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Vacuum insulation panels: An overview of research literature with an emphasis on environmental and economic studies for building applications

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ABSTRACT

The study provides an overview of the research focus on vacuum insulation panels (VIPs). Scientific literature published between 1960 and 2022 is identified, and a database covering 423 documents is amassed. In the first phase, research documents were categorised into three groups: product, other and buildings. In the second phase, data about the studied building applications and research topics were extracted and quantitatively evaluated. In the last phase, the studies evaluating VIPs' environmental and economic implications in buildings were analysed in detail. The study results show an increasing publication trend on VIPs, with almost 90% of the literature published from 2010 onwards. Building applications are the dominant research subject, representing 56% of identified documents. A detailed analysis of life cycle studies pointed to a consensus that in building applications, fumed silica VIPs exert a higher environmental impact and costs than conventional insulation materials if the comparison is based on an equivalent thermal transmittance value. However, several studies showed reasonable payback and environmental neutrality periods for retrofitting scenarios. Benefits could also be achieved if insulation layer thickness is limited. External wall insulation represents the vast majority of the applications analysed. Studies further showed that VIPs in external wall applications could be economically viable compared to conventional insulation if added useable floor space is considered. The characteristics of life cycle studies were analysed, research gaps and possibilities were identified, and research recommendations for environmental and economic studies of VIPs were provided.

1. Introduction

In order to provide for society's needs, buildings and the construction sector consume extensive amounts of energy and resources [1,2]. Reducing the heating and cooling demand of buildings is considered a crucial aspect of lowering the environmental impact of buildings. Through the development of thermal insulation materials and building codes focusing on the energy efficiency of buildings and building appliances, the heating and cooling demand in buildings is being significantly reduced [3–5].

Many thermal insulation materials available on the market can be used to reduce heat losses through the building envelope [6]. This also includes vacuum insulation panels (VIPs), which are specific thermal insulation products classified as superinsulation materials [7]. They are composite materials with a core, wrapped in an air- and vapour-tight barrier envelope. Depending on the core material characteristics, the envelope is evacuated to an air pressure below 5 mbar and (heat) sealed. Due to air evacuation, the core materials must have an open porous structure [8]. Various open porous materials can be applied (e.g. open-cell polyurethane [9], aerogel [10]). However, the most commonly used core materials are glass fibre and fumed silica (see Fig. 1) [11]. The VIP envelope provides an air and vapour-tight barrier that prevents air from the external environment from penetrating the core [12]. Two types of foils are used for the envelope (aluminium and metalized multilayer [8,13]). Although VIPs are wrapped in sealed barrier foil, they experience a continuous time-dependent increase in thermal conductivity. The main influential factors for this effect are temperature, humidity and panel size ([14,15]), as well as water vapour and other gases diffusion through the envelope [16]. Therefore, the thermal characteristics of VIPs are characterised by using effective (i.e., declared) thermal conductivity, which considers the time dependence of thermal conductivity and the edge effect [17,18]. The later is a consequence of the difference between the thermal conductivity of the evacuated VIP core and the envelope materials [19]. To improve the thermal performance of VIPs, desiccants and getters are added to absorb residual

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Abbreviations

SLR	systematic literature review
WoS	Web of Science
VIP	vacuum insulation panel
EPS	expanded polystyrene
XPS	extruded polystyrene
PUR	polyurethane
U-value	thermal transmittance [W/(m^{2}K)]
PCM	phase changing material
R	thermal resistance [(m^{2}K)/W]
λ_{VIP}	VIP thermal conductivity [W/(mK)]
ETICS	external thermal insulation composite system
SIP	structural insulation panels
LCA	life cycle assessment
LCC	life cycle costing
LCI	life cycle inventory
GWP	global warming potential [kg CO_2 eq.]
ODP	ozone depletion potential [kg. R11 eq.]
EP	eutrophication potential [kg $(PO_4)^{3-}$ eq.]
POCP	photochemical ozone depletion potential [kg C_2H_4 eq.]
AP	acidification potential [kg SO_2 eq.]
ADPE	abiotic depletion potential of elements [kg Sb eq.]
ADPF	abiotic depletion potential of fossil resources [MJ]
PERT	total renewable primary energy [MJ]
PENRT	total non-renewable primary energy [MJ]
PET	total primary energy [MJ]
WRD	water resource depletion

gases or water vapour, while opacifiers are used to reduce radiative heat transfer [8,20,21].

Depending on the core material used, the thermal conductivity of VIPs at the centre of the panel can be below 0.0045 W/(mK) in pristine conditions [24], making VIPs the most effective thermal insulation material on the market in terms of thermal conductivity. Therefore, VIPs are primarily used in applications where their superior insulation performance and low thickness can be an advantage. Among others, these include cold chain applications (e.g., refrigerators, transportation boxes) [25,26], heat storage devices [27] and buildings [28]. The design of VIPs varies depending on the application type. For building applications where a service life of 25 years is to be achieved [17], VIPs with fumed silica core (Fig. 1) are the most suitable [11]. Fumed silica is a nanoporous material, enabling superior thermal conductivity at elevated pressure levels compared to other core materials [22,29]. According to published data, the effective thermal conductivity for fumed silica VIPs with a service life of 25 years ranges from 0.007 to 0.009 W/(mK) [16,30,31].

Due to their superior thermal properties, VIPs were perceived as having considerable potential for building applications [22]. However, although VIPs have been commercially available for over a decade and can be categorised as advanced insulation materials [6], their market share in building applications is negligible (below 1%) [32]. According to 2014 data, 10% of the global VIP production was intended for building applications, whereas the remaining 30% was used for transportation boxes and 60% for refrigerators [11]. The main disadvantages of VIPs compared to conventional building insulation materials are higher costs [33], sensitivity to damage on the construction site [34,35], inability to adapt their size on the construction site [24], challenges with on-site installation [33] and concerns regarding their service life [24]. Although buildings represent only a small share of commercial VIP applications, the published body of research on VIPs in the context of buildings is substantial. The researched topics range from service life determination (e.g. Refs. [36,37]), thermal performance and impact on building energy consumption (e.g. Ref. [38]), hygrothermal characteristics of building elements with VIPs (e.g. Refs. [39,40]) and life cycle evaluations of VIPs environmental and economic performance (e.g. Refs. [41,42]).

Vacuum insulation panels played a crucial role in the COVID-19 vaccine distribution [43] and were an essential part of the complex mosaic of mitigating adverse effects of the pandemic. As society struggles with rising energy prices and adverse climate change consequences, it is time to re-examine the role of superinsulation materials such as VIPs, as they could become a viable passive technique for greater energy efficiency in buildings. Furthermore, Secher et al. [44] discussed that the construction industry and its products are strongly connected to the ability to reach key UN sustainable development goals. It can be concluded, therefore, that commercial building products should be competitive from an environmental and economic standpoint to be perceived as sustainable. Thus, the primary focus of this study is to examine the research about environmental and economic implications of applying VIPs in buildings. The analysis focuses on the findings from life cycle assessment (LCA) and life cycle costing (LCC) studies. Both methods are recognised as suitable for evaluating the environmental and cost-related impacts of various systems [45,46]. By examining the studied literature, this research will assess the environmental and

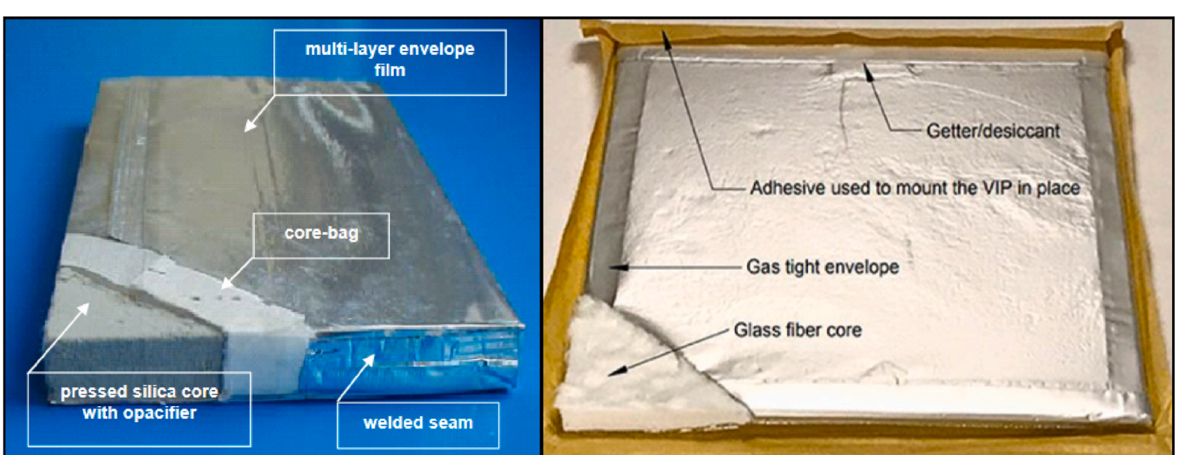

Fig. 1. Components of a fumed silica core (left) and glass fibre core VIP (right) [22,23].

cost-related hotspots and how VIPs compare to conventional building insulation products. Additionally, the research characteristics of the life cycle studies and possible knowledge gaps will be identified.

Furthermore, the study identified that per reviewed literature for VIPs is substantial and covers various research topics. However, no study attempt has been made to evaluate the past research on VIPs quantitively. Therefore, a systematic literature review (SLR) was performed on past VIP research, focusing on building applications. The literature review was performed on three levels of data extraction complexity, progressing from a general overview of VIP research and finishing with a detailed evaluation of life cycle studies (funnel approach). The study structure is presented in Fig. 2. The 1st step provides past research trends on VIPs between 1960 and 2022. The identified documents were divided into groups, depending on the research focus: (i) product, (ii) other applications and (iii) building applications. For the latter, the studied building applications and dominant research topics were identified in the 2nd step. Finally, the environmental and cost-related research was analysed in the 3rd step to identify methodological approaches, research trends and environmental and economic hotspots for VIPs and VIPs in building applications.

Thus, the work presents an overview of past research on VIPs and discloses the environmental and economic implications of applying VIPs in buildings. The primary focus of the study are environmental and economic studies regarding VIPs in buildings. Our preliminary assumption is that although plenty of building applications for VIPs exist, only a handful were evaluated through LCA and LCC studies. A quantitative review of the research focus of studies evaluating building applications will provide context on how much attention environmental and cost-related studies received compared to other research topics. Furthermore, the most frequently studied applications will also be determined.

The study's novelty is that no previous attempts have been made to categorise and quantitatively evaluate past research on VIPs. Furthermore, the study is the first to provide a detailed review of past studies evaluating the environmental and economic implications of VIPs in buildings. Therefore, the consequential findings and recommendations could direct future life cycle-related research on VIPs. Additionally, the database on VIP research is published in a research data document [47], enabling filtering and further analysis of surveyed documents.

The following sections include the methodology (section 2.0), describing the SLR structure and information about the research data document. Section 3.0 provides the results for the quantitative evaluation of VIP research (section 3.1), research focus for VIPs in buildings (section 3.2) and findings from the analysis of life cycle studies (section 3.3). Sections 4.1 and 4.2 provide an overview of findings and recommendations for future life cycle studies on VIPs. Additionally, the limitations and potential errors of the conducted SLR are discussed (section 4.3), while Section 5.0 provides an overview of the study's topic, goals and findings.

2. Methodology

2.1. Systematic literature review of VIP research – search strings, databases and categorisation

The scooping search [48] aimed to identify the number of VIP research papers published before 2023. Three databases were used; ScienceDirect [49], Web of Science – WoS (All Databases) [50] and Scopus [51]. The search protocol for the scooping phase included the item "vacuum AND insulation AND panels", searched within the title, keywords and abstracts and excluded patents. The search returned 233 results for ScienceDirect, 566 for Web of Science and 675 for Scopus.

After the scooping phase, the literature search was narrowed to buildings and building applications and the WoS database (the reasoning for using WoS is explained in Section 4.3), and the search item was extended to "vacuum AND insulation AND panels AND (buildings OR building OR building application)". After excluding patents, the search returned 339 results.

The third search string refined the results to studies focusing on the life cycle-related environmental and economic implications of VIPs. Initially, various search strings were tested (e.g. including the words "environmental" and "economic"). Finally, the string including LCA and LCC was best suited. The search item was "vacuum AND insulation AND panels AND (life cycle assessment or LCA OR life cycle costing OR LCC)".

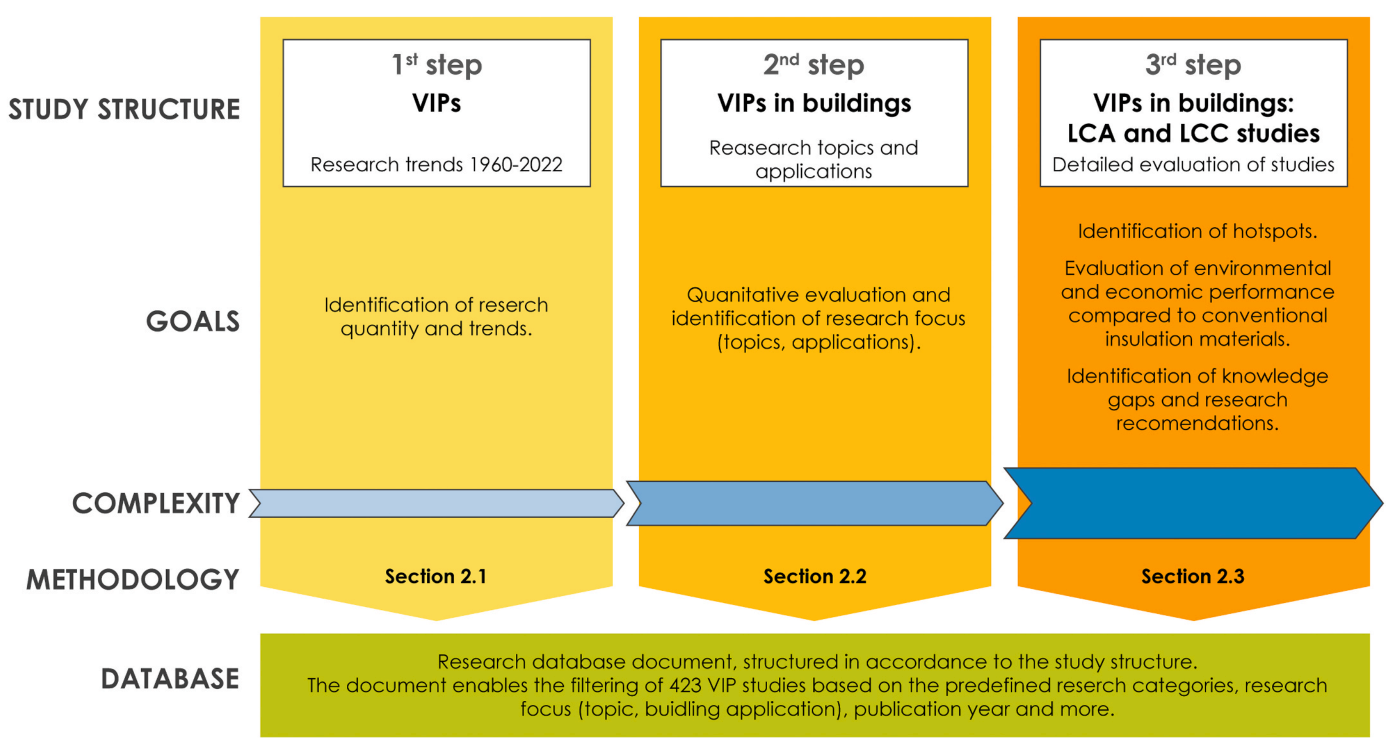

Fig. 2. Block diagram presenting the study structure.

The search in the Web of Science database returned 23 results.

The results were filtered through exclusion by title and abstract to exclude documents unrelated to VIPs. This step also included categorisation, where the documents were divided into three groups.

- PRODUCT – documents focused on basic VIP research or fundamental research regarding their elements (e.g., core materials, barrier envelope, etc.).
- BUILDING – documents related to research on VIPs in building applications.
- OTHER – documents researching VIPs in applications unrelated to buildings (e.g., cold chain, thermal energy storage, etc.).

The final number of documents for the three groups was obtained after more detailed data extraction, explained in sections 2.2 and 2.3. Only peer-reviewed research studies and expert group technical reports are included in the final database. Proceedings from scientific conferences were excluded. The entire database is presented in the research data document [47].

2.2. VIP in buildings – identification of research focus (applications, research topics)

The second step of the SLR is focused on identifying building applications for VIPs and evaluating which building applications and research topics have been studied. Data extraction from the building application database aims to quantify past research focusing on VIPs in buildings. The authors relied upon their experiences with VIP building applications acquired during several years of research involvement in this field. Furthermore, potential building applications were also defined by additional grey literature and by scanning the documents in the database for building application types, which helped identify possible novel applications. The data about VIP building applications were extracted by a full-text examination of documents in the literature database according to the following criteria (i) the identification of application type (e.g., external wall, roof): and (ii) the research topic (e.g., thermal performance, acoustics).

Potential VIP building applications were presented and described by Johansson in 2012 [52]. Table 1 provides an overview and references for the identified VIP applications in the building envelope elements and other specific envelope applications/systems. These comprise specific applications such as glazed façades/spandrel, attic hatches, and VIP systems (e.g., structural insulation panels – SIPs). The structure of building applications presented in Table 1 will serve as a starting point for evaluating the analysed documents from the point of view of building applications of VIPs. The insulation layer position was determined for the external wall application, where "cavity" stands for insulation in the plane of the load-bearing structure (e.g., between studs).

Regarding the research topics related to VIPs in building applications, the following were identified in the studied literature.

1. **Thermal performance of buildings and building elements –** incorporates all studies dealing with heat transfer and hygrothermal properties of VIPs, including topics such as experimental or numerical evaluation of heat flow, building energy simulation or thermal bridging.
2. **Service life (i.e., ageing)** – studies analysing the thermal performance of VIPs over time.
3. **Product and application development** – includes research presenting VIPs in the context of building applications as building products or specific applications (e.g., VIP protection, attachment to surfaces, new building products).
4. **Environmental and economic impact** – includes documents that evaluate environmental and cost-related implications of using VIPs in buildings.
5. **Acoustics** –research regarding the acoustic properties of VIPs in buildings.
6. **Reaction to fire** – contains documents dealing with the fire reaction of VIPs in buildings.
7. **Review/general information** – contains reviews and studies that discuss VIPs in the context of building applications but do not present any novel VIP research.
8. **Other** – contains documents analysing topics that do not fit previously listed topics.

The information on how much research attention has been attributed to individual topics and applications will provide a general overview of the structure of past research on VIPs in buildings. A single research paper can cover multiple research topics and application types. Therefore, the total application and research topic count will be greater than the total number of documents in the database. The research data document enables a complete overview of research topics and building applications affiliations for individual studies [47].

2.3. Studies on the environmental and economic impact of VIPs in buildings – snowballing and detailed full-text examination

A detailed full-text examination of documents focusing on the environmental and cost-related impacts of VIPs was performed. The goal was to identify all the documents that provide relevant information for VIPs in building applications. Through the snowballing approach [55], the initial 23 documents were used as a starting set for further examination. The literature added through the snowballing approach was limited to peer-reviewed scientific studies and technical reports. Documents such as product brochures, case studies or reports from VIP manufacturers were omitted. From each relevant document, the following data were extracted.

- type of building application (e.g., external wall, roof),
- VIP core material,
- life cycle stages covered,
- environmental and economic indicators calculated,
- assumed VIP service life,
- VIP thermal conductivity used in the calculation,
- building type (i.e., residential, office),
- project type (i.e., retrofit, new construction),
- climate type,

Table 1
Identified VIP building applications with relevant references for application descriptions and examples.

building envelope position	roof		internal partition (ceiling/floor)	external walls (above ground)			base floor
	flat	pitched		insulation layer position			ground floor
				external	cavity	internal	
reference	[52]						
specific position/ system	shading shutters	dormer windows		attic hatches and stairs	structural façade panels/structural insulation panels (SIP)	glazed façade/ spandrel	doors
reference	[52]				[52,53]	[52,54]	[52]

- study scope (context and goal of the study), and
- study take-away (what the results reveal about VIPs' economic and environmental performance).

The study scope reveals the context, goal and methodological specifics related to VIPs, whereas the study take-away presents what the results reveal about VIPs' economic or environmental performance. Appendixes A and B present an overview of the study scopes and take-aways for the evaluated documents. The identified environmental and cost-related studies are separately listed in the research data document [47].

3. Results

3.1. VIPs: research quantity and trends

Fig. 3 illustrates the publication trend from the database's first peer-reviewed study onwards (Strong et al., in 1960 [56]). This study is an outlier, as there is a gap of three decades between this document and the second one identified in the database. Studies on VIPs have been published continuously since 1993. The number of published studies increased significantly after 2010, focusing primarily on basic research (i.e., PRODUCT category) and building applications (i.e., BUILDING category). After 2009, 87% (368 out of 423) of identified research documents were published. As a remark, the EU's Energy Performance of Buildings Directive [57] was passed in 2010, which might have contributed to the increase in research publications on VIPs, specifically those related to building applications.

Between 1993 and 2009, the average number of total annual publications was 3.2, dominated by research in the PRODUCT category (Table 2). In contrast, between 2010 and 2022, the average annual number of publications rose to 28.3 per year, with the vast majority (16.8 publications per year) falling into the BUILDING category.

The earliest studies on VIPs focused on the material and physical properties of various evacuated materials (e.g., open-porous polyurethane foam [58]). The first identified studies from the OTHER and BUILDING categories were published in 1997 [59] and 2001 [60], respectively. The former discusses the application of VIPs in the refrigerator envelope, whereas the second one analyses the application in building facades.

Table 2
Amount of research documents and the average number of published VIP research for the pre- and after-2010 periods.

Database data	PRODUCT	OTHER	BUILDING	TOTAL
COUNT	139	46	238	423
SHARE [%]	32.9	10.9	56.3	100
Average number of annual publications [publications/year]				
1993–2009	1.7	0.3	1.2	3.2
2010–2022	8.4	3.2	16.8	28.3

Until the end of 2022, 423 research documents were identified, from which over one-half (56.3%) focused on VIPs in building applications. Approximately one-third of the published studies fall in the PRODUCT category and 10.9% in the OTHER category (Table 2). The most studies were published in 2019 (44 documents) and 2020 (45 documents). In the latter case, 32 documents (71%) fall into the BUILDING category.

Only 10.9% of the total publications are related to the OTHER VIP applications, such as refrigerators or thermal insulated packaging. Fig. 4 presents the share of topics studied in the OTHER category, and as expected, cold chain applications dominate, with a combined share of 61%. Refrigerator applications were the most studied, accounting for 30% of documents. Thermal insulation packaging (15%) also received considerable research attention. Thermal insulation protection of electronic devices (e.g. Ref. [61]) and the development of specific hot-box apparatus [62] are examples of the other VIP research areas, accounting for 13% of documents.

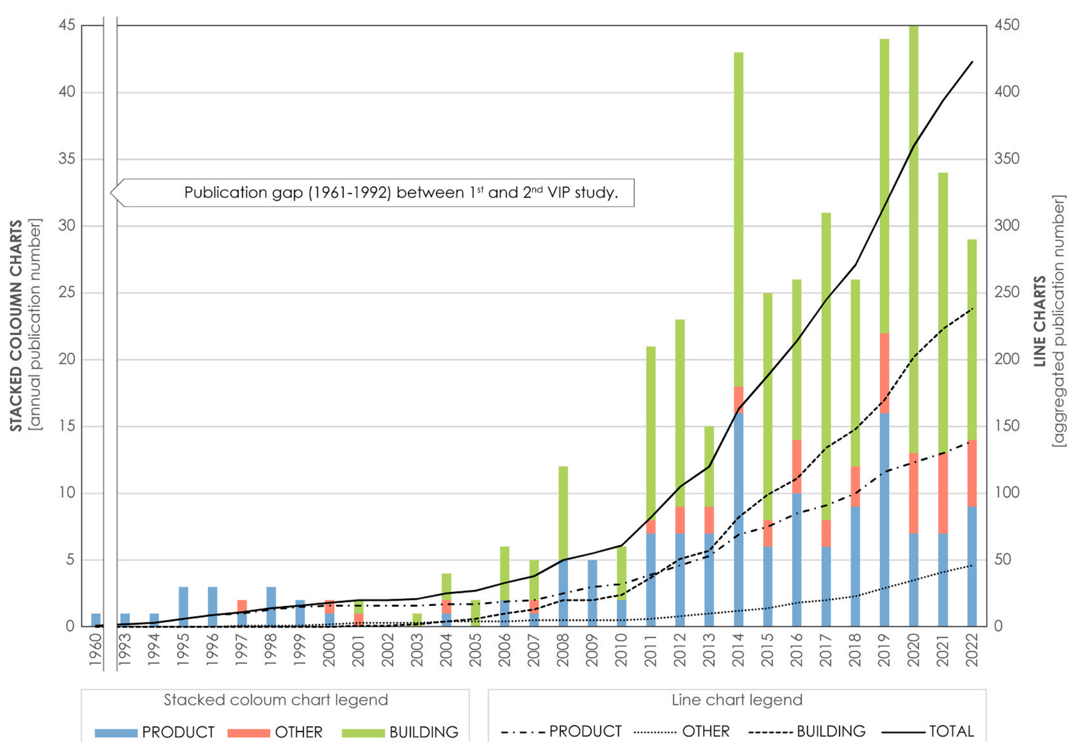

Fig. 3. Publication trend for research on VIPs from 1960 to 2022 based on research focus categorisation.

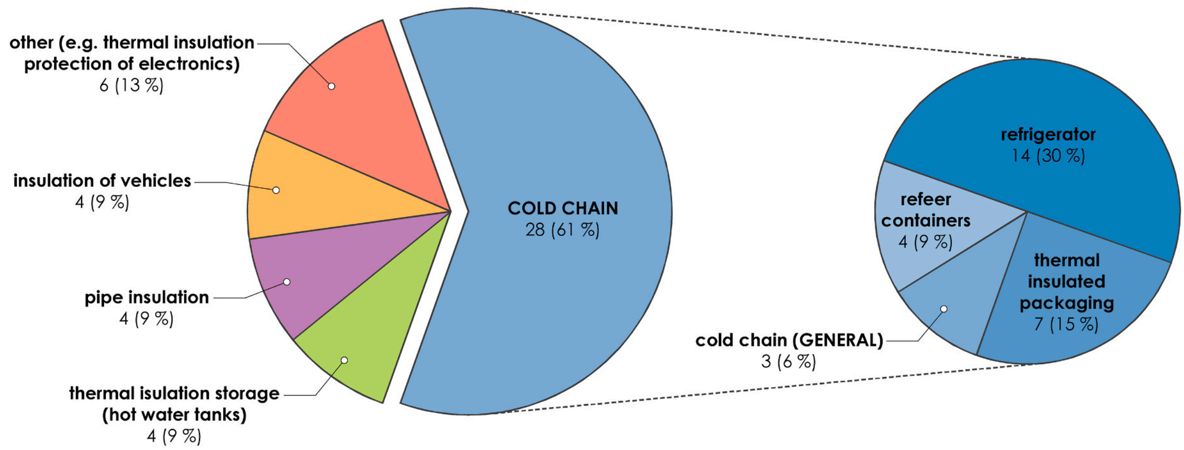

Fig. 4. Research focus on VIPs in the OTHER applications category, represented by the number and share of documents for identified areas.

3.2. VIPs in buildings: quantitative information for building applications and research topics representation in scientific literature

Fig. 5 presents the count and share for the building applications analysed in the VIP studies. External wall applications were the most frequently addressed building applications, accounting for approximately two-thirds of the studied applications. Among these, 40% of publications dealt with the VIP position on the outer side of the wall. The internal position accounts for 15% and the cavity for 8% of identified applications. Interestingly, roof applications account only for 9% (6% flat and 3% pitched roof), whereas ground floor and internal partitions account for 3% and 2% of VIP applications evaluated. Specific positions/system applications account for 23% of identified applications. Among these, façade panels/SIPs and glazed façade/spandrel applications account for the majority, with a respective share of 12% and 6%. The remaining applications (e.g., attic hatches and stairs, shading shutters, etc.) were evaluated in less than 5% of research documents.

Table 3 shows how different research topics were represented in the identified documents. As expected, research on the thermal performance of VIPs in the context of buildings was identified as the most frequently studied topic, accounting for 46.7% of the research focus on VIPs. The second most studied topic was related to product and application development, accounting for 18.5%. Studies on service life determination represent an 11.9% share, and review and general information studies account for 12.4%. Environmental and economic impact research on VIPs represents a 7.1% share, whereas the remaining research topics (i.e., acoustics, reaction to fire and others) comprise 3.3% of research.

3.3. VIPs in buildings: research findings for environmental and economic studies

3.3.1. Quantitative information

Of the 23 documents in the initial WoS search, 14 did not qualify as life cycle studies relevant for building applications or were unrelated to VIPs. By applying the snowballing approach on the remaining 9 documents and including technical reports, a further 21 documents were identified. Therefore, the final number of studies dealing with the environmental and economic evaluation of VIP considered in this review is 30, with 28 documents classified in the BUILDING and two ([63,64]) in the PRODUCT groups.

Fig. 6 provides quantitative information about the publication type and trend of published VIP life cycle studies. All published works are either LCA or LCC studies, except for some review papers where no environmental or economic information was calculated (e.g. Ref. [65]). Most studies are journal papers (54%), whereas technical reports account for approximately one-quarter of the documents.

The first identified LCA study evaluating the environmental impacts of VIPs is from 2003 [66], which makes it one of the first building-related studies on VIPs (the third oldest document identified for the BUILDING category). Only after another seven years did LCA and LCC studies on VIPs start being published annually. The first LCC studies evaluating cost-related implications were published in 2011 (ref. [9, 50]), while the second identified LCA study was published in 2014 (ref. [67]). From 2011 onwards, 1.3 LCA and 1.5 LCC studies have been published annually. In 2021, the largest number of studies were published, three related to LCA and LCC, resulting in six publications on the environmental and economic impacts of VIPs in buildings. Although no research documents were published in 2022, an increasing trend in the publication of LCA and LCC studies can be observed. From the 30 documents identified in the database, 13 (43%) evaluate the environmental and 15 (50%) the cost-related characteristics of VIPs. Two studies (7%) were identified where the environmental and cost-related impacts of VIPs were analysed simultaneously (ref. [48,52]), both published in 2020.

3.3.2. Findings from studies analysing the environmental and economic impact of VIPs

3.3.2.1. General outtakes of reviewed LCA and LCC studies – comparison with conventional insulation materials. Table 4 presents an overview of the main characteristics of the identified LCA in LCC studies. First, the life cycle characteristics on the product level will be discussed and later, the environmental and economic implications of using VIPs in the building envelope. Before evaluating the life cycle results, one must consider that directly comparing results from different life cycle studies can be challenging. This is particularly true for the LCA studies, as crucial information that would allow comparison is often missing or differs significantly due to unaligned goals of different studies and methodological approaches [68]. Therefore, care has to be taken to evaluate life cycle analysis results in line with study scenarios and boundaries. Tables 6 and 7 present the main characteristics of the reviewed studies, while Appendices A and B provide the scope and take-away descriptions. Based on the presented data, it can be observed that some studies do not reveal information (e.g., VIP thermal conductivity or VIP core material) that would allow broader contextualization of the presented research results.

On the product level, most life cycle studies analyse the environmental impact. Those focusing on costs only provide general cost information as part of review articles. Fumed silica is the most common core material evaluated in the life cycle studies. This was expected, as fumed silica core VIPs are the most suitable choice for building applications.

A key take-away from the product-oriented LCA studies is that fumed

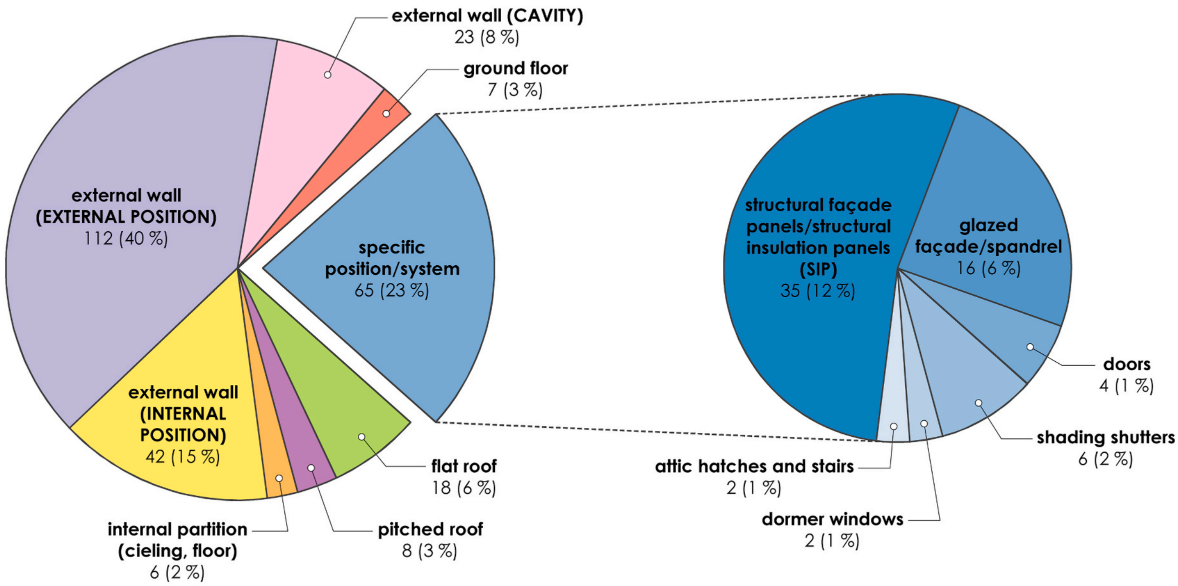

Fig. 5. Research focus on VIPs in building applications: quantitative information (count and percentage share) about researched building applications.

Table 3
Research focus on VIPs in building applications: quantitative information about research topics.

	Thermal performance of buildings and building elements	Service life (i. e. aging)	Product and application development	Environmental and economic impact	Acoustics	Reaction to fire	Review/general information	Other
COUNT	184	47	73	28	4	5	49	4
SHARE [%]	46.7	11.9	18.5	7.1	1.0	1.3	12.4	1.0

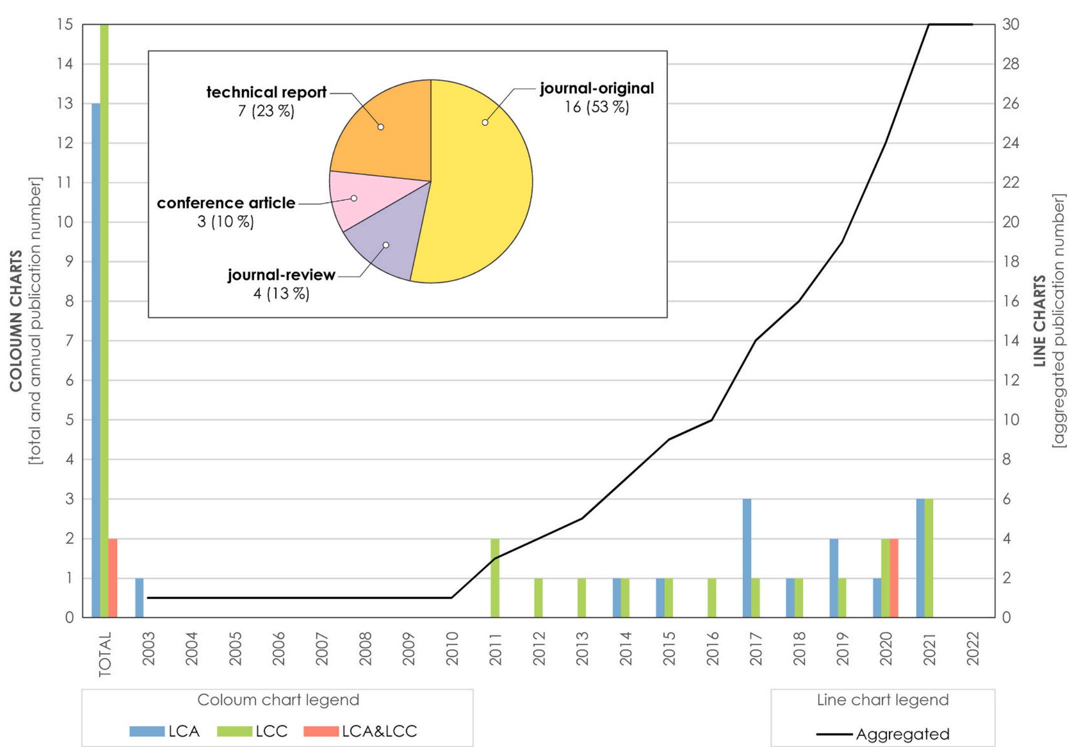

Fig. 6. Quantitative information about the publication type and trend of published studies evaluating VIPs' environmental and economic impact.

Table 4
Overview of the main characteristics of LCA and LCC studies analysing VIPs.

	LCA	LCC
studies analysing VIP on the product level [number (share of total); references]	**8 (53%);** [63–66, 69–72]	**2 (13%)** [33,65]
studies analysing VIP in building applications [number (share of total); references]	**7 (47%);** [41,67,73, 74–77]	**15 (87%)** [7,42,78, 73,79–89]
VIP core materials in studies [material: count]	fumed silica: 10 glass fibre: 1 EPS: 1 perlite: 2 aerogel: 1 ND: 5	fumed silica: 11 glass fibre: 3 perlite: 2 ND: 3
building applications analysed [application: count (share)]	external walls: 7 (70%) - external position: 6 (86%) - internal position: 1 (14%) roof: 3 (30%)	external walls: 14 (74%) - external position: 4 (40%) - internal position: 6 (60%) roof: 3 (16%) base floor: 1 (5%) SIP: 1 (5%)
assumed fumed silica VIP service life [range]	25–50 years	20–65 years
comparison to conventional insulation [material: count]	EPS: 5 mineral wool[a]: 6 aerogel: 4 polyurethane: 4 wood fibre: 4	EPS: 8 mineral wool[a]: 3 aerogel: 2 polyurethane: 1
building type [type: count]	residential: 3 other: 2 - hypothetical building: 1 - demonstrational house: 1	residential: 6 office: 5 retail: 2 other: 1 - experimental building: 1
retrofit/new building [count]	retrofit: 3 new building: 1	retrofit: 6 new building: 4
climate for energy calculations [heating or cooling dominated: count]	heating dominated: 7 cooling dominated: 4	heating dominated: 12 cooling dominated: 4

ND – not defined.
REMARK: the summation of counts for each characteristic does not add up to the total number of publications. One study may contain multiple features and some studies do not report particular characteristics because they are not relevant for the goal and scope of the study.
[a] Some studies label glass or rock wool as mineral wool; therefore, mineral wool is used as an umbrella term for both.

Table 5
Primary energy consumption for the cradle-to-gate life cycle modules of 1 kg fumed silica VIP. The values given in the table should be considered orientational only, as the LCA details (e.g., allocation, LCI database) are unknown and, therefore, not considered.

	2003 [66]	2015 [41]			2021 [63]
		EPD 1	EPD 2	EPD 3	
PENRT [MJ/kg]	133.9	162	147	120	201,4
PERT [MJ/kg]	30.4	64	38	29	86.1
PET [MJ/kg]	164.3	226	185	149	287.5

silica is an environmental hotspot of VIPs. The fumed silica core contributes most to the environmental burden in the cradle-to-gate life cycle stages (A1 – A3 according to EN 15804 [71]). Based on the study by Resalati et al. [63], which evaluated the environmental impact of various VIP core materials, the environmental burden of fumed silica exceeded 60% in all environmental categories and could reach values as high as 90%. Other life cycle stages, such as transportation, manufacturing of VIPs or other VIP materials (i.e., barrier envelope), showed a minimal contribution to the overall life cycle impact of the final product.

The high environmental impact of fumed silica VIP core is a direct consequence of using silicon tetrachloride (or tetrachlorosilane), a key component from which fumed silica is produced. For the cradle-to-gate life cycle modules, the contribution of silicon tetrachloride to the overall impact exceeds 60% [66]. For the Global Warming Potential (GWP) category, the contribution of silicon tetrachloride is 70% and can reach even higher values in other environmental categories [63]. Optimising fumed silica production (or silicon tetrachloride production) is therefore considered essential for reducing the environmental impact of VIPs [63, 66]. However, when comparing primary energy (PE) data from studies published in 2003, 2015 and 2021 (ref. [30,49,56], see Table 5), no trend of reducing the PE can be observed. It should be noted that the life cycle inventory (LCI) data used for fumed silica production in the most recent LCA study from 2021 [63] are based on 2007 data [91]. Efforts have been made to calculate results using more recent LCI data, but these were unsuccessful due to confidentiality concerns of pyrogenic silica manufacturers [63,73].

Four studies that compared the environmental impact of VIPs directly to two or more conventionally used building insulation materials were identified [66,69,70,72]. Based on these studies, it can be concluded that fumed silica VIPs exert a more significant environmental impact in the cradle-to-gate life cycle modules if the comparison is based on an equivalent thermal transmittance value. However, this is not true for all environmental indicators and all insulation materials. For example, EPS exerts higher Photochemical Ozone Creation Potential (POCP) values [69] and a higher Eco-indicator 99 environmental score [66]. At the same time, according to Kunič [70], foam glass boards and aerogel insulation have a higher carbon footprint than VIPs.

Although fumed silica VIPs have a higher environmental impact than conventional building insulation materials, it is important to consider the purpose of insulation materials in buildings – to reduce heating and cooling demand. Under such constraints, the carbon and energy payback period calculations showed that fumed silica VIPs achieved environmental neutrality in approximately 5 years, compared to inferior insulated baseline scenarios [70,72]. This indicates that VIPs used in retrofit applications may have a net positive environmental impact for about 20 years, assuming a 25-year service life.

Finally, it has to be stressed that the fumed silica VIP core can be recycled at the end of its service life [63,71]. Using a sensitivity analysis, Schonhardt et al. [66] calculated that reducing the impact of fumed silica by 50% and replacing silicon carbide with a 10 times less contributing material could make the environmental impact of VIPs comparable to that of glass wool insulation. Brown et al. calculated that a 60% recycling rate would be needed for fumed silica VIPs to be competitive with polyurethane insulation from an environmental standpoint [71].

3.3.2.2. Overview of building LCA studies. Most reviewed building LCA studies focused on VIPs in external wall applications, where the external insulation position dominated. The impact of VIPs on the operational phase was analysed in heating and cooling-dominated climates. Residential buildings and retrofitting scenarios were most often evaluated (Tables 4 and 6).

Three studies were identified where the application of VIPs in the building envelope was compared with conventional insulation materials based on equivalent thermal transmittance values (ref. [41,67,76]). Loli and Hestnes [67] compared retrofitting scenarios for a typical Norwegian residential apartment building. The study included the comparison of mineral wool, aerogel and VIP external wall applications, considering different electricity mix carbon intensities. Considering a 50-year reference service life for all materials, the VIP retrofitting scenarios showed the highest carbon footprint. As the embodied impacts were the environmental hotspot for VIPs, the relative difference was most pronounced for the low carbon intensity electricity mix scenario. The VIP life cycle impacts were 10–25% higher than for the mineral wool scenarios. The aerogel insulation alternative demonstrated slightly smaller

Table 6
Main characteristics of LCA studies evaluating the environmental impact of VIPs in the context of buildings.

study	functional unit OR VIP application (position)	life cycle modules according to EN 15978 (module B period [years]); VIP service life	environmental (& economic[a]) indicator	core material; λ_{VIP} [W/(mK)] for calculations	comparison with other insulation materials; equivalent thermal transmittance	climate – cooling (C) or heating (H) dominated	building type; retrofit/new construction
Schonhardt et al., 2003 [66]	1 m^2 insulation according to U-value = 0.15 W/(m^{2}K)	A1-A3	Eco-indicator 99, UBP97, KEA (embodied energy)	fumed silica; 0.0048[b]	yes (glass wool, EPS); yes	/	/
Lolli and Hestnes, 2014 []	building; wall (external position)	A1-A3, A4, A5, B5, B6 (50 years), C1, C2; 50 years	GWP, embodied energy	fumed silica; 0.008	yes (aerogel, mineral wool); yes	H	residential (apartment); retrofit
Karami et al., 2015	building; wall and roof (external position)	A1-A3 + B6 (50 years); 50 years	GWP, PE, ODP, AP, EP	fumed silica; /	yes (mineral wool, EPS); yes	H	residential (apartment); new construction
Dovjak et al., 2017 []	1 m^2 insulation according to U-value = 0.25 W/(m^{2}K)	A1-A3	GWP, ODP, POCP, AP, EP, ADPE, ADPF	fumed silica; /	yes (multiple conventional and alternative); yes	/	/
Kunič R., 2017 []	(i) 1 kg of material and (ii) 1 m^2 insulation according to fixed U-value	A1-A3, B6	GWP (GWP payback period – environmental neutrality)	/(fumed silica?); 0.006	yes, (multiple – EPS, XPS, …); yes	H	/
Yang and Tang, 2017 []	1 m^2 insulation according to fixed U-value	A1-A3, B6 (30 years)	embodied energy, energy payback time	/(fumed silica?); 0.005	yes, (polyurethane, mineral wool); no	H	/
Zhuk P., 2018 [64]	1 m^2	A1-A3	GWP, ODP, AP, EP, POCP	/	no	/	/
Papadaki et al., 2019	1 m^3 of building internal volume; wall (external position)	A1-A3, A4, B6 (25 years), C, D; 25 years	ReCiPe midpoint and endpoint, hierarchic	/	no	C	/
Brown and Resalati, 2019 []	building; wall (external position), roof (internal position)	A1-A3, B6 (30 years), D; 30 years	carbon emissions (GWP)	fumed silica, perlite; /	no	C & H	residential; retrofit
Brown et al., 2020 []	1 m^2 insulation according to U-value = 0.27 W/(m^{2}K)	A1-A4, D	GWP, ODP, POCP, AP, EP, ADPE, ADPF, PENRT, PERT	fumed silica, perlite; /	yes (polyurethane); yes	/	/
Kumar et al., 2020 [65]	per m^3 (cost), per kg (environmental impact)	/	/(review article – a general comparison of cost and embodied energy and carbon)	/	yes (multiple); /	/	/
Wallbaum and Kono, 2020 []	building; wall (internal position)	A1-A3, B6	carbon and economic payback period	fumed silica; 0.0035	yes (aerogel); yes	H	hypothetical building; retrofit
De Masi et al., 2021 []	wall (external position)	A1-A3, A5, C, D; 50 years	GWP, AP, EP, ODP, POCP	fumed silica; 0.008	yes (wood fibre); no	C	/
De Masi et al., 2021 []	building; (wall and roof -external position)	A1-A5, B1, B6 (50 years), B7, C1 and D; 50 years	GWP, AP, EP, ODP, POCP; greenhouse gas payback time (GPBT)	fumed silica; 0.0046	yes (wood fibre, cellular glass); yes	C & H	demo house; new construction
Resalati et al., 2021 [63]	1 m^2 insulation according to U-value = 0,27 W/(m^{2}K)	A1-A3	GWP, ODP, POCP, AP, EP, ADPE, PENRT, PERT, WRD	multiple VIP core materials with corresponding thermal conductivities	no; yes	/	/

/not declared or not relevant to the study goal and scope.
[a] For [55,65], which simultaneously evaluated the environmental and economic performance.
[b] Calculated based on the assumption of 5% damaged panels during the service life of VIP.

life cycle environmental impacts, in contrast to other studies (ref. [73, 70]), where aerogel insulation application resulted in higher environmental impacts than VIPs with the same thermal transmittance value.

The study from Karami et al. [41] focused on a scenario for a new residential building in Sweden in which large quantities of other construction materials (e.g., concrete, gypsum boards, etc.) were included in the LCA calculation. Except for the Ozone Depletion Potential (ODP) environmental category, the LCA results showed a substantially higher cradle-to-gate (i.e., production) impact of VIPs compared to the alternative scenario applying EPS and mineral wool as external wall and roof insulation. Considering the operational energy use over a 50-year service period, the building alternatives with conventional insulation materials had lower GWP and a lower total PE than the VIP insulated materials. Furthermore, the LCA results revealed that using two times lower U-values for the VIP scenario than for the conventional insulation materials does not contribute to reducing the life cycle impacts of the

Table 7
Main characteristics of LCC studies evaluating the economic impact of VIPs in the context of buildings.

study	functional unit OR VIP application/ position	life cycle modules according to EN 15978 (module B period [years]); VIP service life	economic indicator	core material; λ_{VIP} [W/(mK)] for calculations	comparison with other insulation materials; equivalent thermal transmittance	climate – cooling (C) or heating (H) dominated	building type; retrofit/new construction
Jelle B·P., 2011 [7]	residential room; wall (internal position)	A (insulation material costs), B (profit due to increased living area); /	Profit in EUR/(m^2 living area) and EUR/ (100 m^2 living area)	fumed silica; /(6 cm VIP corresponding to 35 cm mineral wool)	yes (mineral wool); yes	H	theoretical residential space; /
Alam et al., 2011 []	/ (various scenarios)	/	payback period	/	yes (EPS); yes	H	/
Deniz et al. [89]	external wall (cavity)	A (insulation material costs), B (10 years); /	payback period, present worth	/; 0.004	yes (rock wool, glass wool, EPS, XPS)	H & C	/
Kosny et al., 2013 [79]	wall (external position, ETICS)	A (material costs + installation/retrofit costs); /	cost in $/($ft^2$ wall area)	multiple (fumed silica, fibre glass); /	yes (aerogel, XPS, EPS, PUR); yes	H	residential (single family); retrofit
Cho et al., 2014 [80]	building; VIP in external wall (internal position)	A (material and installation costs) + B (40 years); 40 years	present worth method	/; 0.0045	yes (EPS); no	H	residential (single family); new construction
Kim et al., 2015 [81]	wall	A (material costs + installation) + B6; /analysis of damaged pannels	net present cost	fumed silica & glass wool; 0.120 (?) & 0.002	no	H	residential (apartment); /
Abdul Mujeebu et al., 2016	building; wall and roof (external position)	A (material costs) + B6 (energy costs)	simple payback period	fumed silica; 0.003	yes (EPS); no	C	office, retrofit
Alam et al., 2017 [83]	buildings; wall, floor and roof (all internal position)	A1-A3, A5, B5, B6 (60 years); 60 years for fumed silica and 10 for glass fibre	profit on investment (discounted payback period)	fumed silica, glass fibre; fumed silica: initial 0.008 + annual increase of 0.0001 glass fibre: initial 0.007 + annual increase 0.0018	yes, (mineral wool) yes	H	3 non-residential (2 retail, 1 office); retrofit
Maddock et al., 2018 [84]	building; wall (external position), roof (internal position)	A (material and installation costs for insulation), B6 -heating and cooling (30 years); 30 years	cost-optimal method (net present value -global cost)	fumed silica, perlite; fumed silica[a]: 0.00544 perlite[a]: 0.006	yes, (EPS or medium-cost insulation); yes	C & H	residential; retrofit
Fantucci et al., 2019 [42]	office room; wall (internal position)	A (material and installation costs for insulation), B6 (25 years); 25 years	discounted payback period and break-even rental value	fumed silica; effective λ_{VIP} including ageing and edge effect, initial value: 0.004	yes, (EPS); yes	C & H	office; retrofit
Gonçalves et al., 2020 []	wall (external position – ETICS)	A (insulation material costs)	cost per unit area and thermal resistance (EUR/m^2, EUR/R)	fumed silica, aerogel, perlite, polyurethane, glass fibre; various λ_{VIP} values	no	/	/
Resalati et al., 2020 [85]	building; wall (internal and external position)	A (material and installation costs for insulation), B2, B6 -heating and cooling (20 years); multiple VIP service life assumptions 20–50 years	cost-optimal method (net present value -global cost), payback period	fumed silica, perlite; /	yes (EPS); yes	H	residential apartment & office room; new construction
Simões et al., 2021 [86]	wall (external position – ETICS)	A (material and installation costs for ETICS), B2, B6 -heating and cooling (20 years); multiple VIP service life assumptions 20–50 years	cost-optimal method (net present value -global cost), payback period	fumed silica; 0.0095 - 0.0132 (λ_{VIP} depending on thickness)	yes (EPS); yes	H	office building; new construction
Geng et al., 2021 [87]	building; roof and wall structural insulation panels	A (material and installation costs for ETICS), B2, B6 -heating (45 years); 45 years	P1–P2 method, discounted payback period	fumed silica; time-dependent λ_{VIP} (ageing), initial value: 0.004	no	H	experimental building; new construction
Wernery et al., 2021 [88]	external wall (external and internal position)	A (material and installation costs), B (profit due to increased living area); /	equation for calculation of additional space creation costs compared to conventional insulation	/	yes (generic conventional material); yes	/	/; new construction or retrofit

[a] Calculated based on the U-value for 20 mm thickness.

VIP-insulated building. The overall GWP value in this case was only 6% lower, whereas the PE use increased by approximately 25% for the building using VIPs.

The study performed by De Masi et al. [76] evaluated the environmental impact of VIPs for three climates (Naples, Paris, Munich) and compared them to building scenarios with wood fibre and cellular glass insulation. The impact of thermal insulation (wall and roof application) was evaluated, combined with various glazing and window frame types. Similar to previous studies where the comparison was based on the equivalent thermal transmittance of the building envelope, the operational energy had minimal influence on the results. Wood fibre insulation applications resulted in the smallest GWP values, whereas the building alternatives with cellular glass insulation exerted the highest GWP values. However, the relative differences between the smallest and highest life cycle results were minor (approximately 5%), indicating a small life cycle impact of the insulation materials for the observed scenarios.

Papadaki et al. [74] explored the possibility of using VIPs in combination with phase-change materials (PCMs) as a retrofit measure for warm Mediterranean climates. They conducted an LCA analysis on two identical demonstrational houses in Greece. One was used as a base case, while the other had an additional insulation layer of VIPs and PCMs in the external wall assembly. The results showed that adding VIPs and PCMs substantially increased the cradle-to-gate environmental impacts of the building. However, this increase was compensated in 14 months due to the cooling demand reduction coupled with the high environmental impact of the electricity mix (approx. 80% based on fossil fuels). Applying VIP and PCM insulated walls would yield a 57% lower environmental impact over the 25-year lifespan than the inferior insulated base case.

Brown and Resalati [75] performed an interesting LCA study. They calculated embodied and operational carbon emissions for three cities (Berlin, London, and Lisbon) by considering the projected electricity mix carbon reduction. They evaluated various VIP thicknesses for roof and external wall applications in the retrofit of a residential building and compared them to the reference case (20 mm thick VIP panels). The results showed that reducing the embodied impact of VIPs is necessary to reach carbon neutrality under the presumed 30-year service life. In Berlin, a recycling share of 20% would be required, while in London, a 60% share would exert a net positive carbon effect. For Lisbon, even a 90% recycling rate results in a net disbenefit, indicating that an increase in insulation thickness above 20 mm does not reduce the life cycle impact.

Finally, Wallbaum and Kono [92] calculated the carbon payback period for a retrofit scenario of a theoretical two-story (15 m × 15 m x 6 m) building, where fumed silica VIPs were installed as façade insulation on the interior side. The calculations were done for four heating-dominated locations (London, Berlin, Zurich, and Gothenburg). They showed a CO_2 payback time ranging from 4.4 to 8.6 years, with shorter payback periods in colder climates.

3.3.2.3. Overview of building LCC studies. The average cost of VIPs depends on the core material used. The price range for fumed silica VIPs per volume is between 2500 and 3300 EUR/m^3 [90]. Unlike the LCA studies, the LCC ones do not provide a detailed cost breakdown for the cradle-to-gate life cycle modules of VIP production. The cost of fumed silica may be considered confidential information for VIP manufacturers, so no precise data are available. We assume that VIP manufacturing (labour costs, technology, energy) and other materials (e.g., barrier envelope) are significant contributors to the total cost and that fumed silica is not the only hotspot, as is the case with the environmental burden.

The reviewed LCC studies focused predominantly on external wall VIP applications. Maddock et al. [84] calculated the theoretical thickness and material costs of VIP to be directly competitive in external wall and roof applications. The Berlin, London and Lisbon calculations showed that the climate type (heating/cooling demand) and energy costs significantly influence the optimal insulation thickness and cost calculations. VIPs should generally reach a price of about 700 EUR/m^3 to be directly competitive with conventional insulation materials, such as EPS (assuming a price of 120 EUR/m^3).[1]

The study of Cho et al. [80] compared the life cycle costs of XPS and VIP insulation applied on the interior side of a residential building façade wall. The comparison was not based on an equivalent thermal transmittance value and assumed a 75 mm thick XPS layer and 20 and 30 mm thick VIP applications. Consequentially, the external wall thermal transmittance value was lower by a factor of 2 and 3 for the VIP alternatives. The study showed a considerable reduction in heating demand and cost benefits by using VIP insulation compared to XPS. Although the assumed thermal conductivity of VIPs (0.0045 W/mK) is unrealistic for the 40-year calculation period, the results indicate that VIPs could be economically viable compared to conventional insulations if the thickness of the insulation layer is limited.

Nevertheless, most LCC studies comparing VIPs with conventional materials focused on the landlord/investor perspective, where the benefit of added useable floor space due to the thinner insulation layer is accounted for. These studies range from simple (e.g., Jelle [7]) to more sophisticated, covering various influencing factors (e.g. Refs. [42,86]). However, all concluded that the use of VIPs in external wall applications could be economically beneficial compared to conventional insulation, considering the high rental/purchase prices of a unit of useable floor space. Varying between cities (due to climate, energy costs, etc.), the yearly rental values per floor space should be higher than 150–350 EUR/m^2 for fumed silica VIPs to be cost-efficient compared to conventional insulation (e.g., EPS) [42,85,86].

Wernery et al. [88] derived an equation that quantifies the cost of creating additional living space when using superinsulation materials for wall applications instead of conventional ones. The equation variables are the thermal conductivity, the cost of the insulation materials, and two building geometry parameters. They present real estate prices for major cities in Europe, Asia and North America show that applying superinsulation materials as external wall insulation is already profitable in several cities.

Wallbaum and Kono [92] calculated the economic payback period for a retrofit scenario of a theoretical two-story building (identical building and scenario as described for the carbon payback period – see Section 3.3.2.2). The results indicate that when the added floor area of a building is included in the calculation (comparison based on an EPS reference) and it results in additional rental income, the application of VIPs has an economic payback period ranging from 3.3 to 7.0 years (depending on the city). The calculated economic payback periods were longer in the study performed by Resalati et al. [85]. They concluded that for yearly rental values above 200 EUR/m^2, the economic payback period is under 10 years (assuming a VIP price of 3000 EUR/m^3).

Another remark on the life cycle cost of VIPs in building applications relates to the climate type. Geng et al. [87] studied the cost-optimal thickness of VIPs in SIPs and concluded that 30 mm VIPs are required in cold climates, whereas under the less severe climate of Beijing, VIPs are not cost-effective in SIP applications. Fantucci et al. [42] showed that VIPs in external walls require higher rental prices under warmer climates to be cost-effective compared to conventional insulation (e.g., 220 EUR/m^2 in Tampere, Finland and 320 EUR/m^2 in Palermo, Italy). Abdul Mujeebu et al. [82] explored the possibilities of applying VIPs as retrofit measures for the wall and roof of an office building located in the hot desert climate of Saudi Arabia. The calculations showed that VIPs exert considerably higher payback periods than EPS insulation, although the wall and roof assemblies with VIPs have much lower thermal

[1] The cost per m^3 calculated based on the results per m^2 presented in Maddock et al. ([84] p. 13–17).

transmittance values (no benefits from space savings were included in the calculations). The study by Deniz [89] compared the payback period of VIPs to conventional insulation for external wall applications in 5 Turkish cities and with different fuel types for building conditioning. The results showed that climate and fuel type notably influence the payback period of VIP; in cold climates and with high fuel costs, VIPs are comparable to conventional insulation materials. The study performed by Maddock et al. [73] also indicates that applying VIPs for retrofitting scenarios is most cost-effective in colder climates, while in warmer climates (e.g., Lisbon), reducing the U-value with high-cost insulation is not economically justified. All the stated findings indicate that VIPs are more cost-effective and competitive to conventional insulation materials in colder (heating-dominated) climates and when energy prices are high.

4. Discussion

4.1. Characteristics of VIP research and focus

The review of conducted VIP research revealed that publication significantly accelerated from 2010 onwards, as only 55 out of 423 documents (13%) were published before this year (Fig. 3). This can be attributed to the increasing interest in VIPs in building applications, as average annual publication increased from 1.2 for the 1993–2009 period to 16.8 for the 2010–2022 one.

Altogether, 238 documents (56%) focused on VIPs in building applications. Out of these, external wall and thermal performance were the most studied applications and topics (63% and 47%, respectively). Basic research on VIP characteristic and their components (i.e. core materials, barrier envelope, etc.) presents one-third of the documents. In contrast, studies evaluating VIPs in other applications (e.g., cold chain and thermal energy storage devices) present roughly 10% of analysed studies. Such research focus distribution contrasts the market share distribution of VIPs, where, according to 2014 data, only 10% of the global VIP production was intended for buildings and 90% for cold chain applications (30% for transportation boxes and 60% for refrigerators [11]).

Altogether, 30 studies provided information about VIPs' environmental and economic characteristics. Out of these, two evaluate VIPs at the product level and the remaining 28 in building applications. Cumulatively, the life cycle studies represent 7.1% of all research documents in the building applications category.

4.2. Findings and recommendations for life cycle studies of VIPs in buildings

Studies focusing on economic performance proved to be more complex and methodologically more coherent than those studying environmental impacts. However, both LCA and LCC studies often failed to provide important information necessary for transparent communication, adequate interpretation of results and research repetition (e.g., thermal conductivity, VIP core material). At the same time, some were based on unrealistic thermal conductivity data for VIPs in building applications. In many instances, the pristine centre of panel thermal conductivity was used to calculate the VIP thermal performance or the thermal conductivity was not aligned with the VIP service life used for the calculations. Effective thermal conductivity accounting for the edge effect and ageing should be used for the calculations to represent a realistic real-life scenario. Of the evaluated documents, the LCC studies performed by Fantucci et al. [42] and Simoes et al. [86] stand out in terms of realistic input data, coherent goal and scope description, complexity, and results interpretation (see Tables 6 and 7 and Appendices).

Based on the analysis of the studies focusing on the environmental and economic implications of using VIPs in buildings, the following conclusions can be highlighted.

- Although there are some exceptions, the study results indicate that fumed silica VIPs as building insulation exert higher environmental impact and costs than conventional insulation materials. This is true if the comparison is based on an equivalent thermal performance, i.e., the thermal transmittance value of the compared building envelope components is equal.
- Fumed silica is the environmental hotspot, contributing over 60% to the VIPs' cradle-to-gate environmental impact. The LCI data for calculating fumed silica production impact in most recent studies are based on 2007 data.
- LCA and LCC studies primarily evaluated VIP use in external wall applications. Some studies also analysed roof applications (along with wall applications), and only two identified studies included the evaluation of other applications (base floor and SIP).
- Residential, office and retail buildings were evaluated in the life cycle studies. The first two dominate, as only one study evaluated retail buildings.
- In building applications, the life cycle impact of VIPs was most often compared to EPS and mineral wool insulation.
- If the functional unit was based on an equivalent thermal transmittance value, no study showed the environmental benefits of using fumed silica VIPs in buildings compared to conventional insulation-based solutions.
- Studies showed that using VIPs in external wall applications could be cost-effective if the functional unit was based on an equivalent thermal transmittance value and performed from the landlord/investor perspective, considering the added floor space due to the thinner insulation layer and the additional income due to an increased living area. However, a high rent is required for space savings to outweigh the higher cost of VIPs.
- VIPs show better environmental and economic performance in buildings under colder climates and high-impact/cost fuel types locations.

Nevertheless, reviewed research has shown that fumed silica VIPs can be environmentally and economically viable when a thick conventional insulation layer is not feasible (e.g., in building retrofit situations). In such cases, VIPs could exert a lower life cycle impact than conventional insulation materials due to a more significant reduction of operational energy use. Studies also demonstrated that fumed silica VIPs' environmental and economic payback periods can be reasonably short and comparable to conventional insulation in colder climates and with higher cost/impact fuel types. Therefore, there is considerable potential for future LCA and LCC studies evaluating scenarios where a thick insulation layer is not an option or where it would lead to a disproportional increase in the usage of other building materials and additional costs.

The reviewed life cycle studies predominantly focused on external wall applications in residential and office buildings. However, the literature review identified 11 additional building applications that were not analysed from the point of environmental and economic benefits. For example, no LCA and LCC studies of spandrel, door, terrace or shading shutter applications were identified. Also, other building types, such as museums, cultural heritage buildings, elderly care facilities, hospitals and educational buildings, could have a high VIP utilisation potential for retrofitting and new buildings. Therefore, our preliminary assumption that only a handful of VIP building applications were evaluated through LCA and LCC studies proved correct.

For VIPs to be directly competitive from an environmental and economic standpoint, their impact should be comparable to conventional insulation materials on the product level. Additionally, studies showed that fumed silica recycling is necessary if the LCA also accounts for the future decarbonisation of the energy mix. As fumed silica in VIPs is the environmental hotspot, recycling the core material is a realistic scenario for obtaining a commercially superior material for VIP cores. Another alternative is to develop novel core materials suitable for building applications that would exert lower environmental impacts. Therefore, LCA and LCC studies should substantiate future research on fumed silica recycling and novel core material development.

The study shows the untapped potential for LCA and LCC research in VIP building applications. Past life cycle research provides valuable information regarding VIPs' environmental and economic characteristics, particularly concerning scenarios where equivalent thermal transmittance is considered. Future research should complement and upgrade these findings to identify which scenarios and applications make VIPs cost-effective and environmentally acceptable alternatives to conventional solutions. At the same time, these studies should adhere to the following.

- Life cycle studies should use effective thermal conductivity and realistic service life scenarios.
- The goal, scope, and methodological specifics of LCA and LCC studies should be coherently described to enable results interpretation and comparison between different studies. Therefore, life cycle studies should adhere to relevant LCA and LCC standards for buildings (e.g., EN 15978 [93], EN 16627 [94], ISO 15686 [95]).
- LCA results should comprise multiple environmental categories, not only those regarding energy use and global warming effects.
- The functional unit, study goal and scope should be unambiguously described and presented.

To summarise, past life cycle studies on VIPs in buildings focused on general applications with high potential for mass production, like walls and roofs. However, many VIP applications and scenarios lack holistic LCA and LCC evaluation. Until a suitable VIP alternative with reduced environmental impact and price is available, future LCA and LCC studies will need to analyse VIPs from a different perspective. Future research should focus on specific applications where VIPs lead to design simplifications and reduced operational energy and material requirements. These studies should be done from the building designer's perspective, with the scenarios being building design-oriented and evaluated accordingly. The study boundaries should, therefore, include all energy and material implications resulting from the application of VIPs in buildings. Examples of such studies have already been investigated in LCC studies, where the potential benefits of VIP applications result from added useable floor space area.

4.3. Limitations and potential errors

The study aimed not to amass all the published research literature on VIPs. To do so, the SLR should extend beyond the WoS database and include results from other databases (e.g., Science Direct and Scopus). However, the study aimed to present general trends and past research focusing on VIPs in general and VIPs in buildings. Therefore, the conducted review focused exclusively on the WoS database, as it provided a substantial number of documents and straightforward data manipulation ability (see section 2.1). Nevertheless, for the part of the research that focused on the environmental and economic impact of VIPs (the primary focus of the study), a broader approach (i.e. snowballing) was adopted by including additional literature that was not limited to the WoS database. As a result, the potential sources of errors in the analysis could be attributed to limiting the search to the WoS database and the English language. We assume that more documents could be amassed without these barriers. However, we assume the general trends and relations discussed in section 4.1 would not be affected as widening the search scope would primarily influence the annual publication numbers (results in Figs. 3 and 4).

Further potential source errors could be the full-text examinations carried out in the 2nd and 3rd steps of the study (see Fig. 2 for reference). To reduce potential errors, we applied multiple screenings of the database documents. Because the primary focus was on the 3rd study step, we assume the possibility of errors is low due to the small number of reviewed documents and multiple data screenings. Therefore, the results of the study's primary objective (section 3.3) can be considered solid, and the main findings and recommendations (section 4.2) representative.

Although the amassed database could be extended and the possibilities for errors are identifiable, the resulting research data document [47] is a relevant practical tool. It is suitable for finding studies analysing VIPs, specifically those about building applications. The resulting database can be considered exhaustive for studies providing relevant information on the environmental and economic implications of VIPs in buildings. However, the database is not exhaustive for other VIP research categories. Although the database size is substantial (423 documents), the VIP research community could benefit from an extended literature review and research database.

5. Conclusions

The paper explores past research on vacuum insulation panels (VIPs), published until the end of 2022. A systematic literature review was conducted based on the Web of Science-indexed publications. The identified research was categorised as products, other applications and building applications. The latter were further evaluated to determine which research topics and building applications were studied. The study's primary goal was to provide a detailed analysis of research on the environmental and cost-related implications of using VIPs in building applications. By applying a snowballing approach for LCA and LCC studies, additional literature was added to the database, available in the research data document.

Of the 423 research documents identified, 56% evaluate VIPs in the context of building applications, and approximately one-third of these were basic research on the product level. Only 11% of the published studies evaluates VIPs in the context of other applications (e.g., refrigerators). Publication growth is noticeable, mainly due to the increasing research on building applications. External wall applications and the thermal performance of VIPs were the primary research focus in studies dealing with VIPs in building applications.

A total of 30 studies were identified, providing relevant information on the environmental and economic impacts of VIPs in building applications. The studies were analysed to present the study characteristics and a clear picture of VIPs' environmental and economic implications in buildings. The findings showed that a substantial reduction in material costs and embodied environmental impact is needed for fumed silica VIPs to compete directly with conventional insulation materials. However, due to the potential to reduce operational energy and the benefit of space savings, VIPs are effective in applications that offer benefits due to a thinner insulation layer. There is substantial potential for further life cycle studies, as many building applications, building types and scenarios were not evaluated from a holistic perspective. The main findings with recommendations for further research are provided in the discussion section.

Author contributions

David Božiček: Conceptualisation, Methodology, Software, Formal analysis, Investigation, Data Curation, Writing – Original Draft, Visualization **Jitka Peterková:** Methodology, Formal analysis, Investigation, Writing – Original Draft, **Jiří Zach:** Methodology, Validation, Resources, Writing – Review & Editing, Project Administration, Funding Acquisition **Mitja Košir:** Conceptualisation, Methodology, Validation, Resources, Writing – Review & Editing, Visualization, Supervision, Project Administration, Funding Acquisition.

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.

Data availability

Data is shared on Mendeley Data and also available on request.

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Appendix A

Table A1
Study scope and take-away description for studies evaluating the environmental impact of VIPs.

#	Study	SCOPE & TAKE-AWAY
1	Schonhardt et al., 2003 [66]	**SCOPE:** The environmental impact of a fumed silica VIP was calculated and compared to glass wool and expanded polystyrene (EPS) insulations. The results were calculated for the production (cradle to gate) of 1m^2 of insulation materials, with a thickness corresponding to a thermal transmittance value of 0,15 W/(m2K). The thermal conductivity for VIP was 0,004 (0,0048) W/(mK). The environmental impact was evaluated based on three environmental indicators; Eco-indicator 99, UBP97 and KEA (embodied energy). **TAKE-AWAY:** Fumed silica production is identified as the dominant environmental hotspot, contributing approximately 90 % to the results. The production of silicontetrachlorid contributes over 60 % to the VIP impact. The comparison shows that VIP have the greatest environmental impact for the embodied energy and UBP 97 indicators, whereas EPS exerts the highest impact for the Eco-indicator 99 metrics. The impact relation for glass wool/EPS/VIP is 0,5/0,9/1 for embodied energy and UBP97, and 0,5/1,4/1 for the hierarchical Eco-indicator 99 score. Based on a sensitivity analysis, that assumes a 50 % environmental impact reduction due to silicious tetrachloride and a replacement of silicon carbide (SiC) with a 10 times less contributing material, the authors calculated that a significant reduction of the environmental impact of fumed silica VIP is possible, making its environmental impact comparable to glass wool insulation.
2	Lolli and Hestnes, 2014 [67]	**SCOPE:** Retrofitting scenarios for a typical Norwegian residential apartment were evaluated. The LCA analysis which included various energetic refurbishment scenarios with different TI materials (MW, aerogel, VIP) and U-values (0.18, 0.15 and 0.10). The reference is a situation with MW a U-value of 0.12. The environmental indicator included is the embodied energy and GWP, the cradle-to-grave life cycle stages (50 year RSL) are used. Assumed VIP RSL is 50 years and TC 8 mW/(mK). Also the influence of electricity mixes are evaluated. **TAKE-AWAY:** The mineral wool scenarios showed the lowest environmental impacts compared to aerogel and VIP. VIP scenarios showed the highest impact, due to the highest embodied environmental impact (production phase). If the average EU electricity mix is considered. The GWP due to operation significantly dictates the overall environmental impact (19 times larger CO2 emissions) if the average EU emission factors are used (0.361 kgCO2-eq/kWh) compared to Norwegian inland production (0.019 kgCO2-eq/kWh).
3	Karami et al., 2015 [41]	**SCOPE:** LCA study (cradle-to-gate + use stage – energy for heating) was conducted for a residential reference building. Three scenarios were evaluated; (i) standard building applying mineral wool (Uwall = 0.196, Uroof = 0.13) and two well insulated buildings (low U-values, Uwall = 0.09, Uroof = 0.065), one using additional mineral wool and EPS layers and the second applying VIP insulation. GWP, PE, ODP, AP, EP environmental indicators were used, however, the last three only for the cradle-to-gate phase. **TAKE-AWAY:** Compared to the standard building, the well-insulated building with VIPs shows only 6 % reduced GWP, while the primary energy is increased by approximately 25%. The well-insulated building with conventional insulation performs better than its VIP alternative when comparing the GWP and PE results. Compared to the standard building, the GWP values is reduce by 22 % and the PE by approximately 15%. The reason for such a high environmental impact compared to conventional insulation options is the larger embodied environmental impact, due to the core material, fumed silica (approx. 90 % share of VIP environmental impact).
4	Dovjak et al., 2017 [69]	**SCOPE:** Compares the environmental impact (cradle to gate) of 15 insulation materials (EPS, stone wool, glass wool, XPS, …, VIP), which were classified into natural and synthetic groups. The most influential drivers for environmental impact were identified. The functional unit for comparison was 1 m^2 of TI material with a thickness corresponding to a thermal transmittance value of 0.25 W/(m2K) **TAKE-AWAY:** VIPs have the largest environmental impact in 6 of 7 categories. Over 90 % of the environmental burden is due to the extraction and production of fumed silica. No info about the considered thermal conductivity values of materials.
5	Kunič R., 2017 [70]	**SCOPE:** The carbon footprint of common building insulation materials was calculated and compared based on different functional units (i.e. kg, m2 with aligned U-value). A simple calculation of environmental neutrality (time needed to offset the embodied carbon), due to the application of TI materials was calculated. **TAKE-AWAY:** Calculating environmental impacts per kilogram mass of selected TI materials is misleading, as they significantly differ compared to calculated results per m2 for a fixed thermal resistance. VIPs are among the materials with the highest carbon footprint and the longest carbon offset time, however, foam glass and aerogel TI materials show higher impact.
6	Yang and Tang, 2017 [72]	**SCOPE:** The study analyses the optimal thickness and energy payback time for mineral fibre, polyurethane and VIP insulation materials. This is done by a simplified steady-state heat flow calculation (based on heating degree days) and comparison to the corresponding embodied energy of insulation materials (energy payback time calculation). **TAKE-AWAY:** VIP has the longest energy payback time from the compared TI materials.
7	Zhuk P., 2018 [64]	**SCOPE & TAKE-AWAY**: General debate about the environmental impacts of VIPs compared to conventional insulation. VIPs exert high embodied energy than mineral wool and EPS, while its Eco-indicator 99 score is lower than EPS and higher than mineral wool.
8	Papadaki et al., 2019 [74]	**SCOPE:** The embodied impact and energy demand (Mediterranean climate) of two demo houses was compared. One was constructed with conventional materials and the other with PCMs and VIPs. The alternative with VIPs has a lower wall thermal transmittance. LCA is carried out by Simapro software, including the production, operation (25 years) and end-of-life cycle stages. Multiple midpoint and endpoint categories according to the ReCiPe's methods were evaluated. **TAKE-AWAY:** Higher embodied impacts due to the application of VIPs and PCMs (34 % higher) is compensated in 14 months due to the energy demand reduction (cooling). The overall environmental score for the 25-year calculation period was 57% lower for the VIP & PCM building alternative. One has to consider the high Greek electricity mix, which uses over 80 % of fossil fuels.
9	Brown and Resalati, 2019 [75]	**SCOPE:** The embodied carbon and operational carbon due to increasing the thickness of VIP panels from the base case (20 mm VIP on wall and roof) to a thickness of 40 mm (in 5 mm steps) was analysed for the cities of London, Berlin and Lisbon. **TAKE-AWAY:** In warmer climates (Lisbon), a minimal thickness of VIPs shows the smallest carbon intensity (embodied + operational), whereas in colder climates (Berlin and London) a thickness of 40 mm for both walls and roof exerts the smallest total carbon emissions. Considering the projected decarbonisation of the electricity grid, a net positive benefit of reducing the VIP panel thickness can be shown only if VIPs are produced by recycling the cores. In Berlin, a recycling share of 20 % shows a net positive effect and a recycling share of 60% in London.

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Table A1 (*continued*)

#	Study	SCOPE & TAKE-AWAY
10	Brown et al., 2020 [71]	**SCOPE:** As part of the INNOVIP project, the report calculates the environmental impact of an innovative VIP and compares it to a conventional VIP (fumed silica) and PUR insulation. The comparison is based on a functional unit representing the amount of material to reach a U-value of 0,27 W/(m2K) over an area of 1m^2. The innovative VIP is also based on fumed silica, but has a different design and composition (not displayed due to confidentiality). The LCA was performed for the following modules: A1-A4 and D. **TAKE AWAY:** The novel VIP reached a 17–28 % reduction of the environmental impact, compared to the conventional fumed silica VIP. Fumed silica is the environmental hotspot. 60 % recycling rate of core material at the end-of-life module is needed for the GWP to be comparable with PUR insulation.
11	Kumar et al., 2020 [65]	**SCOPE:** Review article, comparing thermal insulation materials based on different physical properties (TC, density, acoustic properties, fire retardant, hygroscopic), costs and embodied energy and carbon. **TAKE AWAY:** As data extracted from literature, important information regarding cost and environmental impact related impacts is missing. Comparison of environmental per kg of material, which does not correspond to their actual function in building envelope applications.
12	Wallbaum and Kono, 2020 [73]	**SCOPE:** A literature review of super insulation materials (SIMs) was carried out on LCA and LCC. An LCI for SIMs (including VIP) was established from literature data. Also a simple calculation of economic and CO2 payback periods of VIP and aerogel TI was performed for a hypothetical building refurbishment (external walls – internal side) for 4 different cities (London, Berlin, Zurich, Gothenburg) **TAKE-AWAY:** Fumed silica determines the GWP for FS VIPs, as over 90% of GWP impact can be contributed to fumed silica production. Economic and CO2 payback time of VIPs (3.7–8.6 years) is shorter than for aerogel.
13	De Masi et al., 2021 [77]	**SCOPE:** Comparison of 3 different external wall assemblies in a Mediterranean climate (South Italy). One was a reference wall without insulation only concrete), one a ventilated façade with wood fibre insulation and the other closed air gap façade with VIP insulation. Experimentally measurements of surface outside and internal temperatures and heat flux measurements. LCA calculation: comparison of wood fibre and VIP insulation (life cycle stages A1-A3, A5, C, D – no use phase). **TAKE-AWAY:** The core material (FS) contributes the largest share to the environmental impact. VIP have larger environmental impact than wood fibre insulation. The use stage is not considered.
14	De Masi et al., 2021 [76]	**SCOPE:** A NZEB building was evaluated for different scenarios. The scenarios included different glazing systems, PV system, locations, window frames and also the application of VIP panels in the external side of the roof and wall assemblies. The LCA study evaluated the following stages: A1-A3, A4, A5, B1, B6, B7, C1 and D1 stages. The calculated service life was 50 years. Assumed VIP thermal conductivity is 4,6 mW/(mK). **TAKE-AWAY:** VIP panels reduce the operational environmental impact (B6), however increase the whole life cycle environmental impact, compared to the base situation and reference cases. However, the variations are in the range of few percentage points only.
15	Resalati et al., 2021 [63]	**SCOPE:** A LCA study of various VIP core materials was conducted, analysing the environmental impact (multiple indicators) of the production phase (A1-A3). A hotspot analysis for each core material and a comparison between VIPs was carried out. **TAKE-AWAY:** Fumed silica core VIP has the highest environmental impact, except in the POCP category, where EPS core VIP showed higher impact.

Appendix B

Table B1
Study scope and take-away description for studies evaluating the economic impact of VIPs.

#	Study	SCOPE & TAKE-AWAY
1	Jelle B·P., 2011 [7]	**SCOPE:** An overview of conventional, state-of-the-art (i.e., VIP) and future building TI materials with an emphasis on the advantages and disadvantages for building applications. The properties, requirements and possibilities evaluated were; thermal conductivity, perforation vulnerability, adaptability and cuttability, mechanical strength, fire protection, costs and environmental impact, etc. **TAKE-AWAY:** A simplified calculation of potential cost savings showed that VIP in external wall application can be profitable in locations with high market value (above 3000 EUR/m^2 living area), compared to conventional insulation (mineral wool).
2	Alam et al., 2011 [78]	**SCOPE & TAKE-AWAY:** A simplified calculation of payback periods with limited data about the studied building (PART OF INTRODUCTION). VIPs cost effective in high rent location, when the positive effect of space savings are included in the calculation.
3	Deniz et al. [89]	**SCOPE:** The study compares VIPs and conventional insulation materials (rock wool, EPS, XPS, glass wool) as part of external wall insulation (cavity in double-layer brick wall). The optimum insulation thickness, energy savings and payback period were calculated for four cities with varying climate characteristics. The analysis also included different fuel types (coal, natural gas, oil, LPG, and electricity). The present worth factor (PFW) was calculated considering a 10-year time frame. **TAKE-AWAY:** VIP optimum insulation thickness is much lower for VIPs than for conventional insulation. In general, payback periods for VIPs are longer than for conventional insulation materials, however in colder climates and for certain (more expensive) fuel types they are comparable to conventional insulation.
4	Kosny et al., 2013 [79]	**SCOPE:** A cost estimation comparison between superinsulation solutions (VIP, aerogel blankets) and conventional insulation (XPS, EPS, PUR) was performed, considering retrofitting costs. A typical North American residential building was assumed and prices of deep energy retrofitting compared, where VIPs were applied in external walls (ETICS), between two layers of XPS insulation. **TAKE-AWAY:** Installing fumed silica VIP can be cost-competitive with foam insulation. However, multiple VIP core materials were assumed (mineral wool) and optimistic values for VIP costs.
5	Cho et al., 2014 [80]	**SCOPE:** LCC study for VIP in external wall application for a representative single-family building in South Korea. An internal application was assumed for three external wall insulation scenarios: 75 mm of extruded polystyrene, 20 and 30 mm VIP. The assumed calculation period was 40 years. **TAKE-AWAY:** The study showed a considerable cost benefit of applying VIP panels instead of XPS in external wall (137 % and 88 % more economic benefit). However, some methodological specifics need to be considered. The functional unit of comparison is significantly in favour of VIP, as the VIP external wall assembly's thermal transmittance values are smaller by a factor of 2 and 3. Also the thermal conductivity of VIPs is assumed 4.5 mW/(mK) over the 40 year calculation period. This contributes to significant annual heating energy savings, resulting to economic benefit of using VIP panels compared to conventional insulation.
6	Kim et al., 2015 [81]	**SCOPE & TAKE-AWAY:** Life cycle cost of FS and GF VIP are compared for a scenario representing damaged panels. Glass fibre VIPs have a higher thermal conductivity under atmospheric pressure than fumed silica ones. Therefore, their LCC when punctured are higher.
7	Abdul Mujeebu et al., 2016 [82]	**SCOPE:** Evaluates the energy performance and economic feasibility (simple payback period) of aerogel glazing and VIP (external wall + roof), for a multi-story office building in Saudi Arabia (hot desert climate). The performance is compared to a situation without thermal insulation in the envelope (base case) and with conventional insulation (polystyrene). In both cases, double-glazed windows are assumed (WWR 50 %). Nine variations are analysed and evaluated. **TAKE-AWAY:** Even though the thermal transmittance value of wall and roof assemblies are substantially reduced by the application of VIPs the

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Table B1 (*continued*)

#	Study	SCOPE & TAKE-AWAY
		total energy demand is negligibly influenced. The simple payback period (SPP) calculation showed, that VIP are not economically feasible compared to the base and polystyrene insulation cases (e.g., SPP 288 years compared to the base case).
8	Alam et al., 2017 [83]	**SCOPE:** The authors studied the effect of refurbishing the walls, roof and floor of three non-domestic building with fumed silica and glass fibre VIPs and EPS (thickness corresponding to a fixed thermal transmittance value). They conducted a payback period analysis by including time varying techno-economic parameters (thermal conductivity, fuel price, rental income). The studied location was London, UK. **TAKE-AWAY:** The results showed that fumed silica VIP are the most cost effective, resulting in the shortest payback periods. However, it was assumed that they VIP have a reference service life of 60 years, whereas EPS insulation 20 years and glass fibre VIPs 10 years. The economic benefits of space reduction assume very high rental prices, ranging from 1000 to 4000 pounds/year (benefits calculated for VIPs in comparison to EPS).
9	Maddock et al., 2018 [84]	**SCOPE:** For three locations (Berlin, London, Lisbon) with different climates and energy prices. Cost-optimal calculations were performed for low (60 EUR/m^3), medium (120 EUR/m^3) and high (240 EUR/m^3) insulation material costs, over a period of 30 years (included a variation of energy prices). For each location, the optimal U-value relation between external wall and roof was calculated. These calculations were used to estimate the price of VIPs, in order to become competitive to EPS (conventional) insulation. **TAKE-AWAY:** The location importantly influences the cost-optimal U-values and therefore determines the cost-optimal insulation thickness. Lower U-values and higher thicknesses of insulation are cost-optimal in cold location combined with high energy prices. In these locations, higher thickness of insulation materials is needed and consequentially, higher process of VIPs per m^2 are competitive. Considering a medium EPS cost (120 EUR/m^3), in Berlin a 40 mm VIPs should cost 28 EUR/m^2, in London a 30 mm VIP 22 EUR/m^2 and in Lisbon a 16 mm VIP 11 EUR/m^2 in order to be competitive. This translates to an approximate VIP price of 700 EUR/m^3.
10	Fantucci et al., 2019 [42]	**SCOPE:** A detailed dynamic thermo-economic analysis of the cost effectiveness of fumed silica VIP insulation compared to conventional (EPS) was performed. A refurbishment scenario of a theoretical office room was assumed for three climates (extremely cold, cold, warm) and the heating demand calculated. The other variables were: insulation thickness (thermal transmittance value), aspect ratio, heating system efficiency, space benefit, aging and office rental price (from 50 to 800 EUR/m2 per year). Also, the effect of linear thermal bridges in VIP joints was assumed (2 mm air gap). The used metrics were the discounted payback period (DPBP) and break-even rental value (BERV). **TAKE-AWAY:** The analysis showed, that the rental price should be over 200 EUR/m^2 (220–320 EUR/m^2) per year for VIPs to be considered cost-effective compared to conventional insulation. The warmer climates, the rental price must be higher compared to colder climates (e.g., 220 Tampere and 320 EUR/m^2 Palermo). The increased efficiency of heating system increases the payback period quite significantly, however the BERV is lower for a more efficient heating system.
11	Gonçalves et al., 2020 [90]	**SCOPE AND TAKE-AWAY**: The article explores challenges for applying VIPs in ETICS. One of the challenges is the cost competitiveness in comparison to conventional insulation materials. A table presenting cost of various VIPs normalized to different units (m2, thermal resistance) is displayed.
12	Resalati et al., 2020 [85]	**SCOPE:** Cost-optimal analysis of internal and external VIP applications in both residential and commercial (office) buildings was performed considering three variables; VIPs performance degradation over time, panel size and rental value analysis. The calculation was performed for typical rooms in a multi-family and office building for three cities (London, Berlin, Helsinki). The calculations have been performed for VIPs and EPS insulation from the perspective of property owners, who would benefit from high rental prices. **TAKE-AWAY:** Fumed silica VIPs can become cost-competitive with EPS insulation when considering the larger rental space coupled with high rental values. Larger panels are more economically viable than smaller ones (e.g., 0,4 × 0,4 m). The cost-optimal rental price or cost-optimal VIP price depends on the location due to factors influencing the energy demand (climate) and energy prices. For a VIP cost of 3000 EUR/m^2 and the location of Berlin, areas with rental are of 150 EUR/m^2 have lower global costs than EPS insulation.
13	Simões et al., 2021 [86]	**SCOPE:** A detailed study comparing fumed silica VIP and EPS in ETICS façade for an office building. Multiple influencing factors were evaluated. Effective thermal conductivity for VIPs considered. **TAKE-AWAY:** VIP cost-effective in high rental locations. For VIP price of 3000 EUR/m^3, VIPs are cost-effective for rental prices above 350 EUR/m^2 per year compared to EPS insulation.
14	Geng et al., 2021 [87]	**SCOPE:** Determination of optimal thickness of VIP in a structural insulation panel - SIP (PUR-VIP insulation) based on a cost analysis. 5 cold subregions were analysed and a VIP-SIP thickness optimisation caried out (P1–P2 method). **TAKE-AWAY:** In extremely cold climates (HDD >6000) SIP with VIP can be cost-effective, with an optimal VIP thickness of 3 cm. However, for the cold climate of Beijing, the optimal VIP thickness is only 3 mm. The results indicate that fumed silica VIPs in SIPs can be cost-effective in extremely cold climates. (REMARK: the considered thermal conductivity of VIPs corresponds to centre of panel values, not effective (including thermal bridging))
15	Wernery et al., 2021 [88]	**SCOPE AND TAKE-AWAY:** An equation was derived, that enables the quantification of cost for creating additional space using superinsulation materials instead of conventional insulation. The analysis of typical construction types (external wall – external and internal insulation position and equivalent thermal transmittance value) shows that silica aerogel and VIPs are already clearly profitable in several global cities if accounting for the added floor space due to thinner insulation layers. The article also presents real estate price distribution for major cities around the world (Europe, North America, Asia).

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