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Internal Or External Thermal Superinsulation Towards Low/Zero Carbon Buildings? A Critical Report

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ABSTRACT

The effort to create low-carbon societies is now more than just a need for a sustainable world. According to the sectoral energy analyses carried out to reduce world energy consumption figures and greenhouse gas emissions, buildings are one of the most striking potential measures within the net zero target of the International Energy Agency (IEA) by 2050. Low/zero carbon standards are developed in this regard, which basically propose low-emission design and operational performance for buildings. Rather than using conventional insulation materials and techniques, drastic measures like thermal superinsulation are required to meet these standards in buildings. Among thermal superinsulation materials, aerogel blankets (ABs) and vacuum insulation panels (VIPs) attract attention day after day owing to their very low thermal conductivity ranges. Despite the slim, lightweight, and highly thermally resistive features of building envelopes retrofitted with ABs and VIPs, there are still some challenges, such as thermal bridges, hot and cold spots, durability, and especially cost issues. The aforesaid challenges usually take place when a wrong decision is made to internal or external insulation. There are still numerous discrepancies in the pros and cons of internal and external thermal superinsulation retrofit. Therefore, this short communication deals with the said discussion through the in-situ performance findings of retrofitted buildings.

Düşük/Sıfır Karbonlu Binalara Yönelik İç veya Dış Isı Yalıtımı? Kritik Bir Rapor

ÖZ

Düşük karbonlu toplumlar yaratma çabası artık sürdürülebilir bir dünyaya duyulan ihtiyaçtan daha fazlasıdır. Dünya enerji tüketimi rakamlarını ve sera gazı emisyonlarını azaltmak amacıyla yapılan sektörel enerji analizlerine göre, Uluslararası Enerji Ajansı'nın (IEA) 2050 yılına kadar net sıfır hedefi kapsamında en dikkat çekici potansiyel önlemlerin başında binalar geliyor. Düşük/sıfır karbon standartları Bu bağlamda geliştirilen ve temel olarak binalar için düşük emisyonlu tasarım ve operasyonel performans öneren bir proje. Binalarda bu standartları karşılamak için geleneksel yalıtım malzemeleri ve tekniklerini kullanmak yerine ısı yalıtımı gibi sert önlemlere ihtiyaç duyulmaktadır. Isıl süper yalıtım malzemeleri arasında aerojel battaniyeler (AB'ler) ve vakum yalıtım panelleri (VIP'ler) çok düşük ısı iletkenlik aralıkları nedeniyle her geçen gün dikkat çekmektedir. AB'ler ve VIP'lerle donatılan bina kaplamalarının ince, hafif ve termal açıdan yüksek dirençli özelliklerine rağmen, termal köprüler, sıcak ve soğuk noktalar, dayanıklılık ve özellikle maliyet sorunları gibi bazı zorluklar hâlâ mevcut. Bahsedilen zorluklar genellikle iç veya dış yalıtım konusunda yanlış karar verildiğinde ortaya çıkar. İç ve dış termal süper yalıtımın güçlendirilmesinin artıları ve eksileri arasında hâlâ çok sayıda tutarsızlık var. Dolayısıyla bu kısa yazıda, güçlendirilmiş binaların yerinde performans bulguları üzerinden söz konusu tartışma ele alınmaktadır.

Anahtar Kelimeler: İç veya dış izolasyon, termal süper yalıtım, termal köprüler, aerojel battaniye, vakum yalıtım paneli

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1. Introduction

The approximately 50% increase in primary energy consumption in the last 20 years and the associated increase in carbon emissions have necessitated measures related to the effective minimisation of energy [1]. Sectoral energy consumption analyses carried out in this context have revealed that buildings are responsible for now more than 40% of total energy consumed globally [2], in which drastic measures are required in the short term. The considerable share of buildings in total energy consumption is the result of insufficient thermal resistance of building envelopes [3], airtightness problems [4], and inefficient energy systems used in heating, cooling, ventilation, and lighting. Especially building envelopes with a high overall rate of heat transfer (U-value) cause significant heat losses, thus slim, lightweight, and highly thermally resistive building elements are required for energy-efficient retrofitting of buildings rather than still sticking to conventional insulation materials [5].

Thermal superinsulation (TSI) is adopted as a key solution to overcome the abovementioned problems of building envelopes. Materials with a thermal conductivity below 0.01 W/mK are accepted as thermal superinsulation materials (TSIMs). ABs and VIPs are such materials [6]. Despite their extremely high thermal resistance features, TSIMs are not yet where they should be due to their high costs. Aerogel, for instance, is formed at different properties like ABs is made of microscopic air pores (97% of total volume). The fact that the air has truly little room to move in the aerogel prevents both convection and gas phase conduction, which makes aerogel the lowest-density material and most thermally resistive insulator. Similarly, VIPs are highly insulative building materials that provide a form of thermal insulation consisting of a gas-tight enclosure surrounding a rigid core with a perfect vacuum. VIPs are regarded as one of the most promising thermal superinsulation solutions in the market despite their fragile structure, limited application options on the building envelope, and degradation of thermal resistance over time [7].

Both ABs and VIPs are adopted as key thermal superinsulation solutions towards low/zero carbon building targets. Since cost is still an issue for these materials, retrofit applications based on ABs and VIPs usually take place at a project level. Moreover, in the post-retrofit case, undesired thermal bridging issues occur due to the inappropriate implementation of insulation material, including non-optimised insulation thickness, improperly specified insulation methodology, and unsuitable retrofit techniques for building physics. Specifically, the orientation of insulation (internal or external) is of vital importance for the entire success of the retrofit applications of ABs and VIPs. Therefore, in this short communication, internal versus external thermal superinsulation is evaluated in terms of several performance perspectives, which can be useful for researchers, builders, residents, and policymakers.

Table 1. Thermophysical properties, global market share, and application areas of TSIMs.

TSIMs	Silica aerogel	VIPs
ρ	30 – 180 [8]	150 – 300 [14]
k	~0.008 [9]	0.0041 [14]
c	0.7 – 1.15 [10]	800 [14]
D_{pore}		-
Fire Resistance	Excellent [11]	Low [15]
Global market price	USD 1.04 billion by 2022 [12]	USD 10 billion by 2027 [16]
Application Areas	Roofs, facades, windows, historical buildings [13], solar collector covers [11]	Refrigeration and cold storage [11], external-internal reinforcement, retrofitting of historical building [17]

Table 1 outlines the thermophysical characteristics, worldwide market expenditure, and the practical uses associated with TSIMs [8-17]. Both aerogel and VIPs are expected to be in market with a rapidly increasing rate in the near future owing to their ever-expanding application areas. Especially in modern architecture, there is an outstanding tendency to aerogel and/or VIP based retrofitting of external walls, roofs, windows as well as thermal energy storage systems. Cost is still a challenge for both aerogel and VIPs, however it can be emphasised that serious progress has been made to date in terms of cost reduction.

2. Aerogel and VIP Insulation

Aerogel can be utilised in buildings as thermal superinsulation material for different purposes owing to its lightest solid structure, translucent feature, and remarkably low thermal conductivity (~0.008 W/mK) [18]. There are three types of aerogels: silica, carbon, and alumina aerogels. Among these, silica aerogels are the most common type owing to their somewhat outstanding features. SiO_2 chains with numerous air pores provide extraordinary thermal resistance to the structure. The diameter of these pores ranges from 10 to 100 nm, which yields an extremely low bulk density below 5 kg/m^3. However, in building applications, aerogels with an overall density of over 100 kg/m^3 are utilised since the lighter structures are remarkably fragile. Silica aerogels are highly preferred in modern architecture as roof, façade [19], and window applications [20]. Granular aerogels are highly utilised in fenestration products for not only thermal features but also acoustic comfort [21]. The translucent feature and airtight design of aerogel glazing products make them an alternative retrofit solution for lower heat losses over glazed areas [4]. Figure 1 illustrates examples of aerogel insulation for building roofs and facades [5]. Aerogel glazing provides efficient daylighting besides its highly thermally resistive structure. For facade applications, external opaque aerogel insulation prevents possible thermal bridging issues as well as minimising undesired heat losses from the building envelope. Bob Stoker's house is reported as the first aerogel-insulated building in the UK in 2007.

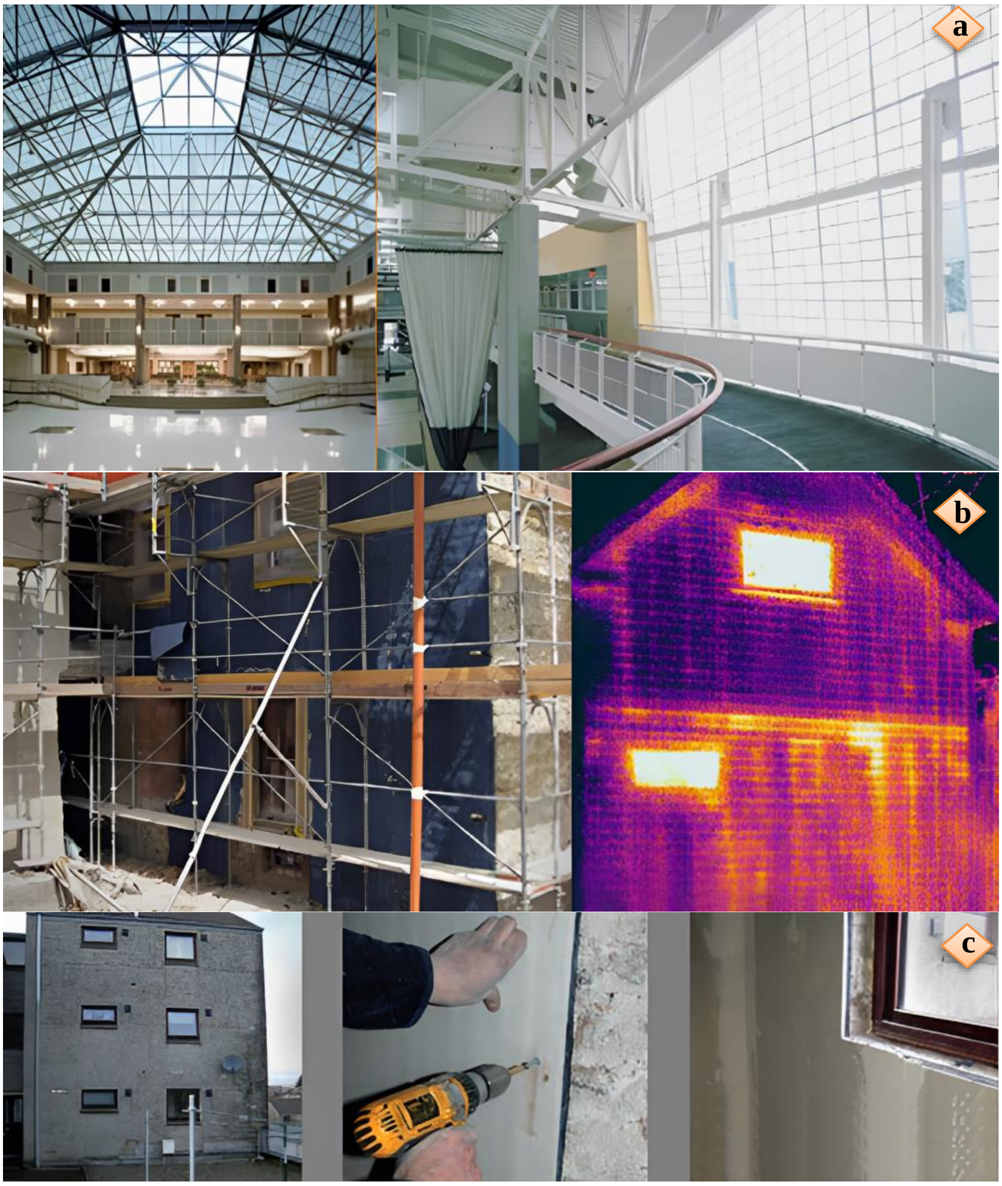

Figure 1. a) Aerogel glazing applications for building roofs and facades, b) aerogel-insulated and non-insulated building facades for heat loss assessment, c) and the first aerogel-insulated building in the UK in 2007 [5].

Vacuum technology is another key solution to meet the latest low/zero carbon building standards [22]. Vacuum medium is often considered the best-known thermal insulator owing to its complete lack of atoms. VIPs are the efficient applications of the vacuum concept in buildings. In most cases, VIPs are accepted as the most effective TSIMs since they are an ideal, reliable, and easy-to-implement option for retrofitting old and poorly insulated buildings [23]. Especially in recent years, low-cost and highly insulative VIPs are at the centre of interest, there are several attempts in this respect as shown in Figure 2. The thermal conductivity of the said VIPs is about 0.0041 W/mK at room temperature conditions, which is outstanding [23]. The fact that VIPs allow efficient insulation not only from the outside but also from the inside makes these products remarkable, especially in the restoration of historical buildings [17]. VIPs, in some cases, are also used in combination with conventional insulation materials like expanded polystyrene (EPS) foams both to maximise the surface covered by VIPs and to prevent potential thermal bridges [24].

Figure 2. a) Low-cost VIPs for energy-efficient retrofit of external walls [23], and b) hybrid external wall insulation of VIPs with EPS foams [24].

VIPs represent a great potential to achieve the nearly zero energy buildings target. In this regard, it is possible to integrate VIPs in conjunction with facade cladding elements for a remarkable reduction of heat losses or gains by means of slim wall details [25]. VIP-integrated ventilated facades draw attention in this respect besides the conventional internal insulation applications shown in Figure 3. The U-value of the said VIP-assisted ventilated facade and internal VIP-retrofitted wall is reported to be 0.28 and 0.14 W/m^2K, respectively.

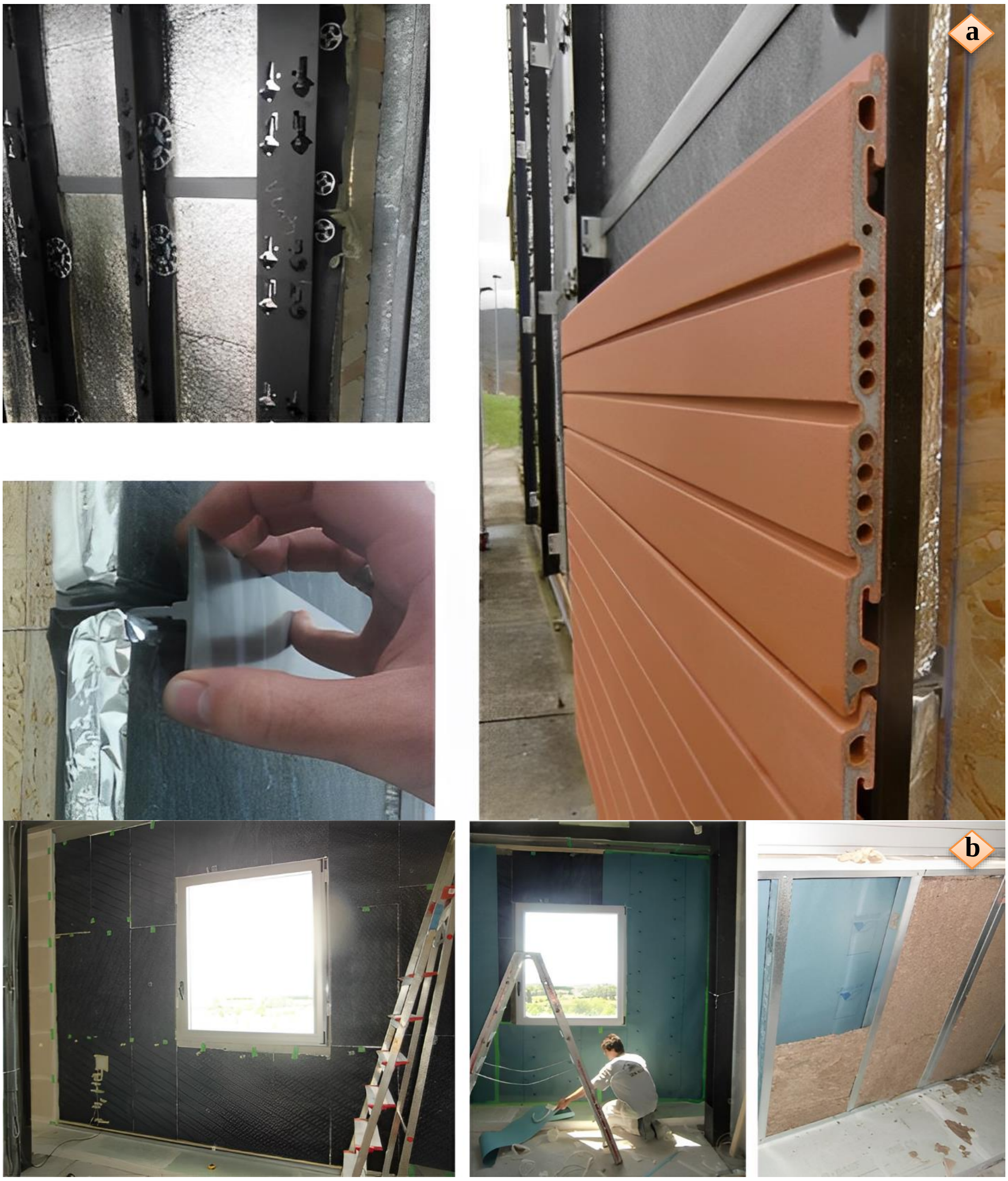

Figure 3. a) Ventilated facade design with VIP-based external wall insulation, and b) standard stud-mounted internal wall insulation of VIPs [25].

3. Pros and Cons of External TSI Based on Aerogel and VIP

External wall insulation obviously increases the energy efficiency of the building. For instance, if the VIP technology is used on the ventilated exterior, the U-value decreases up to almost 0.28 W/m^{2}K. With its low U-value, the airflow in the outdoor environment will be cut off so that the heat distribution will be equal at every point in the indoor environment, so unwanted air currents are eliminated, and thermal comfort conditions are reached. Therefore, once the building is heated, even if the system is turned off, it keeps giving heat to the indoor environment thanks to its return to the internal environment from the resistance of the thermal superinsulation, and the indoor environment remains at the desired level for an extended time. Approximately 35% of energy savings are achieved if all building exterior walls are insulated. In external wall insulation, it is mounted on the outer shell of the building, providing protection against external influences as well as improving the ability to withstand the elements as it acts as a support. It also offers aesthetic benefits, such as covering bad plaster and cracks. External wall insulation prevents moisture from entering the building and minimises the loud noises that may come from the outside. It means that the floor occupants will not be disturbed since all operations are carried out outside during the reinforcement of the building's exterior insulation.

Although external wall insulation has plenty of advantages, it also has some disadvantages. As an example, in the selection of external wall insulation, attention should be paid to both material quality and the selection of the company in matters that require workmanship, like bonding or mechanical fixings. Otherwise, if the insulation is separated from the building wall after a while, it may bring about much more costly results. In most cases, either the bottom surface (the piece of roof that hangs over the wall) is more than 100 mm, so the insulation needs to be sealed from the top in order to prevent moisture from going down the back, or the roof needs to be extended over the insulation. In some cases, such as living on private property, it is not only enough to decide to insulate the outer wall, but also, in some regions, necessary permits must be obtained. The installer should not go near the damp road but rather start over with the insulation. However, this means that a cold bridge will be created there. In high-rise buildings, employees may need scaffolding, provided that the necessary precautions are taken during external wall insulation, which means extra cost.

4. Pros and Cons of Internal TSI Based on Aerogel and VIP

Just as it is significant to insulate the outer wall in buildings, insulating the inner wall in various situations is of vital importance for energy saving. However, even though it has some pros, such as energy savings, it has also cons. Many people care about interior appearance; with insulation, it is easy to improve appearance. It can be a better choice to insulate one room at a time from the inside in order to prevent deterioration. Also, it is relatively easy to insulate inside compared to external. Additionally, there is no necessary for scaffolding as in external insulation. Internal insulation is preferred in mandatory situations where temporary rapid heating is required in places such as cinemas, theatres, and conference halls that are not used continuously.

On the other hand, there are some disadvantages to getting internal insulation. Internal space loss, which is a massive problem for many people, is inevitable during internal insulation. For instance, in a 5m×5m room, insulating 10 cm from all interior walls will result in both space losses and high costs relative to the material quality. Although there is an unlimited right to insulate the outer wall, it may not be possible due to limited conditions in the indoor environment. With interior wall insulation, it creates a thermal bridge between floors which means there will always be heat loss unless the floorboards are removed, and the insulation is installed continuously along the wall. Before starting the interior wall insulation, it is necessary to check whether any moisture has penetrated the walls. Otherwise, the result will become even more costly. One of the challenges installers face is that they must use a wet course layer during internal wall insulation.

5. Conclusion

Although the building envelope, which is later equipped with ABs and VIPs, has very high thermal resistance, so tiny and lightweight feature, it is of vital importance to use it consciously due to thermal bridge formations and extremely high costs. Therefore, in this short paper, the pros and cons aspects of insulation from the inside and outside are discussed in order to mitigate the negative situations that may occur. The following bullet points are used in this respect:

- As the ABs have very high thermal performance properties and can be used in much thinner thicknesses, it is more reasonable to use them indoors.
- Internal TSI usage area is very restricted due to the limitation.
- It is a huge problem as there will be shrinkage in the area together with insulating from the inside. On the other hand, there is no problem with space reduction in insulation from the outside.
- Aerogel can be used to solve thermal bridge problems in buildings.
- It can also be prevented from thermal bridges which may exist in the external wall with the combination of VIP and EPS.
- Using merely 20 mm thick ABs for insulation from external walls enables it to reduce heat loss through the walls by up to 90%.
- In combination with 20 mm ABs and gypsum plaster, it can decrease the heat loss rate by up to 63% by insulating from the inside.
- External TSI is observed as an advantage in protecting building elements against corrosion.
- Due to the limited area of internal TSI, it is concluded that external TSI will be more accurate, as

understood from above.

• In 2022, the annual market budget for silica aerogel is USD 1.04 billion, but it is projected to surpass USD 10 billion for VIPs by the year 2027.

• In the forthcoming investigation, topics to be explored include enhancing energy efficiency through eco-friendly approaches and achieving low thermal conductivity by integrating TSI with conventional building components, while proactively mitigating the current high costs.

Conflict of Interest Statement

The authors declare that there is no conflict of interest.

Symbols and Abbreviations

K	Thermal conductivity (W/mK)
U	Overall heat transfer coefficient (W/m^{2}K)
ρ	Density (kg/m^3)
c	Specific heat capacity (kJ/kgK)
Dpore	Pore diameter (nm)
IEA	International Energy Agency
Abs	Aerogel blankets
VIPs	Vacuum insulation panels
TSI	Thermal superinsulation
TSIMs	Thermal superinsulation materials
EPS	Expanded Polystyrene

References

[1] E. Cuce and S. Riffat, "A comprehensive assessment of sectoral energy consumption in the UK: past, present and future," *International Journal of Low-carbon Technologies*, vol. 11, no. 3, pp. 424–430, Jun. 2015, doi:10.1093/ijlct/ctv013

[2] E. Cuce, "An overview of domestic energy consumption in the UK: past, present and future," *International Journal of Ambient Energy*, vol. 37, no. 4, pp. 428–435, Oct. 2014, doi:10.1080/01430750.2014.973120

[3] E. Cuce, "Accurate and reliable U -value assessment of argon-filled double glazed windows: A numerical and experimental investigation," *Energy and Buildings*, vol. 171, pp. 100–106, Jul. 2018, doi:10.1016/j.enbuild.2018.04.036

[4] E. Cuce, "Role of airtightness in energy loss from windows: Experimental results from in-situ tests," *Energy and Buildings*, vol. 139, pp. 449–455, Mar. 2017, doi:10.1016/j.enbuild.2017.01.027

[5] E. Cuce, P. M. Cuce, C. J. Wood, and S. Riffat, "Optimizing insulation thickness and analysing environmental impacts of aerogel-based thermal superinsulation in buildings," *Energy and Buildings*, vol. 77, pp. 28–39, Jul. 2014, doi:10.1016/j.enbuild.2014.03.034

[6] J. Wernery, F. Mancebo, W. J. Malfait, M. J. O'Connor, and B. P. Jelle, "The economics of thermal superinsulation in buildings," *Energy and Buildings*, vol. 253, p. 111506, Dec. 2021, doi:10.1016/j.enbuild.2021.111506

[7] R. Bætens et al., "Vacuum insulation panels for building applications: A review and beyond," *Energy and Buildings*, vol. 42, no. 2, pp. 147–172, Feb. 2010, doi:10.1016/j.enbuild.2009.09.005

[8] C. Li et al.,"Silica Aerogels: From materials research to industrial applications," *International Materials Reviews*, pp. 1–39, 2023. doi:10.1080/09506608.2023.2167547

[9] E. Cuce, P. M. Cuce, C. J. Wood, and S. Riffat, "Toward aerogel based thermal superinsulation in buildings: A comprehensive review," *Renewable & Sustainable Energy Reviews*, vol. 34, pp. 273–299, Jun. 2014, doi:10.1016/j.rser.2014.03.017

[10] S. Mahesh and S. C. Joshi, "Thermal conductivity variations with composition of gelatin-silica aerogel-sodium dodecyl sulfate with functionalized multi-walled carbon nanotube doping in their composites," *International Journal of Heat and Mass Transfer*, vol. 87, pp. 606–615, 2015. doi:10.1016/j.ijheatmasstransfer.2015.04.046

[11] S.B. Riffatand and G. Qiu, "A review of state-of-the-art aerogel applications in buildings," *International Journal of Low-Carbon*

Technologies, vol. 8, no.1, pp. 1–6, 2012. doi:10.1093/ijlct/cts001

[12] S. Ahmad, S. Ahmad and J. N. Sheikh, "Silica centered aerogels as advanced functional material and their applications: A Review," *Journal of Non-Crystalline Solids*, vol. 611, p. 122322. doi:10.1016/j.jnoncrysol.2023.122322

[13] Z. Kovács, A. Csík and Á. Lakatos, "Thermal stability investigations of different aerogel insulation materials at elevated temperature," *Thermal Science and Engineering Progress*, vol. 42, p. 101906, 2023. doi:10.1016/j.tsep.2023.101906

[14] D. Bozsaky, "Application of nanotechnology based thermal insulation materials in building construction," *Acta Technica Jaurinensis*, vol. 9, no. 1, p. 29, 2016. doi:10.14513/actatechjaur.v9.n1.391

[15] S.S. Alotaibi, and S. Riffat, "Vacuum insulated panels for sustainable buildings: A review of research and applications," *International Journal of Energy Research*, vol 38, no. 1, pp. 1–19, 2013. doi:10.1002/er.3101

[16] N. Simões, et al., "Can vacuum insulation panels be cost-effective when applied in building façades?," *Building and Environment*, vol. 191, p. 107602, 2021. doi:10.1016/j.buildenv.2021.107602

[17] P. Johansson et al., "Interior insulation retrofit of a historical brick wall using vacuum insulation panels: Hygrothermal numerical simulations and laboratory investigations," *Building and Environment*, vol. 79, pp. 31–45, Sep. 2014, doi:10.1016/j.buildenv.2014.04.014.

[18] E. Cuce, P. M. Cuce, C. J. Wood, and S. Riffat, "Toward aerogel based thermal superinsulation in buildings: A comprehensive review," *Renewable & Sustainable Energy Reviews*, vol. 34, pp. 273–299, Jun. 2014, doi:10.1016/j.rser.2014.03.017

[19] E. Cuce and P. M. Cuce, "The impact of internal aerogel retrofitting on the thermal bridges of residential buildings: An experimental and statistical research," *Energy and Buildings*, vol. 116, pp. 449–454, Mar. 2016, doi:10.1016/j.enbuild.2016.01.033

[20] E. Cuce and S. Riffat, "Vacuum tube window technology for highly insulating building fabric: An experimental and numerical investigation," *Vacuum*, vol. 111, pp. 83–91, Jan. 2015, doi:10.1016/j.vacuum.2014.10.002

[21] E. Moretti, F. Merli, E. Cuce, and C. Buratti, "Thermal and acoustic properties of aerogels: Preliminary investigation of the influence of granule size," *Energy Procedia*, vol. 111, pp. 472–480, Mar. 2017, doi:10.1016/j.egypro.2017.03.209

[22] E. Cuce and S. Riffat, "Aerogel-Assisted Support Pillars for thermal Performance Enhancement of vacuum glazing: a CFD research for a commercial product," *Arabian Journal for Science and Engineering*, vol. 40, no. 8, pp. 2233–2238, Jun. 2015, doi:10.1007/s13369-015-1727-5

[23] K. Biswas, T. Patel, S. Shrestha, D. L. Smith, and A. O. Desjarlais, "Whole building retrofit using vacuum insulation panels and energy performance analysis," *Energy and Buildings*, vol. 203, p. 109430, Nov. 2019, doi:10.1016/j.enbuild.2019.109430

[24] P. Johansson, C.-E. Hagentoft, and A. S. Kalagasidis, "Retrofitting of a listed brick and wood building using vacuum insulation panels on the exterior of the facade: Measurements and simulations," *Energy and Buildings*, vol. 73, pp. 92–104, Apr. 2014, doi:10.1016/j.enbuild.2014.01.019

[25] A. Uriarte, I. Garai, A. Ferdinando, A. Erkoreka, O. Nicolas, and E. Barreiro, "Vacuum insulation panels in construction solutions for energy efficient retrofitting of buildings. Two case studies in Spain and Sweden," *Energy and Buildings*, vol. 197, pp. 131–139, Aug. 2019, doi:10.1016/j.enbuild.2019.05.039