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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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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,

A handwritten signature in blue ink, appearing to read "Harjit Singh".

Dr. Harjit Singh

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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 $0.020 \text{ Wm}^{-1}\text{K}^{-1}$.”

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.

- 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

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

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4
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13

14 **Abstract**

15 The potential savings in space heating energy from the installation of Fumed Silica
16 (FS) and Glass Fibre (GF) Vacuum Insulation Panels (VIPs) were compared to
17 conventional expanded polystyrene (EPS) insulation for three different non-domestic
18 buildings situated in London (UK). A discounted payback period analysis was used
19 to determine the time taken for the capital cost of installing the insulation to be
20 recovered. VIP materials were ranked using cost and density indexes. The
21 methodology of the Payback analysis carried out considered the time dependency of
22 VIP thermal performance, fuel prices and rental income from buildings. These
23 calculations show that VIP insulation reduced the annual space heating energy
24 demand and carbon dioxide (CO₂) emissions by approximately 10.2%, 41.3% and
25 26.7% for a six storey office building, a two floor retail unit building and a four storey
26 office building respectively. FS VIPs had the shortest payback period among the
27 insulation materials studied, ranging from 2.5 years to 17 years, depending upon the
28 rental income of the building. For GF VIPs the calculated payback period was
29 considerably longer and in the case of the typical 4 storey office building studied its
30 cost could not be recovered over the life time of the building. For EPS insulation the
31 calculated payback period was longer than its useful life time for all three buildings.
32 FS VIPs were found to be economically viable for installation onto non-domestic
33 buildings in high rental value locations assuming a lifespan of up to 60 years.

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

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49	6.2 Four storey office	15
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54

55 **1 Introduction**

56 The combustion of fossil fuels to generate energy is recognised as the major cause
57 of anthropogenic climate change. To mitigate this, the international community has
58 agreed to collectively endeavour to limit global temperature rise to within 1.5°C
59 above pre-industrial levels by reducing emissions of greenhouse gases through the
60 use of cleaner energy sources and increased energy efficiency [1]. In 2013,
61 emissions from space heating energy use in UK buildings accounted for 98 million
62 tonnes of carbon dioxide (CO₂), constituting 17% of total UK greenhouse gas
63 emissions [2]. Energy efficiency requirements for UK buildings are continuously
64 improved through stricter stipulations in the building regulations. The aim is to reduce
65 overall UK CO₂ emissions by at least 80% from the 1990 level by 2050 as set in the
66 Climate Change Act 2008 [3]. With over 60% of the energy consumed in the
67 buildings used for space heating [4], the development of building fabrics with
68 substantially improved insulation properties are essential for the UK to achieve its
69 long term carbon reduction goals.

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

75

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

94
95 Table 1. Core materials other than FS and glass fibre reported in previous studies
96

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]

97
98 Published research on the materials listed in table 1 have primarily focused on the
99 thermo-physical performance of VIPs neglecting the potential for energy savings and
100 the associated economic analysis. Cho et al. [21], Alam et al. [10] and Tenpierik [22]
101 published economic analysis of VIPs but only considered domestic building
102 applications. Kucukpinar et al. [11] demonstrated that VIP insulation reduced annual
103 energy consumption by 25% for two mock-up rooms situated in Poland and Spain.
104 Mujeebu et al. [23] predicted using ECOTECT software that VIPs fixed to the roof
105 and external walls would reduce annual energy consumption by 0.62% for a single
106 office building and 0.79% for a multi-storey office building compared to EPS.

107 Clearly, the energy saving potential of VIPs is dependent on the type of building and
108 its location (climatic and economic factors) thus further research to clarify the energy
109 saving potential of VIPs is required. Mujeebu et al. [24] predicted the simple payback
110 period of VIPs to be 5.3 times longer than that of EPS if installed in a multi-storey
111 office building in Saudi Arabia. The, simple payback method used by Mujeebu et al.
112 [24], did not consider the impact on energy savings from the deterioration of the VIP
113 thermal performance with time, the economic value of space savings due to thinner
114 section of VIPs and the varying time value of money. These factors significantly
115 influence payback periods and must be considered to enable a more accurate
116 calculation to be made of the cost effectiveness of VIPs compared to other insulation
117 materials.

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

130 **2 Cost and density indices for VIP types**

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

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

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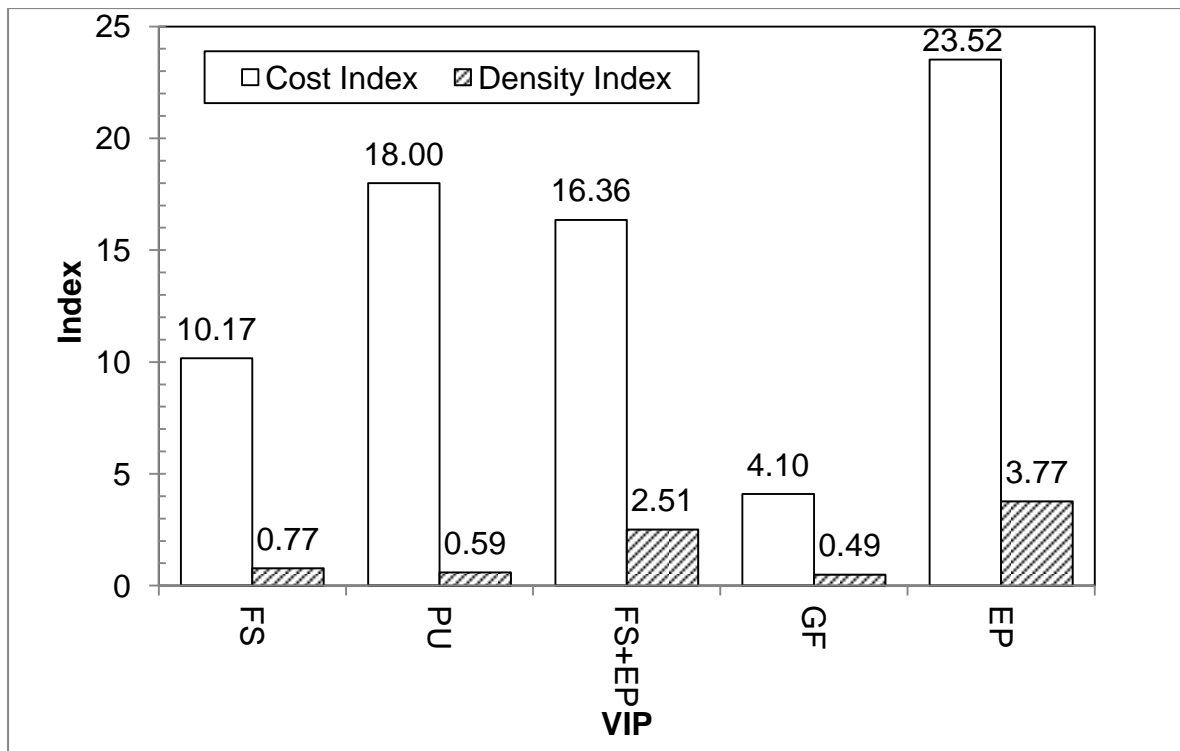
Table 2. Cost and main physical properties of different types of VIPs

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

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

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

153



154

155

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

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

166 **3 Payback period calculation**

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

$$178 \quad POI = \left[\frac{86400 \times HDD \times \Delta L \times C_F}{H_v \times \left(\frac{\eta_i - x \times n}{100} \right)} \times \frac{1}{(1+r)^n} \right] + \left[Y \times \Delta d \times 2 \{ (L_f + \Delta d) + (W_f + \Delta d) \} \times \frac{1}{(1+r)^n} \right] -$$

$$179 \quad [C_{Mt} + C_M + C_I] \quad (1)$$

181 where

182 C_{Mt} is the material cost of VIP core and envelope (£)

183 C_M is the manufacturing cost of VIP (£)

184 C_I is the installation cost of VIP (£)

185 HDD is the heating degree days (°C days)

186 C_F is the cost of fuel (£m⁻³)

187 H_v is the calorific value of fuel (Jm⁻³)

188 η_i is the initial thermal efficiency of the heating system, boiler (%)

189 x is the annual rate of decrease of thermal efficiency of heating boiler (%)

190 ΔL is the difference of total building transmission heat loss coefficient (L) before and
 191 after applying insulation (WK⁻¹)

192 n is the number of year

193 r is the annual discount rate (% fraction)

194 Y is the annual rental value (£m⁻²)

195 A_s the floor area saved (m^2)
 196 F is the number of floors
 197 Δd is the difference in thickness of conventional insulation and VIP insulation (m)
 198 L_f is the length of internal floor (m)
 199 W_f is the width of the internal floor (m)

200
 201 Total building transmission heat loss coefficient (L) is described as equation (2)

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

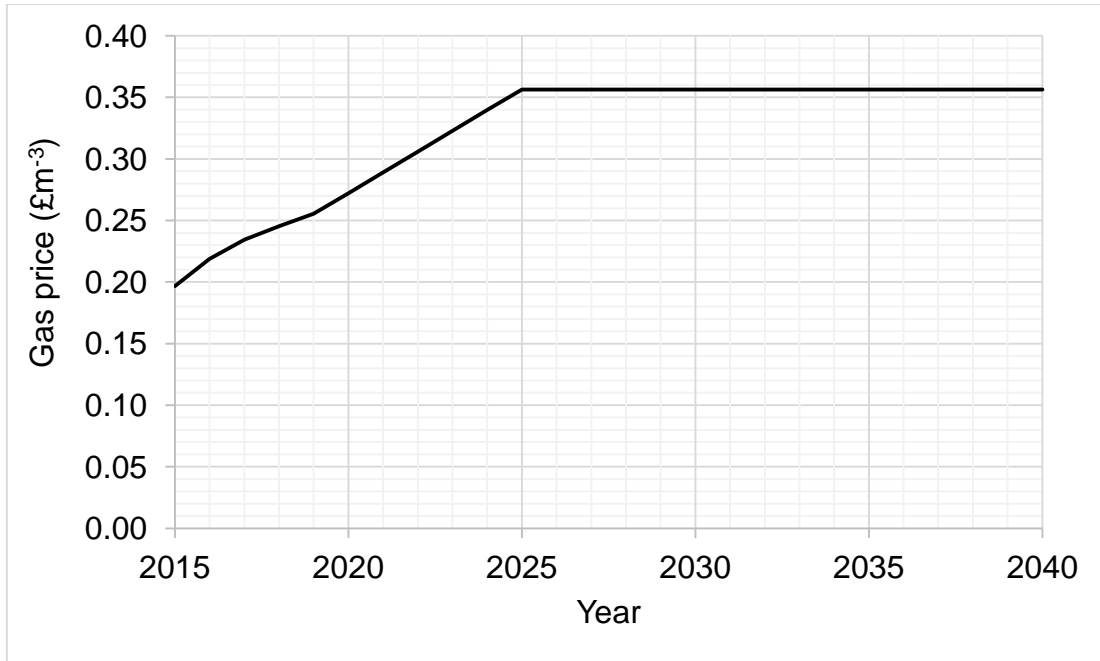
202 where

203 A_i is the insulated area of the building element i (m^2)
 204 U_i is the U-value of the building element i ($Wm^{-2}K^{-1}$)
 205 I is the air exchange rate per hour (ach^{-1})
 206 V is the internal volume of the building (m^3)
 207 $(\rho c_p)_{air}$ is the volumetric thermal capacity of air ($Jm^{-3}K^{-1}$) taken as $1200 Jm^{-3}K^{-1}$.
 208 Hence, the equation (2) can be rewritten as

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

209
 210 In equation (3), term $\frac{IV}{3}$ is the ventilation conductance (WK^{-1}) [28].

211
 212 The different parameters used for calculating the discounted payback period analysis
 213 presented in this study are detailed in table 3. The long term price forecast reported
 214 by the UK Department of Energy and Climate Change [29] for natural gas which is
 215 shown in figure 2 and extrapolated for the assumed life time of the buildings under
 216 investigation was used to calculate space heating energy savings
 217 The HDD data used to determine energy consumption for space heating was the 5
 218 year average (2011 to 2015) for a base temperature of $15.5^\circ C$ for St. James Park
 219 London [30]. Gas condensing boilers are assumed to suffer from an annual fall in
 220 their thermal efficiency by 0.5% with a useful lifespan of 20 years. The installation
 221 cost was assumed to be the same for all VIP types investigated so was not included
 222 in the calculations.
 223
 224
 225



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Figure 2. Gas price forecast [29]

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Table 3. Parameters used for payback period calculation

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232

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

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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.

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246

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

247 where

248 U is the thermal transmittance ($\text{Wm}^{-2}\text{K}^{-1}$)

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

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

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

252

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

258

$$259 \quad U(t) = \frac{1}{R_{si} + (\sum R_e) + R_{vip}(t) + R_{sx}} \quad (5)$$

260 where

261 $R_{vip}(t)$ is the time dependent thermal resistivity of the VIP layer in a building element
262 and calculated using equation (6):

$$263 \quad R_{vip}(t) = \frac{d_{vip}}{\lambda_{vip}(t)} \quad (6)$$

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

266 For the U-value calculations used by this research, design thermal conductivity
267 values of $0.008 \text{ Wm}^{-1}\text{K}^{-1}$, $0.007 \text{ Wm}^{-1}\text{K}^{-1}$ and $0.035 \text{ Wm}^{-1}\text{K}^{-1}$ were used for FS VIP,
268 GF VIP and EPS respectively. For FS VIPs and GF VIPs the annual increase in
269 thermal conductivity was assumed as $0.0001 \text{ Wm}^{-1}\text{K}^{-1}\text{a}^{-1}$ [31] and 0.0018
270 $\text{Wm}^{-1}\text{K}^{-1}\text{a}^{-1}$ respectively [26].

271

272 **4 Details of the non-domestic buildings investigated**

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

277 The two floor retail unit building is representative of 10% of the current retail building
278 stock in the UK by age of construction (1989-90) and 13% by floor area ($250\text{-}500 \text{ m}^2$)
279 [32]. The four storey office building type accounts for 9% of the office building stock
280 in the UK by age of construction (1981-85) and 20% by floor area ($2500\text{-}10,000\text{m}^2$)
281 [32]. The six storey office building accounts for 11% of the office building stock in the
282 UK by age of construction (1986-90) and 20% by floor area ($2500\text{-}10,000\text{m}^2$) [32].

283 Table 4 shows the relevant details for each of the buildings investigated. Each
284 building was assumed as refurbished to current building regulation standards by
285 applying internal insulation on all opaque elements achieving U-values of $0.30 \text{ Wm}^{-2}\text{K}^{-1}$,
286 $0.18 \text{ Wm}^{-2}\text{K}^{-1}$ and $0.25 \text{ Wm}^{-2}\text{K}^{-1}$ for wall, roof and floor respectively [33]. Table 4
287 shows U-values before and after applying insulation on all buildings considered in
288 the study along with their thickness values. It was assumed that VIPs covered 95%
289 of the opaque elements with phenolic foam insulation covering the remaining 5%.

290 The thermal conductivity of the Phenolic foam used was assumed as of $0.020 \text{ Wm}^{-1}\text{K}^{-1}$.

291

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

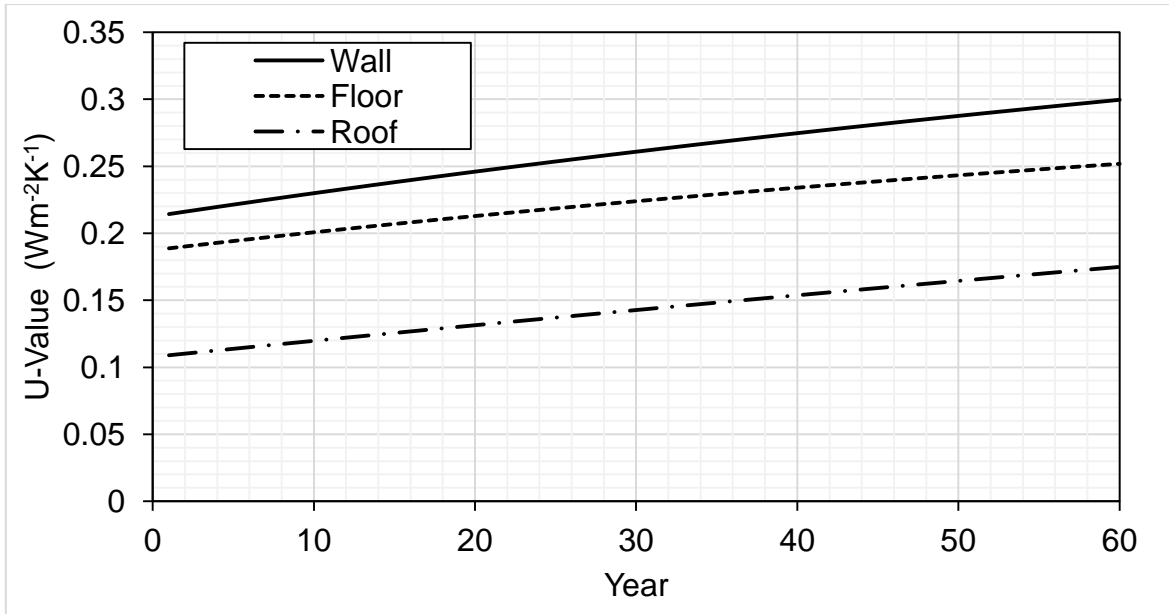
Building	Parameter	Wall	Floor	Roof
Retail Unit	Existing U-value ($\text{Wm}^{-2}\text{K}^{-1}$)	0.65	0.46	0.96
	U-value after applying insulation ($\text{Wm}^{-2}\text{K}^{-1}$)	0.30	0.25	0.18
	FS VIP Thickness (mm)	25	25	65
	GF VIP Thickness (mm)	40	40	110
	EPS Thickness (mm)	60	65	155
4 Storey Office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

294 **5 Space heating energy saving potential**

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

299
$$E_A = \frac{86400 \times HDD \times \Delta L}{H_v \times \left(\frac{\eta_i - x \times n}{100} \right)} \quad (7)$$

300 The building transmission heat loss coefficient (L) incorporates the U-values of all
 301 building elements. In the case of applying VIP insulation the U-value varies with time
 302 and can be calculated using equations (5) and (6). The time dependent U-values of
 303 the wall, floor and roof of the retail unit building insulated with VIPs is shown in figure
 304 3.
 305



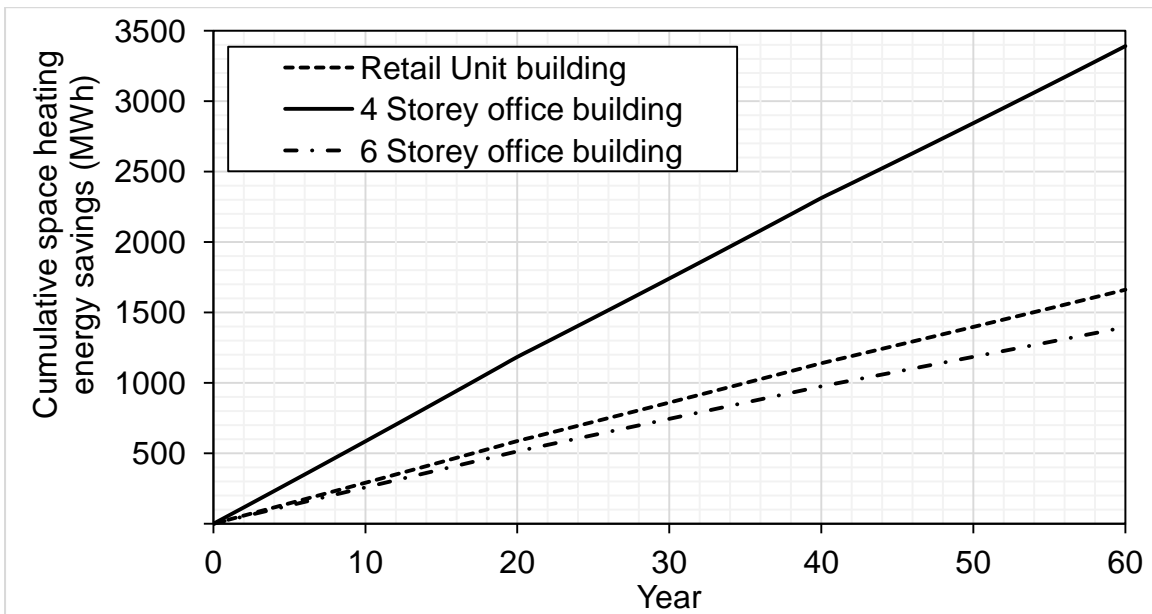
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307 Figure 3. Time dependent U-values of VIP insulated wall, floor and roof of the two
 308 floor retail unit building studied
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311 Applying VIP insulation reduced the U-value of building elements, as shown in table
 312 4, saving space heating energy. The energy saved over the assumed 60 year life
 313 time of the three buildings considered is shown in figure 4.

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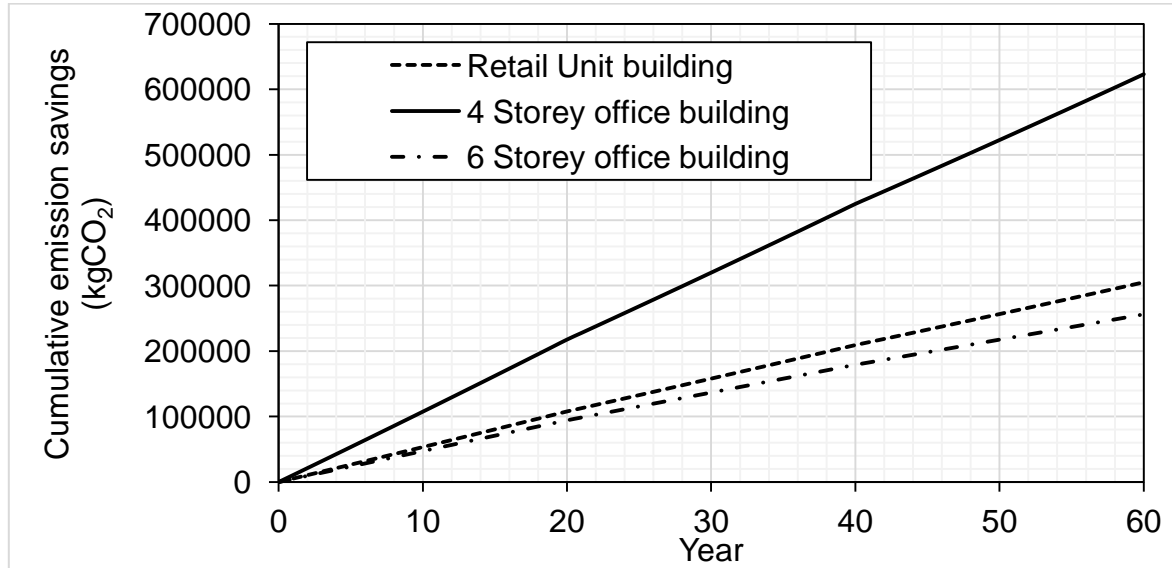
315

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

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319 Using the parameters outlined previously in table 4 over the assumed building life
 320 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

321 reduction in CO₂ emissions was calculated using a fuel emission factor of 0.18365
 322 kgCO₂/kWh [34] and shown in figure 5. Use of VIPs was calculated to potentially
 323 reduce CO₂ emissions by 10.2%, 41.3% and 26.7% respectively for six storey office
 324 building, retail unit building and four storey office building.
 325



326 Figure 5. Reduction in CO₂ emissions for three buildings studied
 327

328 6 Payback period results

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

332 6.1 Two floor retail unit

333 Geometric and thermal features of the buildings studied are shown in table 5. The
 334 wall, floor and roof U-values are shown in table 4.

335 The cost of installing sufficient EPS for achieving current building insulation
 336 standards could not be recovered within its lifetime, see figure 6. For EPS, no space
 337 saving revenue is possible, which means that investments are solely recovered
 338 through fuel cost savings. Also, EPS due to a comparatively shorter service life of 20
 339 years requires replacement three times over an assumed 60 year building life span
 340 leading to a higher insulation cost. A life span of 60 years for building was assumed
 341 to match the

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 343

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345

346 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

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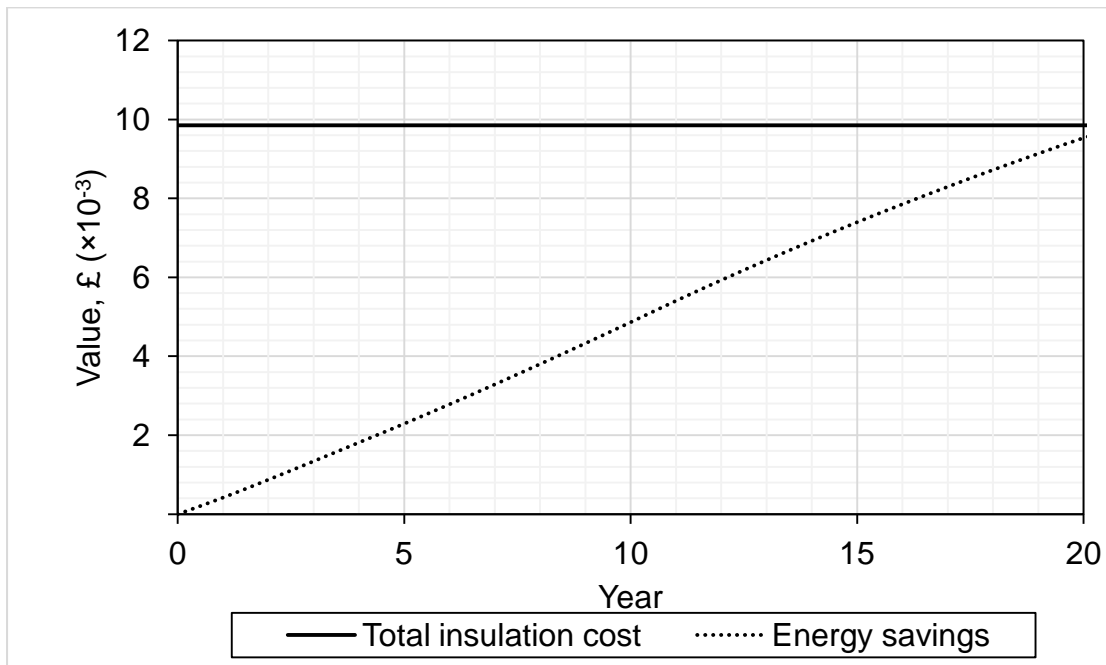
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prescribed life span of VIPs used for buildings in the UK. In the case of VIPs, the additional benefit of commercial space saving can partially offset higher initial insulation costs. The Results of payback period analysis for two different types of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



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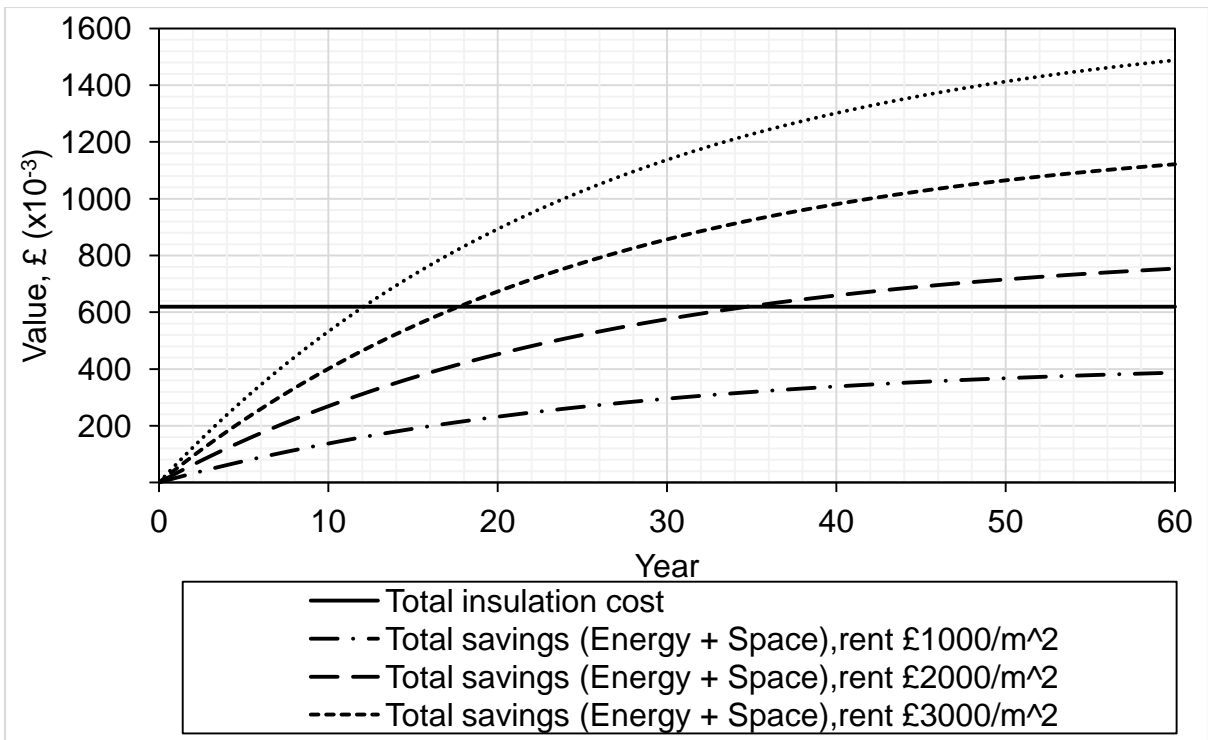
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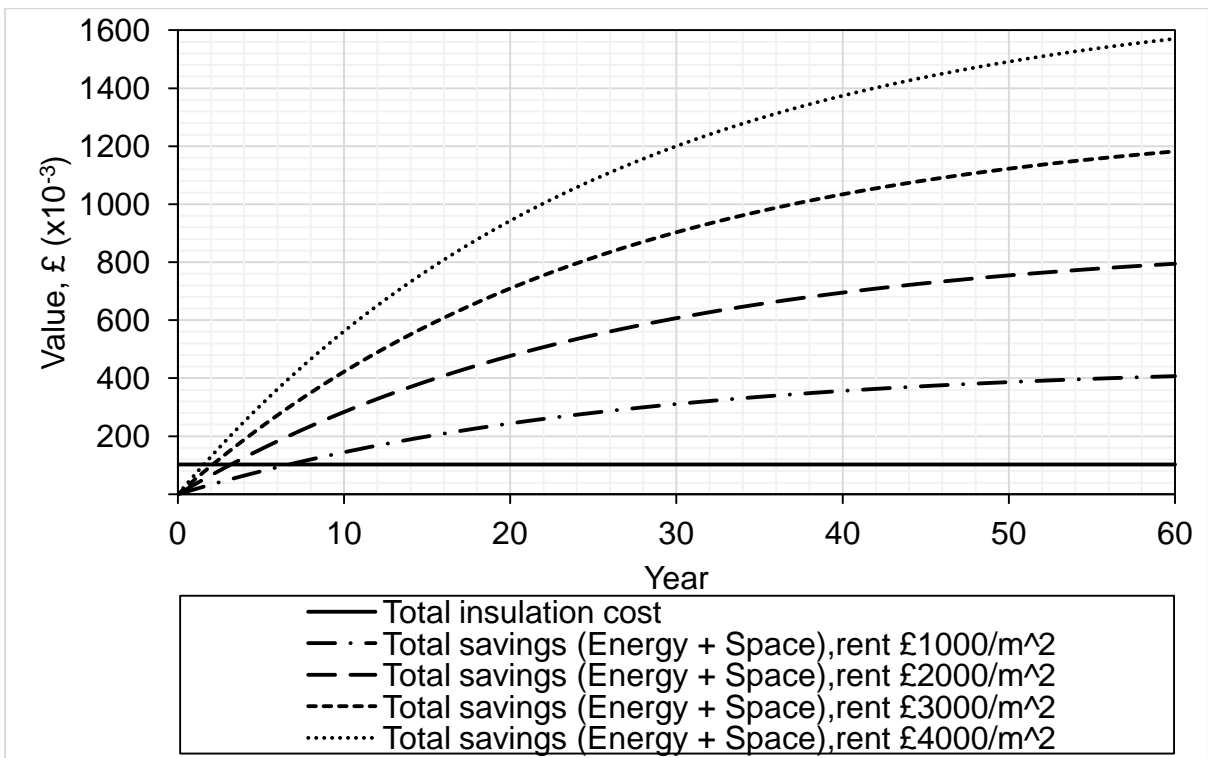
Figure 6. Cost and savings of applying EPS insulation in a retail unit building

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



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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

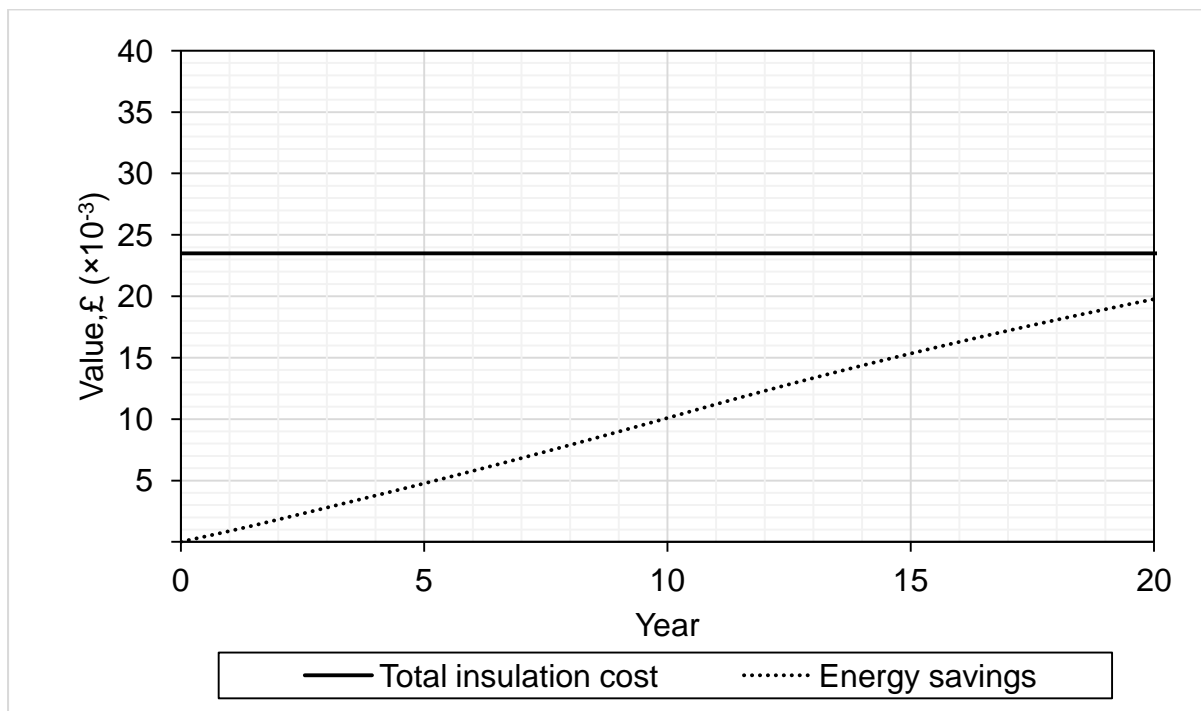
373 £2000 m⁻² and £3000 m⁻² the discounted payback period was 35 years and 18 years
 374 respectively for GF VIP and 4 years and 3 years for FS VIP. For average rental value
 375 of £4000 m⁻² payback period of FS VIP becomes approximately 2 years, whereas it
 376 is still prohibitively longer (12 years) for GF VIPs.

377 6.2 Four storey office

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

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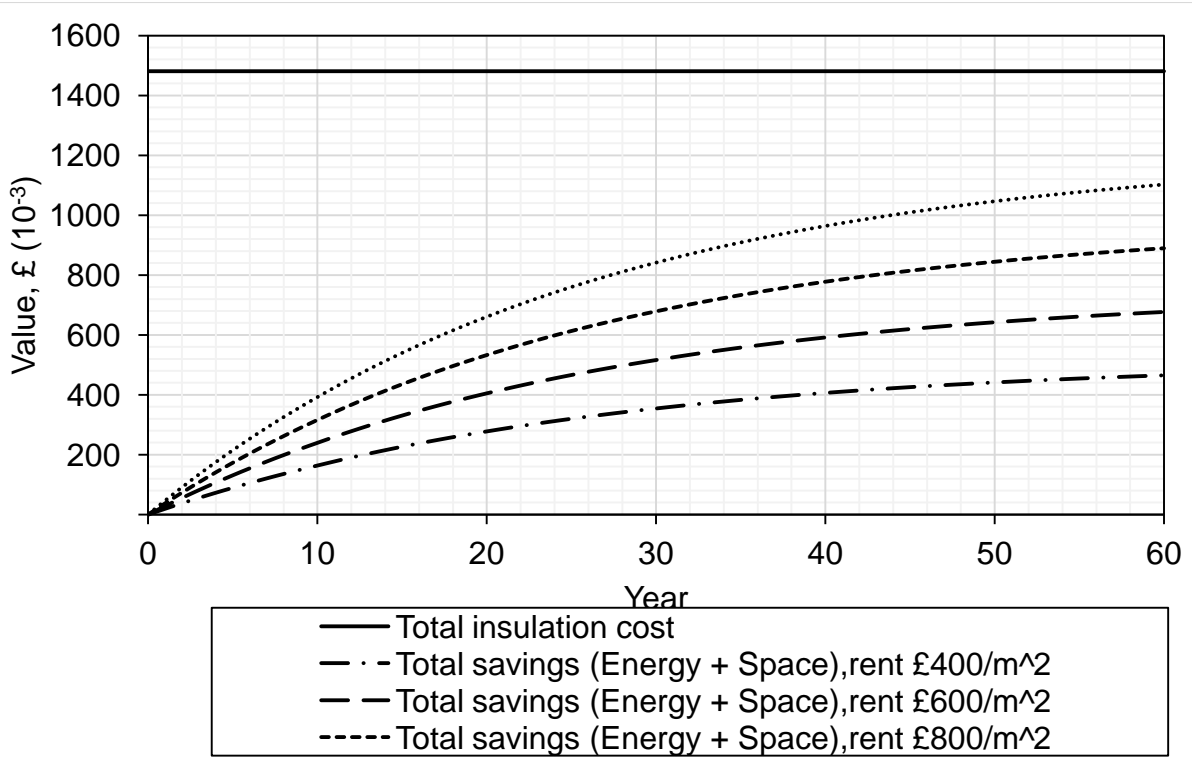
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385 Figure 9. Cost and savings of applying EPS insulation in the 4 storey office building
 386 studied

387 Figure 9 demonstrates that EPS insulation cannot recover the initial capital cost over
 388 its life time of 20 years. For GF VIPs the cost of insulation cannot be recovered over
 389 the life time of building as shown in figure 10 even with the additional economic
 390 benefits from space saving with average annual floor rents ranging from £400 m⁻² to
 391 £1000 m⁻² [36]. As discussed in section 6.1, the reason for long payback period for
 392 GF VIPs is their short service life (10 years) requiring replacement six times during
 393 60-year life time of the building.

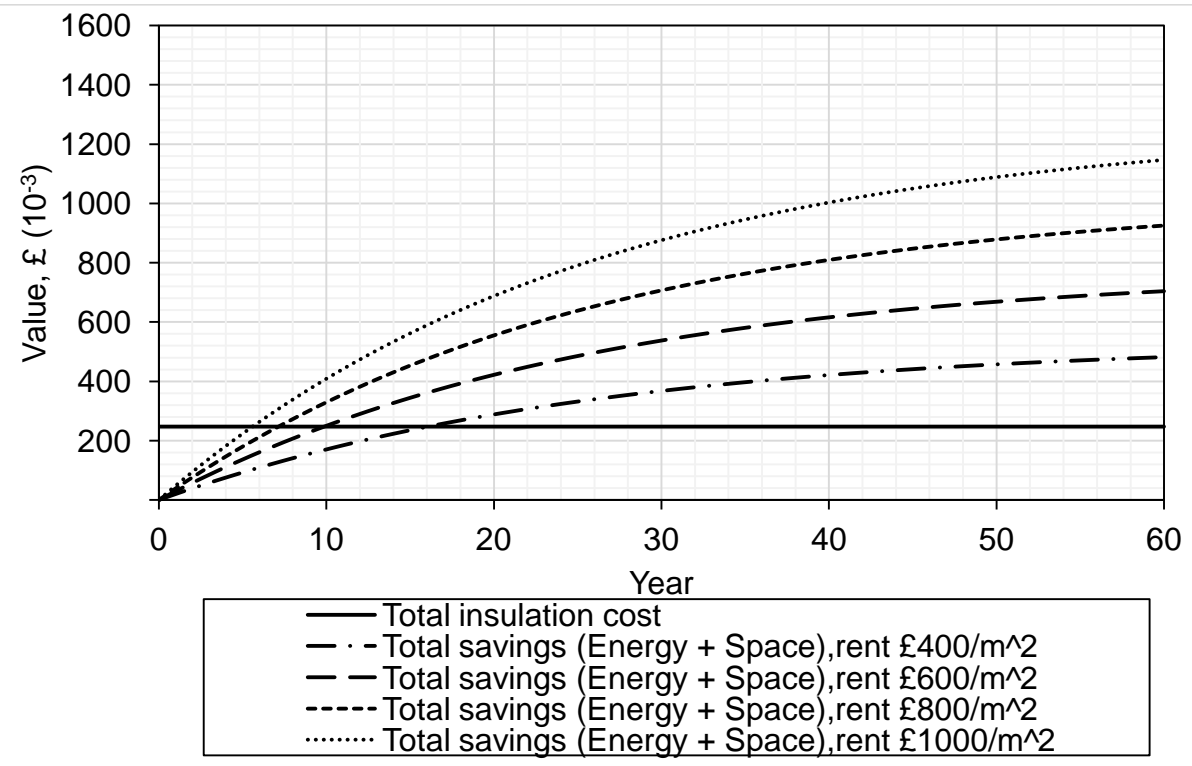


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Figure 10. Cost and savings of applying GF VIP insulation in the 4 storey office building studied

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

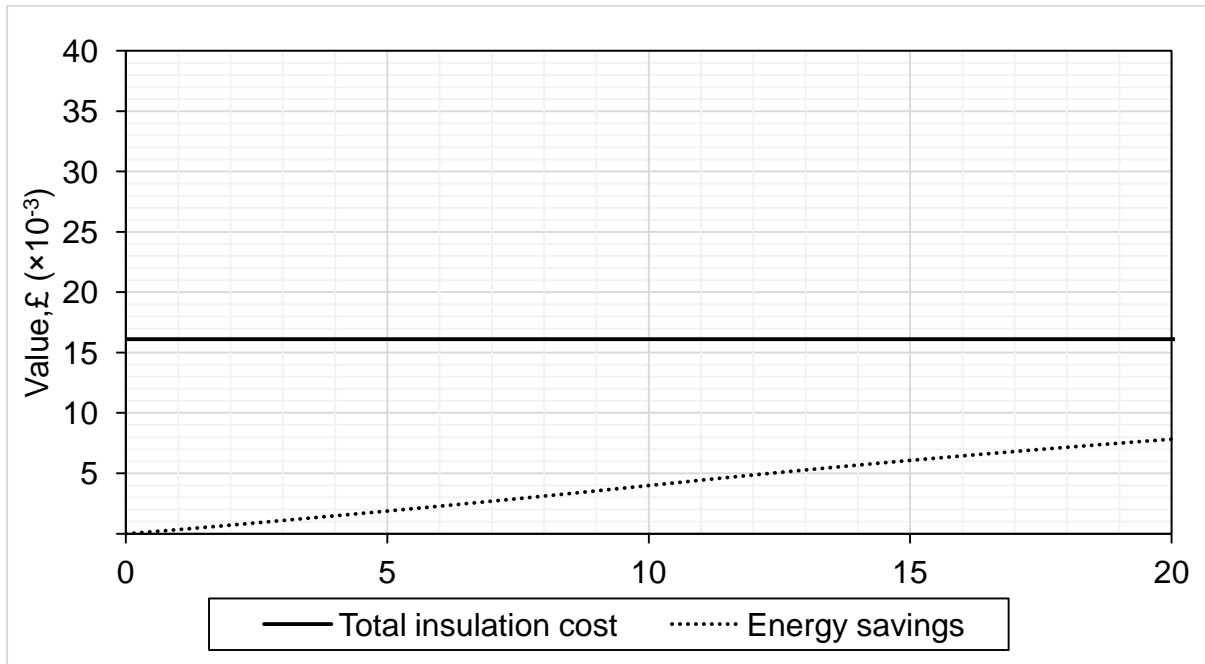
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400 From figure 11, it can be seen that upgrading the 4 storey office with FS VIP
 401 insulation to comply with current building regulations resulted in payback periods of
 402 17 years, 10 years, 7 years and 6 years for rental values of £400 m⁻², £600 m⁻², £800
 403 m⁻² and £1000 m⁻² respectively.

404 **6.3 Six storey office**

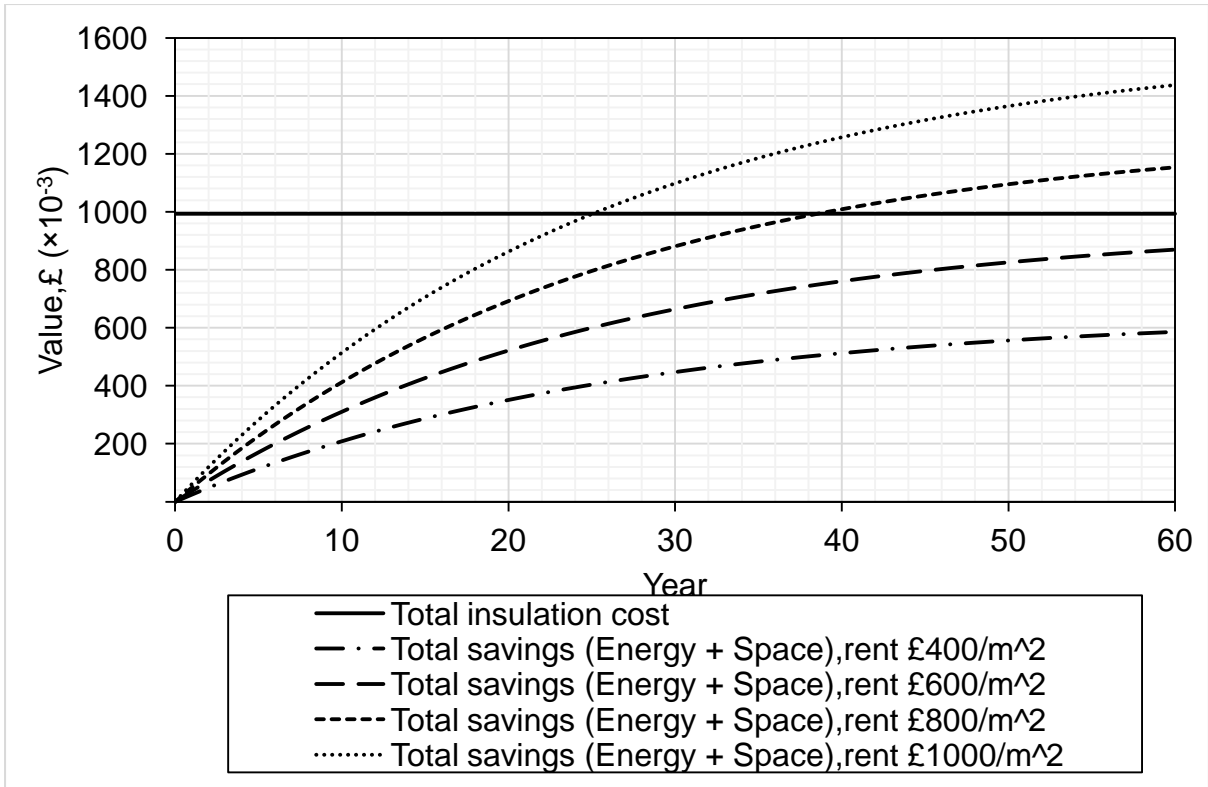
405 Geometric and thermal features of the six storey office are detailed in table 4 and
 406 table 5. Results of the discounted payback period analysis for the six storey office
 407 building are shown in figures 12 to 14.
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 410 Figure 12. Cost and savings of applying EPS insulation in the 6 storey office building
 411 studied

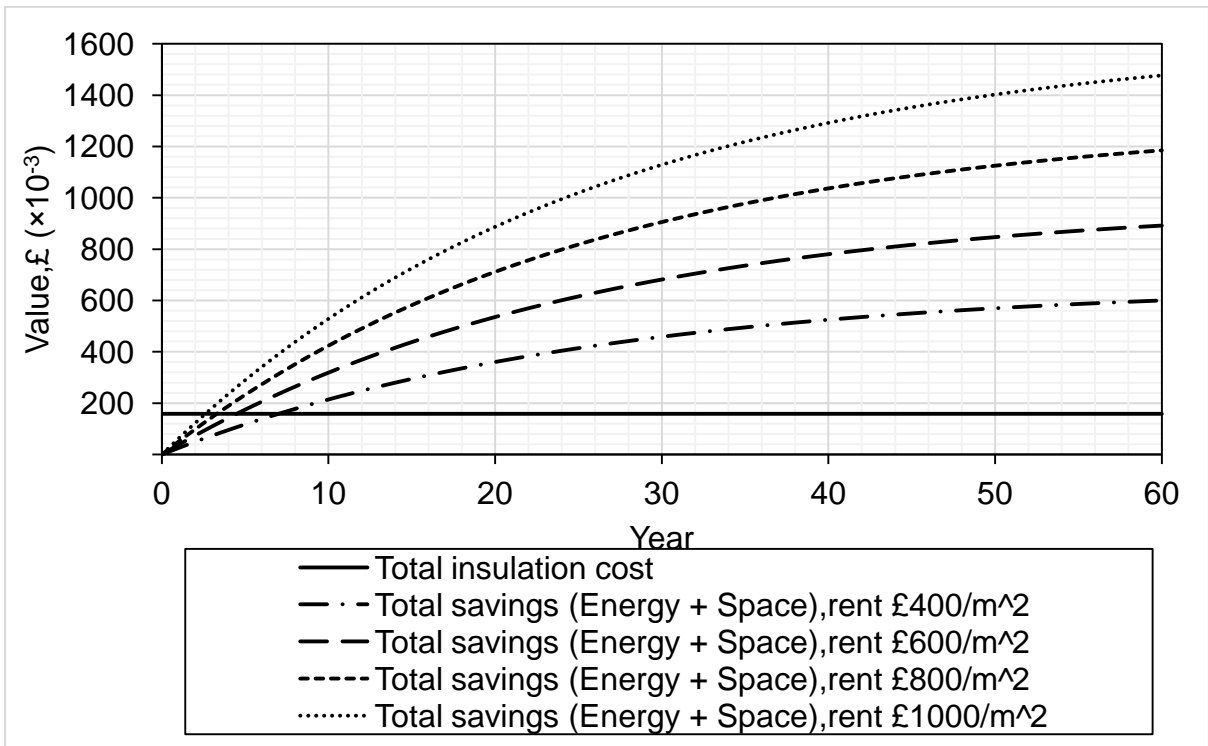
412 Figure 12 shows that EPS insulation had a discounted payback period longer than its
 413 assumed life time of 20 years. It can be seen from figure 13 that in the case of GF
 414 VIP, the cost of insulation cannot be recovered with average annual rent of £400 m⁻²
 415 and £600 m⁻². For higher annual rents of £800m⁻² and £1000m⁻² payback periods of
 416 respectively 39 years and 25 years are predicted. It is clearly observed, from figure
 417 14, that FS VIPs had a shorter payback period than EPS or GF VIPs. FS VIP was
 418 found to have a payback period of 7 years, 5 years, 3 year and 2.5 years with rental
 419 values of £400 m⁻², £600 m⁻², £800 m⁻² and £1000 m⁻² respectively. These results
 420 clearly show that FS VIPs are economically viable to be used in high-rise office
 421 buildings despite their higher initial cost and decreasing thermal performance over
 422 service life.

423



424

425 Figure 13. Cost and savings of applying GF VIP insulation in the 6 storey office
 426 building studied
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 429

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

432 **7 Conclusions**

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

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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 (CO₂) 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 ~~at 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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40 in high rental value locations ~~due to their better performance over a longer~~ assuming
41 a lifespan of up to 60 years.

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

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52 **Contents**

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79 | **1 Introduction**

80 | ~~Use~~The combustion of fossil fuels ~~have been~~to generate energy is recognised as the
81 | major cause of ~~the current trend of~~anthropogenic climate change ~~and~~. To mitigate
82 | ~~this, the~~ international community has ~~recently~~ agreed to collectively endeavour to
83 | limit global temperature rise to within 1.5°C above pre-industrial levels ~~[1]~~by
84 | ~~reducing emissions of greenhouse gases through the use of cleaner energy sources~~
85 | ~~and increased energy efficiency [1]~~. In 2013, emissions from space heating energy
86 | use in UK buildings accounted for 98 million tonnes of carbon dioxide (CO₂),
87 | ~~constituting~~ 17% of total UK greenhouse gas emissions [2]. Energy efficiency
88 | requirements for UK buildings are ~~being~~continuously improved through ~~stricter~~
89 | ~~stipulations in the~~ building regulations. ~~The aim is~~ to ~~assist in reducing~~reduce overall
90 | UK CO₂ emissions by at least 80% from the 1990 level by 2050 as set in the Climate
91 | Change Act 2008 [3]. With over 60% of the energy consumed in ~~buildings used for~~
92 | ~~space heating [4], building envelopes with the lowest U-value are critical for the UK~~
93 | ~~to achieve its long term carbon reduction goals. However, to achieve the lowest U-~~
94 | ~~value, either a prohibitively thick layers of conventional insulation, which may not be~~
95 | ~~feasible in existing and new buildings, or advanced insulation material such as~~
96 | ~~Vacuum Insulation Panel (VIP) are needed. VIPs offer thinner alternative due to their~~
97 | ~~thermal resistance potentially being 5-8 times higher than the conventional insulation~~
98 | ~~[5,6,7,8]. VIP is produced as a rigid panel made of evacuated inner core board~~
99 | ~~laminated in an outer barrier envelope. VIPs can be applied in buildings on external~~
100 | ~~or internal surfaces of walls, on ceiling or roof, ground floor, door and window frames~~
101 | ~~and on hot water cylinders~~the buildings used for space heating [4], the development
102 | ~~of building fabrics with substantially improved insulation properties are essential for~~
103 | ~~the UK to achieve its long term carbon reduction goals.~~

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

110 |
111 | ~~A VIP is a composite rigid sheet comprising an evacuated (pressure ≤0.5 mbar)~~
112 | ~~inner core board laminated inside an outer barrier envelope [10]. VIPs can be~~
113 | ~~installed on opaque building surfaces (externally or internally) and on hot water~~

114 storage cylinders to improve their thermal resistance. For façade applications,
 115 transparent insulation materials [11,12] are under development.
 116 In 2014, only 10% of the VIPs currently produced are production were used infor
 117 insulating buildings with, refrigeration and transportation industry were the main
 118 users of this technology consuming 30% and 60% of the annual production of VIPs
 119 respectively 60% and 30% [9]. Uptake[13]. The uptake of VIPs in the buildingsfor
 120 building applications has not achieved its full potential due to their high installed cost-
 121 compared with other insulation products. Presently their, VIP use can only be
 122 justified in a few construction scenarios such as difficult to insulate buildings on
 123 account of their; for example, heritage status and narrow city centre buildings with
 124 unique architectural features or limited usable indoor space. High
 125 The high cost of VIPs is caused by the materials used in VIP production and it is of
 126 utmost importance to develop low cost due to the materials which can be used to
 127 produce in VIPs having equal or better thermal performance. Bulk of the required for
 128 manufacturing, necessitating the development of lower cost core and envelope
 129 materials with similar or improved thermal insulation properties than those currently
 130 in use. Previous research work considered expensive fumed silica as VIP core
 131 material for building applications on VIP core materials has focused mainly on Fumed
 132 Silica (FS) due to its suitable excellent thermo-physical properties, for example, Singh
 133 et al. (2015) [10]. Several studies have reported investigations into various core
 134 materials, such as Melamine-formaldehyde fibre fleece [11], expanded perlite and
 135 fumed silica composite [12], open pore melamine formaldehyde foam [13], granular
 136 silica [14], phenolic foam [15], achieving initial centre of panel thermal conductivity
 137 values of 0.0023 Wm⁻¹K⁻¹, 0.0074 Wm⁻¹K⁻¹, 0.006 Wm⁻¹K⁻¹, 0.014 Wm⁻¹K⁻¹ and 0.005
 138 Wm⁻¹K⁻¹ respectively. However, these studies have restricted themselves to scientific
 139 investigations whilst [14]. But, FS is expensive and several studies, as shown in
 140 table 1, have proposed alternative core materials.

141
 142 Table 1. Core materials other than FS and glass fibre reported in previous studies
 143

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

144

145 Published research on the materials listed in table 1 have primarily focused on the
146 thermo-physical performance of VIPs neglecting the potential for energy savings and
147 the associated economic analysis of VIPs has been largely overlooked with few
148 exceptions such as. Cho et al. (2014) [16][21], Alam et al. (2011) [17][10] and
149 Tenpierik (2009) [18], though these three studies have only covered [22] published
150 economic analysis of VIPs but only considered domestic buildings–building
151 applications. Kucukpinar et al. [11] demonstrated that VIP insulation reduced annual
152 energy consumption by 25% for two mock-up rooms situated in Poland and Spain.
153 This paper reports the most comprehensive and realistic Mujeebu et al. [23] predicted
154 using ECOTECH software that VIPs fixed to the roof and external walls would reduce
155 annual energy consumption by 0.62% for a single office building and 0.79% for a
156 multi-storey office building compared to EPS.
157 Clearly, the energy saving and economic potential of VIPs is dependent on the type
158 of building and its location (climatic and economic factors) thus further research to
159 clarify the energy saving potential of VIPs is required. Mujeebu et al. [24] predicted
160 the simple payback analysis of VIPs when used in period of VIPs to be 5.3 times
161 longer than that of EPS if installed in a multi-storey office building in Saudi Arabia.
162 The, simple payback method used by Mujeebu et al. [24], did not consider the impact
163 on energy savings from the deterioration of the VIP thermal performance with time,
164 the economic value of space savings due to thinner section of VIPs and the varying
165 time value of money. These factors significantly influence payback periods and must
166 be considered to enable a more accurate calculation to be made of the cost
167 effectiveness of VIPs compared to other insulation materials.
168 The objective of this paper is to calculate the payback period of VIPs through a
169 discounted economic analysis whilst simultaneously accounting for the other
170 identified factors which affect it. To investigate this, an energy saving and economic
171 payback analysis of FS and GF VIPs installed on three representative
172 non-domestic non-domestic buildings situated in London (UK) was undertaken. A
173 novel methodology has been developed which is able to take into account which
174 considered the change of VIP thermal performance with over time, fuel price
175 variability, heating system efficiency degradation with time as well as and the
176 money economic value of space savings resulting realised from using comparatively
177 thinner VIPs. was developed. No such information currently exists in the peer
178 reviewed literature. Realistic cost Cost and density indices linked with to the thermal
179 conductivity of FS and GF VIPs were calculated and presented. Payback. The
180 discounted payback period for VIPs has been was then compared with to that of
181 conventional expanded polystyrene (EPS) insulation in order, to assess their
182 comparative the cost effectiveness of each.

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183 2 Cost and density indices for VIP types

184 VIPs are typically classified based on by the type of main core materials used for in
185 their manufacturing, which includes fumed silica (FS), expanded perlite (EP), FS
186 and EP composites (FS+EP), glass fibre (GF) and polyurethane foam (PU) along

187 with opacifiers, getters and desiccants. VIPs with ~~different~~diverse core materials
 188 have ~~varying~~different expected life ~~times~~times, which determines their suitability for a
 189 specific ~~application~~. ~~Cost~~applications. The ~~cost~~ of ~~VIP~~ core ~~materials~~ can account for
 190 ~~up to 40-45%~~ of the total ~~VIP~~ cost. ~~Table 1 shows the price, initial centre of panel~~
 191 ~~thermal conductivity (λ) (thermal conductivity at the time of manufacturing at centre~~
 192 ~~of panel), design thermal conductivity (thermal conductivity including the thermal~~
 193 ~~bridging effect and ageing effect) and density of VIPs made with different core~~
 194 ~~materials~~cost.
 195 ~~Cost~~The price, initial (measured at the time of ~~VIPs~~ can be linked with their main
 196 ~~physical properties such as manufacturing~~ centre of panel thermal conductivity (λ)
 197 ~~design thermal conductivity (thermal conductivity including the thermal bridging effect~~
 198 ~~and ageing effect) and density~~ to compare performance of ~~VIPs made with~~ different
 199 ~~types of VIPs. For this~~core materials are shown in table 2.

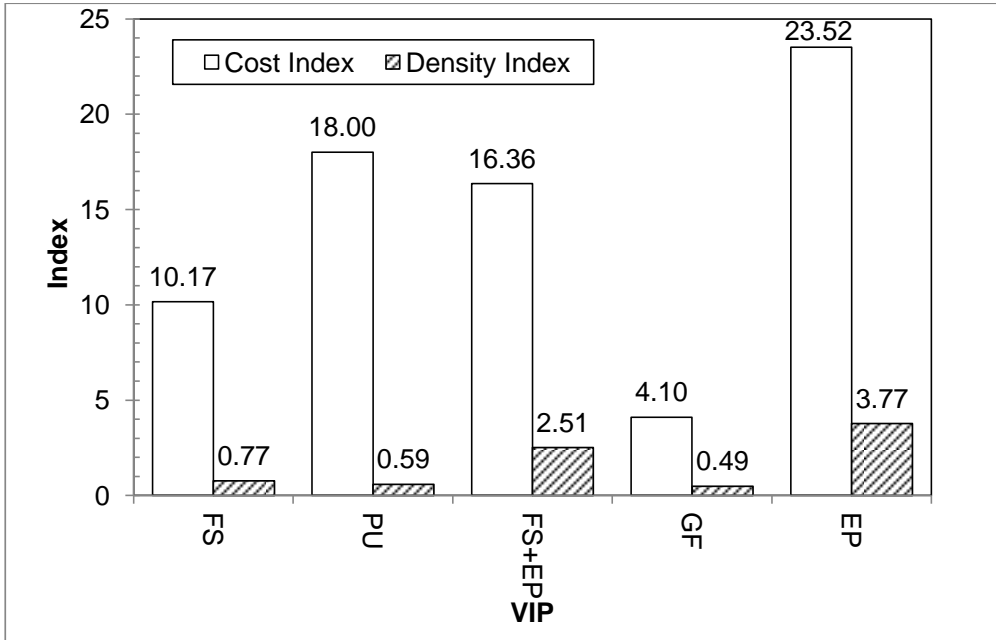
205 Table 42. Cost and main physical properties of different types of VIPs

Type of VIP	Cost (£m^{-3})	Initial centre of panel λ ($\text{Wm}^{-1}\text{K}^{-1}$)	Design λ ($\text{Wm}^{-1}\text{K}^{-1}$)	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

206 ^a va-Q-tec AG (2016) [1925]; ^b Alam et al.(2014) [1216]; ^c Di et al.(2013) [2026]

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

210 initial centre of panel thermal conductivity, ~~were calculated as shown in figure 1.~~
 211 VIPs with smaller values of these indices are more desirable. Figure 1 shows the
 212 calculated cost and density index of the materials listed in table 2.
 213



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

216 ~~desired compared to those having higher values.~~ Calculating the cost and density
 217 index of VIPs allows the relationship between cost and thermo-physical properties to
 218 be observed. From figure 1, GF VIP returned the smallest cost index of 4.10 (best
 219 performance) followed by FS, FS+EP composite, PU and EP in that order. ~~With~~
 220 respect to Comparing the values of density index shown in figure 1, GF ~~VIP has~~ VIPs
 221 have the least/lowest calculated value of 0.49, ~~again performing best,~~ whilst EP ~~VIP~~
 222 ~~returned a~~ VIPs the highest value of 3.77. FS VIP, ~~due to its~~ with a comparatively
 223 lower initial thermal conductivity and density, has ~~2.4 times~~ 4X and ~~1.5 times~~ 5X lower
 224 cost and density indices respectively than that of FS+EP composite VIP. ~~One~~
 225 ~~interesting fact that came out of this analysis is that~~ FS VIP ~~has had~~ a calculated cost
 226 ~~index 2.48 times~~ and density index 2.48X and ~~1.57 times higher~~ 57X greater
 227 respectively than ~~that of~~ GF ~~VIP~~ VIPs. However, GF ~~VIP suffers from~~ VIPs have a
 228 significantly shorter life time, ~~approximately~~ of 10-12 years, compared to the lifetime
 229 of 50-60 years ~~expected for~~ FS ~~VIP~~ VIPs.

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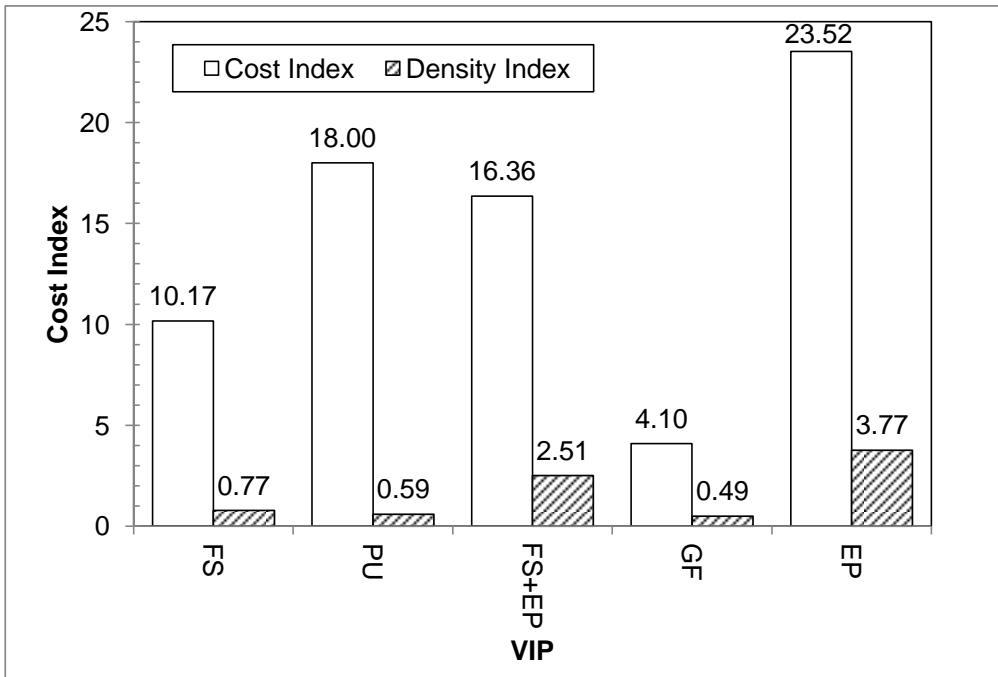


Figure 1. Cost and density index of different types of VIPs

3 Payback period calculation

Payback period, defined as the least possible time insulation takes installation of VIPs, to recover its installed cost 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 of any investment is reached when NPV the POI equals zero. NPV can be calculated using equation (1):

$$NPV = -C_T + [C_S \times 1/(1+r)^n] + [C_S \times 1/(1+r)^n] \quad (1)$$

where

C_T is the total insulation cost (£)

C_S is annual energy cost saving (£)

n is the number of year

r is the annual discount rate

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

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254
 255 C_T , C_E and C_S can be calculated using equations (2), (3) and (8) respectively.

$$256 \quad C_T = C_{M\&E} + C_M + C_I \quad (2)$$

$$257 \quad POI = \left[\frac{86400 \times HDD \times \Delta L \times C_F}{H_v \times \left(\frac{\eta_i - x \times n}{100} \right)} \times \frac{1}{(1+r)^n} \right] + \left[Y \times \Delta d \times 2 \{ (L_f + \Delta d) + (W_f + \Delta d) \} \times \frac{1}{(1+r)^n} \right] -$$

$$258 \quad [C_{Mt} + C_M + C_I] \quad (1)$$

259
 260
 261
 262 where

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263 C_{Mt} is the material cost of VIP core and envelope (£)

264 C_M is the manufacturing cost of VIP (£)

265 C_I is the installation cost of VIP (£)

$$266 \quad C_E = \frac{86400 \times HDD \times \Delta L \times C_F}{H_v \times \eta (1-x)} \quad (3)$$

267
 268
 269 where

270 HDD is the heating degree days (°C days)

271 C_F is the cost of fuel (£m⁻³)

272 H_v is the calorific value of fuel (Jm⁻³)

273 η_i is the initial thermal efficiency of the heating system (boiler) (%)

274 x is the annual rate of decrease of thermal efficiency of heating boiler (%)

275 ΔL is the difference of total building transmission heat loss coefficient (L) before and

276 after applying insulation (WK⁻¹)

277 n is the number of year

278 r is the annual discount rate (% fraction)

279 Y is the annual rental value (£m⁻²)

280 A_s is the floor area saved (m²)

281 F is the number of floors

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

283 L_f is the length of internal floor (m)

284 W_f is the width of the internal floor (m)

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285
 286
 287 Total building transmission heat loss coefficient (L) is described in as equation (4)

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

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

288 where

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

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

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

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

293 $(\rho c_p)_{air}$ is the volumetric thermal capacity of air ($Jm^{-3}K^{-1}$) taken as $1200 Jm^{-3}K^{-1}$.

294 Hence, the equation (42) can be rewritten as

295

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

297 (53)

298

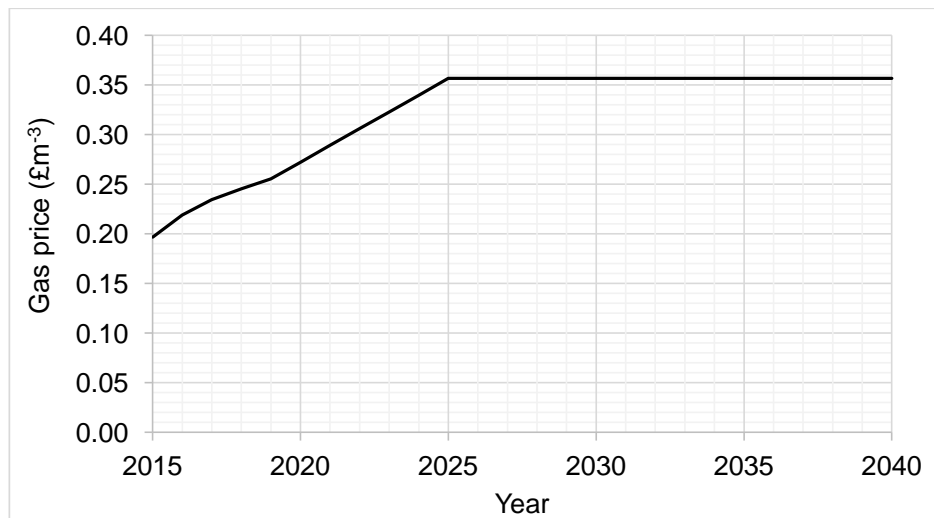
299 In equation (53), term $\frac{IV}{3}$ is the ventilation conductance (WK^{-1}) [2428].

300

301 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 gas long term price has been taken from forecast 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

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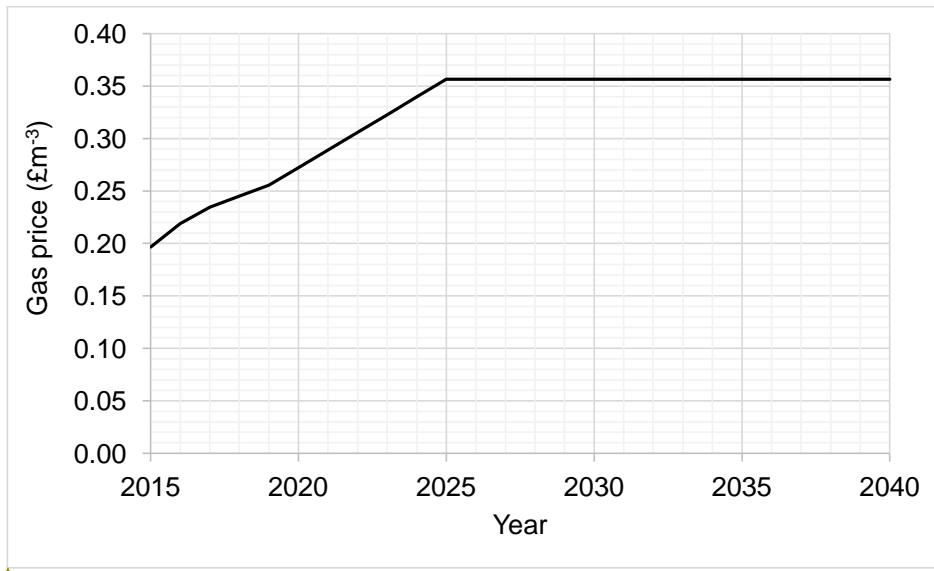
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311

The Figure 2. Gas price forecast [22]

312 Heating degree (HDD) data was used to determine energy consumption for space
 313 heating was the 5 year average (2011 to 2015) for a base temperature of 15.5 °C for
 314 St. James Park London [23]. The rate of decrease of [30]. Gas condensing boilers are
 315 assumed to suffer from an annual fall in their thermal efficiency of gas condensing
 316 boiler system has been taken as by 0.5% per annum. Installation% with a useful
 317 lifespan of 20 years. The installation cost has been assumed to be the same for
 318 all VIP types and has investigated so was not been included in the calculations.
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321 Figure 2. Gas price forecast [29]

322

323

324

325 Table 23. Parameters used for payback period calculation

326

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, $\eta_r \eta_i$, (%)	90
Annual discount rate, r , (%)	4

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334

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

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337 layers as shown in equation (6) and (7) [23]. Thermal 4) [28]. The thermal resistance
338 of any building material layer is the ratio of its thickness to its thermal conductivity.
339

$$340 \quad U = \frac{1}{R_{si} + (\sum R_e) + R_{sx}} \quad (64)$$

342 where
343

344 U is the thermal transmittance ($\text{Wm}^{-2}\text{K}^{-1}$)
345 R_{si} is the internal surface resistance (m^2KW^{-1})
346 R_e is the thermal resistances of a material layer (m^2KW^{-1})
347 R_{sx} is the external surface resistance (m^2KW^{-1})
348

349 ~~The thermal conductivity of a VIP varies decreases with time as the core~~
350 ~~pressure inside VIP increases due to outgassing from core and envelope and, or via~~
351 ~~penetration of to the interior by atmospheric air and moisture to the interiors of VIP.~~
352 ~~This degradation. Degradation in VIP performance should be was accounted for~~
353 ~~whilst when calculating the U-value of any the building element containing VIP~~
354 ~~insulation. Thus, elements insulated with VIPs, by modifying equation (6) can be~~
355 ~~modified to arrive at 4) as shown in equation (75).~~

$$357 \quad U(t) = \frac{1}{R_{si} + (\sum R_e) + R_{vip}(t) + R_{sx}} \quad (75)$$

359 where
360 $R_{vip}(t)$ is the time dependent thermal resistance resistivity of the VIP layer in a
361 building element and can be described as calculated using equation (86):

$$362 \quad R_{vip}(t) = \frac{d_{vip}}{\lambda_{vip}(t)} \quad (86)$$

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

368 ~~In this study For the U-value calculations used by this research, design thermal~~
369 ~~conductivity values of $0.008 \text{ Wm}^{-1}\text{K}^{-1}$, $0.007 \text{ Wm}^{-1}\text{K}^{-1}$ and $0.035 \text{ Wm}^{-1}\text{K}^{-1}$ were used~~
370 ~~for FS VIP, GF VIP and EPS respectively. For FS VIP rate~~
371 ~~of VIPs and GF VIPs the annual increase in thermal conductivity rise of was assumed~~
372 ~~as $0.0001 \text{ Wm}^{-1}\text{K}^{-1}\text{a}^{-1}$ [2431] and for GF VIP $0.0018 \text{ Wm}^{-1}\text{K}^{-1}\text{a}^{-1}$ [20] has been~~
373 ~~adopted. respectively [26].~~

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

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377 valuable space can provide additional revenue for building owners, and has been
378 included in NPV equation (1) as the annual savings (C_s) calculated using equation
379 (9):

$$380 \quad C_s = Y \times A_s \quad (9)$$

382 **Where 4 Details of the non-domestic buildings investigated**

383 The opaque elements (i.e. walls, floor and roof) of three different types of
384 commercial (non-domestic) ~~Y is the annual rental value (£m²) and A_s the floor area~~
385 ~~saved (m²).~~

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

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$$388 \quad A_s = F \times \Delta d \times 2 \times [(L_f + \Delta d) + (W_f + \Delta d)] \quad (10)$$

389 where

390 ~~F is the number of floors~~

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

392 ~~L_f is the length of internal floor (m)~~

393 ~~W_f is the width of the internal floor (m)~~

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395 **4 Insulating non-domestic buildings**

396 ~~Threesituated in London based non-domestic buildings,(UK); a two floor retail unit, a~~
397 ~~four storey office and a six storey office, have been studied to have were considered~~
398 ~~for retrofitting with VIPs and/or EPS insulation on all opaque elements (i.e. walls,~~
399 ~~The two floor retail unit building is representative of 10% of the current retail building~~
400 ~~stock in the UK by age of construction (1989-90) and 13% by floor area (250-500 m²)~~
401 ~~[32]. The four storey office building type accounts for 9% of the office building stock~~
402 ~~in the UK by age of construction (1981-85) and roof), see table 3 for 20% by floor~~
403 ~~area (2500-10,000m²) [32]. The six storey office building accounts for 11% of the~~
404 ~~office building stock in the UK by age of construction (1986-90) and 20% by floor~~
405 ~~area (2500-10,000m²) [32]. Table 4 shows the relevant details for each of the~~
406 ~~buildings investigated. Each building has been was assumed to be as~~ refurbished to
407 current building regulation standards by applying internal insulation on all opaque
408 elements achieving U-values of 0.30 Wm⁻²K⁻¹, 0.18 Wm⁻²K⁻¹ and 0.25 Wm⁻²K⁻¹ for
409 wall, roof and floor respectively [2533]. Table 34 shows U-values before and after
410 applying insulation on all buildings considered in the study along with their thickness
411 values. It has been was assumed that VIPs ~~cover covered~~ 95% of the ~~all~~ opaque
412 elements ~~whilstwith~~ phenolic foam insulation covering the remaining 5%. ~~The~~
413 ~~thermal conductivity of the~~ Phenolic foam ~~has used was~~ assumed ~~to have a thermal~~
414 ~~conductivityas~~ of 0.020 Wm⁻¹K⁻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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419 **5 Space heating energy saving potential**

420 ~~Potential~~The potential space heating energy savings and associated reduction in
421 ~~carbon dioxide~~ (CO_2) emission from using VIP insulation in all three types of
422 buildings (described in table 3) ~~has been~~ were calculated. ~~Annual~~The annual
423 ~~space~~ heating energy ~~savings~~saving (E_A) of buildings for any year (n) was calculated
424 using equation (47).

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

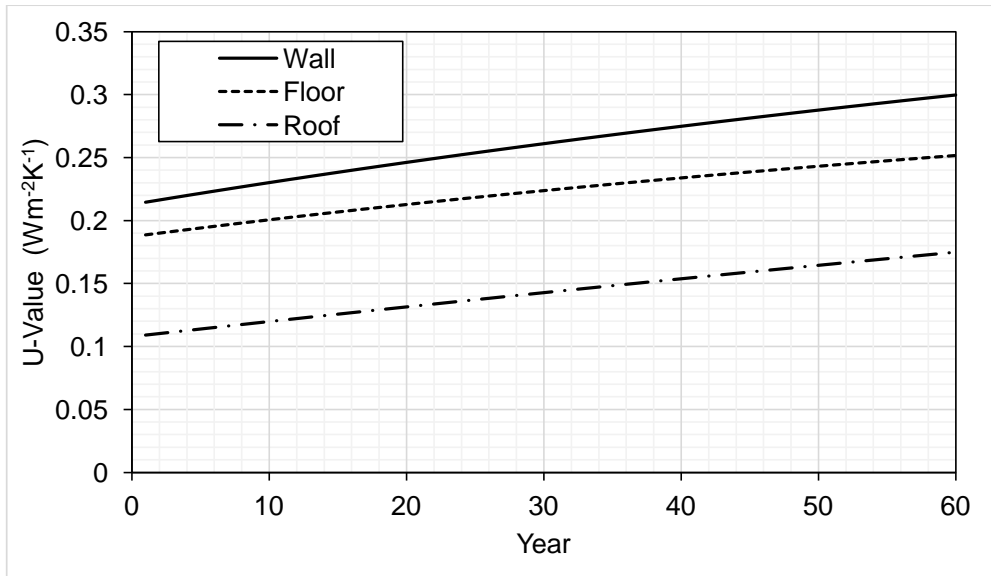
426 ~~(47)~~
$$\frac{86400 \times HDD \times \Delta L}{H_p \times \left(\frac{\eta_i - x \times n}{100}\right)} \quad (7)$$

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427 where
428 HDD is the heating degree days ($^{\circ}C$ days)
429 H_p is the calorific value of fuel (Jm^{-3})
430 η is the thermal efficiency of the heating system (boiler)
431 x is the annual rate of decrease of thermal efficiency of heating boiler
432 ΔL is the difference of total building transmission heat loss coefficient before and
433 after applying insulation (WK^{-1}).

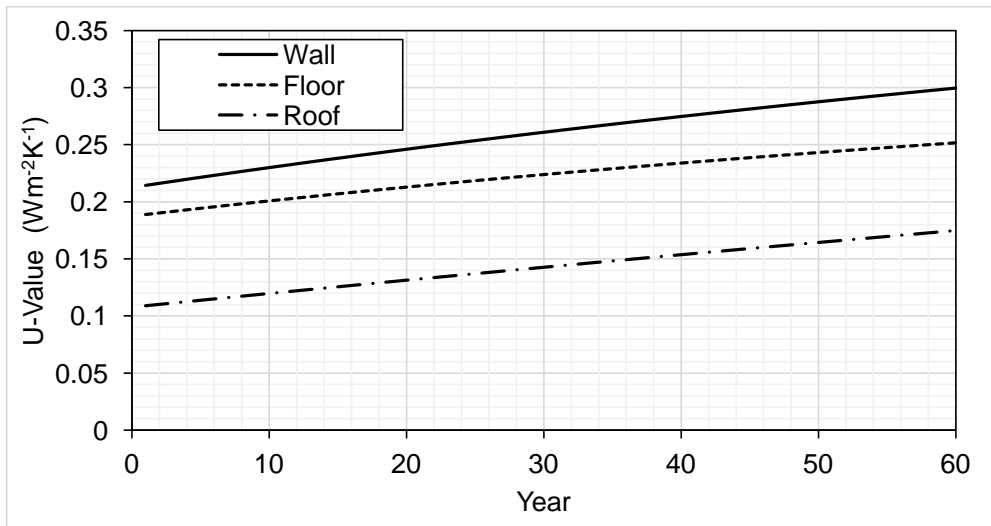
434
 435 ~~Total~~The building transmission heat loss coefficient (L) ~~takes into~~
 436 ~~account~~incorporates the U-values of all building elements. In ~~the~~ case of applying
 437 VIP insulation the U-value varies with time and can be calculated using equations
 438 (75) and (8). ~~Time~~6). The time dependent U-values of ~~the~~ wall, floor and roof of the
 439 retail unit building insulated with VIPs is shown in figure 3.
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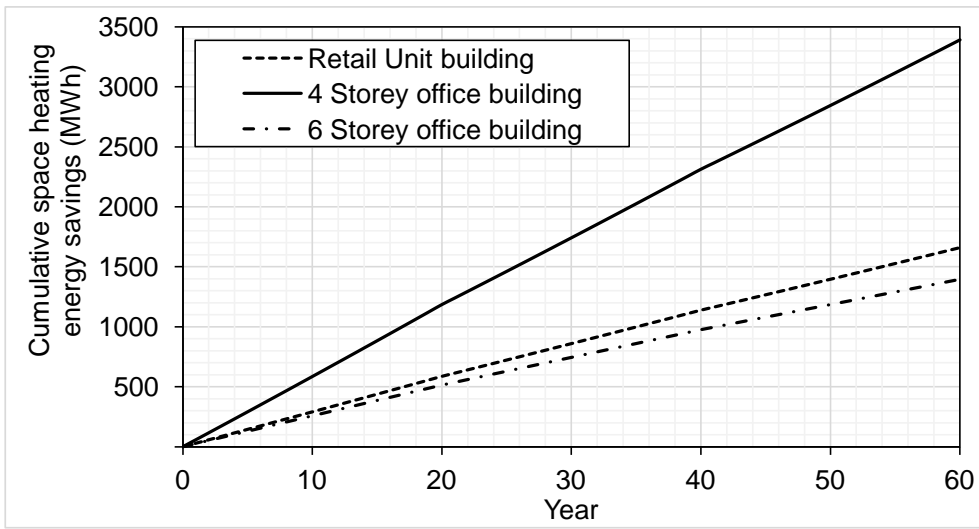
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444 Figure 3. Time dependent U-values of VIP insulated wall, floor and roof of the two
 445 floor retail unit building studied
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447 Applying VIP insulation ~~reduces~~reduced the U-value of building elements, ~~see as~~
448 ~~shown in~~ table 3, ~~and results in~~4, ~~saving~~ space heating energy ~~savings~~. The energy
449 saved over the ~~assumed 60 year~~ life time of the ~~building, assumed to be 60 years,~~
450 ~~for all~~ three buildings considered is shown in figure 4.
451

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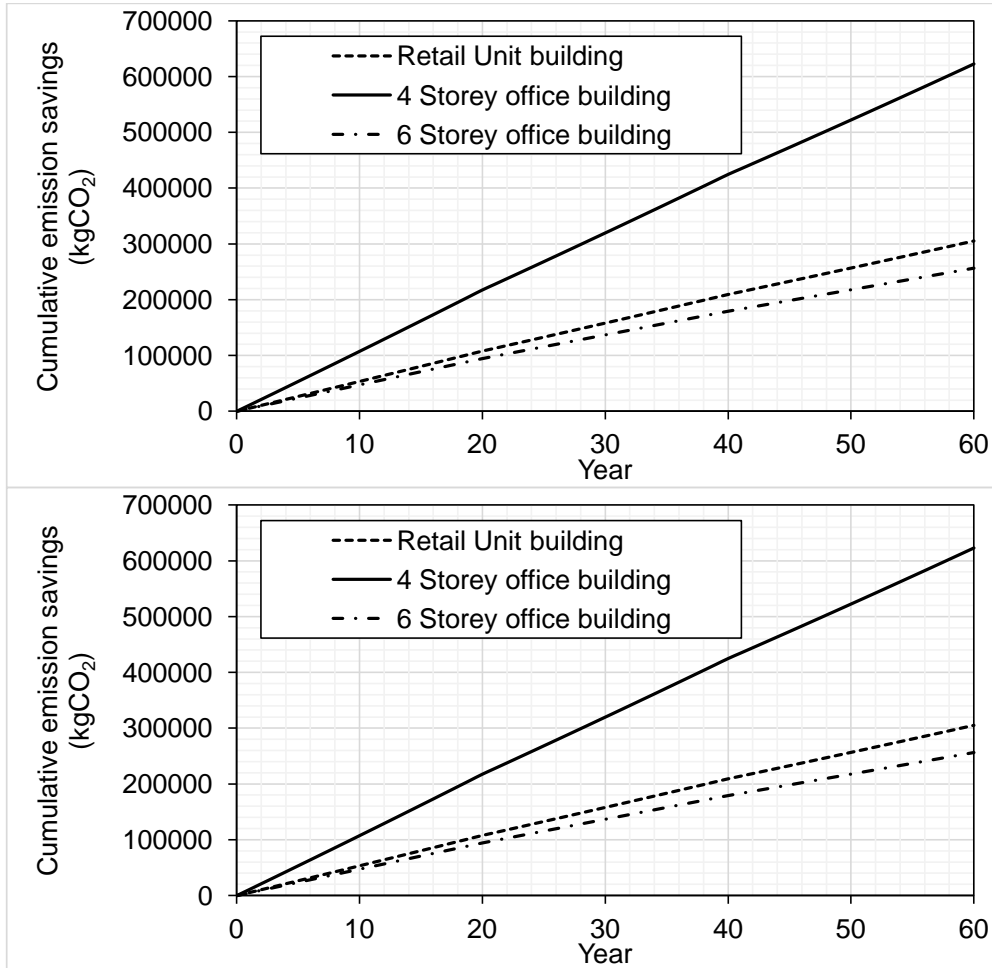
453

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

456 ~~Over~~Using the ~~full~~parameters outlined previously in table 4 over the assumed
457 building life ~~time, span of 60 years, installing VIPs can save~~would reduce the energy
458 ~~used for~~ space heating ~~energy of by~~ 1395.3 MWh, 1661.2 MWh and 3391.6 MWh for
459 ~~the~~ six storey office building, ~~the~~ retail unit building and ~~the~~ four storey office building
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461 | respectively. ~~Potential~~The potential reduction in CO₂ emissions ~~were~~was calculated
 462 | using a fuel emission factor of 0.18365 kgCO₂/kWh [2634] and ~~are~~ shown in figure 5.
 463 | Use of VIPs was calculated to potentially reduce CO₂ emissions by 10.2%, 41.3%
 464 | and 26.7% respectively for six storey office building, retail unit building and four
 465 | storey office building.
 466



467
 468
 469 | Figure 5. Reduction in CO₂ emissions for three buildings studied

470 | **6 Payback period results**

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

474 | **6.1 Two floor retail unit**

475 | ~~The geometric~~Geometric and thermal ~~feature~~features of the ~~building~~buildings studied
 476 | are shown in table 4. ~~This type of buildings account for 10% of the retail building~~

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477 stock in the UK by age of construction (1989-90) and 13% by floor area (250-500 m²)
 478 [27].5. The wall, floor and roof U-values are shown in table 4.
 479 Payback period analysis of FS VIPs and GF VIPs has been carried out employing
 480 equations (1-10) and compared with that of EPS insulation. EPS insulation was
 481 found to take longer than its life time to recover the The cost of insulation installing
 482 sufficient EPS for achieving current building insulation standards could not be
 483 recovered within its lifetime, see figure 6. For EPS, no space saving revenue is
 484 possible, which means that investments are solely recovered through fuel cost
 485 savings. Also, EPS due to a comparatively shorter service life of 20 years will require
 486 to be replaced requires replacement three times over an assumed 60 year building
 487 life span of the building leading to a higher insulation cost. A life span of 60 years for
 488 building has been was assumed to match the
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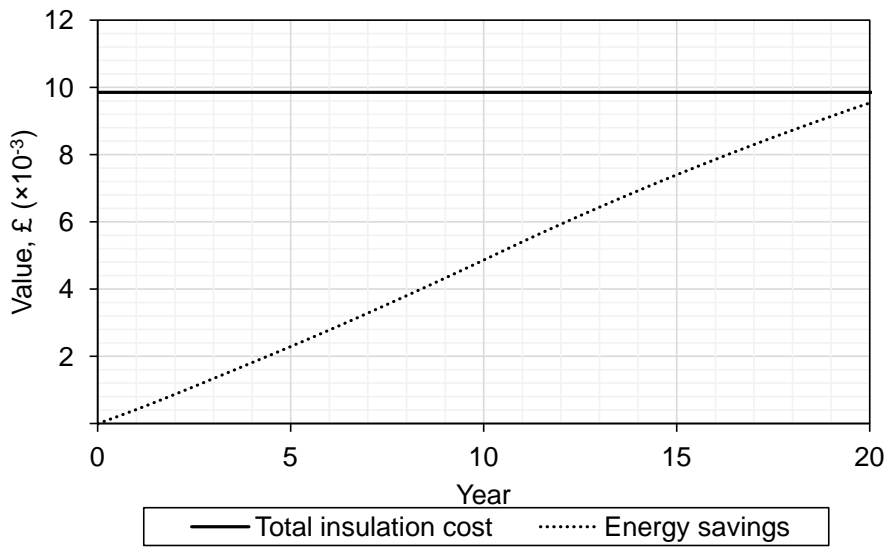
493 Table 45. Geometric and thermal features of the buildings considered in this study

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

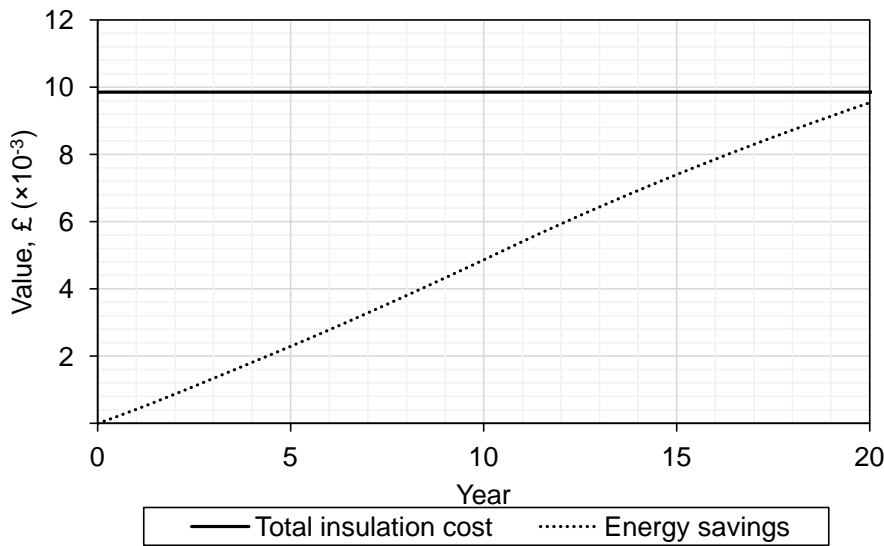
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494
 495 match the prescribed life span of VIPs used for buildings in the UK. In the case of
 496 VIPs, the additional benefit of commercial space saving can partially offset the higher
 497 initial insulation cost. costs. The Results of payback period analysis for two different
 498 types of VIPs (FS and GF) taking into account
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502 Figure 6. Cost and savings of applying EPS insulation in a retail unit building

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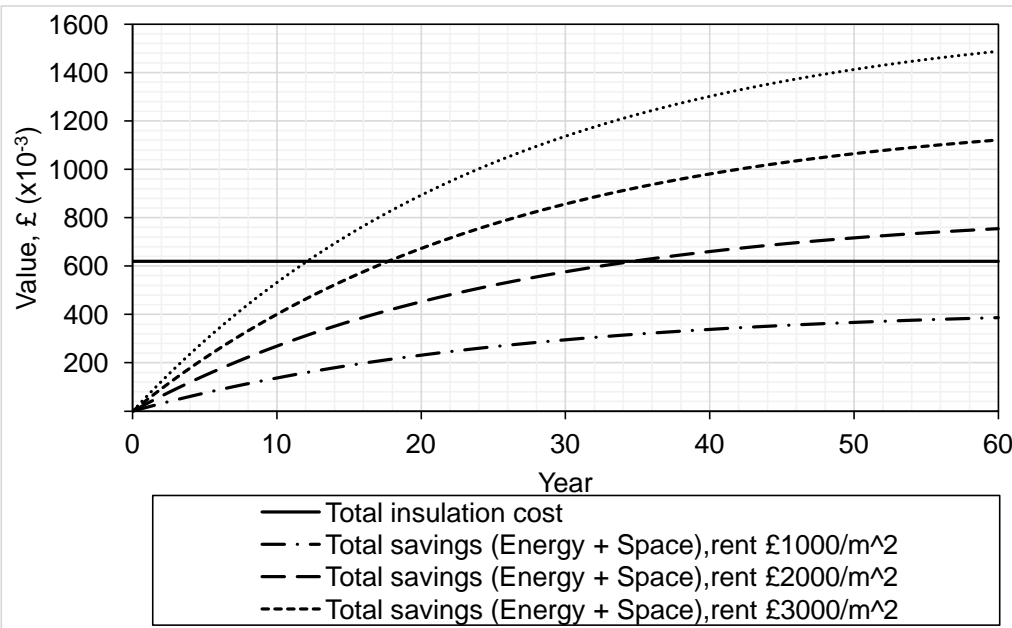
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the economic potential of space saving with average annual rental value in London (UK) ranging from £1000 m⁻² to £4000 m⁻² [28] has been [35] is shown in figure figures 7 and 8 respectively. Results show Figures 7 and 8 demonstrate that the cost of 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 shorter service life (10 years) as, compared to that of FS

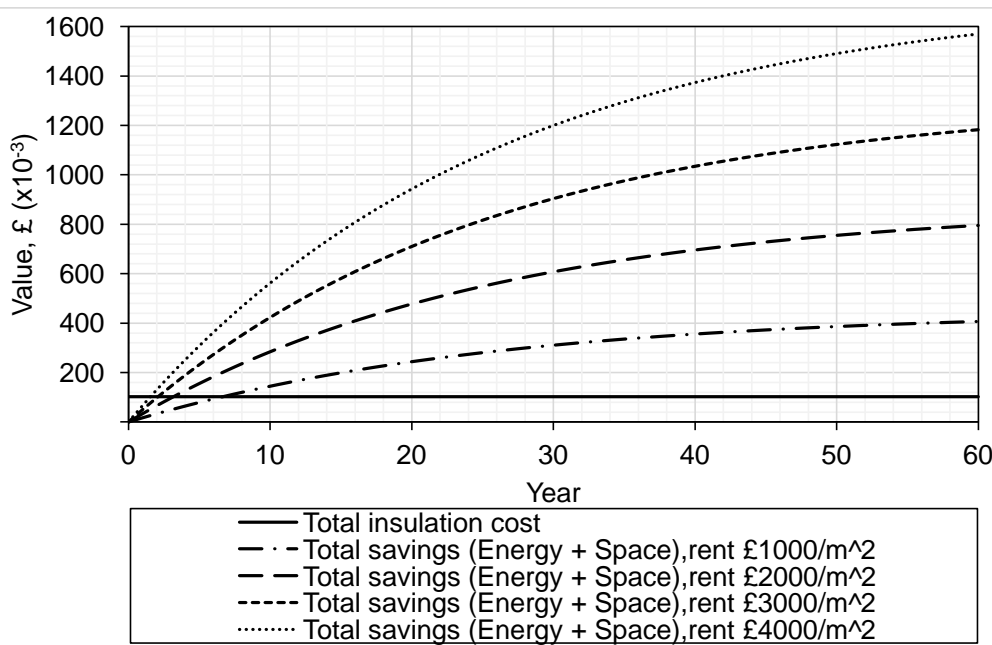
513 VIP (60 years). As expected, as the rental values increase the payback period for
 514 VIP insulation becomes shorter. For rental ~~value~~ values of



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



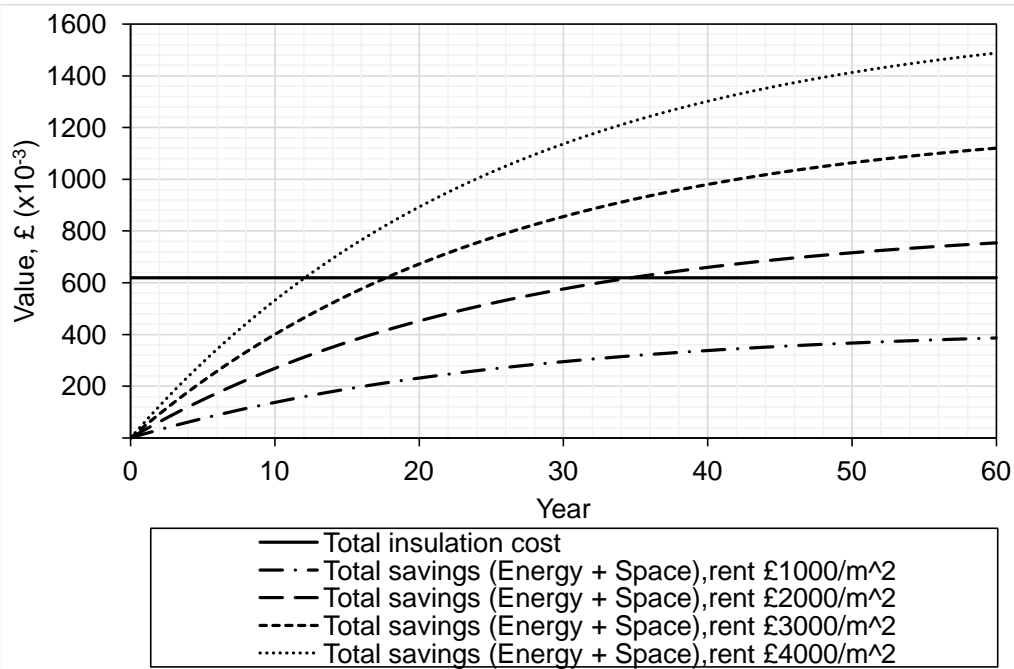
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520

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

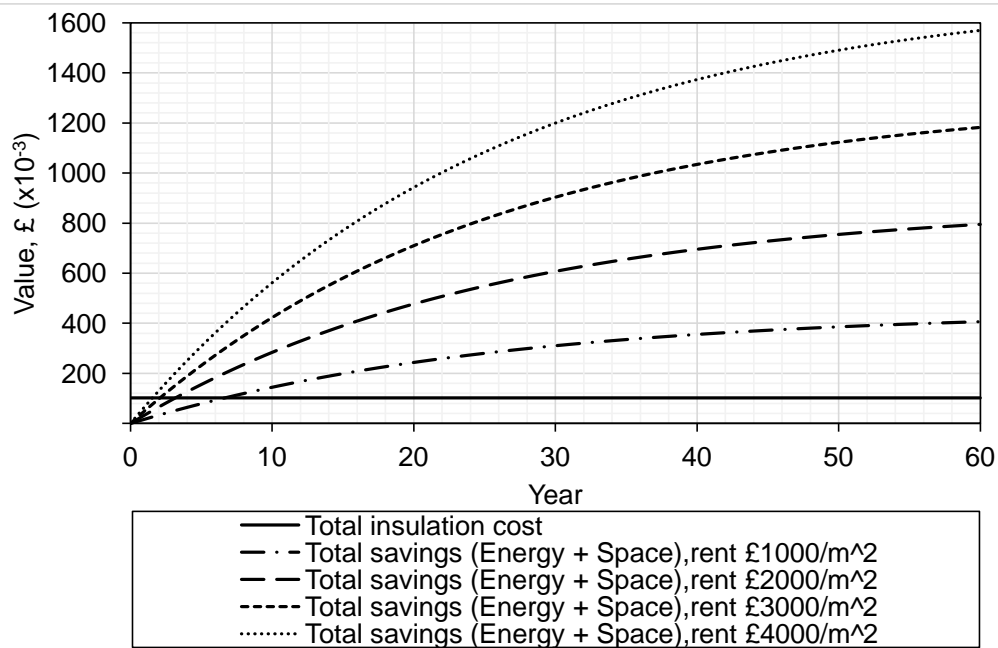
523 £2000 m⁻² and £3000 m⁻² ~~it is~~ the discounted payback period was 35 years and 18
 524 years respectively for GF VIP and 4 years and 3 years for FS VIP. For average
 525 rental value of £4000 m⁻² payback period of FS VIP becomes approximately 2 years,
 526 whereas it is still prohibitively longer (12 years) for GF VIPs.
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528 ~~Figure 7. Cost and savings of applying GF VIP insulation in the retail unit building~~
 529 ~~studied~~
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533

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

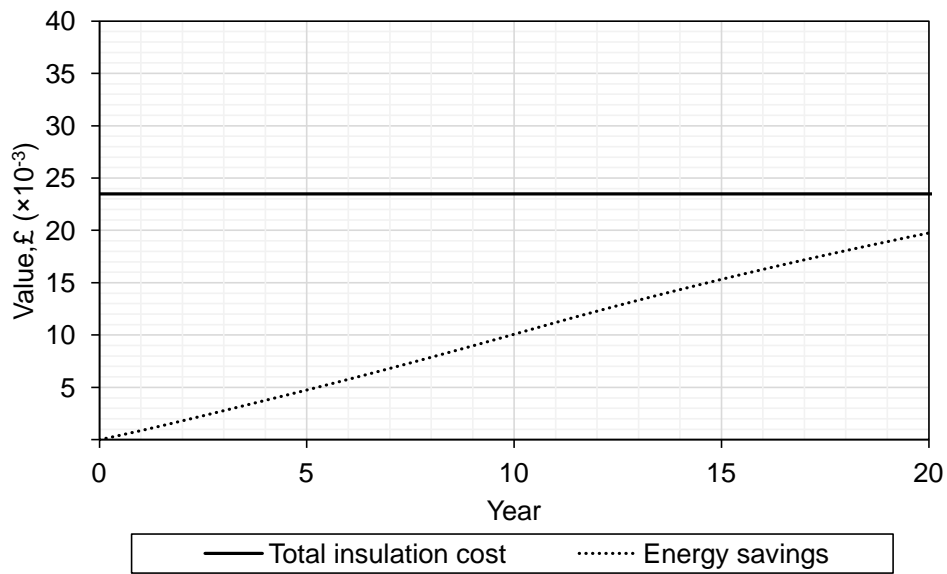
536 6.2 Four storey office

537 ~~The geometricGeometric~~ and thermal ~~featurefeatures~~ of the ~~building studied four~~
 538 ~~storey office~~ are shown in table 4. ~~This building type accounts for 9% of the office~~
 539 ~~building stock in the UK by age of construction (1981-85) and 20% by floor area~~
 540 ~~(2500-10,000m²) [27]. The wall, floor and roof U-values are shown in table 3.~~

541 ~~Payback5. The discounted payback~~ period analysis for ~~the~~ four storey office ~~is~~
 542 ~~presented in figure 9, 10 and 11 for achievingretrofitted to meet~~ current building
 543 ~~insulation standards withusing~~ EPS insulation, GF ~~VIP insulationVIPs~~ and FS ~~VIP~~
 544 ~~insulation-VIPs is presented in figures 9 to 11~~ respectively.

545

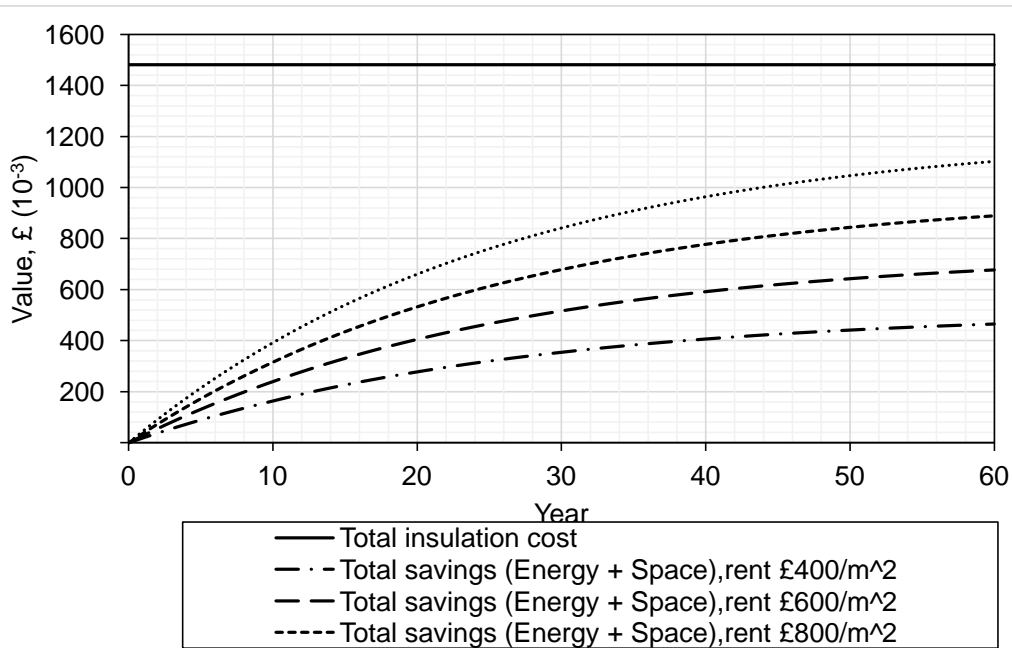
546



547

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

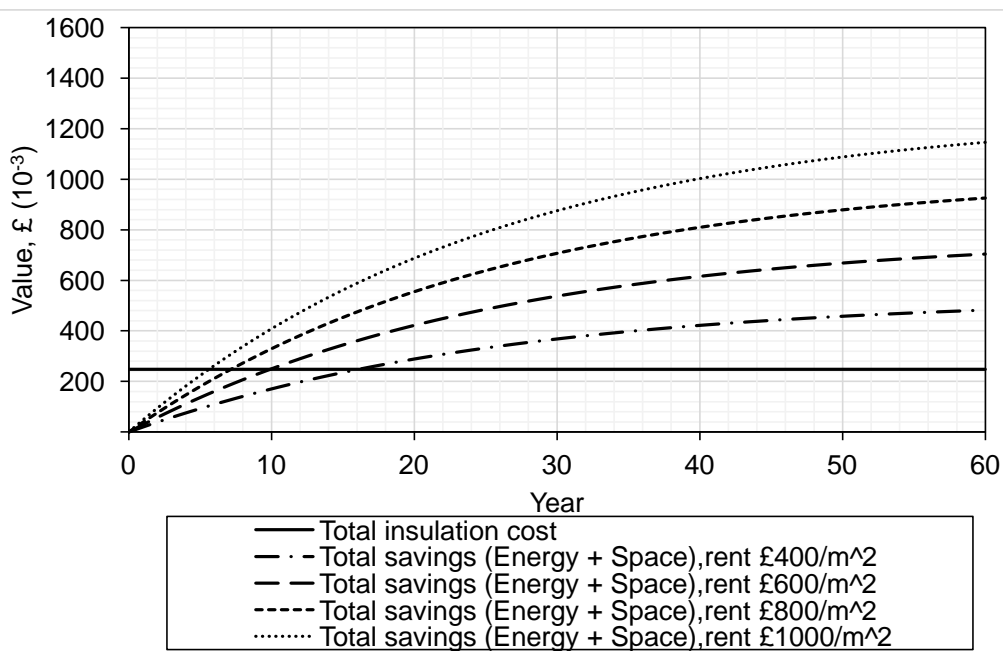
550 Figure 9 ~~shows~~demonstrates that EPS insulation cannot recover the initial capital
 551 cost over its life time of 20 years. For GF ~~VIP even considering additional benefit of~~
 552 ~~the economic potential of space saving with average annual rent ranging from £400~~
 553 ~~m⁻² to £1000 m⁻² [29]VIPs~~ the cost of insulation cannot be recovered over the life time
 554 of building as shown in figure 10. even with the additional economic benefits from
 555 space saving with average annual floor rents ranging from £400 m⁻² to £1000 m⁻²
 556 [36]. As ~~stated~~discussed in section 6.1, the reason for long payback period for GF
 557 VIPs is their short service life (10 years) requiring replacement six times during 60-
 558 year life time of the building.



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



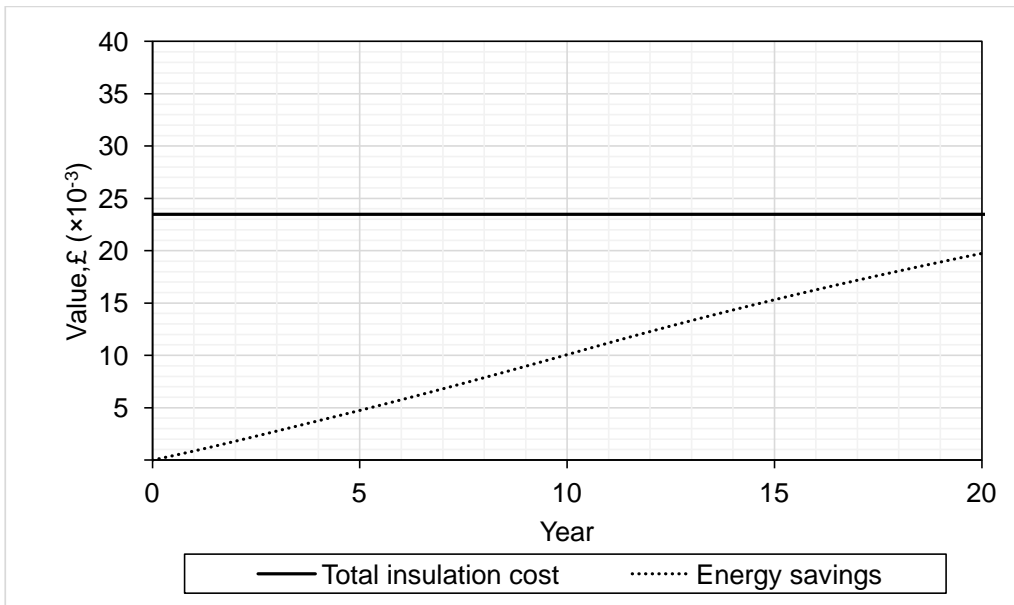
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563 Figure 11. Cost and savings of applying FS VIP insulation returned in the 4 storey
 564 office building studied

565 From figure 11, it can be seen that upgrading the 4 storey office with FS VIP
566 insulation to comply with current building regulations resulted in payback periods of
567 17 years, 10 years, 7 years and 6 years for rental values of £400 m⁻², £600 m⁻², £800
568 m⁻² and £1000 m⁻² respectively.

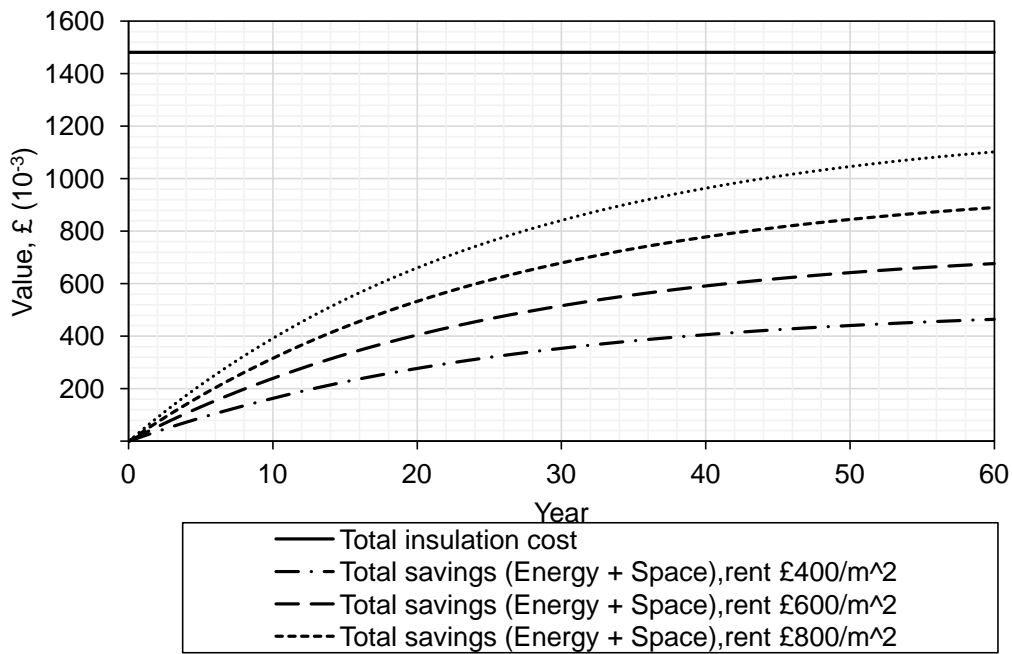
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572 ~~Figure 9. Cost and savings of applying EPS insulation in the 4 storey office building~~
573 ~~studied~~

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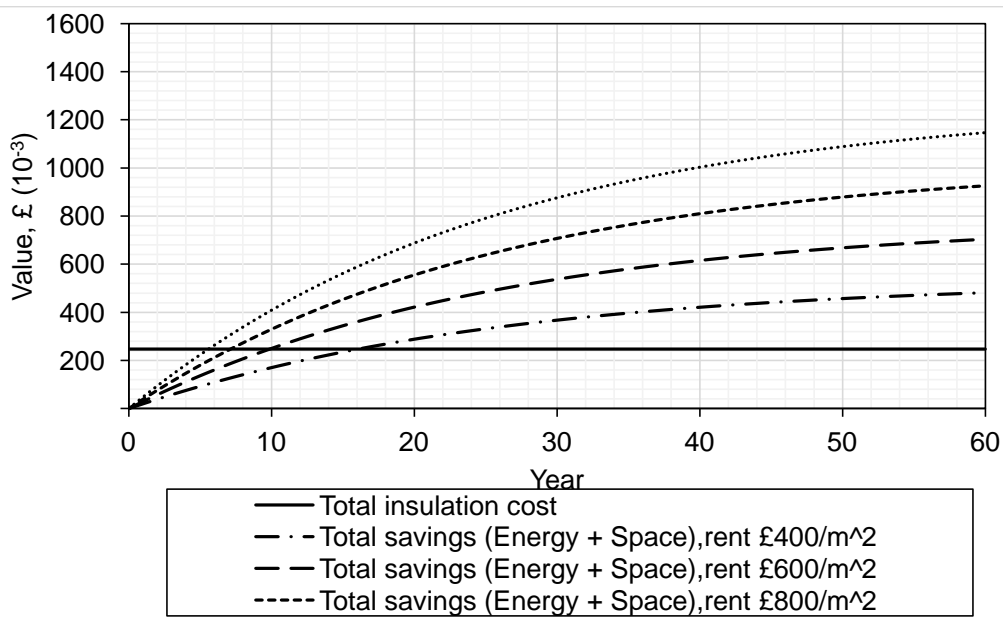


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Figure 10. Cost and savings of applying GF-VIP insulation in the 4-storey office building studied



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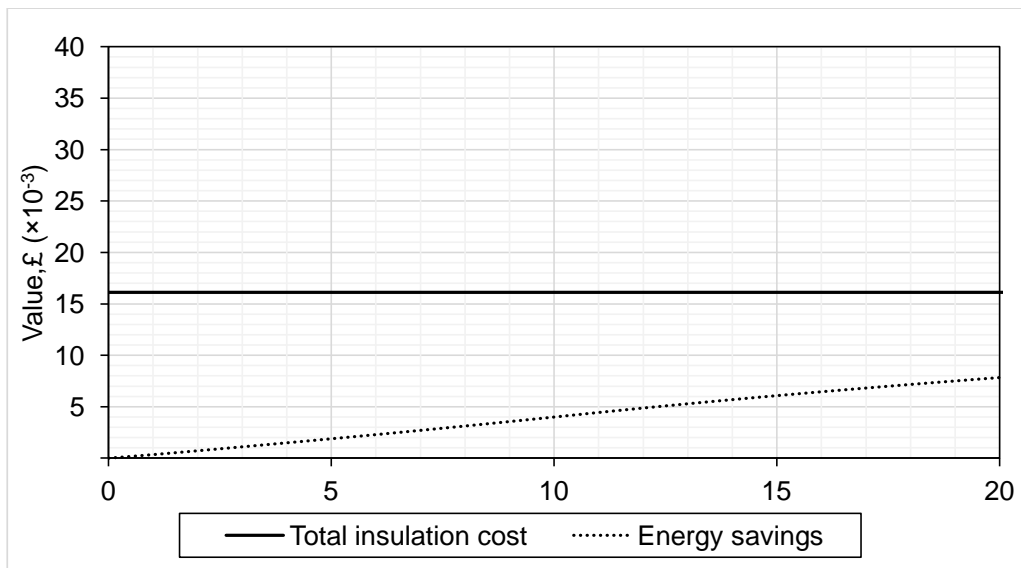
Figure 11. Cost and savings of applying FS-VIP insulation in the 4-storey office building studied

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6.3 Six storey office

The geometric and thermal 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 (2500-10,000m²) [27]. Results of the discounted payback period analysis for the six storey office building are shown in figures 12, figure 13 and figure 14.

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

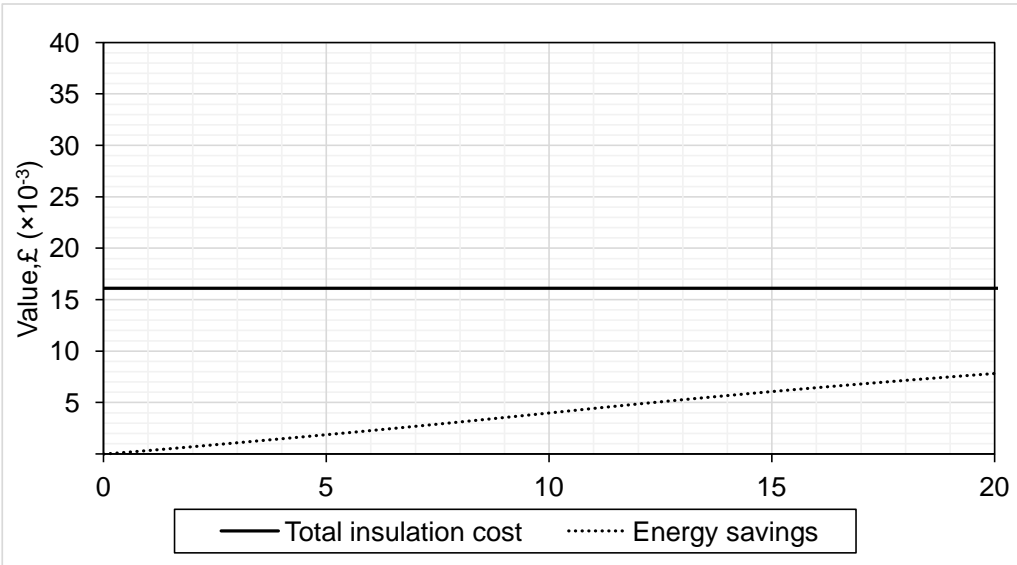
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Figure 12 shows that EPS insulation was found to have had a discounted payback period longer than its assumed life time of 20 years. It can be seen from figure 13 that in the case of GF VIP, the cost of insulation cannot be recovered with average annual rent of £400 m⁻² and £600 m⁻² 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 GF VIPs. FS VIP is shown 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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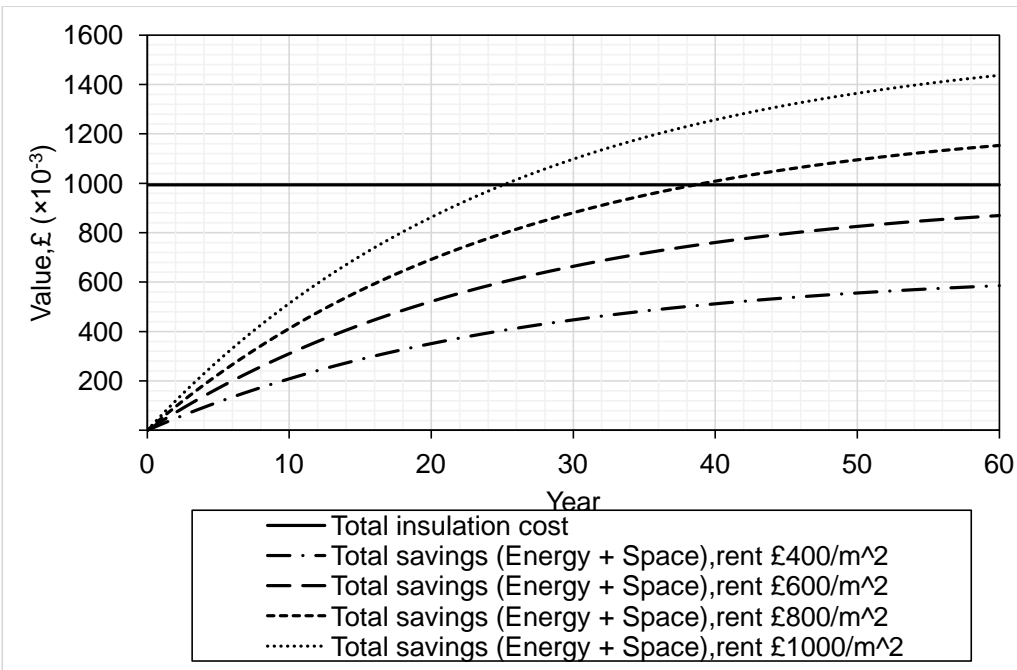
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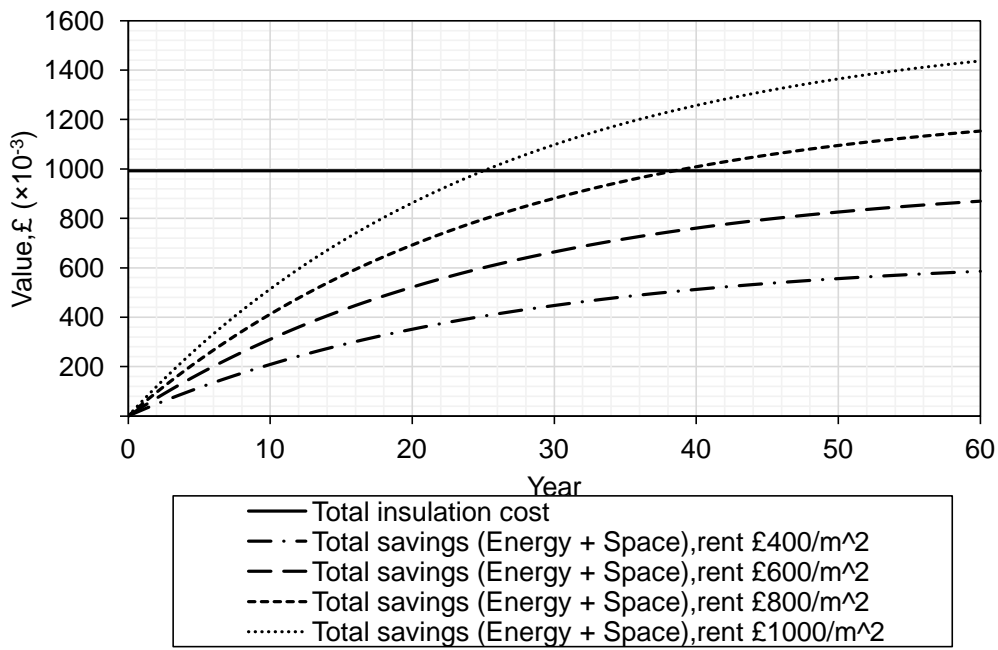
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608 **Figure 12. Cost and savings of applying EPS insulation in the 6-storey office building**
609 **studied**

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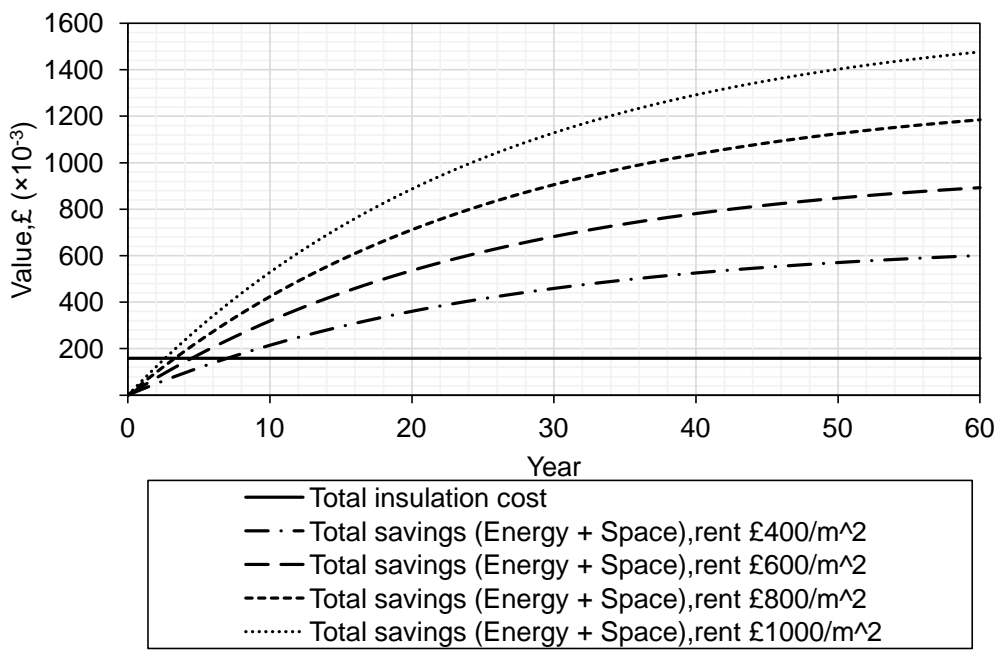
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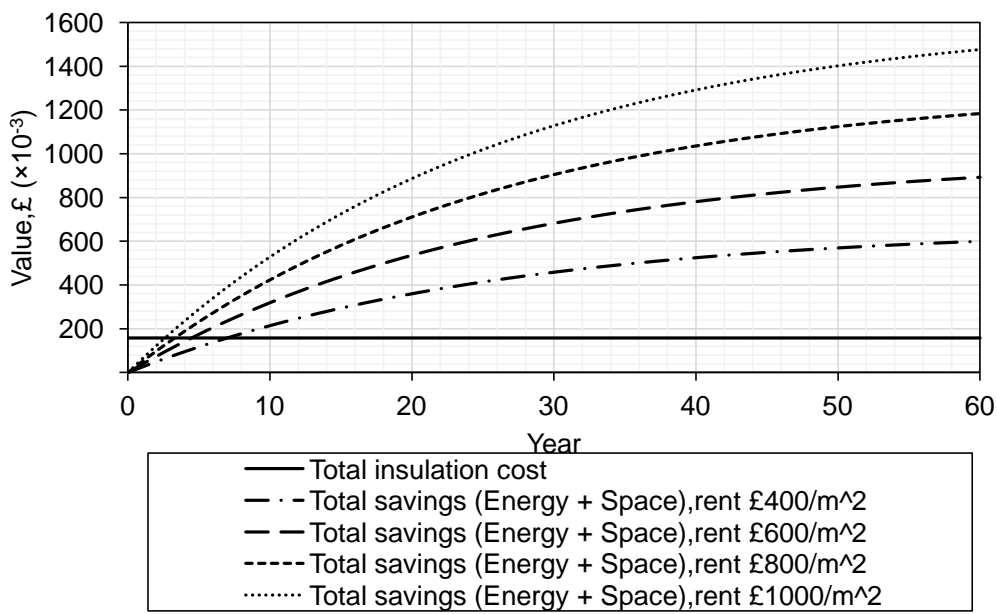
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Figure 13. Cost and savings of applying GF VIP insulation in the 6 storey office building studied



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

621 7 Conclusions

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

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