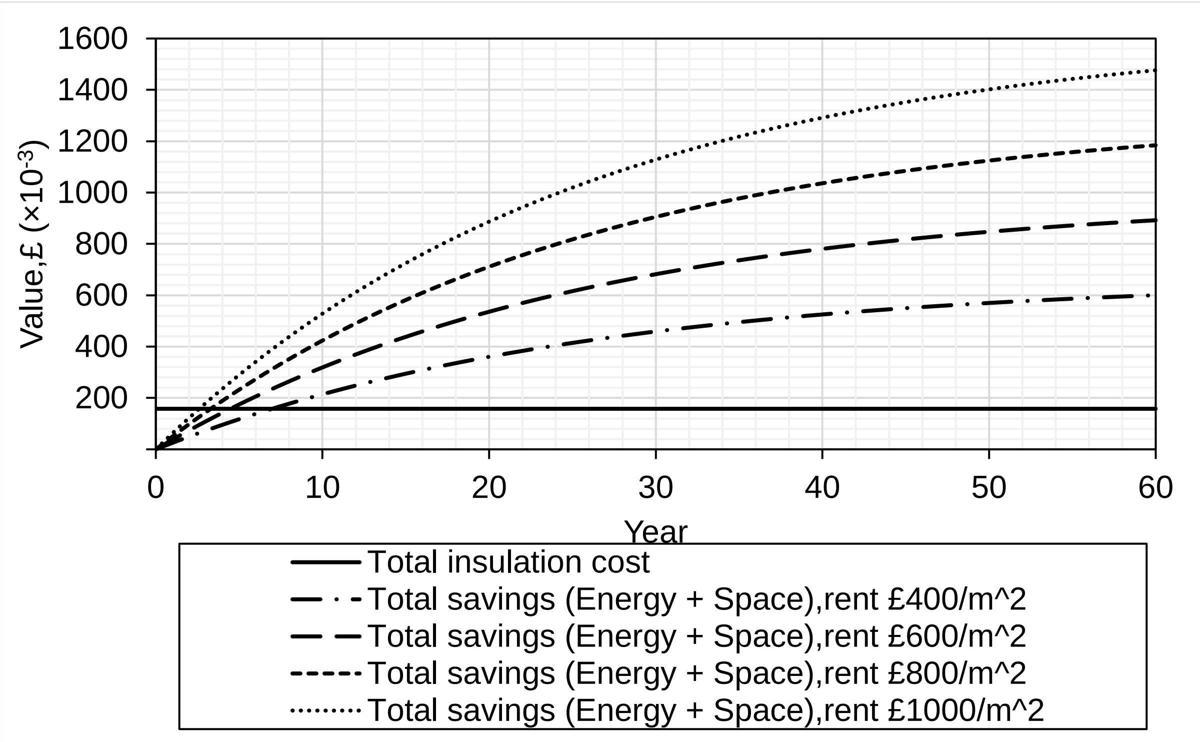


Figure 14. Cost and savings of applying FS VIP insulation in the 6 storey office building studied

## 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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