Can vacuum insulation panels be cost-effective when applied in building façades?

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Abstract

A key factor for achieving nearly-zero energy buildings is to reduce their energy demand using highly efficient thermal insulation materials, such as vacuum insulation panels (VIPs). Currently, the high investment cost of VIPs is hindering the technology penetrating the building market. However, their high thermal performance coupled with reduced thicknesses can lead to economic benefits associated with space savings, significantly changing the economic standing of VIPs. This study presents a comprehensive life cycle cost (LCC) analysis of the application of VIPs in external thermal insulation composite systems (ETICS) in office building façades performed from the landlord perspective. The proposed LCC methodology, based on the EU cost-optimal regulation, allows for comparing the cost-effectiveness of VIPs with conventional insulation materials, taking full account of the additional rental income due to space savings. Energy calculations are performed based on transient heat transfer for a unit area of a wall. The study takes into account varying parameters, such as location, cost of materials, insulation thickness, and rental prices, among others. The results demonstrate that VIPs can be economically viable, in particular in cities where office full-leasing rental prices are high. The range of VIP and rental prices that make their use in buildings cost-effective are identified. This analysis is useful for VIP manufacturers, project owners and landlords that may be looking for competitive insulation products.

Keywords: Life Cycle Cost Analysis; Vacuum Insulation Panels; ETICS; Numerical simulation; Cost-optimal analysis.

1. Introduction

The worldwide demand for energy savings calls for improvements in buildings' thermal performance requirements. In Europe, the Energy Performance of Buildings Directive (EPBD), first published in 2002 [1] and more recently recast as Directive 2018/844 [2], has imposed that Member States set minimum performance requirements based on cost-optimal levels and has established nearly-zero energy buildings targets. Given that 50% of European Union (EU) final energy is used for heating and cooling, of which 80% is used in buildings [2], there is a definite need for promoting the use of renewable sources and the general use of more advanced materials and technologies in the building sector.

The EPBD is pushing countries towards the implementation of high standards of energy efficiency requirements. These requirements are defined by each Member State using a general common framework ([3],[4]) with a view towards achieving the cost-optimal balance between the investments involved and the energy costs saved throughout the life-cycle of the building. However, it is highly recommended that building owners acting as landlords do their own detailed cost-optimality evaluations. In particular, if they are offering a full-service leasing arrangement (i.e., all the costs and benefits of energy investments accrue to the landlord alone), envelope solutions and technical systems selection should be done following the Net Present Value (NPV) criterion which takes into account series of cash flows occurring at different times.

In order to meet the increasingly stricter thermal requirements being put upon the building envelope, designers and builders are being forced to use thicker layers of insulation material. Currently, 500 mm of Mineral Wool (MW) or Expanded Polystyrene (EPS) [5] are being used in some countries to meet the thermal performance requirements and ensure indoor thermal comfort. As the thickness of the building envelope wall increases, the ratio of net to gross floor area calculated on a building perimeter basis is adversely affected. As a result, the rental or sale value of the building may change. From an economic point of view, in buildings with high rental values the savings achieved from the increased insulation material (less energy use) may not make up for the global costs due to the loss of rental value (area reduction). Furthermore, an excessively thick envelope layer may not be desirable for a number of technical and aesthetic reasons such as architectural/design limitations, application difficulties, higher risk of anomalies due to mechanical failure, amongst other issues [6]. Consequently, a new generation of super insulation materials, such as those using vacuum technologies [7], are entering into the market looking to achieve higher levels of thermal resistance with lower thickness.

Vacuum insulation panels (VIPs) consist of an evacuated open core material surrounded by thin laminates, composed by a barrier envelope used to maintain vacuum. VIPs offer significantly lower panel thicknesses for a given unit of thermal resistance (6 to 7 times better performance) when compared to conventional insulation materials. However, it is mainly applied to niche markets, with their total market share in insulating materials being of less than 1% [8]. This is primarily related with the relatively high market price of VIPs, which is due to their production costs being higher [9]. Issues related with the challenges of designing and executing construction works with non-adjustable and fragile panels also contribute to the high cost for current VIPs building products. This is evident in the fact that only 20% of the VIPs used worldwide are for building applications. Since investment profitability in buildings depends on the cost of the insulation material [10], a great challenge facing the vacuum industry and researchers is the development of high performance products for buildings applications with lower costs. Besides initial investments costs, there are also uncertainties surrounding the long-term thermal performance of VIP products, as well as around the thermal bridging effect. Since the VIPs are encased in a metallized barrier against permeation of moisture and gas, special attention has to be given to the edge effect at the joints of the panels [11], where the higher thermal conductivity of the barrier material promotes additional heat losses. Edge thermal bridging effects have a strong impact on the effective thermal conductivity of VIPs, especially in smaller panels ([12], [13], [14]). These issues can influence the profitability of energy efficiency measures and, therefore, should be considered in the economic studies.

The global market for Vacuum Insulation Panels is estimated at US$7.2 Billion in the year 2020, and is projected to reach US$10 Billion by 2027, growing at a Compound Annual Growth Rate (CAGR) of 4.8% [15]. Therefore, the deployment of this insulation solution for new and existing structures has inherently great potential. Additionally, integrating VIPs into already well-known building products and solutions (e.g. External Thermal Insulation Composite Systems (ETICS)) that could facilitate their fast and wide-scale commercialisation is considered to be key to the further development of VIP building products. The advantages and challenges posed by this solution have been described by the authors previously [14].

From a capital investment point of view, VIPs struggle to compete with cheaper conventional insulation materials. However, in some applications the gain of rentable floor area due to the slimness of the solution could outweigh the higher initial investment cost. In the case of non-residential buildings, and, in particular, in offices located in high-priced areas, such as the business centres in European capital cities, rental gains could be maximized without compromising the thermal performance of the building by using VIPs. Annual rental prices in offices are very dependent on location and population density. For example, real full-service leasing rental prices of 300 €/(m^2.year)) in Warsaw, 456 €/(m^2.year)) in Berlin and 882 €/(m^2.year)) in London can be found [16]. Given these values, the potential for achieving higher ratios of rentable floor space relative to overall building area and higher land use rates should be considered at the planning and design stage, particularly for bigger developments. Additionally, it is known that implementing energy efficiency measures in existing buildings can further increase the rental value, benefiting the landlords [17].

1.1 Literature review

There are several research studies focused on the assessment of the profitability and the cost-optimal thickness of the insulation materials in building applications [18–25]. However, few studies consider the use of super insulation materials such as vacuum-based products. The economic feasibility of vacuum technology application in buildings has been recently investigated by following different approaches. Jelle [7] published an insulation materials review paper, which included a simplified approach to quantify the potential cost savings when applying VIPs in the middle of the walls construction. Alam *et al.* [26] analysed the payback period for VIP and EPS and concluded that EPS payback is always lower than VIP solutions. However, space savings were not taken into account. Cho *et al.* [27] showed the economic benefit of VIPs over conventional insulation materials in the Korean market. However, they compared different levels of insulation, which will lead to different levels of thermal comfort and energy savings. A multi-story office building located in Saudi Arabia was also studied regarding the energy performance and economic feasibility of a nano VIP [28]. They concluded that the profitability of VIP in walls is strongly influenced by climate and in the case of high cooling needs it may not be economically viable. Di Giuseppe *et al*. [29] stated that the benefit from super insulation materials was not enough to achieve optimal costs due to the high investment cost of the solution.

The benefits of space floor savings were considered in few studies. Alam *et al.* [30] concluded that fumed silica VIPs were found to be economically viable in high rental value locations assuming a service life of up to 60 years. In this case, the object of the study was a residential reference building and the energy needs were based on steady-state calculations, potentially leading to unrealistic energy use estimations. Fantucci *et al*. [31] proposed the evaluation of office buildings using the test room from ISO 52016 as a reference [32]. The authors calculated the discounted payback period and break-even rental value and found that VIPs can be cost-effective. However, the energy prices evolution during the period of calculation were not included, and the economic indicators for different cities remained fixed. Such economic data can be decisive to evaluate the economic feasibility of investments in insulation materials. These previous studies show a wide disparity of outcomes. Differences like these may be considered acceptable since economic studies such as these depend on a great number of factors such as: methodology approach, climate data, reference building typology, energy carrier, VIPs market prices, energy prices and other economic indicators that strongly influence the results. Only one study [29] used the global cost method proposed in EN 15459 [33] which was subsequently adopted by European cost-optimal methodology framework, published in the Delegated Regulation no. 244/2012 ([3],[4]). However, a macroeconomic perspective including costs of greenhouse gas emissions was not present in this study.

There is a gap in the literature for analysing the cost-effectiveness of vacuum-based ETICS applications, addressed in this paper. Furthermore, the different methodological approaches and assumptions used have led to outcomes that are difficult to compare, with only one study using the global cost methodology framework proposed by the EU.

It should be noted that the EU cost-optimal methodology focuses primarily on operational energy. Nonetheless, research studies have indicated that the embodied energy for thermal insulation materials may be higher than the operational energy they save during service life ([52],[53],[54],[56]). The environmental impacts and the consumption of renewable and non-renewable primary energy on the embodied, transport, and operational energy for vacuum insulation materials should also be addressed, since vacuum panels may have an environmental impact greater than other insulation materials [55].

The present paper aims to assess the cost-effectiveness of using VIPs in ETICS façades by using a comparative methodology based on the European cost-optimal methodology ([3],[4],[34]). Even though the EU cost-optimal methodology does not take into account the embodied energy of insulation materials and focuses solely on the buildings use phase, adopting this standardised methodology will allow for the results to be replicable and comparable, effectively contributing to future decision making processes by the end users of these solutions through providing transparent information regarding their investment.

The cost-optimal methodology is based on calculations of initial investment and annual energy needs for heating and cooling. For these calculations, a reference building is often used to represent the building stock. Methodologies for reference buildings definition have been discussed by researchers ([36],[37]). Different assumptions regarding parameters such as window-wall ratio, internal loads, airflow rate, etc. strongly affect the calculations, leading to inconsistent results with different best solutions. The authors propose to go around this issue by means of an alternative approach considering the energy balance based on transient heat transfer calculations for a unit area of a wall. This methodology allows for a more direct and easier comparison between insulation materials since it avoids other parameters that influence energy use calculations. This is a novel approach when compared with the state-of-the-art. Since no previous works were found with a macroeconomic perspective over VIP insulation, this works also included this analysis.

1.2 Objectives

The main goal of the present paper is to perform a comprehensive LCC analysis is performed looking to assess the cost-effectiveness of using VIPs in ETICS façades in office buildings. The study uses a comparative methodology based on the European cost-optimal methodology framework published in the Delegated Regulation no. 244/2012, with the added benefits of the rental income taken into account, as made possible by ISO 15686-5.

While building owners and developers will often only consider the cost of construction, other costs should be considered in order to evaluate the optimal cost of construction. This is particularly relevant from the landlords' perspective for the case of a full-service lease where the landlord takes care of all operating costs, including energy costs. Such comprehensive LCC analyses support the decision makers and investors when considering VIPs as an option in the early stages of design for new building or retrofitting scenarios. This in particular can be used to evaluate the viability of VIP solutions when compared with conventional thermal insulation materials.

In the following section, the external wall under study is presented and characterized followed by detailing of the methodology employed for estimating the energy performance of the wall. As mentioned, instead of calculating energy needs using a reference building, it is proposed that energy balance through walls is used to evaluate the impact of changing the insulation level. The energy balance between heat losses and solar gains through the walls is calculated using dynamic thermal simulation and is used directly in the LCC analysis. Then, the methodology used to calculate the life-cycle costs is presented. Since this analysis is performed from the landlord perspective considering full-service leasing, the beneficial aspect obtained from increasing rental area (when using VIPS) is considered in the calculations. The results are compared with those obtained for a conventional EPS based ETICS solution, as one of the most commonly used insulation materials on the market. Then, the results are discussed and some limitations are identified. Finally, the main conclusions from the study are drawn up.

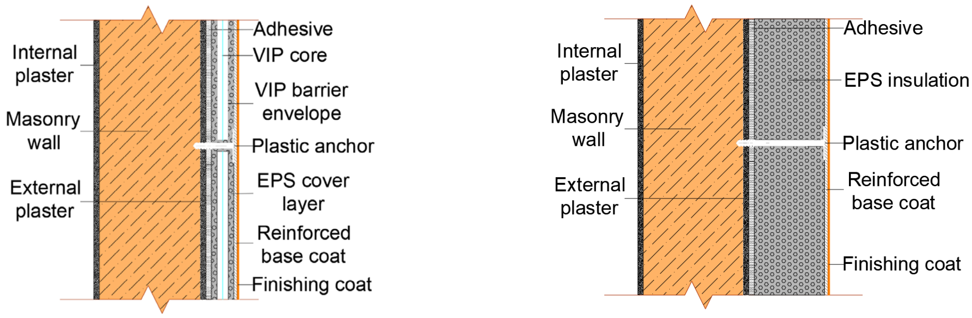
2. Materials and methods

The present study performs a life cycle cost analysis to assess the cost-effectiveness of using VIPs in ETICS façades in office buildings. Several factors that may affect the outcome of economic calculations, in accordance with the cost optimal methodology, are taken into account. These factors include variables that affect the thermal performance of the VIP solution (degradation with time, the edge effect and varying panel size), maintenance costs, energy costs, rental incomes and residual values. Additionally, a sensitivity analysis is carried out to include variations of initial investment costs, energy carriers, energy price predictions, service life of VIPs and rental prices.

Unlike the European common framework methodology which requires the calculation of the energy needs for a reference building, the energy balance calculations are performed at the level of the construction solution (ETICS wall). These calculations are performed for different VIP sizes using a dynamic thermal simulation software (BISTRA [38]). The ETICS wall is considered to be located in Berlin, London and Helsinki as representative climatic zones. These results are compared to those obtained for an ETICS wall with EPS, the most used insulation material due to its low cost [25]. The paper discusses not only a financial perspective but also a macroeconomic perspective. It also presents other financial indicators such as discounted payback period (dPB) and internal rate of return (IRR).

2.1 Definition of the external wall

The solution under study is an external wall with an ETICS application that incorporates a) a VIP product (Figure 1a), and b) a conventional ETICS solution built with EPS (Figure 1b). The product is a fumed silica vacuum panel with multi-layered metalized barrier (thermal conductivity at centre of panel of 0.0042 W/(m.K)) encapsulated in EPS. The EPS cover layer (10 mm thick layers at the faces of the panels and 20 mm thick at the edges) provides protection against mechanical damage which, along with adhesive and supplementary mechanical fixings, allows for the application of the ETICS. The standard size of the VIP product is assumed to be 640 mm x 640 mm. Additionally, a sensitivity analysis was performed and calculations were also made for smaller panels (440 mm x 440 mm) and larger panels (1040 mm x 640 mm). The ETICS solution is applied onto a conventional masonry wall (220 mm) plastered on both sides. The wall is 3 meters tall.



a) b)

Figure 1: Cross-section of external walls: a) VIP ETICS solution; b) EPS ETICS solution.

The thermophysical properties of the external wall materials are shown in Table 1. A solar reflectance of 0.72 is considered for the finishing coating.

Table 1: Thermophysical properties of the materials.

Construction layer	Thickness [mm]	*λ* [W/(m.K)]	*ε* [-]	*ρ* [kg/m³]	*c* [J/(kg.K)]
Internal plaster	10	1.3	0.90	1350	900
Masonry block	220	0.52	0.90	850	840
External plaster	10	1.3	0.90	1350	900
Adhesive	10	0.45	0.90	1650	900
VIP core	10 - 60	0.0042	0.90	210	900
VIP barrier	0.097	0.90	0.10	2800	880
EPS cover layer	20	0.036	0.90	10	900
Plastic anchor	70	0.17	0.90	1390	900
Base coat	5	0.45	0.90	1650	900
Finishing coat	2	0.40	0.91	1650	1000

λ – Thermal conductivity;
Ɛ – Emissivity;
ρ – Density;
c – Specific heat.

2.2 Energy performance assessment

The energy performance of the external walls is performed considering a transient regime. The energy balance over one year was calculated using the hourly dynamic thermal simulation software BISTRA [38], by *Physibel*, considering detailed thermal characteristics (Table 1), different orientations and representative climate data (temperature and solar radiation provided in *DesignBuilder* software). BISTRA is a thermal analysis software for calculating transient heat transfer in two-dimensional free-form objects based on finite elements methods (FEM). A detailed schematic representation of the model considered in the numerical modelling is presented in Figure 2.

In order to evaluate the cost-effectiveness of incorporating the vacuum technology in ETICS, the solution is compared with expanded polystyrene (EPS), a widely used insulation material. The comparison is made on the basis of the equivalent thickness of EPS required to achieve the same thermal resistance as the encapsulated VIP. Over time, the thermal performance of VIPs deteriorates due to increase of inner gas pressure, moisture content and possible changes to the core material of the structure [39]. Based on the literature, a 2% thermal conductivity increase per year during the VIPs service life is considered [40]. For the EPS product, no degradation of performance is considered.

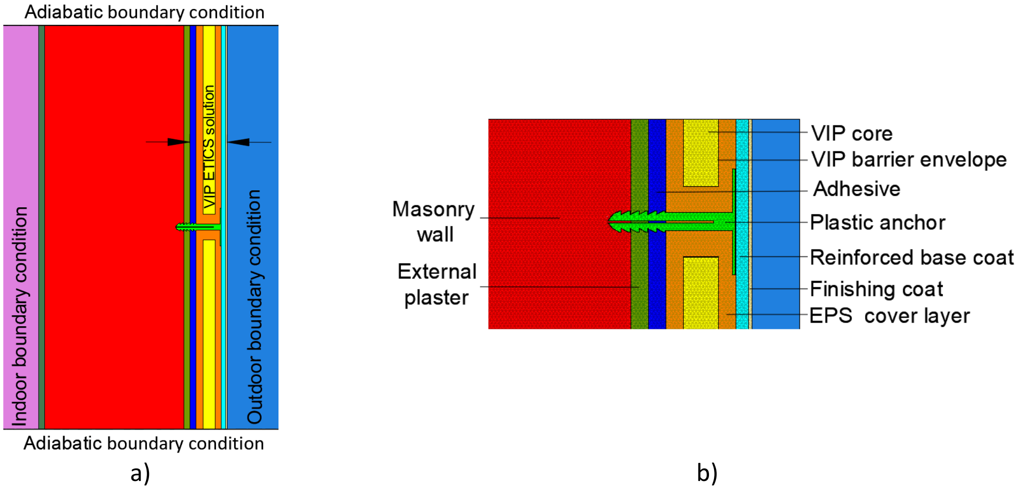


Figure 2: Detailed drawing of the 2-D model using a triangulation mesh: a) complete model and boundary conditions; b) detailed zoom.

2.2.1 Effective thermal conductivity of the VIP

The energy performance calculations are presented in terms of the effective thermal conductivity of the VIP solution to account for the thermal bridging effect that occurs at the edges of the encapsulated panels. The effective thermal conductivity of the VIP product is determined according to equation 1), where A_{VIP} is the VIP surface area, λ_{CoP} is the thermal conductivity at the centre of VIP, d is the thickness of the encapsulated VIP, ψ is the linear thermal transmittance of the joint area (between encapsulated panels), l is the length of the linear thermal bridge and A_p is the surface area of the VIP product (including the EPS edge cover).

$$\lambda_{eff} = \left[\left(A_{VIP} \cdot \frac{\lambda_{CoP}}{d} + \psi \cdot l\right) \cdot d\right] \cdot A_p{}^{-1} \quad \text{[W/(m.K)]} \qquad (1)$$

The linear thermal transmittance, ψ , was determined with BISCO software [38], by Physibel, which allows for steady-state heat transfer simulations in two-dimensional free-form objects based on FEM. Table 2 provides the thermal properties results for a wall with the encapsulated VIP product (640 mm x 640 mm size) with varying VIP thickness. For the external and internal surface thermal resistances, respective values of 0.04 (m^2.K)/W and 0.13 (m^2.K)/W were considered, according to ISO 6946 [41].

The equivalent EPS thickness required for a conventional ETICS solution is also shown in Table 2. It should be noted that simulations were also performed to confirm that the thermal bridging effect occurring between EPS boards in a conventional EPS based ETICS solution is negligible.

Table 2: Thermal properties of an encapsulated VIP with 640 mm x 640 mm.

VIP thickness [mm]	Encapsulated VIP thickness [mm]	λ_{CoP} [W/(m.K)]	Ψ [W/(m.K)]	*l* [m]	λ_{eff} [W/(m.K)]	EPS equivalent thickness [mm]	U-value wall [W/(m^2.K)]
10	30	0.0102	0.0225	2.56	**0.0132**	82	0.34
15	35	0.0085	0.0209	2.56	**0.0120**	105	0.28
20	40	0.0075	0.0190	2.56	**0.0114**	127	0.24
25	45	0.0069	0.0184	2.56	**0.0112**	144	0.22
30	50	0.0065	0.0171	2.56	**0.0111**	163	0.19
35	55	0.0062	0.0159	2.56	**0.0109**	182	0.18
40	60	0.0060	0.0146	2.56	**0.0107**	202	0.16

45	65	0.0058	0.0134	2.56	**0.0105**	223	0.15
50	70	0.0056	0.0121	2.56	**0.0102**	246	0.13
55	75	0.0055	0.0109	2.56	**0.0099**	272	0.12
60	80	0.0054	0.0095	2.56	**0.0095**	304	0.11

In order to account for the effect of varying the dimensions of the VIP product, these calculations were also performed for encapsulated VIP panels with 440 mm x 440 mm and 1040 mm x 640 mm (included in Annex).

2.2.2 Energy balance through walls

In this study, the focus is to perform a comparative analysis at the level of the wall solution. This approach will allow for comparative LCC results that are dependent on climate data (location and wall orientation), but that are mostly independent of other variables.

Following ISO 52016-1 [32], an hourly method for assessing the heat flow through the wall was adopted. This method takes into account thermal capacity, internal air temperature, area of the building element, internal convective surface, thermal properties of the wall components, internal surface temperature, external air temperature and solar radiation.

As mentioned before, the hourly energy balance was calculated using BISTRA software. The heat flow obtained per hour expressed in W/m was converted in kWh/m^2 considering a time integral during one year using the multiple application of the trapezoidal rule.

The internal temperature set-point is 25ºC from June to September and 20ºC for the remaining months. Calculations were performed for North, South, East and West-facing walls. As an example, Figure 3 shows the monthly heat losses (Figure 3-a) and gains (Figure 3-b) through the one square meter of external wall for Berlin, for the case of a ETICS solution with 40 mm of encapsulated VIP. Figure 3 demonstrates that for Berlin, heat losses are dominant when compared with heat gains by a factor of 6.

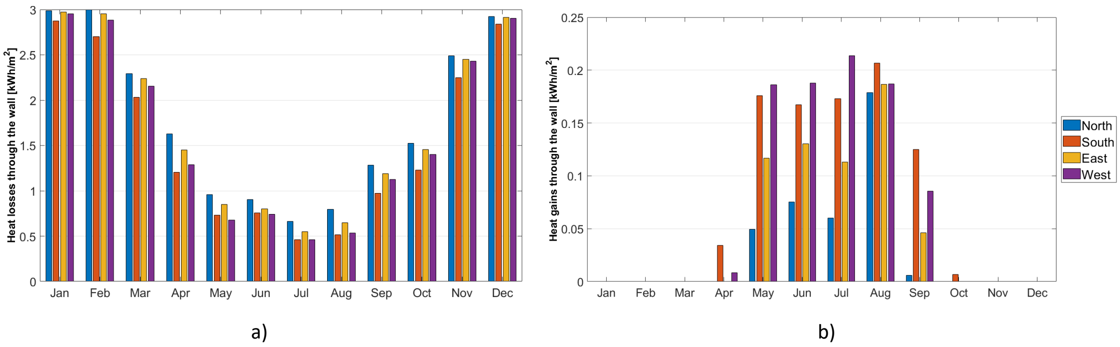


Figure 3: Heat flow through ETICS wall (with 40 mm encapsulated VIP) located in Berlin, expressed in kWh per square meter of façade: a) heat losses; b) heat gains.

Figure 4 shows the calculated monthly average energy balance (difference between losses and gains) for three different locations (Berlin, London and Helsinki). As expected, in Helsinki, which is located in a Nordic climate, the balance of losses over gains is more significant.

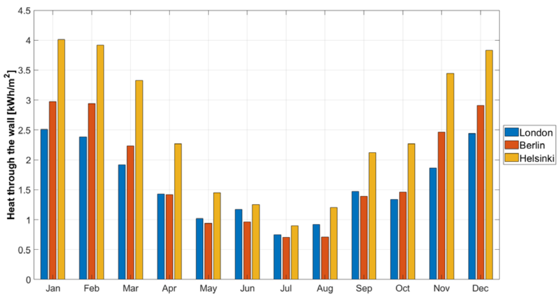


Figure 4: Average difference between losses and gains through ETICS wall (40 mm encapsulated VIP) for 3 locations, expressed in kWh per square meter of façade.

The estimated energy balances are dominated by the heat losses, which are quite similar for the different orientations as presented in Figure 3. Thus, the energy performance of the wall was simulated considering the average energy balance between all four orientations. Final energy use was calculated considering two different systems: an air conditioning unit (AC) with seasonal coefficient of performance of 5.1, class A+++ according to the Energy Label Directive [42], and an electric heater (EH) with an efficiency of 1.0. As recommended in the Commission Delegated Regulation no. 244/2012 the results are expressed in terms of primary energy. A primary energy conversion factor (PEF) of 2.0 kWh_{PE}/kWh for electricity was used ([43],[44]). This value reflects the latest growing share of renewable energy sources and technological progress in the electricity generation sector [45]. Literature review shows different methods for PEF calculation and a forecast of it decreasing in the next few years [46]. However, to avoid uncertainties regarding this parameter, a constant PEF value was considered during the period of calculation.

2.3 Life cycle costing

The proposed LCC methodology was adapted from the cost-optimal methodology framework established in the Commission Delegated Regulation no. 244/2012 and in ISO 15686-5. Calculations are given from both the financial and macroeconomic perspectives. A period of calculation of 20 years was used, as suggested by the Regulation for non-residential buildings.

As mentioned previously, it is considered that the building owner will be paying all costs (initial investment, maintenance and energy costs) and will benefit from an annual rent paid by the tenant. An additional space savings benefits for VIPs, due to their thinner nature, is considered in the calculations. This is represented by an additional rental income, ΔR.

From a financial perspective, the global cost, GC, expressed in € per square meter of ETICS façade, over the calculation period p, is calculated by:

$$GC(p) = \left[C_I + \left[\sum_{i=1}^{p} \left(C_a(i) \cdot D_f(i) \right) - \left(V_p \cdot D_f(p) \right) \right] \right] \times A_f^{-1} \qquad [€/m^2] \qquad (2)$$

Where $V_{p,}$ is the residual value at the end of the calculation period p; A_f is the façade area; $D_f\ (i)$ is the discount factor for year *I*, calculated according equation 5, C_I is the initial investment cost of a ETICS solution (specific thickness) including material costs and installation (see Table 3); C_a is the annual cost during year *i*, calculated as:

$$C_a(i) = C_e(i) + C_m - \Delta R \qquad [€/year] \qquad (3)$$

where C_e is the annual energy cost; C_m is the annual maintenance cost, defined as 1% of initial investment; ΔR is the additional rental income related with the floor area savings for VIP in comparison with EPS, for the same thermal transmittance (U-value). The rental income is calculated according to equation 4:

$$\Delta R = L \cdot \Delta d \cdot R_c \qquad [€/year] \qquad (4)$$

Where the L is the length of the wall (1.0 m for a unit surface area); Δd is difference of wall thickness between VIP solution and corresponding U-value EPS solution and R_c is the rental price for a specific city expressed in €/m^2 of useful area.

The discount factor for year *i*, based on discount rate *r* is calculated as:

$$D_f(p) = \left(\frac{1}{1 + r/100} \right)^p \qquad (5)$$

Where *p* is the number of years from the starting period and *r* is the real discount rate.

For the calculations at the macroeconomic level, an additional cost category related with the costs of greenhouse gas emissions, C_{ghg}, is introduced. The cost of greenhouse gas emissions is defined as the monetary value of environmental damage caused by CO_2 emissions related to the energy use in a building. For this purpose, a CO_2 emission intensity for electricity generation of 0.30 $kgCO_2$/kwh [47] and carbon prices based on emission trading system from EU prediction [48] were considered (see Figure 5). In this perspective, applicable charges and taxes, such as value-added tax (VAT) are to be excluded. Thus, from a macroeconomic perspective, the global cost GC_m over a calculation period p, is calculated by:

$$GC_m(p) = \left[C_I + \left[\sum_{i=1}^{p} \left(C_a(i) \cdot D_f(i) + C_{ghg} \right) - \left(V_p \cdot D_f(p) \right) \right] \right] \times A_f^{-1} \qquad [€/m^2] \qquad (6)$$

Additionally, the discounted payback period (dPB) and the internal rate of return (IRR) from the additional investment on VIP insulation are calculated according to equation 6 to 8.

$$dPB = i + CF_i \cdot (CF_i - CF_{i+1})^{-1} \qquad [years] \qquad (7)$$

Where i is the year before accumulated cash flows become positive, and CF_i is the discounted accumulated cash flow based in annual global costs calculations (equation 2), for the year i expressed by:

$$CF_i = C_i \cdot (1 + r)^{-i} \qquad [€] \qquad (8)$$

Where r is the discount rate and C_i is the net cash inflow-outflows during a single year i.

The IRR is the interest rate that makes the net present value (NPV) of all cash flows (payments) and incomes from the investment equal to zero, where CF_i is the discounted accumulated cash flow for the year i and C_I is the initial investment at the starting year.

$$\text{IRR: NPV} = \sum_{i=1}^{p} (CF_i) - C_I = 0 \qquad [\%] \qquad (9)$$

2.4 Economic parameters

Table 3 presents the economic parameters used in the LCC analysis regarding the cost of the ETICS installation and the insulation materials, as well as their estimated service life. The high installation cost for the VIP solution is due to the need for previous planning (unlike EPS, VIPs cannot be cut to size onsite) and for careful handling to avoid damage to the panels, which implies higher labour costs. The land price, earthworks, cost of lifts, and other materials costs were not considered, since they are the same for EPS and VIP based solutions. Since the period of calculation is 20 years for office buildings, insulation panels service life will impact the residual value according to equations 2 and 6, considering a linear depreciation during the lifetime.

Table 3: Economic parameters used in LCC for the different ETICS solutions.

Product	Insulation cost [€/m³]	Installation cost [€/m²]	Service life [years]
VIP	3000	62.5	25
EPS	120	50	50

The economic parameters of the three investigated cities were considered. Electricity prices for non-residential buildings were obtained from the Eurostat database for the reference year of 2018 [49]. Since LCC analysis is a long-term study, it is necessary to consider the future development of energy prices during the calculation period. The evolution of energy prices was determined according to the Eurostat predictions [48]. Additionally, in order to reflect the impact of a larger energy price increase in the future, a sensitivity analysis was performed considering an increase of 2.8% per year. Figure 5 shows the predicted electricity prices considered in the LCC calculations for both scenarios, regarding Berlin case study, as well as, the carbon prices based in EU projections [48].

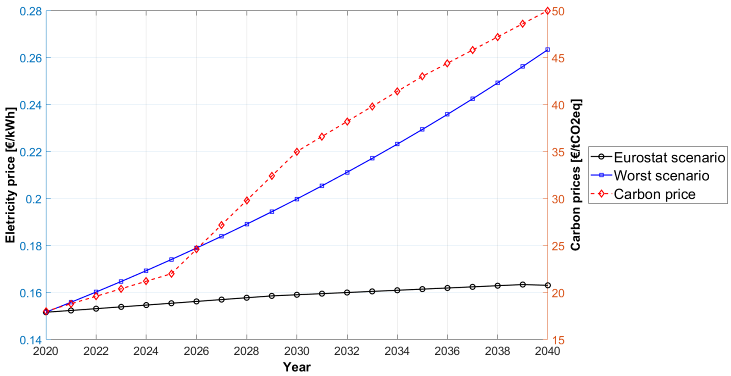


Figure 5: Carbon price and energy price prediction for Berlin for both scenarios.

All of the economic parameters considered in calculations according LCC methodology, are summarized in Table 4.

Table 4: Economic parameters used in LCC analysis for different cities at starting year.

Indicators	Berlin	London	Helsinki
Discount rate	4%	4%	4%
VAT	19%	20%	24%
Electricity cost (without VAT)	0.1516 €/kWh	0.1423 €/kWh	0.0707 €/kWh

As the calculation period is shorter than the service life of insulation panels, disposal costs are not considered. Since the rental prices (full-service leasing) depend on the city zone, LCC calculations were performed for a range between 150 €/(m^2.y) and 800 €/(m^2.y).

2.5 Data availability

To ensure transparency and the replicability of results, all data used in the present study are available in the open-access platform *Figshare* at: dx.doi.org/10.6084/m9.figshare.6025748, according to practice guidance [50]. The data includes: energy calculations results; detailed thermal properties of VIPs, including linear thermal transmittance and effective thermal conductivity for each panel size and thicknesses; economic data for each city, CO2 emissions conversion factors; energy and carbon prices evolution; detailed results for each sensitivity analysis; and other relevant information.

3. Results

In this section, the main results obtained from applying the proposed methodology are presented. Figure 6 is used to present an example of the cost-optimal curve obtained for several insulation levels of the VIP ETICS solutions, as well as for the corresponding EPS solutions. The results shown are for an ETICS wall located in Berlin under financial perspective, with a low efficiency system (EH) and a rental price of 150 €/(m^2.y). These results show a VIP cost-optimal thickness of 40 mm (U-value=0.24 W/(m^2.K)), representing a global cost of 220 € per m^2 of façade for the next 20 years. The best EPS solution, for an identical scenario is 220 mm insulation (U-value=0.15 W/(m^2.K)) for a global cost of 104 € per m^2. All EPS solutions have lower global costs due their lower investment costs in the given example using a relatively low rental value of (150 €/(m^2.y)).

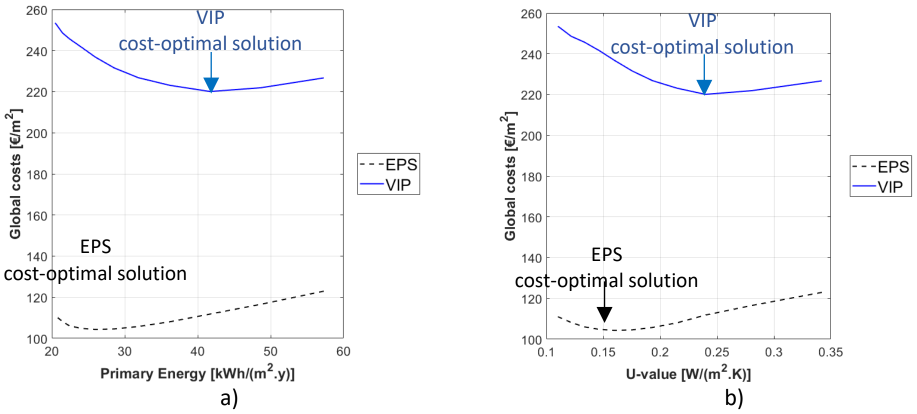


Figure 6: Berlin cost-optimal curves for VIP and corresponding EPS equivalent thickness curve for financial perspective: a) primary energy on horizontal axis; b) corresponding U-values of wall on horizontal axis.

Over the following subsections, the influence that changing certain parameters has on these cost optimal curves is analysed. Parameters such as rental cost, cost of VIP, size of panels, as well as VIP service life duration are explored. Different energy price scenarios are also considered. Additionally, the outcomes of the sensitivity analyses considering different climate zones and taking on a macroeconomic perspective are also presented.

3.1 Rental costs variation

To better perceive the influence of rental costs, the graphs in Figure 7 show the relationship between primary energy use, rental costs and global costs considering the two different heating systems, a highly efficient air conditioning unit (AC) and a lower efficiency electric heater (EH). Negative global costs in these graphs mean a positive benefit for the landlord. This happens when the rental income due the space savings achieved from using the VIP solution exceeds the VIP investment, maintenance and energy costs during the period of calculation. It can be seen that, for both systems, VIP is generally not a profitable solution when rental prices are lower than 350 €/(m^2.y)). However, if the city zone has higher rental incomes, which is the case for Berlin city centre, VIPs could be a cost-optimal solution, especially when transitioning to lower energy demands (nZEB targets).

By comparing Figure 7a (AC system) with Figure 7b (EH system), slightly lower overall costs can be seen for AC system, which is expected, as it is a more energy efficient system. However, the VIP and EPS curves intersect roughly in the same zone, highlighting the relevance of rental costs over building energy use.

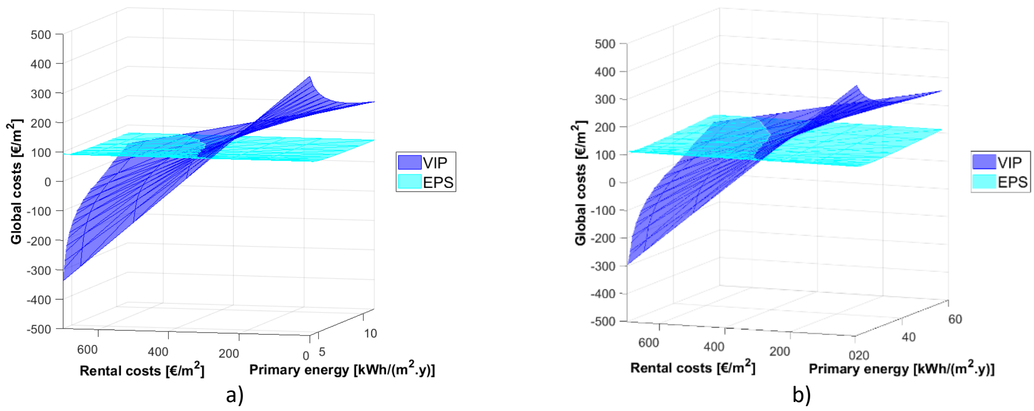


Figure 7: Rental cost analysis for Berlin for financial perspective: a) AC system; b) EH system.

A top of view of the 3D graph given in Figure 7a is shown in Figure 8a. This allows for a clear view of the EPS and VIP cost effectiveness zones in the graphs. In Figure 8, the LCC results obtained for the AC system considering both a financial and macroeconomic perspective can be compared. Although the rental incomes are reduced in macroeconomic perspective, due the exclusion of VAT, it can be seen that the profitability of VIP solutions slightly benefits from a macroeconomic point-of-view (Figure 8b). On one hand, this is due to the fact that the costs of greenhouse gas emissions decrease for higher insulation levels. On the other hand, the investment in VIPs is substantially reduced when not taking into account applicable charges and taxes, such as VAT, benefiting its cost-effectiveness when compared with EPS. Nonetheless, the profitability of the VIP solution is still dependent on rental prices. As can be seen in Figure 8b, for rental prices below 260 €/(m^2.y), the investment in VIPs is not justifiable.

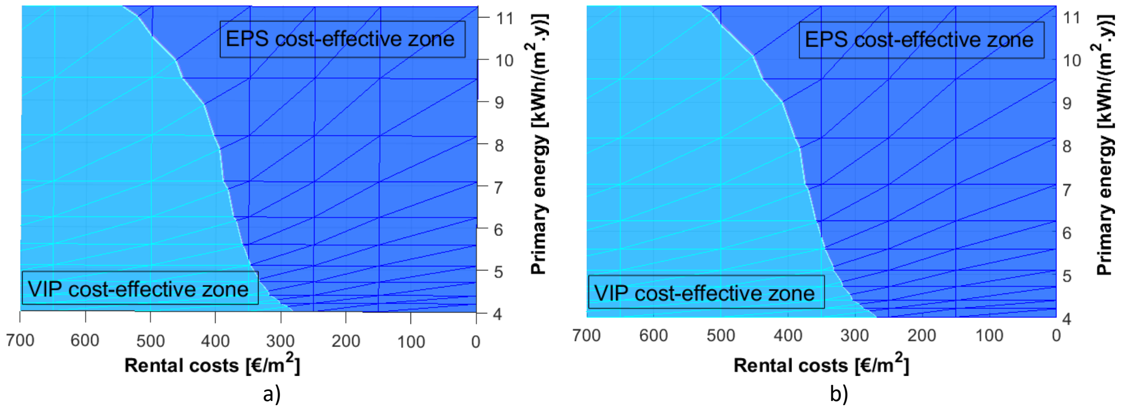


Figure 8: Rental cost analysis for Berlin: a) financial perspective; b) macroeconomic perspective.

3.2 VIP price variation

In addition to the rental prices of each zone, the cost-effectiveness of VIP solutions is also dependent on initial investment costs. Figure 9 shows the results for the calculations performed considering an AC system, a rental price area of 150, 250 and 350 €/(m^2.y) and a range in VIP prices between 1500 €/m^3 and 3000 €/m^3. Considering a low rental price area (150 €/(m^2.y) - Figure 9a) it can be observed that the VIP is not profitable even when the VIP price is lower than 1750 €/m^3.For a fixed value of rental cost of 250 €/(m^2.y) (see Figure 9b), if the cost of VIPs is reduced to less than 2600 €/m^3, it may become a competitive solution against EPS, depending on the insulation level required. As expected, when the rental price is higher (350 €/(m^2.y) - Figure 9c) the VIP profitability is increased. For example, a VIP price of 1750 €/m^3, all the VIP thicknesses are cost-effective compared with EPS solutions.

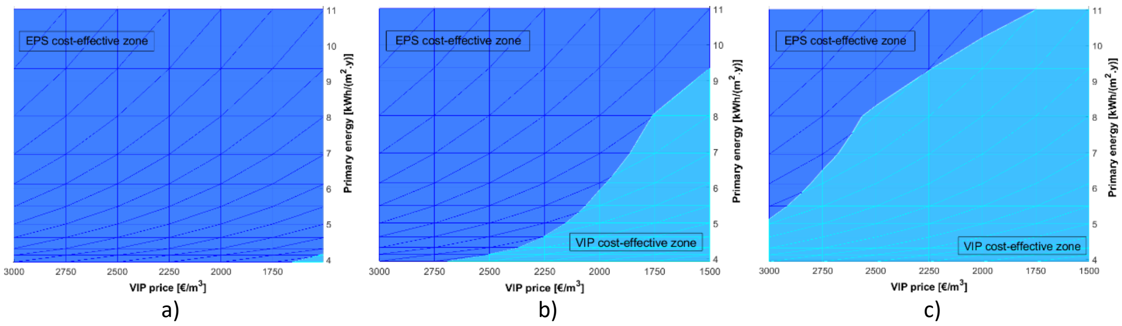
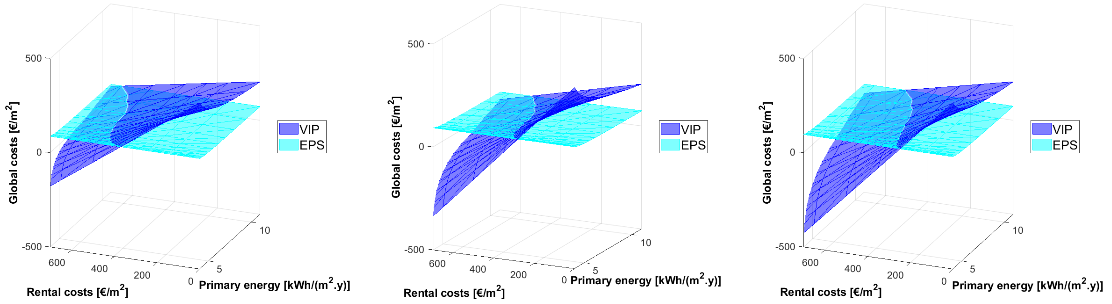


Figure 9: VIP price analysis for Berlin for financial perspective: a) fixed rental cost of 150 €/(m^2.y); b) fixed rental cost of 250 €/(m^2.y); c) fixed rental cost of 350 €/(m^2.y).

3.3 VIP panel size variation

Due to the influence that the edge thermal bridging effects have on VIP equivalent thermal conductivity, panel size variation needs to be considered in the LCC analysis. It is expected that, due to better overall thermal performance, larger panels will lead to lower global costs. Figure 10 shows the influence of panel size on results considering a VIP price of 3000 €/m^3 and an AC system. Bigger panels result in lower primary energy use due to lower equivalent thermal conductivity, as well as in lower global cost, as they are strongly affected by the additional rental incomes. The EPS curves correspond to the different thicknesses of insulation needed to ensure the same thermal transmittance as the VIP products with different sizes of panels. In this case, global costs are affected by the large investment in insulation material required to achieve such high levels of thermal insulation. It can be said that VIP products with 1040 mm x 640 mm (Figure 10c) could compete against EPS when rental prices are around 300 €/(m^2.y), especially if there is a need for high levels of insulation, such as in nZEB buildings. For smaller panels (Figure 10a), only in high rental price areas (over than 460 €/(m^2.y)) could VIP become cost-effective.

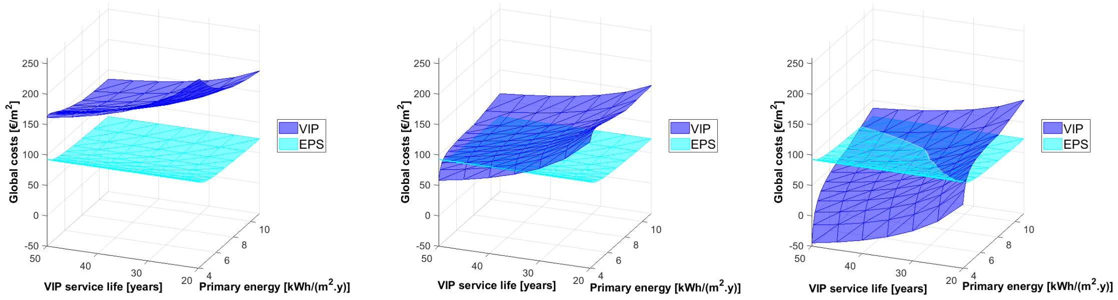


a) b) c)

Figure 10: Panel size analysis for Berlin for financial perspective: a) 440 mm x 440 mm; b) 640 mm x 640 mm; c) 1040 mm x 640 mm.

3.4 VIP service life analysis

The service life duration of VIPs is still an uncertainty for the building industry. However, the influence of VIP durability has relevance on the LCC analysis. If manufacturers improve the service life of VIP products, the economic feasibility of the use of VIP in buildings could be improved, as shown in Figure 11. The graphs in Figure 11 are for a highly efficient system (AC system) and a rental price range between 150-350 €/(m^2.y). For rental price areas of 150 €/(m^2.y), VIPs with current market price (3000 €/m^3) are not cost-effective, even if the VIP service life is increased to 50 years (as can be seen in Figure 11a). However, for the highest rental price areas (350 €/(m^2.y) VIP products with service life of 20+ years could be a cost-effective solution (see Figure 11c). For rental price areas with 250 €/(m^2.y) (Figure 11b) only panels with a service life year of 35+ years could make the VIP products a feasible solution. These results support the need to develop super insulation materials with long-term performance. Only then will the investment in VIPs in buildings instead of conventional insulation materials become economically feasible.



a) b) c)

Figure 11: VIP service life analysis for Berlin for financial perspective: a) fixed rental cost of 150 €/(m^2.y); b) fixed rental cost of 250 €/(m^2.y); c) fixed rental cost of 350 €/(m^2.y).

3.5 Payback period and internal rate of return

Other financial indicators could be used to evaluate the cost-effectiveness of the VIP ETICS products. The resulting discounted payback period for Berlin LCC calculations with AC system are presented in Figure 12 and Figure 13. For the rental price analysis in Figure 12, a VIP investment was fixed at 3000 €/m^3. For the VIP price analysis in Figure 13, a rental price was fixed at 350 €/(m^2.y). For these same assumptions, the internal rate of return results are presented in Figure 14 and Figure 15. The vertical axes were defined for a maximum of 20 years, corresponding to the period of calculation of global costs. Bars with 20 years of payback period suggest that the additional VIP investment will not be recovered in less than 20 years.

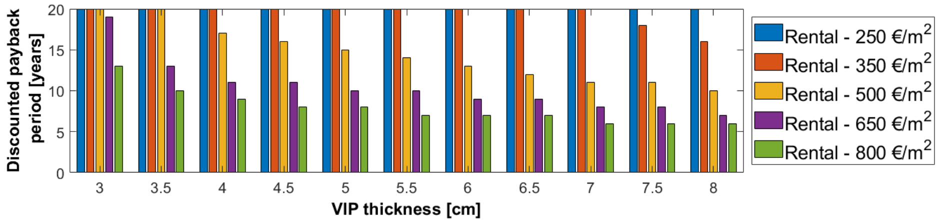


Figure 12: Discounted payback period for Berlin results for financial perspective. – Rental costs analysis.

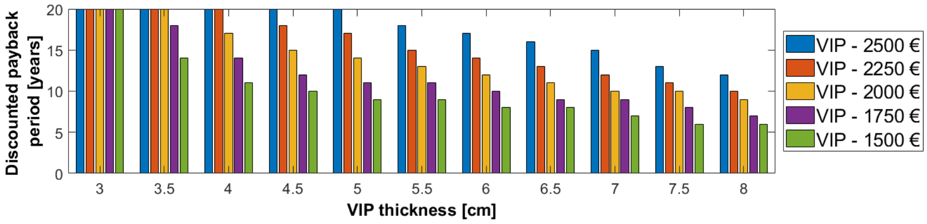


Figure 13: Discounted payback period for Berlin results for financial perspective – VIP price analysis.

The discounted payback period results are in accordance with the previous results. The VIP investment price should be reduced in order to achieve a dPBP that is less than 20 years. Naturally, if the rental price is high, for example an area where it is 500 €/m², the actual VIP price (3000 €/m²) could be cost-effective as shown in Figure 12. Similarly, the IRR results state the same conclusions. IRR higher than 5% would be considered a good investment, since the considered discounted rate was 4%.

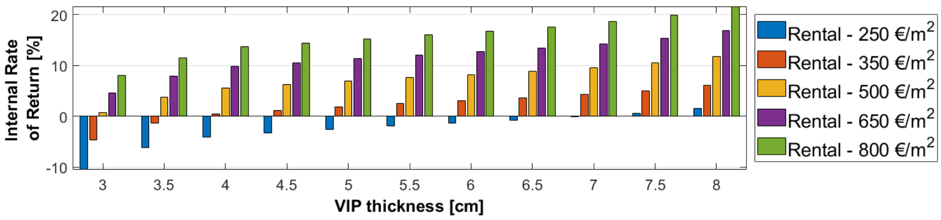


Figure 14: Internal rate of return for Berlin results for financial perspective – rental price analysis.

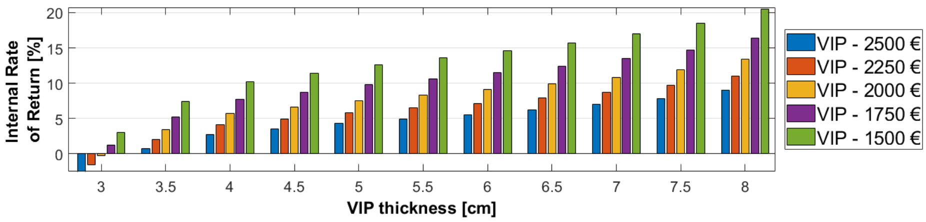


Figure 15: Internal rate of return for Berlin results for financial perspective – VIP price analysis.

3.6 Influence of location

The LCC analysis was extended to consider weather data for buildings located not only in Berlin, but also in Helsinki and London. Figure 16 shows the LCC results for these different locations, all considering an EH system and a rental cost of 150 €/(m².y). Two different scenarios are presented: a) the Eurostat energy prices prediction; and b) a worst-case scenario with an increase of 2.8% per year.

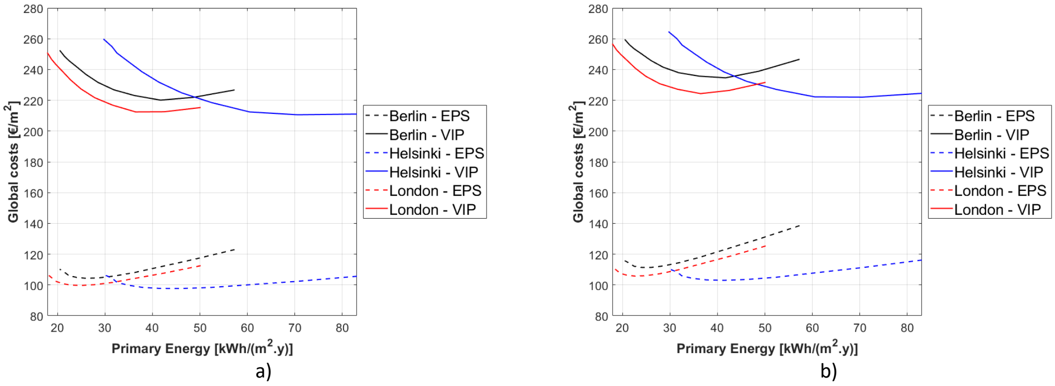


Figure 16: VIPs cost-optimal curves for different locations and corresponding EPS equivalent thickness curves for financial perspective (rental cost of 150 €/(m^2.y)): a) Eurostat electricity prices prediction b) Electricity price with an increase of 2.8 % per year.

Although Helsinki has higher heat losses through the walls due the Nordic climate, it ends up having a global cost similar to Berlin and London. This is due to the considerable difference between the electricity prices charged in these cities (see Table 4). This is noticeable when the curves intersect, where the investment in high VIP thicknesses in Helsinki is not economical feasible due the reduced cost of energy used for heating (electricity). Thus, for a 20-year service life, a higher level of insulation is more cost-effective in Berlin than in Helsinki. The cost-optimal EPS equivalent thickness for Berlin is 230 mm (U-value of 0.15 W/(m^2.K)) against 180 mm in Helsinki (U-value of 0.17 W/(m^2.K)). This last U-value is the same as the current national thermal requirements in Finland [51], while for Berlin it is considerably lower, as the maximum U-value allowed in Germany is 0.28 W/(m^2.K) [51]. The results for London are close to Berlin due similar energy costs and energy balances.

With these results, it can be concluded that, in addition to the influence from climate data, the economic factors of each country/city are particularly relevant in the LCC analysis. That is the reason why strict parameters must be taken into account in this type of studies. Note that the analysis in Figure 16 is for a reduced rental cost of 150 €/(m^2.y). In city zones with high rental costs, VIP becomes a competitive solution, as shown in Figure 17, in which a rental cost of 350 €/(m^2.y) was considered.

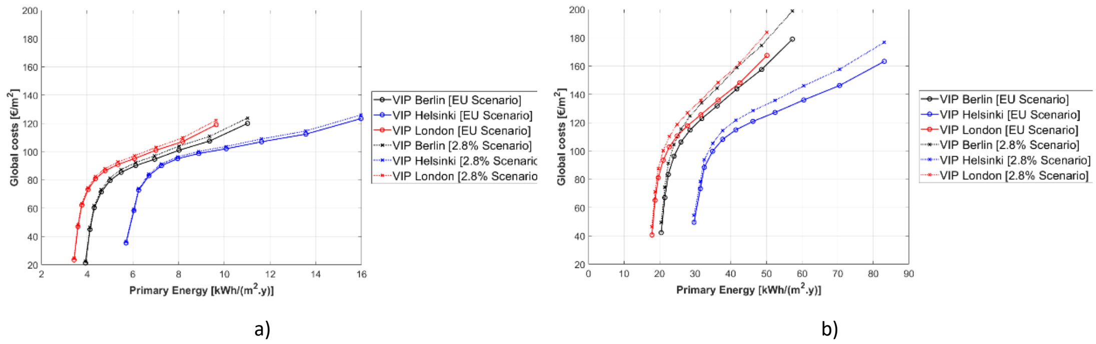


Figure 17: VIPs cost-optimal curves for different locations and energy prices prediction for financial perspective: a) with AC system; b) with EH system.

Similar conclusions can be reached no matter the energy price evolution over the next 20 years. However, higher global costs are obtained, especially when lower levels of insulation along with a system with lower energy efficiency are considered (Figure 17b). For example, with EH system, a 30 mm VIP solution in London results in a global cost of 167 €/m^2 and 184 €/m^2, considering EU predictions and worst-case scenario, respectively. For a high efficiency energy system (Figure 17a) the influence of energy prices predictions is lower, resulting in a global cost of 119 €/m^2 (EU predictions) and 122 €/m^2 (worst-case scenario) for the same case.

4. Discussion

An LCC analysis was performed in order to compare the VIP-based ETICS solutions with conventional EPS-based solutions. This section summarizes and discusses the main results of the LCC calculations. Limitations of this study are also discussed and future works are proposed.

For the energy use calculations, the authors proposed an alternative model by using a numerical software to calculate the unsteady energy balance of a square meter of façade instead of performing a full analysis of a reference building, which typically used in LCC studies. This method allows for the direct comparison of the thermal performance of insulated walls and avoids interference from other factors, such as windows-wall ratio or the geometry of the building. However, this approach also has some limitations, such as neglecting the linear thermal bridges between different junctions, as well as being a time consuming processes due to the high computational power required for the hourly numerical simulations.

A large number of parameters important for determining VIPs economic viability in the building sector were analysed. The assumptions made in each presented case and the most important outcomes are summarized in Table 5.

Table 5: Summary of LCC results and assumptions.

Figure no.	Goal of analysis (perspective)	Location	Heating system	Rental price €/(m².y)	VIP Price (€/m³)	Main results
6	EPS and VIP cost-optimal curves (financial)	Berlin	EH	150	3000	VIP is not cost-effective for low rental prices
7a	Rental costs variation (financial)	Berlin	AC	200-800	3000	VIP is cost-effective for rental prices higher than 350 €/(m².y)
7b	Rental costs variation (financial)	Berlin	EH	200-800	3000	VIP is cost-effective for rental prices higher than 350€/(m².y)
8a	Rental costs variation (financial)	Berlin	AC	200-800	3000	VIP is cost-effective for rental prices higher than 350€/(m².y)
8b	Rental costs variation (macroeconomic)	Berlin	AC	200-800	3000	VIP is cost-effective for rental prices higher than 330 €/(m².y)
9a	VIP price variation (financial)	Berlin	AC	150	1500-3000	VIP is not cost-effective for low rental prices
9b	VIP price variation (financial)	Berlin	AC	250	1500-3000	VIP is cost-effective for VIP price lower than 2600 €/m³
9c	VIP price variation (financial)	Berlin	AC	350	1500-3000	VIP could be cost-effective for VIP market price (3000 €/m³)
10	VIP panel size variation (financial)	Berlin	AC	200-800	1500-3000	Biggest panels are cost-effective for rental prices around 300 €/(m².y), while smaller panels only become cost-effective for areas over 460 €/(m².y)
11	VIP service life variation (financial)	Berlin	AC	150-350	3000	For rental prices areas with 250 €/(m².y), VIP service life needs to assure more than 35 years, to be cost-effective.
16	Influence of location analysis (financial)	Berlin Helsinki London	EH	150	3000	Economic factors of each location have greater influence on LCC results. Rental prices overlap energy use influence.
17	Influence of location analysis (financial)	Berlin Helsinki London	AC and EH	350	3000	Energy prices prediction could change the GC results, especially with lower insulation levels and inefficient energy supply system.

The technical and economic variables, such as climate data, energy costs, taxes, product service life, panel size, edge thermal bridging effects or costs (including material and application), and rental prices may lead to different results, as demonstrated in this work, suggesting that a direct comparison with the previous studies might not be possible. However, in general, the results obtained are in line with previous studies where the VIP was used in internal wall insulation and in which a reference building was considered.

Results showed that VIPs can be a cost-effective alternative to conventional insulation materials when different rental incomes are considered. These results are aligned with previous study [31] that considered a reference building and other methodological approaches. In this case, VIPs are cost-effective for a rental price range of 220-320 €/(m^2.y)), depending on the climate zone. However, if lower rental costs are considered, the VIP is not cost-effective when compared with EPS, as demonstrated in previous works that did not consider space savings benefits ([26],[29]).

Regarding service life sensitivity analysis, the findings support the need to develop super insulation materials with effective long-term performance. Only then, will the investment in VIPs be economically feasible, as suggested by Alam *et al.* [30], although based on different assumptions.

Depending on rental price and initial VIP costs, the investment in VIP products were evaluated in terms of other financial indicators, such as the discounted payback period or the internal rate of return. The additional investment in VIP ETICS solution showed a discounted payback period between 6-20 years. This range of payback periods for VIP investment are close to those found by Alam *et al.* [30] of 3-17 years for VIP fumed silica, depending on rental income of the building.

In addition to factors reflected in the cost-optimal methodology framework, a macroeconomic analysis was also considered taking into account factors such as greenhouse gas emissions. Further research could focus on gathering life cycle inventory for VIP products and processes providing a more holistic analysis for investors and policy makers to consider a life cycle energy approach. Future work could investigate further a sensitivity analysis considering different geometrical models with implications on the energy calculation, such as linear junctions between different building elements. This methodology could also be used to assess the cost-effectiveness of other novel insulation materials, such as aerogels-based products or gas filled panels.

5. Conclusions

The present paper aims to provide information to owners, developers, designers and manufacturers about the cost effectiveness of using VIPs in ETICS instead of EPS, the insulation material most commonly used in conventional ETICS. In particular, the focus of the life cycle cost analysis presented in this study are ETICS wall applications in office buildings that offer full-service leasing. Many relevant economic parameters were considered, such as the VIP performance degradation over time, the thermal bridging effects and the economic benefits from saving floor area by using a slim solution. Also, a sensitivity analysis was carried out in order to better understand the influence of factors like rental price, VIP investments cost, service life of VIP, location, scenario of energy prices prediction, as well as of performing a financial or a macroeconomic perspective.

The proposed LCC methodology allowed for a comparative analysis of the cost-effectiveness of using VIPs in buildings, as opposed to another conventional insulation material that requires a significantly thicker layer in order to achieve the same thermal performance. For this purpose, the additional floor area savings, expressed by additional rental incomes values, were introduced in the global cost calculations. The energy balances were determined based on transient calculations of the heat transfer between a unit area of an ETICS wall. This approach avoids the variability of office buildings characteristics and user profiles, focusing mainly on comparing the performance of the thermal insulation materials. Even though this paper presents an LCC study applied to an VIP ETICS wall, the same methodology could be easily applied to other kinds of constructive solutions, such as internally insulated walls, considering new or retrofitted buildings. Since the results are expressed by square meter of façade, the size of the building is irrelevant for the application of these results.

The results have demonstrated the cost-effectiveness of using VIPs in buildings, in particular in cities where office full-leasing rental costs are high. In comparison with EPS, one of the cheaper insulation materials, and considering actual VIP prices, in cities with rental costs that are higher than 350 €/(m^2.y) VIP solutions can be cost-effective for a current market VIP price of 3000 €/m^3, depending on the level of insulation required. Naturally, if manufacturers together with researchers are able to improve the service life and/or reduce the production costs, they will promote economic competitiveness in areas with lower rental prices, as shown in this paper. It can be stated that rental prices have shown to have a stronger influence on results than building energy use (insulation levels). This is because the contribution of net floor savings is more relevant, especially in high density cities such as Berlin or London. However, unrealistic energy prices predictions may significantly alter the global costs values. Depending on rental price and initial VIP costs, the additional investment in VIP products has a discounted payback period between 6-20 years. Similarly, promising IRR results have also been found. The analysis performed in different locations highlighted the influence of economic factors such as energy costs. Due the high electricity price in Berlin, the estimated global costs were higher than for Helsinki, even though the energy losses in the Nordic climate are greater. Accurate economic data is also essential for performing an adequate LCC assessment.

From the point of view of decision makers and environmental politics, the profitability of VIP solutions is slightly improved when a macroeconomic perspective is taken. Thus, it can be said that using VIPs in building façades can contribute to achieving nZEB targets while ensuring economic competitiveness. However, further studies using a whole system approach which includes the material's embodied energy should be carried out.

The understanding of the actual thermal performance of the insulation is also fundamental for achieving a realistic LCC approach and reliable results. Especially in the case of VIP technology, where uncertainties remain about the actual global thermal performance due the edge thermal bridging effects and about the panels' performance throughout their service life. LCC results showed to be significantly influenced by panel size. These parameters are decisive when assessing the cost-effectiveness of super insulation materials struggling to compete with other insulation materials on the market.

Acknowledgements

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ANNEX

This Annex provides information about the thermal properties of encapsulated VIP with different sizes, namely panels with 440 mm x 440 mm (Table A1), 640 mm x 640 mm (Table A2) and 1040 mm x 640 mm (Table A3). The effective thermal conductivity including the edge thermal bridging effects, as well as the EPS equivalent thickness, were used in LCC calculations. The effective thermal conductivity was calculated according to equation (1), and the wall U-values was calculated according to ISO 6946, taking into account the layered structure of the wall presented in Table 1. The EPS thicknesses were calculated in order to achieve the same thermal resistance obtained with the encapsulated VIPs:

$$R_{EPS} = R_{VIP} \Leftrightarrow R_{wall} + R_e + \frac{d_{EPS}}{\lambda_{EPS}} + R_i = R_{wall} + R_e + \frac{d_{VIP}}{\lambda_{effVIP}} + R_i \Leftrightarrow d_{EPS} = \frac{d_{VIP}}{\lambda_{effVIP}} \times \lambda_{EPS}$$

where *R* is the thermal transmittance of the external wall (with EPS or VIP), *d* is the insulation thickness, λ is the thermal conductivity and R_e and R_i are the external and internal conventional surface thermal resistances, assuming a value of 0.04 W/(m^2.K) and 0.13 W/(m^2.K), respectively.

Table A1: Thermal properties of an encapsulated VIP with 440 mm x 440 mm.

VIP thickness [mm]	Encapsulated VIP thickness [mm]	λ_{COP} [W/(m.K)]	Ψ [W/(m.K)]	*l* [m]	λ_{eff} [W/(m.K)]	EPS equivalent thickness [mm]	U-value wall [W/(m^2.K)]
10	30	0.0102	0.0225	1.76	**0.0146**	74	0.37
15	35	0.0085	0.0209	1.76	**0.0136**	92	0.31
20	40	0.0075	0.0190	1.76	**0.0131**	110	0.27
25	45	0.0069	0.0184	1.76	**0.0132**	123	0.25
30	50	0.0065	0.0171	1.76	**0.0131**	137	0.22
35	55	0.0062	0.0159	1.76	**0.0130**	152	0.21
40	60	0.0060	0.0146	1.76	**0.0129**	168	0.19
45	65	0.0058	0.0134	1.76	**0.0127**	185	0.17
50	70	0.0056	0.0121	1.76	**0.0123**	204	0.16
55	75	0.0055	0.0109	1.76	**0.0119**	226	0.14
60	80	0.0054	0.0095	1.76	**0.0114**	254	0.13

Table A2: Thermal properties of an encapsulated VIP with 640 mm x 640 mm.

VIP thickness [mm]	Encapsulated VIP thickness [mm]	λ_{COP} [W/(m.K)]	Ψ [W/(m.K)]	*l* [m]	λ_{eff} [W/(m.K)]	EPS equivalent thickness [mm]	U-value wall [W/(m^2.K)]
10	30	0.0102	0.0225	2.56	**0.0132**	82	0.34
15	35	0.0085	0.0209	2.56	**0.0120**	105	0.28
20	40	0.0075	0.0190	2.56	**0.0114**	127	0.24
25	45	0.0069	0.0184	2.56	**0.0112**	144	0.22
30	50	0.0065	0.0171	2.56	**0.0111**	163	0.19
35	55	0.0062	0.0159	2.56	**0.0109**	182	0.18
40	60	0.0060	0.0146	2.56	**0.0107**	202	0.16
45	65	0.0058	0.0134	2.56	**0.0105**	223	0.15
50	70	0.0056	0.0121	2.56	**0.0102**	246	0.13
55	75	0.0055	0.0109	2.56	**0.0099**	272	0.12
60	80	0.0054	0.0095	2.56	**0.0095**	304	0.11

Table A3: Thermal properties of an encapsulated VIP with 1040 mm x 640 mm.

VIP thickness [mm]	Encapsulated VIP thickness [mm]	λ_{COP} [W/(m.K)]	Ψ [W/(m.K)]	*l* [m]	λ_{eff} [W/(m.K)]	EPS equivalent thickness [mm]	U-value wall [W/(m^2.K)]
10	30	0.0102	0.0225	3.36	**0.0126**	86	0.33
15	35	0.0085	0.0209	3.36	**0.0113**	111	0.27
20	40	0.0075	0.0190	3.36	**0.0106**	136	0.23
25	45	0.0069	0.0184	3.36	**0.0104**	156	0.20

30	50	0.0065	0.0171	3.36	**0.0102**	177	0.18
35	55	0.0062	0.0159	3.36	**0.0100**	199	0.16
40	60	0.0060	0.0146	3.36	**0.0098**	221	0.15
45	65	0.0058	0.0134	3.36	**0.0096**	244	0.13
50	70	0.0056	0.0121	3.36	**0.0093**	270	0.12
55	75	0.0055	0.0109	3.36	**0.0091**	298	0.11
60	80	0.0054	0.0095	3.36	**0.0087**	331	0.10