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Comparative holistic assessment of using vacuum insulated panels for energy retrofit of office buildings

Mahmood Alam [a,*], Marco Picco [a], Shahaboddin Resalati [b]

[a] School of Architecture, Technology and Engineering, University of Brighton, Moulsecoomb Campus, Lewes Road, Brighton, BN2 4GJ, UK
[b] Oxford Brookes University, Headington Campus, Gipsy Lane, OX3 0BP, Oxford, UK

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ABSTRACT

This research proposes the application of a holistic methodology for the accurate assessment of financial and environmental feasibility of applying thermal insulation materials, including advanced materials such as vacuum insulation panels (VIPs), for energy efficient building retrofit. The methodology is applied to a case study in which different insulation materials, both traditional (Mineral wool; XPS) and advanced insulation (VIPs), are applied as internal insulation to a typical office building requiring retrofit. The building is simulated through dynamic performance simulation under different climate conditions to evaluate its annual energy needs. Financial and energy analysis including embodied carbon are performed using a proposed holistic approach. The financial feasibility highlighted traditional "heating only" approach might be lacking in correctly identifying energy savings, leading to overestimating for traditional materials with payback time as low as 6.4 years for mineral wool. The "holistic approach", accounting for the heating and cooling loads and value of space saved, favours advanced materials such as VIPs as soon as the space reaches high enough value, with payback time between 1.3 and 4.2 years for locations investigated. However, the environmental assessment shows that mineral wool has significantly lower carbon payback time compared to VIPs. For VIPs to be competitive environmentally, lower impact core materials or alternatively higher percentage of recycled/reused fumed silica need to be considered in their production. The holistic methodology presented for the first time allows to consider the implications of embodied carbon of insulation materials used in building retrofitting along with the financial and operational energy considerations.

1. Introduction

Buildings consume significant proportion of energy and are responsible for one third of total carbon emissions [1]. Energy demand in buildings is annually rising due to rapid growth in global building floor area and greater use of energy to provide better quality indoor environment and comfort. This has led to increase in use of non-renewable energy resources worldwide and has raised concerns over depletion of these energy resources and their environmental impact. Improving building thermal envelope insulation is key to enhance energy efficiency of buildings by reducing heating/cooling energy consumption. This is achieved by lowering the overall heat loss coefficient (U-value) of building fabric by applying thermal insulation. Currently used conventional thermal insulation materials require large thicknesses to achieve very low U-values to meet stringent building regulation requirements which may not be feasible for certain construction scenarios especially for refurbishment of old building stock. This requires the use of high thermal resistance advanced insulation materials such as Vacuum Insulation Panel (VIP). VIPs provide 5–8 times higher thermal resistance compared to conventional thermal insulation materials [2,3]. However, use of VIPs has been limited in the building sector due to their higher cost and carbon investment specifically in the case of fumed silica based VIPs [4,5,6], combined with the use of assessment methods which tend to focus only on energy costs and therefore favour cheaper traditional materials. VIPs when applied as internal insulation on walls can potentially lead to economic space savings. Use of VIPs and their effect on the building energy consumption and economic feasibility have been investigated in few studies. Mujeebo et al. [7] simulated the effect of VIPs on energy consumption in multi-story office building located in the hot climate of Kingdom of Saudi Arabia using ECOTECT software. Integration of VIPs in wall and roof of this case study building led to decrease of only 0.8% annual energy consumption compared to that of

* Corresponding author.
E-mail address: m.alam@brighton.ac.uk (M. Alam).

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the base case scenario (uninsulated). Further, simple payback analysis revealed that VIPs are not cost-effective insulation option for this case study building, however, this payback analysis only focused on the capital and energy costs and did not consider wider impacts such as the economic value of space saved by using thinner insulation layers which is an important consideration due to the high cost of VIPs. Alam et al. [8] found that using fumed silica core VIPs in a multi-story office case study building in the UK (London) climate led to reduction in space heating energy by 10.2%, proving an economically feasible insulation option in higher rental locations if economic value of VIP space savings is considered in the payback period calculations. This study however only focused on steady state space heating energy consumption, which is the dominant energy use in buildings in the cold climate regions and did not account for the wider dynamics impacts of the thermal behaviour of the building, cooling energy demand and the embedded carbon in the materials used. Lim et al. [9] simulated the use of VIP insulation in a multi-story apartment building in South Korea using IES energy simulation software and found that application of VIPs has reduced the annual energy consumption of the case study building compared to the base case (Expanded Polystyrene insulated building). However, cost effectiveness and embodied energy analysis of application of VIP was not carried out in this study, as the study only focused on operational energy savings. Simple payback time calculations performed under the IEA Annex 65 subtask IV showed that super insulation materials (VIPs & Aerogels) have long payback time for northern European cities, but this can be reduced if economic value of space saving is considered. This study only considered the steady state heating energy losses and did not account for cooling energy demand and time value of money [10]. Fantucci et al. [11] simulated a reference building with VIP insulation and found that VIPs can be economically favourable options compared to conventional insulation materials when rental value of the building is approximately higher than 220 €/m^2 per year, again the study only focused on heating energy, discarding the impacts on thermal behaviour and embodied carbon implications. Biswas et al. [12] performed the energy analysis of using Modified Low-cost VIP insulation in single story domestic building retrofit in cold climate of New York (USA) and predicted that heating energy consumption can be reduced by 12.5% compared to the baseline building. In their study, payback period of longer than 100 years was calculated for using VIPs for retrofitting the building with no pre-existing insulation. Simões et al. [13] investigated the life cycle cost (LCC) analysis of the application of VIPs in external thermal insulation composite systems (ETICS) in office building façades. They have studied several variables including location, cost of materials, insulation thickness, and rental prices in the context of rental value benefits and demonstrated the cost thresholds for which VIPs can be economically viable in different scenarios, the study however focused on a single façade component, rather than the entire building. Di Giuseppe et al. [14] applied life cycle costing to the use of VIP insulation in a case study building and concluded that the higher capital investment associated with VIPs cannot be recovered by their energy saving benefit to achieve optimal costs, however, did not consider the impacts of embodied energy or space value. Wernery et al. [15] developed a simplistic equation to predict cost of creating extra space in building by using superinsulation materials but did not consider any operational and embodied carbon implications and any future values of costs in their equation.

The life cycle assessment (LCA) of VIPs have been mainly conducted in the context of Environmental Product Declarations (EPD) (available from the operators' websites including IBU, BRE and Norge) with results varying up to 200% [16]. Resalati et al. [6] performed a full LCA analysis of VIPs considering different core materials, (as VIPs' main contributor to the environmental impact [17]), and have concluded that Pyrogenic silica, the most common core material for construction applications, had the highest environmental impact of the core materials considered. This, according to their study, suggests that measures such as recycling of the core material and more efficient manufacturing techniques should be considered if the material is to compete environmentally with the other alternative conventional materials. However, this study only focused on the environmental impact and did not consider the cost implications involved in applying VIPs.

From these previous studies it is evident that viability of using VIPs in buildings depends on the climatic zone, location of building and location of insulation (external or internal). However, none of the studies available in literature has considered holistically the range of implications of using advanced materials such as VIPs against more traditional alternatives. The available studies lack an assessment approach able to both account for financial and environmental implications which can be applied to existing buildings, with each study focusing only on certain aspects of the problem. Some studies are still relying on simplified calculations unable to correctly assess the thermal behaviour of the building.

This paper for the first time investigates the combined financial and environmental performance of VIPs in context of energy retrofit of existing office buildings. To facilitate this, a novel holistic methodology has been developed which is able to take into account the building's dynamic heating and cooling loads, value of space saved and embodied carbon to predict the financial and carbon payback of applying vacuum insulation panels as compared to traditional thermal insulation materials. The application of this new methodology is demonstrated through a case study office building for three different climatic conditions/locations and conclusions are taken based on the obtained results. This methodology provides a comprehensive framework for accurate energy and economic appraisal applicable to both advanced and traditional thermal insulation materials in the context of different typology of buildings and climatic conditions.

2. Methodology

A case study approach is used in the presented research to showcase the results obtainable by applying different approaches to the evaluation of energy efficiency interventions. For this purpose, an ideal building is identified as representative of a subset of existing buildings, which is subsequently investigated assessing both the environmental and financial feasibility of different energy retrofit options including both traditional and innovative insulation materials. It is important to note how the case study included is meant as an example of application of the proposed methodology, and how a different approach can lead to different design choices; although some general conclusions can be made from the case study, results can change depending on the assessed building, and the detailed methodology should be applied to each on a case-by-case basis.

Following the definition of the building, detailed in section 3, a building energy simulation model is developed and simulated through complex Dynamic Building Performance Simulation (BPS) software to assess energy needs of both pre and post refurbishment scenarios through the use of dynamic simulations. Three different locations are identified in this study and implemented in the simulation in order to account for both different climates and different financial conditions, in order to assess the interventions and approaches under variable external conditions.

In this study the well-known EnergyPlus simulation code is used in order to perform simulations, and a simplified building description model is implemented [18], requiring only a limited number of inputs to be defined before the creation of the simulation model. The model is then simulated through a complex dynamic simulation code and annual heating and cooling needs for the case study building are defined as the relevant outputs to be used in this study, for each of the selected locations both pre-refurbishment, identifying the baseline energy needs for the building, and post-refurbishment, identifying the energy savings obtainable.

The capital expenditure required for each of the energy efficiency solutions is then identified based on available commercial prices in order to assess the financial feasibility of the retrofit interventions in each location, in combination with the economic savings derived from the change in energy needs obtained from the simulations.

For this study, three different approaches to perform the financial feasibility are defined in order to show the importance of correctly assessing the thermal behaviour of the building, each progressively including more factors to account for, as defined below:

- "Heating Only" approach: In this approach only the reduction in heating needs caused by the additional insulation layer is taken into account, any change in other energy needs, such as cooling loads, is assumed to be either negligible or counter-able with the implementation of ad-hoc strategies such as changes in ventilation and lighting controls, which are however not modelled in the simulations. This is the simplest approach of the three, and the most likely to be used in practice through the use of simplified steady-state calculations, as previously noted in the literature review.
- "Heating + Cooling" approach: In this approach, both changes in heating and cooling loads are taken into account, taking advantage of the potential of building performance simulation, and assuming a worst-case scenario in which no specific countermeasures are devised to limit the impact of an additional level of insulation on the cooling needs over the warm/hot periods. This approach highlights both the realistic impact on energy needs and also helps understanding the shortcomings of the "Heating Only" approach.
- "Holistic" approach: this approach is defined to both taking into account the changes in energy needs for the building due to the retrofit, and also to account for other changes that can have an impact on the feasibility of the interventions but are usually neglected by more simpler methods, such as the variation in useable space within the building due to the addition of the insulation layer, therefore attempting to better quantify the real repercussions of using different solutions. This approach is also defined to allow to be further expanded to account for other repercussions in the future, such as the potential financial impact of embodied carbon of each assessed solution.

While the two first approaches only account for financial repercussions of energy savings, and the results of the simulations can therefore be directly used in the financial analyses, the holistic approach requires the definition of the variation in internal floor area available due to the refurbishment under the different material solutions considered. In order to attach a value to this variation, the holistic approach implements a comparative analysis between different insulation materials, The amount of space saved must be calculated on a case by case basis depending on the shape of the building, however Equation (1) provides a generalized equation that can be used for buildings with regular shape, as the difference in useable space generated by the use of a better performing material.

$$\mathit{Space\ Saving}\ (m^2) = 2 \times \Delta d \times nf \times \left[\frac{P}{2} - 2 \times (d_1 + d_2)\right] \tag{1}$$

Where:

P = The perimeter of the building being considered [m]
Δd = Thickness difference between insulation materials [m]
nf = Number of floors in the building
$(d_1 + d_2)$ = Sum of thickness of the two insulation materials considered [m]

For each one of the three approaches mentioned above, a detailed financial assessment is performed, based on the Net Present Value (NPV) approach, taking into account the time value of money based on Equation (2), below:

$$\mathit{Cumulative\ NPV} = \sum_{i=0}^{n} \{E_i + Y_i \times 2 \times \mathit{Space\ Saving} - C_i\} \times \frac{1}{(1+r)^i} \tag{2}$$

Where:

E_i = Value in £ of the Energy savings achieved in year i
Y_i = Value in £ of the space saved, in year i
C_i = Expenditure in £ expected, in year i (This expenditure includes the material cost, installation cost and transport cost)
n = Number of years considered in the assessment
r = Discount rate in %

The equation is then appropriately modified in order to disregard the specific cash flows depending on the current approach, with the "Heating + Cooling" approach disregarding the cash flow generated by space savings, and the "Heating Only" approach additionally disregarding the cash flow generated by changes in cooling needs. While performing financial assessment on energy savings, special attention must be given to energy prices, in common practice energy prices are often assumed as constant, and equal to the current energy prices at the time of the assessment, however, since the assessment takes into account a number of years in the future, further refinement can use prediction models to assume a different price of energy for each year in the assessment. This is something that should be considered on a case-by-case basis and is further exemplified in the following case study.

Additionally, the payback time, or payback period, is calculated for each of the above defined approaches and each material used and is defined as the amount of time needed for each intervention to recover its cost through the economic return generated by either the energy or space savings.

In order to calculate this value, a second order polynomial trendline is calculated based on the cumulative NPV of each investment in different years, and the point in time in which such value reaches £0 is identified through inversion of the trendline equation. This allows to calculate the payback time of the investment while also considering the time value of money, which simpler calculation methods do not allow for. Carbon pricing can also impact the financial analysis depending on adopting its different forms including internal carbon pricing, emissions trading system, hybrid schemes, carbon tax, offset mechanism, command and control, and RBCF funding programs [19]. Each mechanism in the context of applied industry can offer specific strengths and weaknesses and will need to be studied in detail for a careful consideration of the most effective mechanism. Carbon pricing is not included in this study but the developed holistic methodology allows for its inclusion for future research, where all other relevant aspects are discussed, informing the decision making process.

Global Warming Potential (GWP – kgCO_2eq) is used as proxy to compare the environmental impact of different insulation materials within the context of the study. These values are extracted from relevant Environmental Product Declarations (EPDs) with a focus on Modules A1–A3 to reduce the uncertainties associated with different service life, transportation and end-of-life scenarios, in line with the requirements of EN 15804 and ISO 14040. Embodied Energy in this study is defined as the primary energy used for the production of the insulation material from cradle to factory gate (including both renewable and non-renewable primary energy). The energy mix in relation to the manufacturing stages are associated with the three locations for which manufacturing data is available due to the lack of data availability for VIP manufacturing in the studied locations. The exploitation values, however, are linked to the energy mix of the exploitation/case study locations. The transportation values have been removed from all insulation materials to keep the uncertainties specific to the material types. Sensitivity analysis is applied to address the range of values presented in the EPDs for the studied materials (Table 1). Unique EPD reference IDs in Table 1 can be used to place the specific studies.

Table 1
Thermal and environmental properties of the studied materials

Material	Operator/reference ID	f.u.	Density (kg/m^3)	λ (W/mK)	GWP (kgCO2eq)	GWP (kg CO2eq/kg)
XPS1	IBU/EPD-DOW-2013111-D	1 m^2-100mm thick	35	0.031	10.2	2.91
XPS2	IBU/EPD-EXI-20140154-IBE1-EN	1 m^2-100mm thick	33.7	0.035	9.4	2.79
XPS3	IBU/EPD-FPX-20140156-IBE1-DE	1 m^2-100mm thick	34.6	0.035	9.5	2.75
XPS4	IBU/EPD-EXI-20140155-IBE1-EN	1 m^2-100mm thick	33.7	0.035	9.4	2.79
MW1	Int-EPD-Sys/S–P-00532	1 m^2-100mm thick	38.5	0.03676	1.2	0.85
MW2	IBU/EPD-KIN-20130163-CBC1-EN	1 m^3	33	0.039	53.7	1.63
MW3	EPD-NORGE/00131E-rev1	1 m^2-100mm thick	29	0.037	1.3	1.21
MW4	IBU/EPD-DRW-2012111-EN	1 m^3	41	0.04	34.4	0.84
MW5	IBU/EPD-DRW-2012121-EN	1 m^3	94	0.04	82.6	0.88
MW6	IBU/EPD-URS-2012131-D	1 m^3	23.5	0.0335	42.6	1.81
MW7	IBU/EPD-URS-2012211-D	1 m^3	22.3	0.0335	41.4	1.86
MW8	IBU/EPD-URS-2012111-D	1 m^3	14.8	0.04	25.4	1.72
MW9	IBU/EPD-URS-2012221-D	1 m^3	15	0.04	28.8	1.92
VIP1	Germany (producer I)/EPD-PDG-2011112-E	1 kg	200	0.007		9.4
VIP2	USA (producer II) – data confidential	1 kg	200	0.007		11.1
VIP3	Belgium (producer III) – data confidential	1 kg	200	0.007		6.4

XPS (Extruded polystyrene insulation); MW (Mineral Wool); VIP(Vacuum Insulation Panel); GWP (Global warming potential); f.u. (functional unit); λ (Thermal conductivity).

The values used for the VIPs are based on fumed silica, the most commonly used core material for building applications.

The final operational energy consumption has been converted to greenhouse gas (GHG) emissions using the following measures for each location as referenced in Ref. [20]:

- UK: 0.233 (kWh to kgCO_2eq).
- Spain: 0.220 (kWh to kgCO_2eq)
- Canada (Ontario): 0.029 (kWh to kgCO_2eq)

The natural gas to GHG conversion factors were used as 0.184 (kWh to kgCO_2eq) for all locations as referenced in Defra's 'environmental reporting guidelines' [21]. These values have been used to calculate the embodied carbon payback time for the analysed scenarios.

This allows for the definition of a carbon payback time on the basis of combined operational and embodied carbon approach allowing for an holistic environmental assessment to be coupled with the financial appraisal described above in this methodology section. In its current form the proposed holistic approach provides two separate figures for financial payback time and carbon payback time. It is important to note based on the proposed methodology those two figures could be combined into a final holistic index if embodied carbon is given a financial impact, for example through the inclusion of carbon pricing; however, this is not currently formalized in the approach as the current carbon pricing approach is too inconsistent and unregulated to be implemented in a robust enough manner.

3. Description of case study buildings

In order to assess the different approaches and retrofit solutions, a case study building is defined in the form of a notional medium-large building of average size and characteristics, the case study has been selected in order to generalise the results obtained from the assessment to a wide number of buildings currently in operation. In England and Wales around 17% of office floor space was built in 1981–1990 and almost one third of that was built in London [22]. In 2011 BPIE survey [23] showed office buildings of floor area greater than 1000 m^2 being the most common architype (47%) in England and Wales.

The building is defined based on the simplified model used to run the energy simulations; therefore, the necessary details are shown in Table 2. The aim is to represent a traditional medium-large multi-storey office building, built between 1985 and 1990 with a total gross floor area of 16,000 m^2. Additionally, the end use category of the building is selected in order to represent the type of building considered to be the most relevant for the proposed holistic approach, for this reason a

Table 2
Case study building details

Building characteristics	Baseline	Refurbished	Units
Length of North/South front	80	–	m
Length of Est/West front	25	–	m
Floor to floor height	3.5	–	m
Number of Floors	8	–	–
End use category	Medium Office		
Structural type	Masonry with concrete floor		
Roof transmittance	0.35	0.18	W/(m^2 • K)
External wall transmittance	0.60	0.28	W/(m^2 • K)
Ground floor transmittance	0.35	0.22	W/(m^2 • K)
Type of windows	Double glazed with PVC frame		
Total north facing windows surface	1120	–	m^2
Total south facing windows surface	1120	–	m^2
Total east facing windows surface	352	–	m^2
Total west facing windows surface	352	–	m^2

medium office type is chosen, assuming this is the type of building where energy refurbishments are more likely to happen at building level and space considerations included in the holistic approach are most relevant due to the rental value of the space. "Building Regulations 1985" [24] and particularly to "Part L" of "schedule 1 – requirements", from UK regulation is used to determine the energy performance of the envelope in the pre-refurbishment stage. This choice has been made to represent realistic standards based on available documentation for the assumed construction period. U-Value of different surfaces within the building are set at the maximum value allowed by the regulations and are detailed in the Table 2, assuming no energy refurbishment took place in the building concerning the opaque envelope.

Since the study aims to assess the impact of different opaque insulation materials it is assumed transparent surfaces have been already refurbished following the building's construction and double-glazed windows with clear glazing and selective filters, with PVC frames are installed with U-Value of 1.66 W/(m^{2}K) and SHGC of 0.42. This assumption is made in order to reduce the impact of unwanted variables on results and restrict the assessment to the above-mentioned insulation materials as described below, although it is expected that in a real refurbishment scenario, attention will be given to all aspects of the building envelope, including transparent surfaces. Similarly, Floors and ceilings, where suitable, are assumed to be insulated with the use of standard materials, independent from the material used for the external walls, in order to better represent the impact of different insulation materials used for vertical surfaces, it is expected that a real application will need to properly consider horizontal surfaces and select appropriate technologies and materials to insulate them.

Finally, it is assumed the case study building features a standard centralized heating system fed by a natural gas boiler with seasonal energy efficiency at 80%, while cooling needs are covered by electric chillers with seasonal cooling energy efficiency assumed at 2.8. No heat recovery is considered for the buildings, and heating and cooling set-points are set at 20°C and 26°C respectively, with setback temperatures during night-time at 17.5°C and 28°C. Those assumptions are kept constant throughout the case study to better highlight the impact of the different materials assessed through the methodology.

It is then assumed that the building needs to be refurbished in order for its envelope to achieve minimum requirements established by current UK regulation, Approved Document L2B: conservation of fuel and power in existing buildings other than dwellings, 2010 edition [25]. Table 2 includes the required transmittance each element in the envelope needs to achieve after the refurbishment in order for the building to be still available for rent. Given the nature of the building and the expected locations, it is assumed that the only available option to improve the envelope U-Values is through the installation of internal insulation, which is expected to have an impact on the internal floor area of the building. For the purpose of this study, three different insulation materials are considered: extruded polystyrene (XPS), mineral wool (MW) and Vacuum insulated panels (VIPs). Since the required transmittance for each component is already established by the regulations, each insulation material is designed to have the appropriate thickness, Table 3 summarizes the basic properties of each assessed material option and provides an estimate on the amount of material used. For VIP design thermal conductivity value of 0.007 W/mK has been used which includes the thermal bridging and ageing effect [8]. The linear thermal bridging at junctions such as walls and floor/ceilings have not been included in any of the scenarios given that these values are case-specific and differ depending on the U-values, construction types, and building element layout adopted, although could offer small changes between the type of material and associated thicknesses used.

Finally, three different locations with variable climate conditions are selected in order for the study to assess the environmental and financial impact of the refurbishment in different climate conditions and financial repercussion. Each location is associated with a large city, in which office buildings are likely to be located and has been selected to represent cold (Toronto), warm (Madrid) and mild (London) conditions in the continental/temperate climate area. The selection was based on the analysis of the typical mean year weather data required to perform the subsequent analyses, and more specifically on the calculation of Heating Degree Days (HDD) for the heating period and Cooling Degree Hours (CDH) for the cooling period. A summary of the weather conditions of the three selected locations: Toronto (CAN), Madrid (ESP) and London (GBR) can be seen in Table 4, below.

In order to allow for direct comparison of the results, all simulations are performed based on the values identified in Tables 2 and 3, and therefore all regulatory requirements are based on the afore-mentioned UK regulations. It is recognised this is a limitation of the current study, as buildings located in each of the three locations analysed are likely to present different requirements based on the enforced local regulations, however, this choice is made to allow for direct comparison of the results between the different locations.

Table 3
Insulation materials properties to achieve refurbishment targets

	Thermal conductivity	Insulation Thickness	Volume of material
	[W/mK]	[m]	[m^3]
XPS	0.033	0.063	369
MW	0.035	0.067	392
VIP	0.007	0.013	78

Table 4
Locations weather summary

	Max. Temp.	Min. Temp.	Av. Temp.	STDEV	HDD	CDH
	[°C]	[°C]	[°C]	[°C]	[°C]	[°C]
Toronto	32.5	−19.4	7.4	10.8	3892	640
Madrid	40.4	−4.6	14.3	8.6	1995	4110
London	31.3	−5.9	10.2	6.0	2923	85

4. Energy consumption analysis

Based on the case study defined in section 3, building performance simulations are carried out using a simplified building description model in line with the inputs defined in Table 2. For each of the three identified simulation, a baseline scenario and each of the defined refurbishment options are simulated. Each simulation is performed with a sub-hourly time step and an hourly reporting step, based on the Typical Mean Year (TMY) weather file available for the location, for the duration of an entire solar year. Both Heating and Cooling needs are identified as the output parameters of the study.

Energy needs for the refurbishment scenario are reported in this study as a single scenario, independently of the material used for the refurbishment, since differences in thermal performances of the different solutions are considered negligible due to how the study is defined; assuming a target U-Value and modulating the thickness of different materials in each scenario in order to reach such value. Nonetheless, simulations have been performed for each material in order to confirm such assumption, variations between the different refurbishment material used have been calculated as less than 0.04% on the annual heating needs and less than 0.06% on the annual cooling needs, without any appreciable variation in the hourly energy needs pattern. This serves as a confirmation of how each of the refurbishment options achieves the same impact on the thermal behaviour of the building, therefore allowing for a direct comparison in terms of cost, space and environmental impact.

Summary results for the Baseline and refurbished scenarios, including both heating and cooling final energy use and energy savings for each location are shown in Table 5. In order to directly compare energy consumption variations between heating and cooling, primary energy for each is calculated through the use of primary energy factors. For the purpose of this case study, primary energy factors published by BRE on behalf of BEIS for the UK have been used, equal to 1.13 for gas and 1.501 for electricity in order to allow direct comparison, however it is expected different countries will have different primary energy factors [29].

Before moving forward with the study, it is important to notice how, depending on the weather conditions of the selected location, simply improving the thermal transmittance of opaque surfaces through the addition of an insulation layer, and not accounting for the impact of such measures on cooling loads can lead to sub-optimal results. Such results can be attributed to the nature of the case study selected, as a medium office, the building is characterized by high internal loads and significant cooling needs throughout the cooling period, even in cold climates.

In each of the analysed location, cooling needs raise due to the installation of additional insulation layers compared to the baseline case, resulting in a reduction in potential energy savings and an increase in the risk of overheating during the summer period. This result is common in each of the analysed locations but becomes increasingly relevant when the warmer and cooling-dominated climate is the selected, as proven by the Madrid case study, where the increase in cooling consumption of 17.7 MWh constitutes a significant portion of the reduction in heating consumptions of 49.4 MWh during the winter periods. It is also useful to note how the rise in electricity consumption in each climatic condition analysed is comparable, despite the significant differences in external temperature patterns, ranging from 18.9 MWh to 11.8 MWh, likely generated by the reduced capacity of the new envelope

Table 5
Summary of Heating and Cooling consumptions and savings

	London		Madrid		Toronto	
	Heating	Cooling	Heating	Cooling	Heating	Cooling
Baseline [MWh]	640.9	45.3	261.4	211.9	1396.2	121.9
Refurbished [MWh]	559.1	54.2	217.6	223.7	1272.6	131.8
Final Energy Savings [MWh]	81.7	−8.9	43.7	−11.8	123.6	−9.7
Primary Energy Savings [MWh]	92.3	−13.4	49.4	−17.7	139.6	−14.8
Total Primary Savings [MWh]	78.9		31.7		124.8	

to disperse energy generated by the internal loads throughout the day. It is suggested that an appropriate design of such a retrofit would need to include adequate measures to remove such excessive energy and reduce the cooling loads, such as the integration of an effective ventilation strategy.

To further assess the shift in energy needs from Baseline to refurbished scenario, Fig. 1 shows the daily energy needs for the building under both assumption for the London location, highlighting both the reduction of heating needs and the increase of cooling needs; where the reduction in heating needs is evenly distributed throughout the heating period, the increase in cooling needs is slightly more uneven and centred around specific days.

5. Space saving calculations

For each refurbishment scenario, difference in building energy requirements is negligible due to achieving the same U-value as detailed in section 4. However, applying different insulation material will have significant impact on required spaced due to their difference in thicknesses needed for achieving the same U-value. This difference in thickness of applied insulation has a direct impact on useable floor space in the building and contributes to generation of economic revenue in terms of rental value of the space.

Equation (1) is applied to the different refurbishment options to calculate the space savings by using thinner VIP insulation compared to XPS and MW. Space saving calculations have shown the floor space saving of 83.12 m^2 and 89.67 m^2 for using VIP instead of XPS and MW respectively. The economic value of this space saving was calculated using average rental value of office space for three city locations (London, Toronto and Madrid). Average rental value in US Dollars for these three locations used for this study are shown in Table 6.

Result of the annual rental income considering the rental value of space saving are shown in Table 7. In all three locations, significant annual rental income can be generated due to applying thinner VIP insulation. The annual rental income in London is almost twice for the similar space saving compared to other two locations due to higher average rental value. This shows in higher rental value locations the use of VIPs can lead to generate higher annual rental income.

Table 6
Rental value for office space in different locations [26,27,28]

	Value per ft^2	Exchange Rate	Value in $\$/m^2$
London	£72.50	1.29	1006.70
Toronto	$59.13	0.75	477.36
Madrid	€ 38.46	1.17	484.36

Table 7
Summary of Space Savings calculations

		VIP vs. XPS	VIP vs. MW
d (m)		0.0495	0.0534
Floor area space saving (m^2)		83.12	89.67
Annual Rental income	London	$83,677.96	$90,267.42
	Madrid	$40,260.44	$43,430.86
	Toronto	$39,678.25	$42,802.83

6. Payback period evaluation

Payback period evaluation can be carried out to assess the financial viability of each refurbishment scenario by considering the capital cost of different insulation material, cost of building thermal energy needs and economic value of space saving. Table 8 shows the summary of cost of different insulation material based on the commercial prices. The cost of each refurbishment scenario has been assumed the same for each location.

Additionally, other assumptions related to thermal energy need calculations are also made for financial payback analysis; seasonal energy efficiency for the heating system is assumed at 80%, powered by a natural gas boiler, with gas costed at 0.04£/KWh; meanwhile seasonal

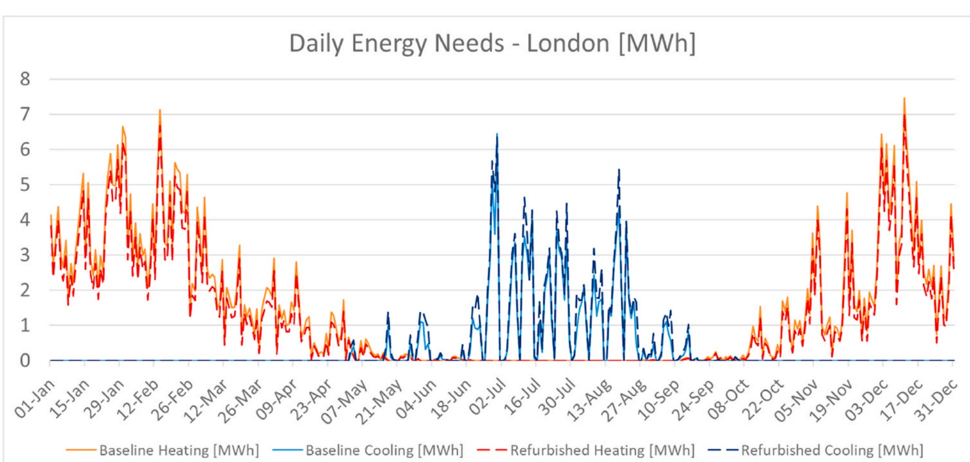

Figure 1. Daily Energy needs for cooling and heating for both baseline case and refurbished case under (London) climate conditions

Table 8
Summary of capital Costs per Refurbishment scenario

	Net Insulation Volume (m^3)	Insulation Cost (£/m^3)	Insulation Cost ($/$m^3$)	Total Insulation cost ($)
Baseline	0.0	0.00	0.00	0.00
XPS	184.4	240.00	309.60	57,084.30
MW	195.8	135.60	174.90	34,255.60
VIP	39.0	2840.00	3663.60	143,059.20

cooling energy efficiency is assumed at 2.8, powered by electric chiller with a unified cost of electricity of 0.19 £/kWh. For this analysis all assumptions are considered to be same for each scenario to allow direct comparison, although it is expected energy costs would vary for different locations.

6.1. Payback period evaluation for heating only approach

Firstly, results of a traditional economic assessment based only on the heating energy demand is performed and shown in Fig. 2, based on a discount rate of 4%. In Fig. 2, the time in years is shown on horizontal axis while vertical axis represents the Net Present value (NPV). It is possible to note how, with this heating only approach, VIPs cannot be financially justified in any of the analysed locations, resulting in an infinite payback time due both to the high capital cost and the limitations of the approach only focusing on energy savings. Additionally, it is possible to note how each refurbishment scenario performs poorly in warm climate conditions, with only mineral wool attaining financial return with a payback time of 24 years, mild and cold climate conditions such as London and Toronto respectively result in more reasonable payback times, with Mineral wool outperforming XPS in each scenario, with the lowest payback time attained being 6.4 years for Mineral wool in cold climate conditions. Nevertheless, even in the most attractive scenario, any energy efficient thermal insulation intervention is difficult to justify from an economic standpoint, with payback time too long for the investment to be financially feasible.

6.2. Payback period evaluation for heating + cooling approach

The traditional approach proposed above lacks to take into account any potential impact on the cooling energy needs, this is typically due to the greater challenge in correctly calculating such values; however, use of building performance simulation a more rigorous approach can be implemented and the assessment can be extended to also include changes in consumptions in cooling during the summer period. Fig. 3 summarizes results of such approach, titled “Heating + cooling” approach.

As shown in Table 5 while assessing the results of the dynamic simulation throughout the paper, cooling loads are increased in each scenario, due the increased U-Values of the walls coupled with the destination use for the building, characterized by significant internal loads and the lack of any measure to reduce cooling loads compared to the baseline buildings. This leads to increased payback times in every scenario, particularly when considering warm climates such as Madrid, in which the increase in cooling loads during summer outweighs, in term of costs, the savings generated by the additional insulation during winter, resulting in an infinite payback time and a downward trending NPV line highlighting the increase in operative costs. Similarly, all other analysed locations also result in worsened outlooks, with Mineral wool still being the best option, but payback times being above 10 years even in the cold Toronto climate, hindering the financial feasibility of the intervention. It must be noted such an increase in cooling loads can be avoided by including specific solutions to reduce cooling loads in the building, however such solution may come at a cost or require a change in behaviour from users in the building and are therefore not accounted in the present assessment.

The above approaches seem to suggest that an energy refurbishment scenario is difficult to justify from a financial standpoint, with even the most optimistic case resulting in a 6.4 year payback time, which is often already too long from a business perspective; additionally traditional insulation is favoured over vacuum insulated panels due to the cheaper installation costs; however such approach is disregarding the impact of the refurbishment on the building in terms of change in useable space,

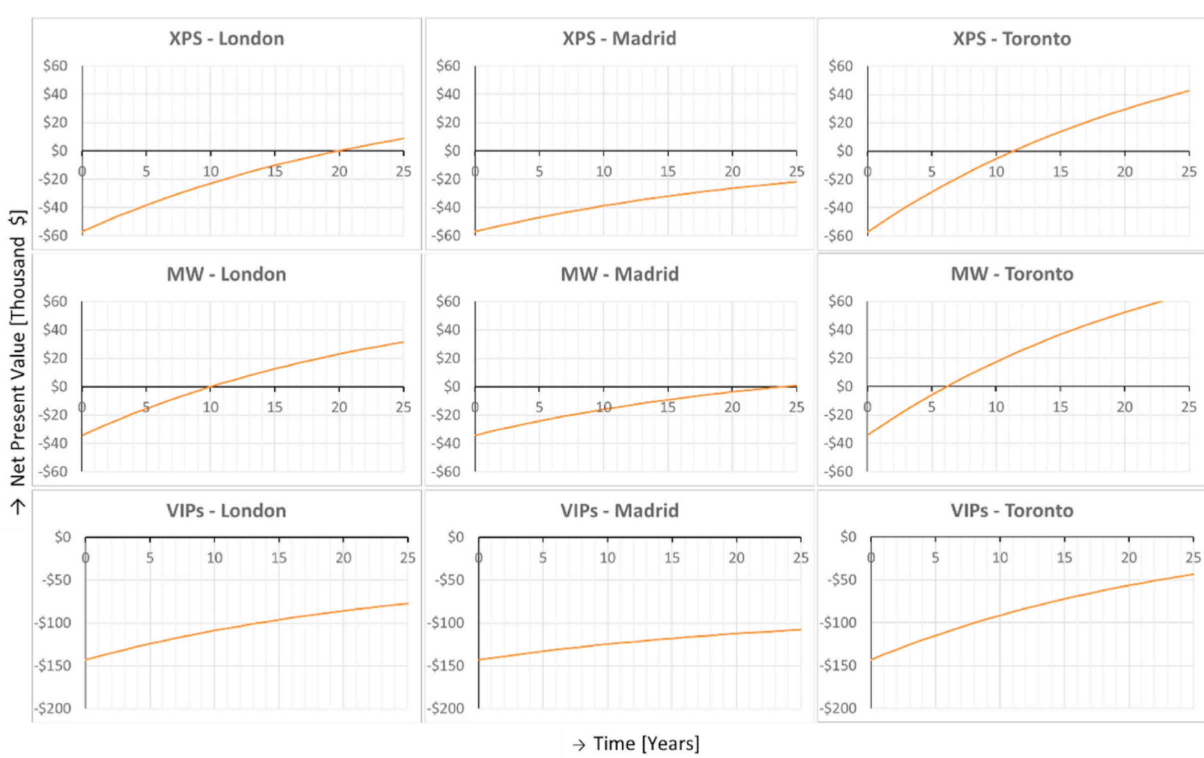

Figure 2. Net Present value (NPV) analysis for Heating Only approach

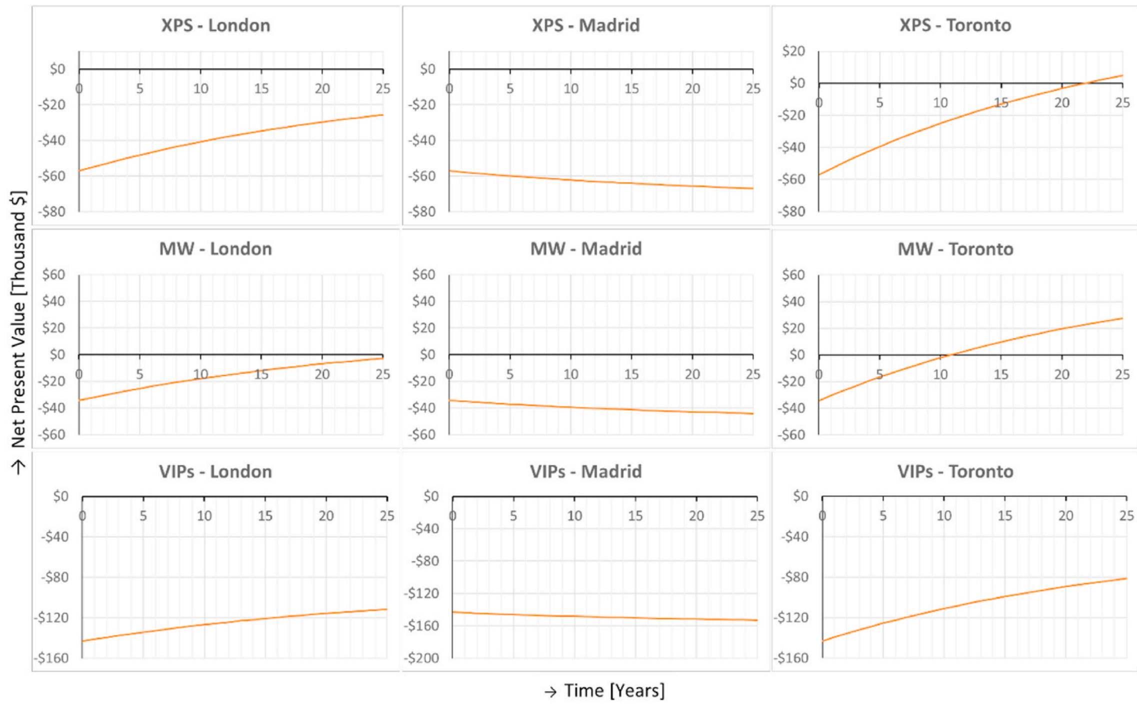

Figure 3. Net Present value (NPV) analysis for Heating + Cooling approach

therefore an holistic approach is used below to account for such impact.

6.3. Payback period evaluation for holistic approach

Under the assumption that the refurbishment to achieve regulatory requirements is necessary to maintain the operation of the building, a more rigorous approach needs to take into account the change in rental value for the refurbished property, due to the loss of space induced by the installation of an internal insulation layer. In this case only focusing on the energy savings is not representative of the real financial impact of the intervention, as long as the space saved by the use of more efficient materials, such as VIPs can be given value, as detailed in Table 6 .

Results of the application of this Holistic approach are shown in Fig. 4; results are shown as a comparative analyses of the use of Vacuum insulated Panels against the other, more traditional, materials addressed in the previous steps, to represent the increase in value generated by the space saved. The assessment only takes into account the physical volume of space saved by the use of VIP panels, which would otherwise be taken up by other materials, and does not take into account the possibility that the need to rely on thick layers of materials within the layout of a real buildings might make some spaces unusable or less attractive due to the reduced size.

The results in Fig. 4 show how, as soon as the space lost due to the installation of an internal insulation layer, is given value in line with the rental market value in any of the three selected locations (shown in Table 6), the business case of using innovative insulation such as VIPs gains favour, quickly recouping the increased capital cost of the intervention due to the additional rent generated by the space saved through the use of a thinner layer of VIP insulation. This is true for each of the locations assessed, ranging from a payback of 4.2 years in Madrid, due to the comparatively low rent value, to 1.3 years in London when compared against mineral wool, due to the high rental value of the

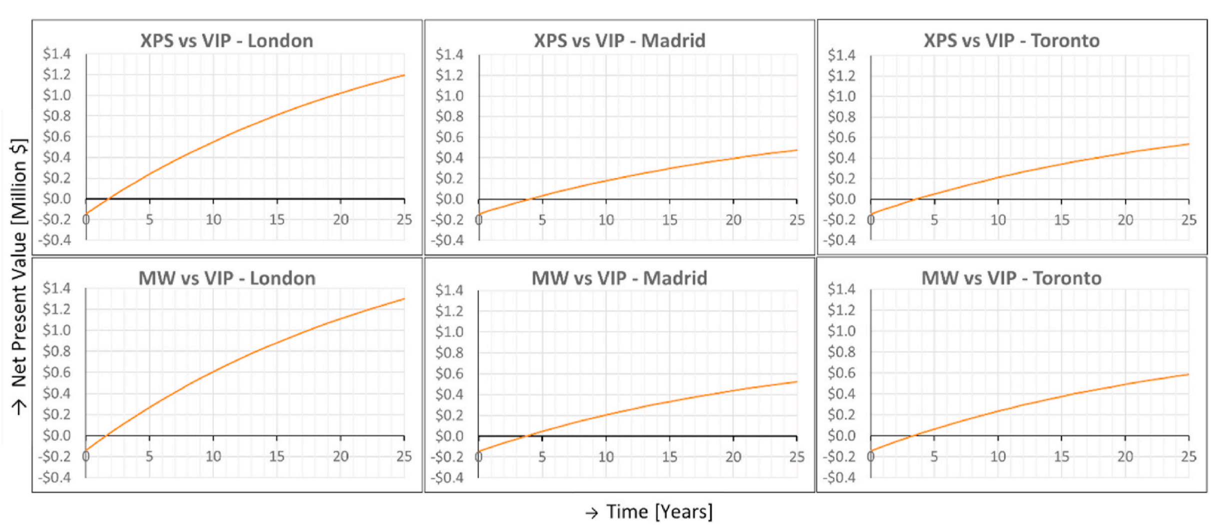

Figure 4. Net Present value (NPV) analysis of VIP compared to XPS and MW using Holistic Approach

space.

Finally, Table 9 include a comparative summary of the results for the financial analysis in the different scenarios and under different approaches, highlighting both how Mineral Wool is the best performing material under a traditional approach, but under the holistic approach, if the space saved by the use of Vacuum Insulated Panels can be given a value, the use of VIPs quickly outperforms any of the traditional insulation materials considered, in each of the locations analysed, with payback times always below 5 years and as low as 1.3 years in London due to the high rent value of the space saved.

6.4. Assessing the impact of changing energy prices

However, the results included in sections 6.1 and 6.2 are assuming constant energy prices for both gas and electricity, at £0.04/kWh and at £0.19/kWh. The holistic approach defined allows us to further enhance the assessment, by studying the impact of varying energy prices throughout time, in order to achieve more robust predictions that can inform the design process. To show this within the case study presented, Table 10 includes the final results in terms of payback time, calculated as done for Table 9 but assuming variable energy prices. For this case study, figures provided in the BEIS 2019 Updated Energy & Emissions Projections [30] for the Service sector have been used for all locations, resulting in a constant annual increase of 3.1% for cost of natural gas, and 0.2% for electricity in the reference scenario. It is important to note due to high volatility of energy price projections, both based on time and location, such values should only be considered as a reference for this case study, and any application of the methodology should consider the use of updated and relevant figures.

By comparing results in Tables 9 and 10, it is possible to note how each analysed scenario shows a reduced payback time, due to the increasing energy prices assumed over the years. This leads to a more positive financial assessment of the energy efficiency measures, with most now showing a solid, albeit long payback time. The holistic approach changes results the least affected by changing energy prices, due to the high financial impact of the space saved, with only minor differences between the two tables. It must be noted how the starting assumptions favour energy efficiency measures, due to the increasing energy prices, and in particular favour energy measures reducing gas consumptions, due to the higher increase in natural gas compared to electricity; this might not be the case under different price change assumptions, including projections that might suggest a decrease in energy price, therefore it is essential to apply the most relevant projections on a case by case basis when performing such analyses.

Furthermore, this approach can be used to account for uncertainty in energy price predictions, by assessing the same intervention under different pricing scenarios and providing as a result a range of potential payback times and financial returns, increasing the confidence in the

Table 9
Payback time summary in years

		XPS	MW	VIP	VIP (vs XPS)	VIP (vs MW)
		[years]	[years]	[years]	[years]	[years]
London	**Heating**	19.8	10.1	Infinite	-	-
	Heat + Cool	Infinite	30.9	Infinite	-	-
	Holistic	-	-	-	1.7	1.6
Madrid	**Heating**	Infinite	24.0	Infinite	-	-
	Heat + Cool	Infinite	Infinite	Infinite	-	-
	Holistic	-	-	-	4.2	3.8
Toronto	**Heating**	11.6	6.4	Infinite	-	-
	Heat + Cool	22.2	11.1	Infinite	-	-
	Holistic	-	-	-	3.8	3.5

Table 10
Payback time summary in years

		XPS	MW	VIP	VIP (vs XPS)	VIP (vs MW)
		[years]	[years]	[years]	[years]	[years]
London	**Heating**	14.5	8.5	40.7	-	-
	Heat + Cool	24.1	15.0	54.0	-	-
	Holistic	-	-	-	1.7	1.6
Madrid	**Heating**	28.7	16.3	Infinite	-	-
	Heat + Cool	57.3	46.7	84.9	-	-
	Holistic	-	-	-	4.0	3.7
Toronto	**Heating**	9.4	5.5	25.1	-	-
	Heat + Cool	13.8	8.4	34.0	-	-
	Holistic	-	-	-	3.6	3.3

investment required to implement the defined energy efficiency measures. For the purpose of this case study, this approach is presented below by focusing on the London climatic scenario and assessing the installation of XPS against VIP.

Based on the BEIS 2019 Updated Energy & Emissions Projections previously used, it is possible to define various price variation scenarios, for this case study, the following scenarios are defined:

- A reference scenario ("Ref") defined as above and based on central estimates of economic growth and fossil fuel prices, where the annual price increase is set at 3.1% for natural gas, and 0.2% for electricity
- A low price scenario ("Low") defined as the reference scenario but with lower projected fossil fuel, where the annual price increase is set at 1.2% for natural gas, and 0.0% for electricity
- A high price scenario ("High") defined as the reference scenario but with higher projected fossil fuel, where the annual price increase is set at 5.3% for natural gas, and 0.5% for electricity

Results for the different scenarios can be seen in Fig. 5 below.

It is possible to notice how, scenarios with high price increase in energy costs favour the installation of energy efficiency measures, resulting in lower payback times, while low price scenarios have the opposite effect. Since those pricing scenarios are all projections, one cannot be considered more likely than the other, and conclusions should be taken based on the range of obtained results, with financial assessments focusing only on energy savings resulting in a range of payback time of 18.1–40.1 years for XPS and 35 to an infinite number of years for VIP. However, the holistic approach remains less influenced by energy price changes, both due to the shorter payback time, and the significant value of the space saved, resulting in a constant 1.73 years payback time throughout all scenarios and a narrow range in financial projections, also visible in Fig. 5.

7. Embodied carbon implications

The values presented in Table 11 demonstrate the embodied carbon (GWP as the proxy) payback time associated with the operational savings. All three climates, the two heating and cooling scenarios, and the range of embodied carbon values from EPDs have been included in the analysis. The effect of embodied carbon variations has been reflected in the range of payback period in each specific scenario and location.

The analysis demonstrates that the embodied carbon investment associated with the refurbishment work takes a significantly longer time for VIPs, compared with the MW and XPS, to be recovered by the operational savings (4–5 times longer for all scenarios). This is attributable to the higher embodied carbon of VIPs as presented in Table 11 due to the use of fumed silica as the core material. This study is not taking into account the use of recycled core materials for the VIPs, but

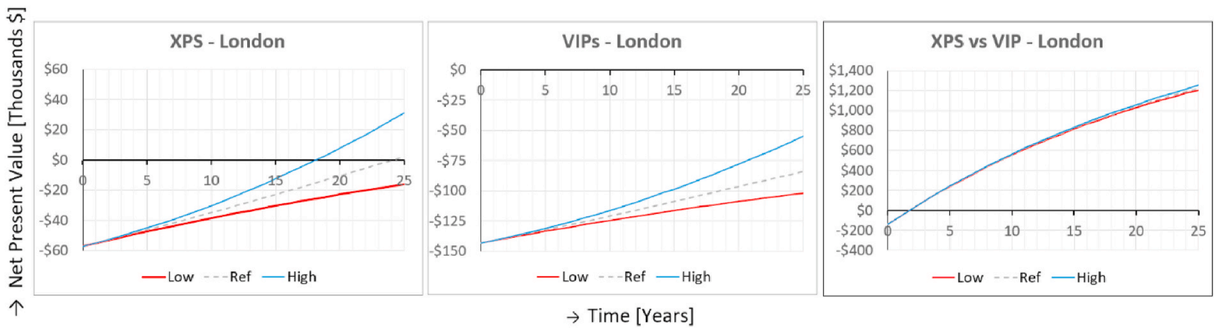

Figure 5. Net Present value (NPV) analysis of XPS and VIP in London for different energy pricing scenarios

Table 11
Embodied carbon payback period for all scenarios

	heating only		Heating and Cooling	
	Net carbon benefit of operational savings (kgCO$_2$)	Carbon Payback (years)	Net carbon benefit of operational savings (kgCO$_2$)	Carbon Payback (years)
	UK			
XPS	12021.6	2.8–3.1	6177.1	5.6–6.1
MW		0.8–1.75		1.6–3.4
VIP		8.3–14.4		16.1 - 28
	Spain			
XPS	6440.7	5.3–5.8	−807.2	Infinite
MW		1.5–3.2		Infinite
VIP		15.5–26.9		Infinite
	Canada			
XPS	18190.8	1.9–2.1	17390.1	2 - 2.2
MW		0.54–1.15		0.57–1.2
VIP		5.4–9.5		5.7–9.95

this can have a significant impact on the environmental competitiveness of VIPs with the other conventional insulation materials.

A more detailed look into the effect of location on the analyses suggest that the improved building fabric in Spain is increasing the cooling loads beyond the heating load savings and therefore the additional associated embodied carbon investment in the materials is not recovered. In the case of Canada although the cooling load is increased as a result of the refurbishment work, the lower grid electricity mix conversion factor (for Toronto) allows for a total operational saving to occur and therefore the embodied carbon investment effectively recovered. Canada is showing the shortest embodied carbon payback time between the locations studied. The UK climate, due to its moderate nature is performing better than Spain in terms of payback time but not as well as Canada.

8. Conclusions

Correctly assessing the environmental and financial impacts of improving energy efficiency through retrofitting building envelope is a fundamental requirement in order to identify the optimal solutions in different contexts. Traditional evaluation methods are tailored toward conventional thermal insulation materials, and their simplified approach poses limits, often leading to undesired or suboptimal results. These limitations become increasingly important in the case of applying new and innovative advanced thermal insulation materials, often needed to achieve stringent energy efficiency targets and regulations. This is the case, for example, for Vacuum Insulated panels, where traditional evaluation methods cannot correctly quantify the impacts of the material compared to traditional alternatives. Hence, the present work introduced a new holistic assessment methodology able to take into account energy, economic and embodied carbon implications for the use of different materials, allowing to correctly evaluate the economic and environmental feasibility of their use.

In order to demonstrate the use of the proposed holistic approach, a case study has been implemented, assessing the refurbishment of an average sized office building under three different climate conditions (London, Madrid, Toronto). This shows how, from a financial standpoint, a traditional "Heating Only" approach would favour the use of traditional materials, such as mineral wool with a Payback time of 10 year under London climate conditions. However, correctly accounting for all energy impacts in the "Heating + Cooling" approach shows how financial returns are less appealing, pushing the payback time beyond 25 years in London for any material assessed, and even generating a negative financial return in warmer climates such as Madrid. Finally, the proposed holistic approach shows how correctly accounting for the financial impact of lost space due to the refurbishment will significantly change outcomes as soon as the space lost has an economic value, such as for rented office buildings, favouring innovative materials requiring a higher initial investment but significantly reducing the amount of lost space due to their reduced thickness, such as the case for VIPs with payback time lower than 4 years under all analysed climates. The methodology also allows and recommends for accounting of projected energy price changes, as demonstrated in the case study, leading to more robust and reliable results to guide refurbishment choices and highlighting how the holistic approach as the one proposed helps reduce the variability of financial results thanks to being more resilient against energy price changes.

However, a correct environmental feasibility cannot only account for operational energy savings, but also needs to consider embodied carbon associated with the use of different materials. Due to the definition of the case study, with the target of reaching a specified U-Value during the refurbishment, operational energy and GHG emission savings are equal for each material, but embodied carbon can be significantly different, and therefore needs to be properly accounted for. The proposed methodology includes embodied carbon assessment, and its application to the case study shows how, in the current environment, traditional materials can be preferable now, with Mineral Wool has the lower Carbon Payback time of 1.6–3.4 years while VIPs have significantly higher Carbon Payback time of 16–28 years in the London Climate. For VIPs to be more environmentally competitive, lower impact core materials or alternatively higher percentage of recycled/reused fumed silica need to be considered in their production.

This holistic approach can also be used to assess other innovative insulation materials in a comparative framework, and if necessary, could be expanded to account for additional aspects and impacts such as loss of performance over time, or impact of climate change. A further step in the definition of the holistic approach would be to unify the two assessment strands, financial and environmental, into one single indicator to provide a singular answer to the assessment of the optimal insulation material to use; however, for this to happen it would be necessary to give an economic value to GHG emissions both for operational and embodied carbon, this would therefore require the introduction of carbon pricing, which at the moment is considered too inconsistent and unregulated to be implemented in a robust enough manner.

The proposed holistic approach to assess the environmental and financial impact of applying thermal insulation materials in building retrofitting will allow designers, assessors, manufacturers, engineers, and the construction industry as a whole to better understand the implication of the use of different materials and make more informed decisions on material selection. The approach will also provide a framework to assess new and innovative materials coming to market, allowing the industry to move beyond the limits of traditional assessment techniques and assess each material based on their expected impact during the life cycle of the building.

CRediT authorship contribution statement

Mahmood Alam: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Marco Picco:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis. **Shahaboddin Resalati:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] UN Environment and International Energy Agency, Towards a Zero-Emission, Efficient, and Resilient Buildings and Construction Sector, 2017. Global Status Report 2017. Available Online: https://www.worldgbc.org/news-media/global-status-report-2017. (Accessed 5 August 2021).
[2] S. Brunner, H. Simmler, In situ performance assessment of vacuum insulation panels in a flat roof construction, Vacuum 82 (2008) 700–707.
[3] S.S. Alotaibi, S. Riffat, Vacuum insulated panels for sustainable buildings: a review of research and applications, Int. J. Energy Res. 38 (2014) 1–19.
[4] M. Alam, H. Singh, M.C. Limbachiya, Vacuum Insulation Panels (VIPs) for building construction industry – a review of the contemporary developments and future directions, Appl. Energy 88 (2011) 3592–3602.
[5] S. Brunner, K.G. Wakili, T. Stahl, B. Binder, Vacuum insulation panels for building applications – continuous challenges and developments, Energy Build. 85 (2014) 592–596.
[6] S. Resalati, T. Okoroafor, P. Henshall, N. Simões, M. Gonçalves, M. Alam, Comparative life cycle assessment of different vacuum insulation panel core materials using a cradle to gate approach, Build. Environ. 188 (2021), 107501.
[7] M.A. Mujeebu, N. Ashraf, A. Alsuwayigh, Energy performance and economic viability of nano aerogel glazing and nano vacuum insulation panel in multi-story office building, Energy 113 (2016) 949–956.
[8] M. Alam, H. Singh, S. Suresh, D.A.G. Redpath, Energy and economic analysis of Vacuum Insulation Panels (VIPs) used in non-domestic buildings, Appl. Energy 188 (2017) 1–8.
[9] T. Lim, J. Seok, D.D. Kim, A comparative study of energy performance of fumed silica vacuum insulation panels in an apartment building, Energies 10 (12) (2017) 2000, https://doi.org/10.3390/en10122000.
[10] H. Wallbaum, J. Kono, Long-Term Performance of Super-insulating Materials in Building Components and Systems Report of Subtask IV: Sustainability Life Cycle Assessment: LCA - Life Cycle Cost: LCC Embodied Energy: EE, International Energy Agency, 2020. EBC Annex 65. available Online:https://vipa-international.org/wp-content/uploads/2021/11/EBC-Annex-65-Final-Report-st4-20-01-03-HW-DQ.pdf. (Accessed 12 October 2021).
[11] S. Fantucci, S. Garbaccio, A. Alice Lorenzati, Thermo-economic analysis of building energy retrofits using VIP - vacuum Insulation Panels, Energy Build. 196 (2019) 269–279.
[12] K. Biswas, T. Patel, S. Shrestha, D. Smith, A. Desjarlais, Whole building retrofit using vacuum insulation panels and energy performance analysis, Energy Build. 203 (2019), 109430.
[13] N. Simões, M. Gonçalves, C. Serra, S. Resalati, Can vacuum insulation panels be cost-effective when applied in building façades? Build. Environ. 191 (2021), 107602.
[14] E. Di Giuseppe, M. Iannaccone, M. Telloni, M. D'Orazio, C. Di Perna, Probabilistic life cycle costing of existing buildings retrofit interventions towards nZE target: methodology and application example, Energy Build. 144 (2017) 416–432.
[15] J. Wernery, F. Mancebo, W.J. Malfait, M. O'Connor, B.P. Jelle, The economics of thermal superinsulation in buildings, Energy Build. 253 (2021), 111506.
[16] S. Resalati, C.C. Kendrick, C. Hill, Embodied energy data implications for optimal specification of building envelopes, Build. Res. Inf. 48 (2020) 429–445.
[17] P. Karami, N. Al-Ayish, K. Gudmundsson, A comparative study of the environmental impact of Swedish residential buildings with vacuum insulation panels, Energy Build. 109 (2015) 183–194.
[18] M. Picco, M. Marengo, A fast response performance simulation screening tool in sup-port of early stage building design, Building Simulation (2019), 2019, September 2nd-4th, 2019, Rome, Italy (2019).
[19] Carbon Pricing Leadership Coalition; International Finance Corporation, Greening Construction: the Role of Carbon Pricing. International Finance Corporation, © International Finance Corporation, Washington, DC, 2019. https://openknowledge.worldbank.org/handle/10986/31765 License: CC BY-NC-ND 3.0 IGO.
[20] T.M. Carbon Footprint, Country specific electricity grid greenhouse gas emissions factors, available Online: https://www.carbonfootprint.com/docs/2020_06_emissions_factors_sources_for_2020_electricity_v1_1.pdf accessed, 2020. (Accessed 15 July 2021).
[21] BEIS 2021, Greenhouse gas reporting: conversion factors 2021, Available Online: https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2021. (Accessed October 2021).
[22] Department for Communities and Local Government (DCLG), Age of commercial and industrial stock, Borough (2010). Available Online: https://data.london.gov.uk/dataset/age-commercial-and-industrial-stock-borough. (Accessed 12 April 2020).
[23] Buildings Performance Institute Europe (BPIE), Europe's buildings under the microscope: a country-by-country review of the energy performance of buildings. https://www.bpie.eu/publication/europes-buildings-under-the-microscope/, 2011. (Accessed 17 August 2020), 9789491143014.
[24] The Building Regulations 1985 no. 1065, Available Online: https://www.legislation.gov.uk/uksi/1985/1065/pdfs/uksi_19851065_en.pdf. (Accessed 12 July 2020).
[25] Approved Document L2B, Conservation of fuel and power in existing buildings other than dwellings, 2010 edition (incorporating 2010, 2011, 2013 and 2016 amendments), Available Online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/540329/BR_PDF_AD_L2B_2013_with_2016_amendments.pdf. (Accessed 12 July 2020).
[26] The London office market Report Q2, Available Online: https://www.knightfrank.com/research/report-library/the-london-office-market-report-q2-2019-6580.aspx, 2019. (Accessed 17 November 2020).
[27] Spotlight Madrid offices Q3, Available Online: https://pdf.euro.savills.co.uk/spain/nat-eng-2019/savills-an-madrid-offices-spotlight-q3-2019-eng.pdf, 2019. (Accessed 17 November 2020).
[28] Toronto, Q1 office market Report, Available Online: https://pdf.euro.savills.co.uk/usa/market-reports/research-mim-toronto-q1-2019.pdf, 2019. (Accessed 17 November 2020).
[29] BEIS 2021. The Government's standard assessment procedure for energy rating of dwellings version 10.2 (2021) table 12: fuel prices, emission factors and primary energy factors. Published on behalf of BEIS by BRE. Available Online: SAP 10.2 - 17-12-2021.pdf (bregroup.com) [Accessed 12/01/2022].
[30] BEIS 2020, Updated energy & emissions projections (2019) Annex M - growth assumptions and prices. https://www.gov.uk/government/publications/updated-energy-and-emissions-projections-2019. (Accessed 14 January 2022).