# The economics of thermal superinsulation in buildings

Jannis Wernery [a],[*], Francisco Mancebo [a], Wim J. Malfait [a], Michael O'Connor [b],
Bjørn Petter Jelle [c]

[a] Empa, Swiss Federal Laboratories for Materials Science and Technology, Laboratory for Building Energy Materials and Components, Überlandstrasse 129, Dübendorf CH-8600, Switzerland
[b] Orlanna Associates Ltd., 1 Eagle Terrace, Dundrum D14, Ireland
[c] Norwegian University of Science and Technology (NTNU), Department of Civil and Environmental Engineering, Trondheim NO-7491, Norway

ABSTRACT

In comparison to conventional thermal insulators, superinsulation materials (SIMs), such as silica aerogel or vacuum insulation panels, provide a similar insulation performance at half to a quarter of the material thickness but this superior thermal insulation performance typically comes at a significantly higher material cost. However, under certain conditions, the use of superinsulation materials in building walls allows for the creation of additional floor space.

Here, we derive a simple equation to quantify the cost to create such additional space using superinsulation materials as opposed to conventional thermal insulators. The equation has six independent variables, namely the thermal conductivity and cost of the superinsulation and conventional insulation materials, as well as two building geometry parameters. Notably, the cost to create additional floor space is independent of the heat transfer coefficient (U-value) of the wall.

The real estate price distributions within major cities around the world are presented in order to compare the cost to create additional space with the potential financial benefit.

The analysis of typical construction types, combined with the real estate data, shows that, from a financial perspective, the use of superinsulation such as silica aerogel or vacuum insulation panels (VIPs) is already clearly profitable in several major cities globally. Improvements of the production processes of superinsulation materials and the associated reduction in costs will be key drivers to make superinsulation materials economically feasible for many other locations in the future.

© 2021 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

## 1. Introduction

Buildings play a significant role in the global challenges of climate change, resource depletion and pollution. For example, they accounted for roughly 36% of the global energy use and for about 39% of the emitted greenhouse gases in 2017 [1]. Of the used energy and emitted greenhouse gases, about 83% and 72%, respectively, are due to building operations [1]. Hence, besides construction itself, building operation needs to be improved in order make the building sector more sustainable. For this, thermal insulation is crucial in climates where heating and/or cooling is necessary, particularly as long as highly abundant renewable energy sources cannot be provided [39]. Improving the thermal insulation performance of buildings is a key approach in this context and for this, good thermal insulators are needed.

Thermal insulation materials can be classified into three different types as described in the following. (i) Low-eco-impact (natural) thermal insulation materials are based on renewable resources, need very little energy to produce and ideally can be sourced locally. Usually, their thermal insulation performance is not very high, with thermal conductivities in the range of roughly 35 to 80 mW/(m·K), hence requiring thick layers of these materials in order to achieve a good insulation performance of the building envelope. Typical low-eco-impact insulation materials are straw bales, cellulose fibres, cork boards, sheep wool, wood fibre boards [7] or other unconventional materials such as reeds or pineapple leaves [3]. (ii) Conventional thermal insulation materials are the most commonly used materials for building insulation, such as expanded polystyrene (EPS), extruded polystyrene (XPS), mineral wool (glass wool and stone wool) and polyurethane (PUR) foam. These materials are characterised by a thermal conductivity in the range of 29 to 40 mW/(m·K) (sometimes lower with filler gases, e.g. in PUR) and by low cost as mass products. Note that the term traditional thermal insulation materials may cover both natural

---

**Nomenclature**

| | |
|---|---|
| EPS | expanded polystyrene |
| XPS | extruded polystyrene |
| PUR | polyurethane |
| SIM | superinsulation material |
| VIP | vacuum insulation panel |

| | |
|---|---|
| PIR | polyisocyanurate |
| ETICS | exterior thermal insulation composite system |
| CLT | cross laminated timber |

and conventional thermal insulation materials. (iii) Thermal superinsulation materials (SIMs), such as vacuum insulation panels (VIPs) and miscellaneous silica aerogel products are usually significantly more expensive than conventional materials but also provide a much better performance with thermal conductivities in the range between 5 and 20 mW/(m·K). This has the advantage that only thin layers of these materials are necessary – which can be crucial in certain applications, especially retrofits.

SIMs were first established in markets that are not as cost-sensitive as the building sector: appliances for VIPs (refrigerators in particular) and oil-and-gas for aerogels (pipelines). However, the last decade has seen strong interest and the emergence of a market for superinsulation for building insulation. SIMs currently constitute a growing niche market with cost as the main barrier to a broader adoption. So far, they have been taken up by early adopters or for special applications.

However, there still seems to be quite an untapped potential for superinsulation in buildings where their application provides additional performance in an economically feasible way. Orsini and colleagues analysed space savings in case of an internal retrofit with an aerogel material, but did not quantify the associated economic benefit [45]. Transport vehicles are a very interesting application for SIMs since the space constraints are typically much stricter than in most building projects. In trains and trams, silica aerogel and VIPs can be used approximately cost-neutrally compared to conventional insulation of the same thickness since the superinsulation leads to energy savings which, over the lifetime of the train, offset the additional cost of the superinsulation materials [59]. Simões and co-workers [50] analysed the life cycle cost of vacuum insulation panels. They concluded that VIPs are cost-effective for annual rental prices of 350 EUR/m$^2$ or higher, assuming a VIP cost of 3 000 EUR/m$^3$. However, a general consideration about the economics of the use of superinsulation has not been published.

Here, a broad economic framework for decision making on thermal insulation material selection will be provided. We derive an analytical equation for the additional cost of superinsulation compared to conventional insulation materials, which together with an overview on global real estate costs can be used to determine if superinsulation provides a financial benefit in a new building project or retrofit. Performance and cost values for the most important SIMs are provided as a starting point. Architects, planners and building owners can use this framework with their own parameter values for building geometry and material performance in order to decide on a suitable thermal insulation material.

Here, we will compare constructions with the same performance (e.g. U-value) and compare the thicknesses and costs of these constructions. It would also be of interest to consider the case of fixed thickness for different materials and discuss the implications on U-value, cost and embodied energy and greenhouse gases. However, this topic is beyond the scope of this current article and could be addressed in future work.

As introduction, an overview on SIMs and their different applications in buildings will be given in the following. Subsequently, an economic framework will be developed and data on real estate prices in high-cost areas around the globe will be presented. The latter will be mainly focused on heating dominated climates. The general analysis is followed by examples of different SIM application scenarios and concluded by an outlook on potential future developments.

## 2. Superinsulation materials

### 2.1. Definition and overview

Superinsulation materials (SIMs) are often defined as thermal insulators with a thermal conductivity of 20 mW/(m·K) or less [34,38]. In order of increasing thermal conductivity, currently available SIMs are vacuum insulation panels (VIPs), silica aerogels, polyisocyanurate foams (PIR) and fumed silica boards (Table 1, Fig. 1). In order to reach very low thermal conductivities, various nanotechnologies can also be applied, e.g. to make nano insulation materials by exploiting the Knudsen effect [29,32].

### 2.2. Vacuum insulation panels

Vacuum insulation panels (VIPs) consist of a core material, typically fumed (pyrogenic) silica particles or silica/glass fibres, and a metallised polymer envelope [23,33,35]. The density of a VIP is in the range of 140 to 220 kg/m$^3$ and its thermal conductivity can be as low as 2 to 4 mW/(m·K) for a new panel [35]. VIPs are sensitive to mechanical damage of the envelope which can lead to leakage and loss of the thermal performance. A perforated VIP with a fumed silica particle core has a thermal conductivity of about 20 mW/(m·K). Furthermore, the internal pressure of a VIP increases over time and with that its thermal conductivity. This effect is called aging. Hence, in the building context, VIP thermal conductivities are declared as a mean value over the panel's assumed lifetime of over 25 years and likely up to 50 years which should not be exceeded within the first 12 years [24]. Hence, official declaration values for VIPs with pyrogenic silica core in Europe are typically 7 mW/(m·K). VIPs are not diffusion open and typically have E fire ratings due to their (metallised) polymer envelope according to the European standard on fire classification of construction products EN 13501-1 [14]. However, with protective layers, much better B1 fire ratings can be reached. The limitations of VIPs in handling – susceptibility to damage, not possible to cut or drill – are among their main disadvantages alongside the inevitable air and moisture diffusion through the VIP envelope and into the core. On the upside, VIPs are clearly the insulation material solution with the best thermal performance per thickness and its performance to cost ratio is more favourable than for silica aerogels. With retail prices around 5 200 EUR/m$^3$ at 40 mm thickness in Switzerland [56], which results in a good U-value of roughly 0.17 W/(m$^2$·K), VIPs are comparable in cost per volume to silica aerogels but have an insulation performance that is superior by a factor of 2 to 2.5. It should be noted that for VIPs, cost is not linear with panel thickness since the cost for the barrier materials and the sealing do not vary much with varying thickness.

VIPs are commonly used as thermal insulation of penthouse terraces in order to allow for a level exit onto the terrace while providing good thermal insulation for the rooms under the terrace. With conventional insulation materials and depending on the insu-

**Table 1**
Overview of properties of most common superinsulation materials.

| | vacuum insulation panel (VIP) | silica aerogel blanket/ board | silica aerogel granule fill | polyisocyanurate (PIR) board | fumed silica board |
|---|---|---|---|---|---|
| thermal conductivity (mW/(m·K)) | 7 [b] | ≥ 15[c] | 18–20 [d] | ≥ 18 [e] | 19[f] |
| density (kg/m$^3$) | 140–220 | ∼ 200 | 80–100 [d] | 30 [e] | 165[f] |
| fire class according to EN 13501–1 | E (B1 with protective layer) | C (A2 version also available) [c] | B | E [e] | A2 [f] |
| Retail cost (EUR/m$^3$) | ≥ 5 200 | ≥ 5 000 | ≥ 2 500 | 500 | ≥ 4 300 |
| thickness for U-value of 0.2 W/(m$^2$·K) [a] (mm) | 34 | ≥ 77 | ≥ 87 | ≥ 87 | 92 |
| cost for U-value of 0.2 W/(m$^2$·K) (EUR/m$^2$) | ≥ 200 | ≥ 390 | ≥ 220 | ≥ 40 | ≥ 390 |
| handling aspects | to be handled with great care to avoid envelope damage | can be cut, drilled, glued; significant dust emissions for some products | dusty when filled in; settling needs to be avoided by compacting | easy to cut, drill and glue; facers limit diffusion of filler gasses to maintain performance | brittle; to be handled with care and/or sandwiched with other materials |
| preferred use cases | terraces, opaque parts of glass façade, internal retrofit | exterior thermal insulation composite system (ETICS), internal retrofit, architectural details | cavity walls, translucent elements | exterior thermal insulation composite system (ETICS), ventilated façade | internal retrofit, façade panel |

[a] calculated according to $d = \lambda_I(1/U - R_{si} - R_{se})$ with definitions according to Table 2.
[b] typical declaration value in Europe, including heat bridges and some ageing.
[c] according to manufacturer, e.g. [51].
[d] according to manufacturer, e.g. [2].
[e] according to manufacturer, e.g. ("swisspor – saving energy | swissporPIR Premium Plus," 2021).
[f] according to manufacturer, e.g. ("CALOSTAT® Product Information – Evonik Industries," 2021).
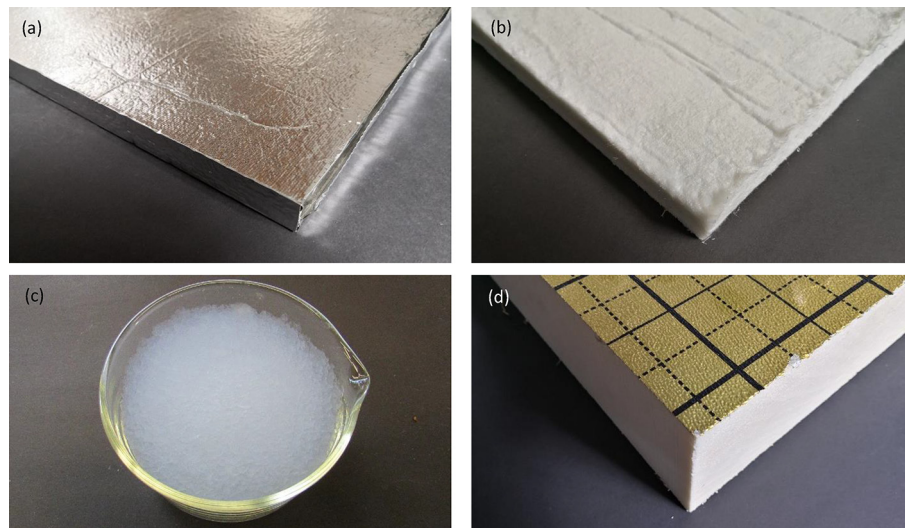


**Fig. 1.** Typical SIM products: (a) VIP, (b) silica aerogel board, (c) silica aerogel granules, (d) PIR board. Images: Jannis Wernery.

lation requirements, the terrace would possibly be higher than the floor inside the building. VIPs can also be used to cover and insulate the steel beams in glass façades in order to reduce the overall façade thickness. In both cases, the VIPs are well protected and the dimensions can be planned easily and produced accordingly or the area to insulate can be covered with a few different standard sizes of panels. There are also systems for inside retrofits with VIPs, minimising losses of internal floor area.

### 2.3. Silica aerogels

Silica aerogels are porous solids made from a three dimensional network of connected silica particles with average pore sizes of several tens of nanometres [4,26,41]. For thermal insulation applications, the silica surface is always modified with organic groups to render it hydrophobic to avoid water ingress into the porous structure. The most commonly used silica aerogel insulation materials are composite blankets or boards, consisting of aerogel-infused mineral or plastic fibre blankets or open-cell foams. Aerogel is also produced as millimetre-sized particles which are the base material for renders, composite boards and cavity fillings. Aerogel blankets and boards have thermal conductivities in the range between 15 and 19 mW/(m·K), aerogel granule fillings between 18 and 20 mW/(m·K) [18,25]. Most silica aerogel products are diffusion open and A2 fire ratings according to EN 13501 can be reached, i.e. a classification as non-flammable. Densities of blankets and boards range from about 150 to 250 kg/m$^3$, granule fillings are in the range of 60 to 100 kg/m$^3$ [18]. Granules are usually significantly cheaper than boards and blankets, starting at roughly 2 500 EUR/m$^3$, whereas the latter cost typically upward of 5 000 EUR/m$^3$ in Europe.

Most silica aerogel blankets and boards can be handled in a very similar way to mineral wool boards: they can be cut, drilled, glued and screwed. Hence, they can be used as exterior thermal insulation composite systems (ETICS), as internal insulation fixed to an

existing wall or as insulation in wooden elements. Aerogel blankets are also often used for architectural details such as roller shutter housings, window reveals in retrofits or dormer windows. A notable difference to mineral wool is that many aerogel products emit dust when handled, so that the appropriate personal protective equipment needs to be worn during processing and application. Due to their building physics properties (very low thermal conductivity, diffusion open, non-flammable, inorganic), silica aerogel blankets and boards are very well suited for retrofits, in particular for historical buildings. Aerogel granules have found their largest application in the building sector in the form of insulating renders. With thermal conductivities of 28 mW/(m·K) or higher due to the binder phases, these are not considered as SIMs in a strict sense, but they outperform conventional insulating renders by a significant margin. Aerogel granules can also be used as filling for translucent insulating panels or for cavities, e.g. in cavity windows or walls, sometimes denoted as solar walls [9,43].

The use of aerogel insulation material in historic buildings has been discussed in detail [18] with recommendations for application and examples for all typical aerogel materials. The retrofit of historic buildings with aerogel blankets and aerogel-based render have been described [21,20]), and the saving potential of aerogel render evaluated for a broad application [36]. New aerogel insulating renders are under development [46]. Aerogel granules can also be compounded into filling composites, for example for insulating bricks [58] and insulating boards [28]. Silica aerogels for translucent and window applications in buildings were discussed by Buratti and colleagues [10]. Miscellaneous experimental investigations carried out by Jelle and co-workers of various aerogel systems for building applications have been summarized in the studies by Jelle and Gao [30–31]. A more general overview of aerogel applications in the building industry was given by Wernery et al. [60].

## 2.4. Polyisocyanurate foams

Due to a continuous optimisation of cell structure and the use of new filler gases, polyisocyanurate (PIR) foam boards have seen significant increases in insulation performance. There are several products currently on the market that have a thermal conductivity below 20 mW/(m·K) (e.g. [55]), so that these can be classified as SIMs. Being completely organic, these materials are flammable with E fire ratings according to EN 13501-1 and with about 30 kg/m³ have considerably lower densities than VIPs and aerogels. PIR foams are diffusion-closed. It is noteworthy that, in contrast to most other insulators, their thermal conductivity is typically higher at lower temperatures than at room temperature [6]. They are subject to aging due to the diffusion of the low thermal conductivity filler gases [6]. PIR boards are significantly cheaper than all other SIMs presented here, with costs of about 400 to 500 EUR/m³ in Switzerland [55]. PIR foams, with a range in thermal insulation performance that covers both conventional and superinsulation materials, are used extensively as façade claddings, both as ventilated façade and as ETICS. In these applications, compared to inorganic materials, the fire safety needs to be considered carefully [42] and the quest for alternative fire retardants is an active area of research [17].

## 2.5. Fumed silica boards

Non-flammable insulation boards can be made from compressed fumed silica. A commercial product is characterised by a thermal conductivity of 19 mW/(m·K), diffusion openness, an A2 fire rating and a density of about 165 kg/m³, according to the manufacturer [11]. Due to its low mechanical stability, it is best used in enclosed systems such as sandwich panels or insulating bricks. The cost for fumed silica boards is in the range of about 4 300 EUR/m³.

Fumed silica boards can used as internal insulation [15], as façade panel or as filling for bricks [11].

## 3. Superinsulation application types

While thermal superinsulation, in principle, can be used just like conventional insulators – bearing in mind specific application parameters such as the protection from puncture for VIPs – only certain applications may make sense economically. In these applications, the additional cost of the superinsulation compared to the conventional insulators may be offset by other financial gains, which will be outlined in this section. For new buildings and upward extensions, these gains can be in the form of additional floor space compared to a structure with conventional insulation and hence thicker walls. For retrofits, it can be financially beneficial to use superinsulation when larger changes to the existing building structure, which would be necessary with conventional insulation due to the thicker insulation layers, can be avoided. Also, if an internal insulation is realised, superinsulation minimises the losses of useable/living area. Finally, for certain details, both in new buildings and retrofits, the use of superinsulation yields benefits in comfort or avoidance of other technical problems, which are undeniably of value but not easy to quantify.

These application types will be described qualitatively in more detail below, followed by a quantitative analysis of the creation of additional space in new buildings, upward extensions and retrofits with internal insulation in Section 4.

### 3.1. New buildings

Depending on the spatial and legal context of a project for a new building, it can be financially advisable to use superinsulation materials and not conventional thermal insulation materials and solutions. In dense inner city areas, the area that can be occupied by a building's spatial footprint is often limited. For example, certain distances to neighbouring plots and buildings or to streets or pavements have to be observed. Also in perimeter block developments, the spatial footprint of the building is a given. In these situations, the thickness of the building envelope influences how much usable space is created: with a thinner envelope, more usable space is available in the building (Fig. 2). Hence, compared to conventional insulation, superinsulation in the façade creates additional usable space. The value of this additional space, i.e. the local real estate value, determines if one should use superinsulation from a financial point of view (Section 4).

Usually, the height of a building is also limited by zoning restrictions. In principle, a thinner roof with superinsulation would also allow for more internal volume. Taller rooms allow for more daylight and are considered more attractive. While these aesthetic benefits are difficult to quantify financially, more daylight can reduce heating demands, but require more cooling. However, taller rooms may also require a larger space to be heated. Hence, in the following mainly superinsulation in the building façade will be considered.

### 3.2. Upward extensions

In an upward extension, one or several storeys are added on top of an existing building. The financial analysis of the use of superinsulation is very similar as for new buildings. The main difference is that in all cases of upward extensions, the outer perimeter of the new building space is limited by the perimeter of the existing building. Hence, for upward extensions the financial potential of using superinsulation should always be evaluated. As with new buildings, this can be performed by calculating the cost to create additional space and comparing the result to local real estate prices.
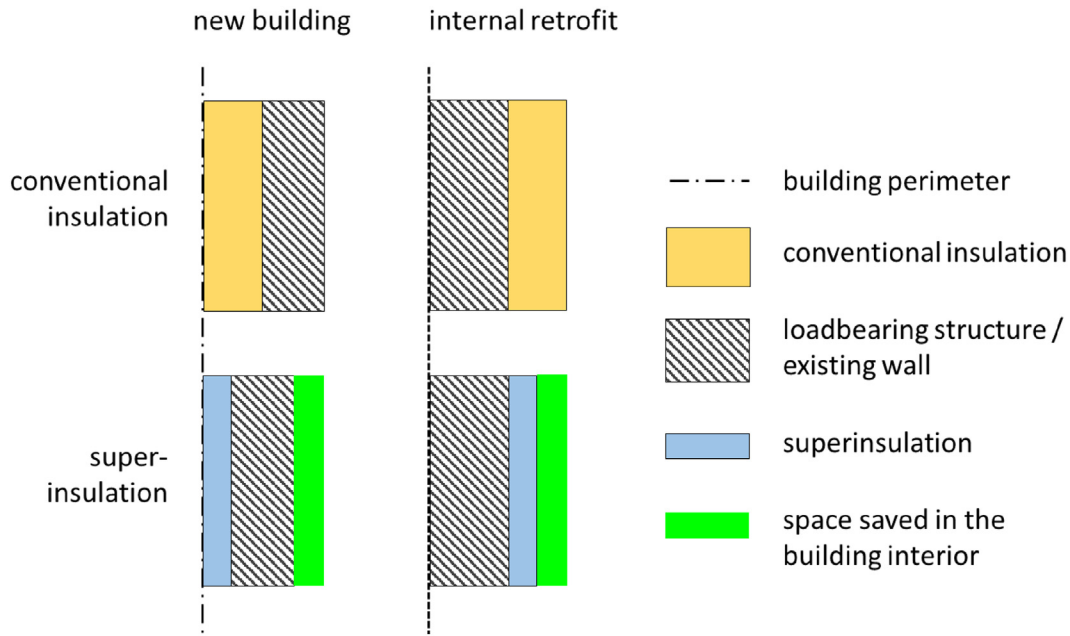
**Fig. 2.** Superinsulation creates space savings in both new buildings with fixed external perimeter (left) and retrofits (right).

### 3.3. Retrofits

Energetic retrofits can be realised by adding insulation on the inside or outside of the existing building envelope. If insulation is added on the inside, the usable space of the building is reduced (Fig. 2) and this loss of space can be considerably smaller if superinsulation is used. Again, the cost-benefit ratio can be calculated according to Section 4. If the building in question is in a high-value area, the use of superinsulation should definitely be considered.

On the other hand, when retrofitting with insulation on the outside of the façade, no usable space inside the building is lost. However, different details of the façade usually have to be adapted: window reveals, doors and in the worst case the roof overhang. With a thin layer of superinsulation, this may be avoided, while still achieving a good improvement of the thermal performance of the building. That is, also for retrofitting, the cost of superinsulation should be compared to the costs of adapting the mentioned details. Here, the consideration of superinsulation is mostly independent of the real estate cost.

Furthermore, in some situations, only a thin outside insulation retrofit is possible, due to spatial restrictions around the building. In such cases, superinsulation may be the only option and a cost consideration should compare the cost of the superinsulation to the invoked (opportunity) costs when choosing not to have an insulation retrofit. The latter costs are higher heating costs over the lifetime of the building and lower comfort inside a poorly insulated building, e.g. due to cold walls, air draught and/or mould growth, to which also a financial value can be attributed.

### 3.4. Architectural details

In certain architectural details, superinsulation may be extremely useful and allow for solutions where conventional materials do not achieve the desired insulation performance. These are usually small surfaces where there is not enough space for conventional insulation. Due to the small areas, often the additional cost of superinsulation is small compared to the benefits achieved by their application. The most common application types are the following (Fig. 3):

a. **Roller shutter housings (new buildings)**: Roller shutter housings integrated into the façade often create a thermal bridge by reducing the space available for insulation. This can be avoided by the use of superinsulation, mitigating potential mould problems and decreasing energy use.

b. **Window reveals (retrofit)**: When retrofitting a façade with insulation, the reveals on the outside of the window need to be insulated to avoid thermal bridging. Superinsulation minimises the loss of window size as a thinner layer of insulation can be used, providing a benefit in comfort and aesthetics.

c. **Dormer windows (new buildings & retrofit)**: The external dimensions of dormer windows are often limited by law. Using superinsulation to insulate the side triangles of dormer windows leaves more space for the actual window, allowing for more solar radiation and daylight to enter. This can lower heating costs and improve visual comfort and aesthetics.

d. **Insulated ventilation ducts in concrete ceilings (new buildings)**: Insulated ventilation ducts can be integrated into the concrete ceiling. The thickness of the duct, its insulation and its minimum coverage by the concrete layer, in combination, are usually thicker than the structural requirements of the ceiling thickness. Hence, reducing the thickness of the duct insulation can lead to a reduced ceiling thickness, saving concrete and providing more vertical space in the building.

e. **Penthouse terraces (new buildings & retrofit)**: Penthouses are often set back from the building perimeter with terraces in that area. The thermal insulation of such a terrace towards the storey underneath usually raises the floor level of the terrace compared to the floor inside the penthouse. This can be avoided by using superinsulation, allowing for a level passage from the inside of the penthouse to the adjoining terrace.

In each of these applications, the cost of superinsulation is relatively small and the benefit of its use is of somewhat subjective nature (gains in comfort, small reductions of energy use). Hence, the use of superinsulation cannot be evaluated in general but needs to be considered by the building owner for the specific application.

**Fig. 3.** Examples of architectural details where the use of superinsulation provides additional benefit compared to conventional insulation: (a) Roller shutter housing insulated on top and behind with silica aerogel blankets. (b) Silica aerogel insulation on window reveal: the thin layer avoids covering the window, whereas the façade is outfitted with conventional insulation. (c) Dormer window wall is insulated with silica aerogel (next to the hammer) in order to maximise window size. (d) Ventilation ducts in a ceiling before concrete pouring, insulated with silica aerogel (white). (e) Penthouse terrace. Images: (a)-(d): AGITEC AG, (e) Jannis Wernery.

## 4. Quantitative analysis

While some of the application types described above create value that is primarily non-financial, e.g. taller rooms, more solar radiation and daylight (which can also have a financial value), the creation of additional space can be quantified systematically in terms of its financial value. Below, we present a cost-benefit analysis for application in new buildings, upward extensions and retrofits with internal insulation. We will neglect the details of mathematical finance, foremost the discounting of the different investments and assets, as well as the consideration of various opportunity costs. We will also not consider the value development of the created or retrofitted building if it is rented after the building process but only compare the investment costs in terms of the used superinsulation with the value of the additional usable space compared to conventional insulation.

This is done in order to present a general analysis that can be applied in different cases and then henceforth adapted according to the specifics of each building project.

It should be noted that for new constructions, these considerations are only relevant if the thermal insulation determines, at least partially, the thickness of the thermal envelope. This is not the case if insulation is only used in cavities in the structural layer (for example in stick-built homes in warm climates).

### 4.1. Superinsulation cost compensation

In the following, an equation will be derived for the cost of additional floor space created by the use of superinsulation instead of conventional insulation while achieving the same U-value. For that, the cost of insulating one metre along the façade with superinsulation compared to conventional insulation and the thickness of the construction including the insulation in each case will be calculated. The cost of the additional floor space is then approximately equal to the cost difference between the two materials divided by the difference in thickness of the construction (for the same thermal insulation performance or U-value). The additional cost of the interior works on the additional space (i.e. floor-

ing, painting of walls and ceilings etc.) will be neglected since these are small compared to the value of the generated space. The same considerations hold for retrofits with internal insulation, with the only difference being that no additional space is created but rather the loss of space is reduced in comparison to the case of applying conventional insulation.

Table 2 provides an overview on the variables and constants used in the following cost calculations.

First, to determine the volume of the needed thermal insulation, one can consider the height $h$ of one storey and the window fraction $f_w$, so that the area $A_I$ to insulate per meter of façade is

$$A_I = h(1 - f_w)1\text{m} \tag{1}$$

Naturally, in both cases, i.e. conventional insulation and superinsulation, the same U-value should be reached, which shall be named $U_{target}$ and which is calculated as follows [27]

$$U_{target} = \frac{1}{R_{si} + R_{se} + \frac{d_S}{\lambda_S} + \frac{d_I}{\lambda_I}} \tag{2}$$

where $d_S$ and $\lambda_S$ are the equivalent thickness and thermal conductivity, respectively, of all layers combined with the exception of the insulation layer, i.e. in most cases more or less the structural layer. $d_I$ and $\lambda_I$ are the thickness and thermal conductivity of the insulation layer, respectively. From this, one arrives at the thickness $d_I$ of the insulation layer as

$$d_I = \left(\frac{1}{U_{target}} - (R_{si} + R_{se}) - \frac{d_S}{\lambda_S}\right)\lambda_I \tag{3}$$

In the following, the approximation is made that the equivalent thickness and thermal conductivity of all non-insulating layers $d_S$ and $\lambda_S$ are the same for both the superinsulation case and the conventional insulation case. As an example, one could think of a brick wall onto which either a silica aerogel or a mineral wool insulation system is attached. Of course, different materials would need somewhat different finishing layers for example, but the main component, in this case the brick layer, would be the same. With this approximation, one has from Equation (3)

**Table 2**
Overview on variables and constants used in the cost calculation and their respective units.

| Symbol | Variable/constant name | Unit |
|---|---|---|
| $h$ | height of one storey of the building | m |
| $f_w$ | fraction of windows on façade area | dimensionless |
| $A_I$ | area to be insulated per meter of façade | m² |
| $U_{target}$ | target U-value of façade | W/(m²·K) |
| $R_{si}$ | fixed internal thermal surface resistance | m²·K/W |
| $R_{se}$ | fixed external thermal surface resistance | m²·K/W |
| $d_S$ | equivalent thickness of all layers in the wall combined, apart from the insulation layer | m |
| $\lambda_S$ | equivalent thermal conductivity of all layers in the wall combined, apart from the insulation layer | W/(m·K) |
| $d_I$ | thickness of the insulation layer | m |
| $\lambda_I$ | thermal conductivity of the insulation layer | W/(m·K) |
| $\lambda_{SI}$ | thermal conductivity of superinsulation | W/(m·K) |
| $\lambda_{CI}$ | thermal conductivity of conventional insulation, with $\lambda_{CI} > \lambda_{SI}$ | W/(m·K) |
| $R_{SI} = R_{CI} = R$ | thermal resistance of the insulation layer, for both the superinsulation and conventional insulation | m²·K/W |
| $c_{1\text{m}^2}$ | cost to create 1 m² of additional usable space | EUR/m² |
| $d_{SI}$ | thickness of superinsulation to reach $U_{target}$ | m |
| $d_{CI}$ | thickness of conventional insulation to reach $U_{target}$ | m |
| $c_{SI}$ | cost of superinsulation | EUR/m³ |
| $c_{CI}$ | cost of conventional insulation | EUR/m³ |

$$d_{SI} = \left(\frac{1}{U_{target}} - (R_{si} + R_{se}) - \frac{d_S}{\lambda_S}\right)\lambda_{SI} = R_{SI}\lambda_{SI} = R\lambda_{SI} \tag{4}$$

and

$$d_{CI} = \left(\frac{1}{U_{target}} - (R_{si} + R_{se}) - \frac{d_S}{\lambda_S}\right)\lambda_{CI} = R_{CI}\lambda_{CI} = R\lambda_{CI} \tag{5}$$

where $R_{SI} = R_{CI} = R$ is the thermal resistance of the insulation layer, equal for both the superinsulation and the conventional insulation as the target U-value is the same for both cases.

To calculate the cost to create one square metre of additional floor space, one subtracts the cost to insulate one metre of façade with conventional insulation from the cost to insulate the same façade with superinsulation and divide by the product of the difference in thickness between the two insulators (for the same thermal insulation performance or U-value) and one metre of façade. The cost per metre of façade is given as the area to insulate multiplied by the insulation thickness and the cost per volume of insulation. Hence, the cost to create one additional square metre is obtained as

$$c_{1\text{m}^2} = \frac{A_I d_{SI} c_{SI} - A_I d_{CI} c_{CI}}{(d_{CI} - d_{SI})1\text{m}} = \frac{A_I(d_{SI}c_{SI} - d_{CI}c_{CI})}{(d_{CI} - d_{SI})1\text{m}} \tag{6}$$

Note, that for this equation, $\lambda_{SI} < \lambda_{CI}$ is required since a superinsulation material should have a lower thermal conductivity than a conventional one, and hence $d_{SI} < d_{CI}$ so that the denominator is positive.

Inserting the results for $d_{SI}$ and $d_{CI}$ from Eqs. (4 and 5) into Eq. (6) and then simplifying the fraction, the following is obtained

$$c_{1\text{m}^2} = \frac{A_I(R\lambda_{SI}c_{SI} - R\lambda_{CI}c_{CI})}{(R\lambda_{SI} - R\lambda_{CI})1\text{m}} = \frac{A_I(\lambda_{SI}c_{SI} - \lambda_{CI}c_{CI})}{(\lambda_{SI} - \lambda_{CI})1\text{m}} \tag{7}$$

Finally, entering $A_I$ of Eq. (1) and again simplifying the fraction, the following, final equation is obtained

$$c_{1\text{m}^2} = \frac{h(1 - f_w)(\lambda_{SI}c_{SI} - \lambda_{CI}c_{CI})}{\lambda_{CI} - \lambda_{SI}} \tag{8}$$

Hence, with the assumptions and approximations made above – (i) it is required that the superinsulation insulates better than the conventional insulation, (ii) it is assumed that the non-insulating layers of the façade are identical for both cases and (iii) the cost of the interior finish of the additional floor space is neglected – the cost to generate (or save, in the case of retrofitting) one additional square metre of floor space is determined by only six variables.

$c_{1\text{m}^2}$ depends *linearly* on four of them, namely linearly on storey height $h$, inversely linearly on window fraction $f_w$, linearly on the cost of the superinsulation $c_{SI}$ and inversely linearly on the cost of the conventional insulation $c_{CI}$.

For the variables $\lambda_{SI}$ and $\lambda_{CI}$ the behaviour of $c_{1\text{m}^2}$ is *non-linear*. One can consider certain extreme values of these input parameters to better understand Eq. (8).

When $\lambda_{SI}$ approaches $\lambda_{CI}$, $c_{1\text{m}^2}$ approaches infinity. This makes sense, since it would not be indicated to pay a higher price for superinsulation if its thermal conductivity is not considerably lower than the one of conventional insulation. The limit of $\lambda_{SI}$ going to infinity is not considered, since $\lambda_{SI} < \lambda_{CI}$ is required.

To examine what happens if the superinsulation material becomes increasingly better, one considers $\lambda_{SI}$ approaching zero, i.e.

$$\lim_{SI \to 0} c_{1\text{m}^2} = -h(1 - f_w)c_{CI} \tag{9}$$

In this limit case, $c_{1\text{m}^2}$ becomes negative, indicating that using the SIM would be cheaper than using the conventional material, as the thickness of the SIM would approach zero. Hence, the better the thermal performance of the SIM, the less relevant is its cost $c_{SI}$ – which has disappeared in Eq. (9).

Furthermore, it is worthwhile to consider another limit for Eq. (8), namely when the cost of the SIM approaches the one of the conventional one. One calculates

$$\lim_{c_{SI} \to c_{CI}} c_{1m^2} = \frac{h(1 - f_w)(\lambda_{SI}c_{CI} - \lambda_{CI}c_{CI})}{\lambda_{CI} - \lambda_{SI}} = h(1 - f_w)\frac{c_{CI}(\lambda_{SI} - \lambda_{CI})}{\lambda_{CI} - \lambda_{SI}}$$
$$= -h(1 - f_w)c_{CI} \qquad (10)$$

Again, the limit is negative. If the superinsulation and conventional materials are equally expensive per volume, using superinsulation is actually cheaper, since the thickness of the material needed to achieve the same U-value is smaller.

Finally, it should be noted that the cost to create additional floor space does not depend on the target U-value at all under the given assumptions. That is, for the cost efficiency, it does not matter if there are stringent or more relaxed requirements for the thermal properties of the wall. The question whether to insulate conventionally or with SIMs can be answered just by considering the material properties and the building geometry alone, which is an important result. Of course, the amount of space saved does depend on the U-value: the lower the U-value, the more pronounced the additional space gained by the use of superinsulation compared to conventional insulation becomes.

To get a better feel for the behaviour of Eq. (8), the dependence of $c_{1m^2}$ on its six input parameters is plotted. Fig. 4 shows the behaviour of $c_{1m^2}$ for different thermal conductivity values of both the SIM and the conventional insulator, while Fig. 5 illustrates the dependence on the cost of the two materials. In Fig. 6 the dependence of the cost to create additional floor space on the storey height and the window fraction is shown. Since it is not possible to illustrate the influence of all six input parameters at the same time, two or three parameters in the plots are varied and the remaining three to four parameters are kept fixed. For that, the following default values are used in this example: $\lambda_{CI}$ = 34 mW/(m·K), $c_{SI}$ = 6 000 EUR/m³ (with a range from 4 500 to 7 500 EUR/m³ indicated by shaded area), $c_{CI}$ = 200 EUR/m³, h = 3 m and $f_w$ = 0.4.

The graphical plots of Fig. 4 show how the cost to generate additional space increases strongly as the two thermal conductivities, $\lambda_{SI}$ and $\lambda_{CI}$, approach each other. Since superinsulating materials are usually defined by a thermal conductivity of 20 mW/(m·K) or less [38], this scenario would only be realistic for $\lambda_{SI}$ and $\lambda_{CI}$ approaching 20 mW/(m·K) from below and above, respectively. From Fig. 4(a), one also sees that a small improvement of a SIM makes a large difference in terms of its economic feasibility. For example, when comparing with a competitive conventional insulator at 30 mW/(m·K), an aerogel blanket with a thermal conductivity of 15 mW/(m·K) "breaks even" at about 10 000 EUR/m², whereas one with a thermal conductivity of 13 mW/(m·K) does so already at about 7 500 EUR/m². On the other hand, the higher the thermal conductivity of the compared conventional insulator, the cheaper it is to generate more usable space (Fig. 4(b)).

Regarding the cost of superinsulation, one learns from Fig. 5(a) that superinsulation would "break even" financially much more easily, if its cost would drop to the range of 2 000 to 3 000 EUR/m³. In that case, for many cities globally the use of superinsulation would be financially indicated as will be seen later. In addition, Fig. 5(a) also shows that the dependence on SIM cost is much more pronounced the higher the thermal conductivity of the SIM. That is, for a very good SIM, a cost increase or decrease does not affect economic outcome as strongly as for a SIM with a higher thermal conductivity. It is noteworthy that $c_{1m^2}$ becomes negative, when the product $\lambda_{SI} \cdot c_{SI}$ becomes smaller than $\lambda_{CI} \cdot c_{CI}$, which is seen for very low costs of the supersinsulators in Fig. 5(a).

The cost for most conventional insulators is in the range of 0 to 250 EUR/m³. Fig. 5(b) shows that the variation of $c_{1m^2}$ in that range is about 1 000 EUR/m². Hence, the outcome of Eq. (8) is not very sensitive to variations of $c_{CI}$ within its typical price range.

Fig. 6(a) shows us how storey height linearly increases the cost to create additional floor space. Again the effect is stronger the higher the thermal conductivity of the superinsulating material. Larger window areas on the other hand make superinsulation more feasible financially, as seen by the linear decrease of $c_{1m^2}$ with $f_w$ in
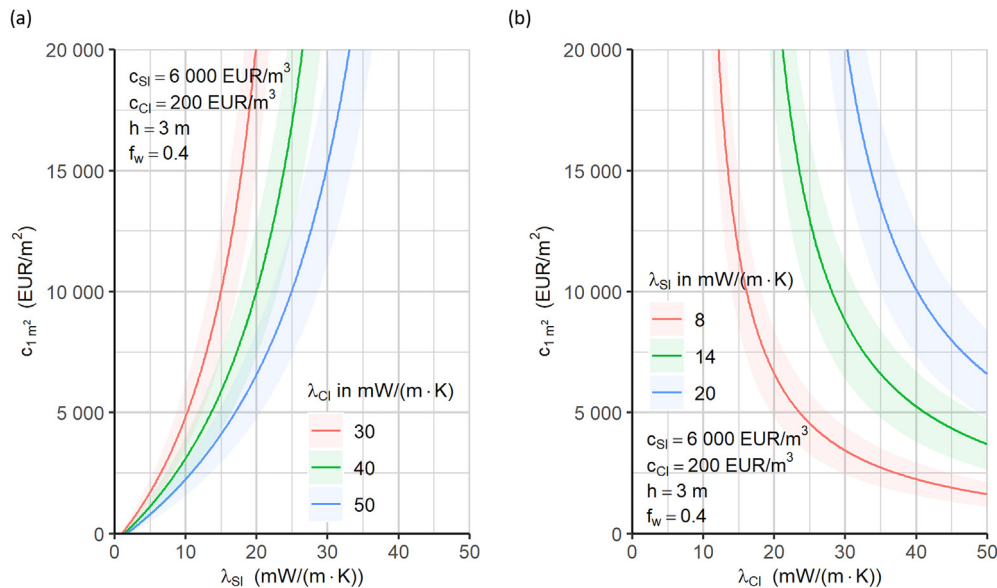


**Fig. 4.** Dependence of $c_{1m^2}$ on the thermal conductivity of the compared materials according to Equation (8). (a) $c_{1m^2}$ as a function of the thermal conductivity of the considered superinsulation $\lambda_{SI}$ with three different values for $\lambda_{CI}$, namely 30, 40 and 50 mW/(m·K). (b) Dependence of $c_{1m^2}$ on the thermal conductivity of the considered conventional insulation $\lambda_{CI}$ for three different values of the superinsulation thermal conductivity $\lambda_{SI}$, namely 8, 14 and 20 mW/(m·K). For both plot (a) and (b), the cost for the superinsulation $c_{SI}$ is set at 6 000 EUR/m³ with the shaded areas indicating the range from 4 500 to 7 500 EUR/m³; the remaining values are set at h = 3 m, $f_w$ = 0.4 and $c_{CI}$ = 200 EUR/m³. It should be noted that superinsulation is usually defined as $\lambda_{SI} \leq 20$ mW/(m·K). Hence, the realistic range for plot (a) is with $\lambda_{SI}$ from 0 to 20 mW/(m·K) and for plot (b) with $\lambda_{CI}$ from 20 mW/(m·K) and upwards. Wider ranges are shown here in order to illustrate the behaviour of the derived equation.
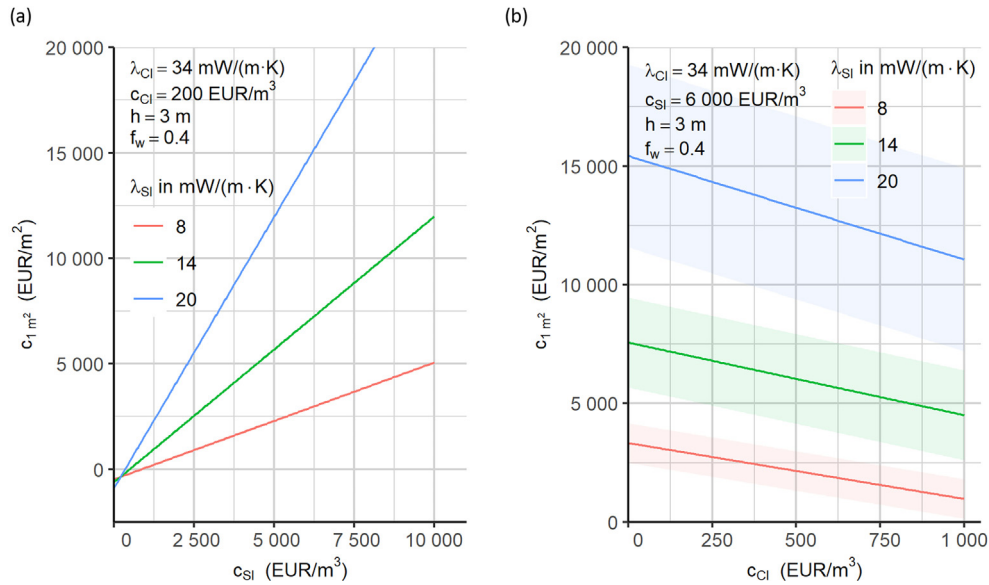
**Fig. 5.** (a) Dependence of the cost $c_{1m^2}$ to create one square metre of additional floor space on (a) the cost of the superinsulation $c_{SI}$ and (b) the cost of the conventional insulation $c_{CI}$ according to Equation (8). For both cases, three values for the thermal conductivity of the superinsulation $\lambda_{SI}$ are considered, namely 8, 14 and 20 mW/(m·K), respectively. For (a) $c_{CI}$ is set at 200 EUR/m³ and for (b) $c_{SI}$ is set at 6 000 EUR/m³ with the shaded areas indicating the range from 4 500 to 7 500 EUR/m³. For both plots, the thermal conductivity of the conventional insulation is set at 34 mW/(m·K), the window fraction $f_w$ at 0.4 and the storey height at $h$ = 3 m. Note that the vertical axis range of plot (a) is extended to negative values, since $c_{1m^2}$ is negative when $\lambda_{SI}c_{SI} < \lambda_{CI}c_{CI}$. In this case, using superinsulation saves money in addition to the value of the gained floor space.
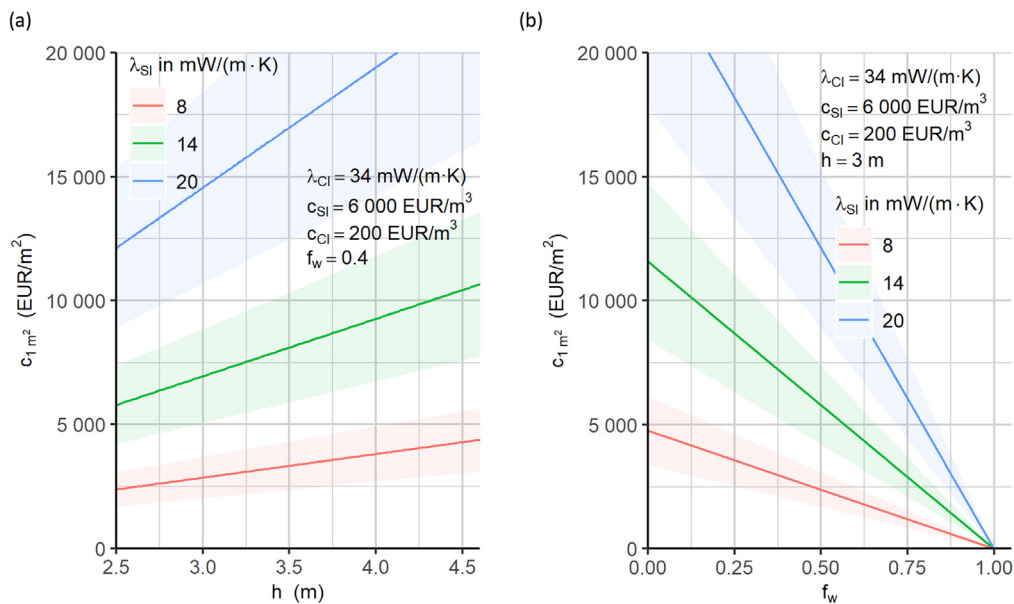


**Fig. 6.** Dependence of the cost $c_{1m^2}$ to create one square metre of additional floor space on (a) the height of the storey of the building $h$ and on (b) the window fraction of the façade $f_w$ according to Equation (8). In both cases, two thermal conductivities of the superinsulation are considered, namely 8, 14 and 20 mW/(m·K), respectively. The shaded areas indicate the parameter ranges from 4 500 to 7 500 EUR/m³ for the cost of the superinsulation, with the solid line representing a cost of 6 000 EUR/m³. The cost of the conventional insulator $c_{CI}$ is fixed at 200 EUR/m³ and the thermal conductivity of the conventional insulation is set at 34 mW/(m·K) for both plots. For (a) the window fraction $f_w$ is set at 0.4, for (b) the storey height is set at $h$ = 3 m.

Fig. 6(b). These variations correspond to more (increasing storey height in Fig. 6(a)) or less (increasing window to wall area fraction in Fig. 6(b)) wall area to thermally insulate as compared with gained floor space.

In order to verify the correctness of Eq. (8), the cost to create one additional square metre of usable space was calculated directly from numerical input parameters, using only Eqs. (1 and 2) or rearrangements of them, for three different examples. The steps and results of these calculations are shown in Table 3. The results for the explicit calculation are the same as the results of entering the numerical values into Eq. (8) directly. One also sees that the results are independent of the target U-value when comparing the first and the second example. Of course, the amount of created space depends on the target U-value as can be seen in the third row from the bottom of Table 3, indicating the thickness difference between superinsulation and conventional insulation: the lower the target volume the greater the space savings due to superinsulation.

**Table 3**

Calculation of the cost to create additional usable space for three different practical examples. In a first step, the cost was calculated using Eqs. (1 and 2) (or rearrangements of them) and then inserting the chosen numerical values. As a second step, in the last table row, the same values were entered into Equation (8) to confirm its correctness. In order to make the calculations easier, in the three examples, only a structural layer and an insulation layer were considered. In a more realistic scenario, one would add finish layers etc., but these usually do not influence the thermal properties significantly and if so would most likely be very similar in their effect for both conventional and superinsulation.

| | Unit | Brick wall with mineral wool vs. aerogel insulation; low target U-value | Brick wall with mineral wool vs. aerogel insulation; high target U-value | Concrete wall with EPS vs. PIR insulation; low target U-value |
|---|---|---|---|---|
| Storey height | m | 3 | 3 | 3.5 |
| Window fraction | dimensionless | 0.4 | 0.4 | 0.6 |
| Area to insulate per metre facade | $m^2$ | 1.8 | 1.8 | 1.4 |
| Target U-value | W/($m^2 \cdot$K) | 0.2 | 0.4 | 0.2 |
| $R_{si}$ | $m^2$K/W | 0.13 | 0.13 | 0.13 |
| $R_{se}$ | $m^2$K/W | 0.04 | 0.04 | 0.04 |
| Thermal conductivity superinsulation | mW/(m·K) | 16 | 16 | 18 |
| Thermal conductivity conventional insulation | mW/(m·K) | 34 | 34 | 29 |
| Cost of superinsulation | EUR/$m^3$ | 6000 | 6000 | 500 |
| Cost of conventional insulation | EUR/$m^3$ | 200 | 200 | 100 |
| Equivalent thickness structural layers | m | 0.25 | 0.25 | 0.2 |
| Equivalent thermal conductivity structural layers | mW/(m·K) | 800 | 800 | 1500 |
| Thickness of superinsulation to reach U-value | m | 0.072 | 0.032 | 0.040 |
| Volume of superinsulation per metre facade | $m^3$ | 0.130 | 0.058 | 0.055 |
| Cost for superinsulation per metre facade | EUR | 781 | 349 | 28 |
| Thickness of convent. insulation to reach U-value | m | 0.154 | 0.069 | 0.064 |
| Volume of convent. insulation per metre facade | $m^3$ | 0.276 | 0.123 | 0.089 |
| Cost for convent. insulation per metre facade | EUR | 55 | 25 | 9 |
| Cost difference for insulation per metre facade | EUR | 725 | 324 | 19 |
| Thickness difference | m | 0.081 | 0.036 | 0.024 |
| Cost to create 1 $m^2$ additional floor space (Eqs.1–2) | EUR/$m^2$ | **8920** | **8920** | **776** |
| Cost according to Eq. (8) | EUR/$m^2$ | **8920** | **8920** | **776** |

Having understood the behaviour of Eq. (8), it may be applied it to any given building project by determining the input parameters. For that, one may note that a typical storey height is about 3 m for residential buildings and about 3.5 m for office buildings whereas window fractions of façades are typically in the range from 15 to 60%.

Regarding the remaining parameters of the insulation materials, one should examine which comparisons and scenarios are practical. Apart from thermal conductivity, some other important material properties should be considered when choosing an alternative for a conventional insulation, e.g. applicability (how to fix, adjust, ability to cut, drill, etc.), various mechanical properties, water permeability, fire behaviour, climate exposure, ageing resistance and environmental impact. These need to be considered when evaluating possible building constructions and the use of superinsulation instead of conventional insulation. Hence, it makes sense to compare conventional insulation with superinsulation of similar properties. That is, aerogel boards should be compared to mineral wool, since they are similar in their applicability, are both vapour diffusion open and non-flammable (at least for some aerogel blankets). PIR foams on the other hand, are similar to expanded polystyrene (EPS) in their building physical properties (flammable, vapour diffusion closed). VIPs are somewhat of a special case, since they are the only insulation material that needs to be handled with special care so that their envelope is not damaged and they cannot be cut or drilled. On the other hand, they have definitely the lowest thermal conductivity available as of today. Hence, for VIPs it may make sense to compare them in those applications where they can be used safely, e.g. terrace insulation or insulation cover on metal beams in glass façades, to the materials that are usually applied in these contexts, e.g. EPS or PIR.

### 4.2. Superinsulation in different cities

In order to classify the results of Eq. (8), one needs to compare the cost of creating or saving floor space with the real estate value of the building. Of course, real estate prices can vary strongly between countries, regions, cities and even within these. With the current cost of superinsulation, its use is financially viable mostly in high-price inner city areas. In order to evaluate for which cities superinsulation is a financially interesting option, real estate data from several cities around the globe were compiled.

As the main source for the data, Numbeo [44] was used, a global, crowd-sourced database for cost of living and quality of life. Users can enter indicators such as cost of food, housing, transportation and average salaries. For all analyses, the parameter "Price per Square Meter to Buy Apartment in City Centre" was used. The great advantage of using Numbeo is the centralised and easy access of the data. Hence, it was used here as a single source to compare cities globally. But since this data was not compiled by the official offices of the respective cities, the real estate data on Numbeo for the cities of London, Cambridge, Brighton, Paris, Geneva and Zurich was compared to that of other sources in order to validate our approach.

For London, Cambridge and Brighton, data from PropertyData [47] was imported, a professional real estate online database. The corresponding boxplots are shown in Fig. 7. For Paris, Geneva and Zurich, official data from local offices was considered. The Chamber of the Notaries of Paris published an apartment index of 10 220 EUR/$m^2$ for old apartments in Paris in 2019 [22], compared to the median price listings of 11 000 EUR/$m^2$ in Numbeo. For the city of Geneva, the latest real estate cost data are the summary statistics of freehold apartment sales for the year 2018, published by the statistical office of the canton of Geneva [53]. These are shown in Table 4, compared to the Numbeo data of all residential building types in the period in the same year. The statistical office of the city of Zurich published the median value of 11 390 EUR/$m^2$ for sales of freehold apartments in Zurich in the year 2019 [52] (currency conversion with 1 EUR = 1.1124 CHF [16]), compared to the median of 11 538 EUR/$m^2$ for the Numbeo listings (including all residential building types) for the same year.

Considering the boxplots and the listed median values, for London, Cambridge, Brighton, Paris and Geneva, the real estate prices on Numbeo are roughly 10 to 20% higher than the respective other
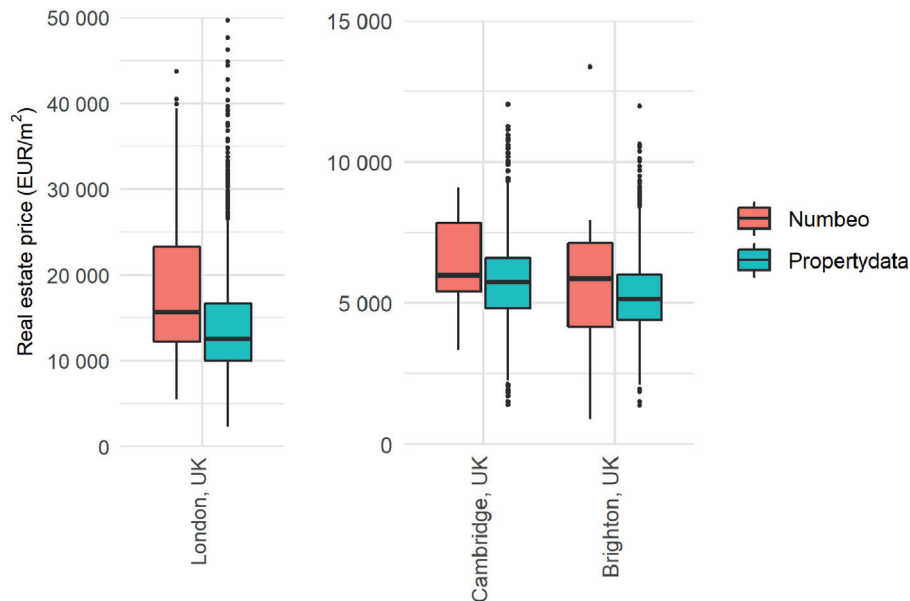
**Fig. 7.** Boxplots of real estate prices for the cities of London, Cambridge and Brighton, from the different sources Numbeo and PropertyData. Note the different price axis for London due to the higher real estate prices. The data points from PropertyData were imported according to postcodes, using the following specific postcodes for the city centres: London: W1, W2, W8, W9, SW1, SW3, SW5, SW6, SW7, SW10, SW11, WC1, WC2; Cambridge: CB1, CB2, CB3, CB4, CB5; Brighton: BN1, BN2. Data sources: numbeo.com and propertydata.co.uk, accessed January 2021.

**Table 4**
Summary statistics for the distribution of real estate prices in the city of Geneva for freehold apartment sales in 2018 according to the statistical office of the canton of Geneva ([53] and for all real estate type sales in 2018 according to Numbeo [44]. Currency conversion with 1 EUR = 1.1549 CHF for 2018 [16]).

| Real estate price [EUR/m$^2$] | minimum | 25th perc. | median | 75th perc. | maximum |
|---|---|---|---|---|---|
| Statistical office of the canton of Geneva (2018) | 2 535 | 6 395 | 8 659 | 10 187 | 21 449 |
| Numbeo (2018) | 8 456 | 9 777 | 10 401 | 12 482 | 17 380 |

sources, whereas for Zurich, the Numbeo data matches the official data very well. It is likely that the official sources and the data from Propertydata, which impresses with a very high number of data points, are more precise than Numbeo and that the real estate prices from Numbeo should be reduced by 10 to 20% to better reflect the actual real estate prices.

Nevertheless, the Numbeo data is an excellent starting point to get an overview of the global real estate market and to identify those cities that are most attractive for the application of superinsulation. Based on this initial evaluation, other data sources could then be identified for individual cities. One should also consider that any analysis of the real estate market reflects a specific point in time and that the real estate prices in different cities are likely to grow or fall at different rates in the future compared to each other, making it necessary to update the market analysis presented here.

For the mentioned overview of cities where superinsulation is financially attractive, the analysis was limited geographically to Europe, Northern America (US and Canada) and the Asian countries of China, Taiwan, Hong Kong, Japan, Singapore and South Korea. The real estate data for the years 2015 to mid-June 2021 of all cities listed in these countries in Numbeo was loaded. Any city with less than 18 entries for the real estate cost was excluded from further analysis. The remaining cities were ordered according to their median real estate price in the city centre. Boxplots of the 25 most expensive cities in each of the three geographic regions – Europe, Northern Amercia, Asia – were created as shown in Fig. 8, Fig. 9 and Fig. 10, respectively. The European tax haven Monaco has by far the highest real estate price in Europe and is shown in a separate boxplot with a different y-axis range in order to make the other data more readable. For Northern America, the data entries

for towns in the San Francisco Bay Area and in Los Angeles County were merged to create aggregated data sets for these areas according to the official lists of incorporated towns [5,40]. Otherwise, most of the 25 most expensive towns in Northern America in our analysis would have been from these two agglomerations, thus not giving a good overview over all of Northern America. For the three Asian countries, only 19 cities fulfilled the criterion of at least 18 data points. Apparently, Numbeo is more frequently used in western countries.

Boxplots were used to indicate the distribution of real estate prices in each of the cities. These show the central tendency of the data, i.e. the median (here as a black horizontal line), as well as the spread of the data indicated by the so called whiskers (black vertical lines). The ends of the whiskers are at the extreme value of the data set or at distance of 1.5 times the interquartile range from the edge of the box – whichever value is closer to the box. The interquartile range is the height of the box. The top and bottom line of the box itself mark the 25th and 75th percentile of the data. Thus, the boxplots indicate which is the cheapest quarter of real estate prices, the second cheapest, the second most expensive and the most expensive.

The analysis of the real estate market in the described regions shows that there is a large economical potential for the use of superinsulation in inner cities. For example, for VIPs with a thermal conductivity around 8 mW/(m·K) all median values of all cities presented above are in or above the economically feasible range as indicated in Fig. 4(b), assuming a conventional insulator with a thermal conductivity of 35 mW/(m·K) as comparison. Comparing a high-end silica aerogel with mineral wool and with the remaining parameters set as in Fig. 4, the cut-off value is about 7 000
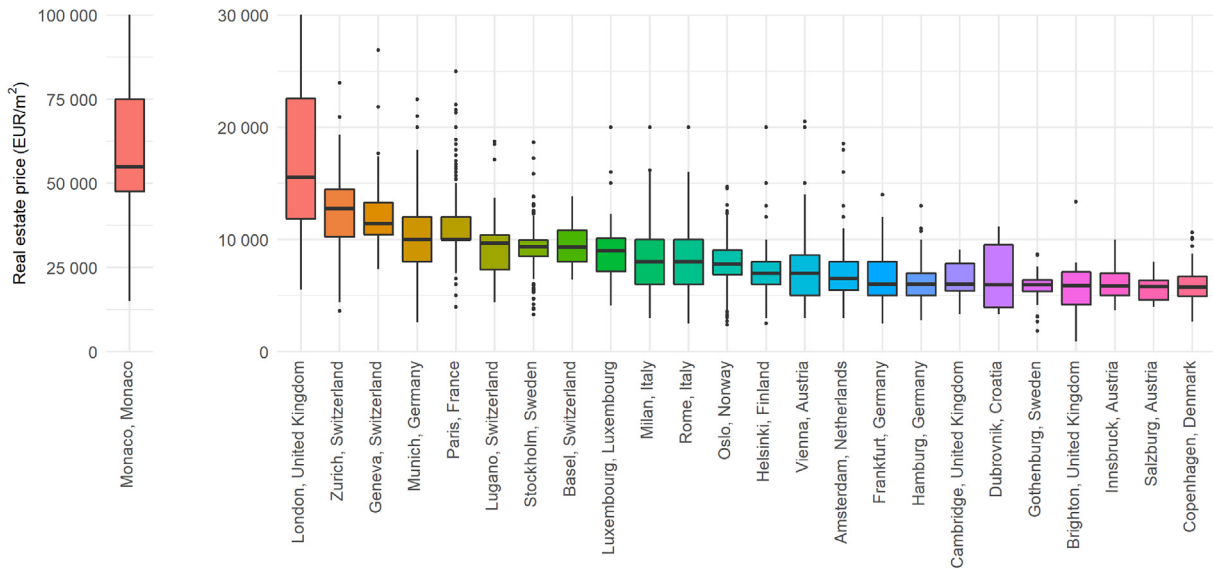
**Fig. 8.** Real estate price distributions for 25 most expensive cities in Europe according to Numbeo. Note the different axis scale for Monaco due to the very high price range. The boxplots indicate the range of the price distribution (from the extreme ends of the black vertical lines), the median (horizontal black line) and the 25th and 75th percentile (lower and upper edge of the coloured boxes, respectively). That is, 50% of all data points are located within the box, 25% below and 25% above the box. Single points above or below the vertical line are classified as outliers. The cities are ordered according to their median real estate prices. Data source: numbeo.com, accessed June 2021.

$EUR/m^2$. For this scenario, the median real estate price for many European cities is above this value: from Monaco to Vienna as indicated in Fig. 8. For Northern America, it is for the cities from New York to Waikiki in Fig. 9. For the considered Asian cities, it is the ten most expensive cities in this analysis where the median real estate price is higher than the cut-off value for silica aerogel insulation. To be on the safe side, the cut-off value can be raised by 10 to 20% to take into account a potential overestimation of real estate prices by the Numbeo data as discussed above.

Using the median as criterion, indicates that for half of the properties in the inner city the use of superinsulation is financially viable. Alternatively, the lower or upper boundaries of the boxes, i.e. the 25th and 75th percentile can be used as easy visual guides for evaluating the superinsulation potential in a given city.

Taking the current real estate prices as a baseline, one can make an estimate of the future potential of superinsulation in different cities since their cost might also change over time. For example, for aerogel, advances in the production process of aerogel granules
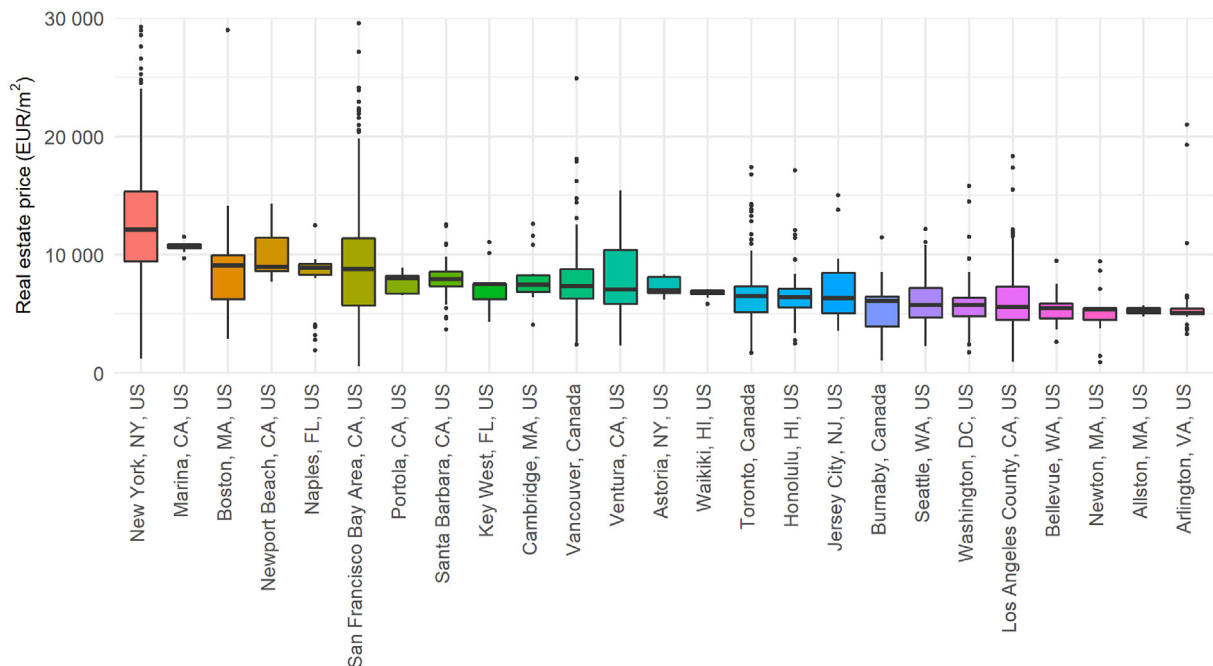


**Fig. 9.** Real estate price distributions for 25 most expensive cities in Northern America according to Numbeo. The cities are ordered according to their median real estate prices. Data from individual towns in the San Francisco Bay Area and Los Angeles County were aggregated. The boxplots indicate the range of the price distribution (from the extreme ends of the black vertical lines), the median (horizontal black line) and the 25th and 75th percentile (lower and upper edge of the coloured boxes, respectively). Data source: numbeo.com, accessed June 2021.
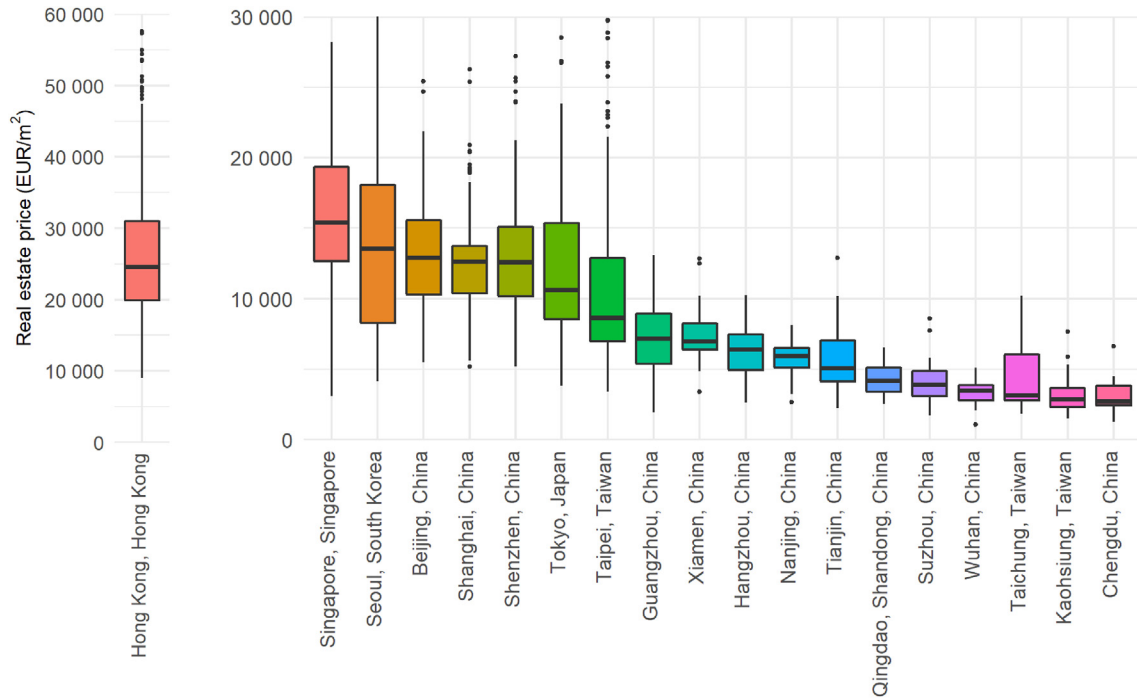
**Fig. 10.** Real estate price distributions for 19 most expensive cities in the Asian countries of China, Taiwan, Hong Kong, Japan, Singapore and South Korea according to Numbeo. Note the different axis scale for Hong Kong due to the very high price range. The cities are ordered according to their median real estate prices. The boxplots indicate the range of the price distribution (from the extreme ends of the black vertical lines), the median (horizontal black line) and the 25th and 75th percentile (lower and upper edge of the coloured boxes, respectively). Data source: numbeo.com, accessed June 2021.

[25,54] may lead to lower cost for insulation materials and systems. If the price of silica aerogel insulation drops to 2 500 EUR/m$^3$, which is not an unrealistic scenario, the break-even price for real estate would go down to 2 500 to 4 000 EUR/m$^2$ (cf. Fig. 5 (a)). This would alter the market analysis significantly, since then the medium square metre price for all cities shown in Fig. 8 would be higher than this break-even price range. The question of insulation cost as well as real estate market development will be discussed in more detail in Section 6.

## 5. Examples

### 5.1. Theoretical example

Let us consider first a theoretical example that is representative for a modern inner city residential building with limited outer spatial dimensions. Of course, also in dense cities, the outer dimensions of a building are not always fixed – often building laws limit the gross internal area that is created in a building project (i.e. the internal area without the area covered by the external walls). But it is not uncommon to have restrictions on the outer spatial dimensions of a building. In such a case, the thinner the building envelope is, the larger the usable space becomes and hence the larger the value of the building becomes (all other factors being equal).

For this building example, it is assumed that the spatial footprint of the building is 10 m by 10 m in its outer dimensions, that it has five storeys and that it is constructed using cross-laminated timber (CLT), a modern sustainable building system [8] with an exterior thermal insulation composite system (ETICS). For this, a conventional insulator suitable with this approach, a wood fibre board, and a superinsulation material in the form of an aerogel insulation board will be compared.

One could argue that instead of a structural building envelope, a non-load-bearing curtain façade with superinsulation would be even more suitable to optimise the net internal area (useable floor area) since it would be considerably thinner. On the other hand, a building with a curtain façade would require more or thicker load-bearing building elements in its interior, reducing the net internal area, which might compensate the space gains in the curtain façade.

The parameters for the insulation comparison of our example building are listed in Table 5. It is assumed that the CLT construction is 100 mm thick and that a 10 mm layer of render is added as the exterior finishing layer of the ETICS. Taking the thermal conductivity of the CLT to be about 130 mW/(m·K) and the one of the render to be about 500 mW/(m·K), the equivalent thermal conductivity of the non-insulating layers is 139 mW/(m·K) at an equivalent thickness of 110 mm. For the wood fibre board, a thermal conductivity of 42 mW/(m·K) is assumed and for the aerogel board one of 16 mW/(m·K) – which is at the lower end of the currently available products. An aerogel price of 5 000 EUR/m$^3$ is considered which is at the lower end of the price range. This is reasonable, since for a large building project with an insulation material volume good pricing options might be available.

As listed in Table 5, the wood fibre board insulation comes at a thickness of 170 mm to reach the target U-value of 0.2 W/(m$^2$·K), whereas the silica aerogel board is only 65 mm thick. This reduction of thickness of 105 mm results in a space saving of 0.105 m$^2$ per metre façade. The resulting gross internal areas (measured to the internal face of the external walls and including internal walls etc.) can be calculated for both insulation types from the interior façade lengths, which is the exterior façade length minus the thickness of the construction at each end of the façade. The results are also shown in Table 5 and there is a marked difference between the insulation materials, with a gross internal area of 93.1 m$^2$ for the SIM and a gross internal area of 89.1 m$^2$ for the conventional insulation material. That is, 4 m$^2$ are saved per storey at a cost of

17 624 EUR per storey (four times 4 406 EUR – the cost to save one square metre in this example according to Eq. (8)). Assuming, for the conventional insulation case, a typical ratio of gross floor area (exterior building dimensions, in this case 100 m$^2$) to net internal area of 0.8, the net internal area is 80 m$^2$ (excluding internal walls and other deducted areas such as lobbies, etc.). For the superinsulation case, the net internal area would be 4 m$^2$ higher, i.e. 84 m$^2$, which corresponds to a 5% increase. For the whole five-storey building the superinsulation allows for the creation of an additional net internal area of 20 m$^2$ at a cost of 88 120 EUR. In Fig. 11, the profit for this building is depicted for different real estate prices.

From the profit plot in Fig. 11, one can see that the break-even point for this specific example is at a real estate price of about 4 500 EUR. Of course, this is known more precisely already from the cost to create additional usable space of 4 406 EUR according to Eq. (8) and Table 5. The plot, though, indicates the overall profit that can be made for different real estate prices and hence in different locations. For example, for Paris or other cities of comparable real estate costs such as Munich, Basel, Stockholm or Boston, the return on investment of using superinsulation is significant at over 100 000 EUR for the whole building. In the centre of London it would be even higher, with about 220 000 EUR.

### 5.2. Perimeter block development in Zurich, Switzerland

The first new building insulated almost exclusively with silica aerogel blankets in Switzerland was erected between 2015 and 2019 in the inner city of Zurich [49]. The reason to use superinsulation was to create more useable area, the value of which would be higher than the additional cost of the aerogel insulation. The building codes of the Canton of Zurich usually do not limit the external perimeter of a building but the created internal area in order not to penalise thick, highly insulating façades which are more energy efficient. In this case, however, the plot was part of a perimeter block development and hence the new construction had to be in line with the neighbouring building. For the building façade facing the street and the courtyard, the opaque part of the

building envelope was realised using non-load-bearing wooden elements insulated with 50 mm of silica aerogel blanket (cf. Fig. 12). To mitigate the thermal bridges created by the wooden connectors in the element, it was covered by another 30 mm of aerogel blanket on the outside as an exterior thermal insulation composite system (ETICS). The total thickness of the aerogel wood façade is only 140 mm. The façade reaches a U-value of about 0.285 W/(m$^2$·K) (unpublished data of a hot-box measurement). A comparable construction with a conventional insulation material would be around 200 mm thick. For the whole building, this lead to space savings of about 30 m$^2$. Considering the median real estate value mentioned above for Zurich of about 11 400 EUR/m$^2$, this would correspond to a value increase of about 342 000 EUR for the whole building. The volume of aerogel used is around 25.5 m$^3$. Almost twice that would be needed in conventional insulation. Assuming a cost of 5 000 EUR/m$^3$ for the aerogel insulation and of 200 EUR/m$^3$ for the conventional insulation, the added cost can be estimated to be around 120 000 EUR. Thus, in total, the use of aerogel in this case can be assumed to have generated a profit of about 222 000 EUR.

### 5.3. Retrofit of historical multi-family home in Zurich, Switzerland

An example of how superinsulation can help to avoid having to change many architectural details is the retrofitting of a historical multi-family home in Zurich, Switzerland. The building, shown in Fig. 13, was energetically retrofitted with silica aerogel blankets in 2020. For that, the existing render of the building was removed (cf. Fig. 13(b)), 20 mm of silica blankets were installed and a new render was applied on top. Thus, a strong improvement of the thermal properties of the building could be achieved while keeping the characteristic appearance of the building with the stone ornaments on the façade and around the building. With a thicker insulation this would not have been possible. Rather, the building exterior would then have changed drastically and the window reveals would have had to be redesigned.

## 6. Future scenarios

After our analysis of the economic feasibility of superinsulation at the present moment, it is of interest to consider how it may develop in the future. The cost of superinsulation and the development of the real estate market probably have the largest potential to drive change. The values of the other parameters of Eq. (8) are not very likely to be subject to strong systematic changes in the
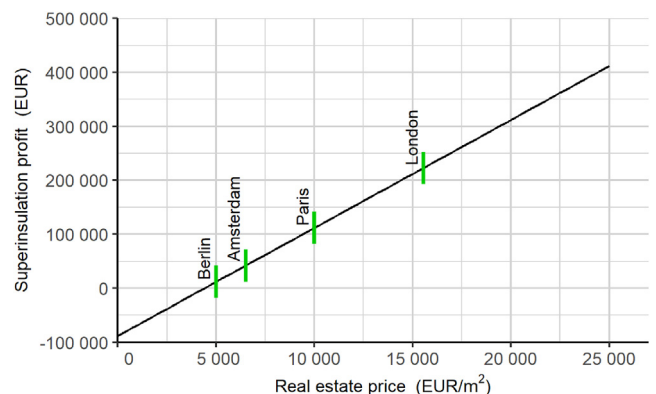
**Table 5**
Input variables and cost calculation for a building example with a cross-laminated timber (CLT) load-bearing structure and a comparison between aerogel and wood fibre board as exterior insulation with a render finish (ETICS).

| Façade length (square spatial footprint) | m | 10 |
|---|---|---|
| Target U-value | W/(m$^2$·K) | 0.2 |
| $R_{si}$ | m$^2$K/W | 0.13 |
| $R_{se}$ | m$^2$K/W | 0.04 |
| Thermal conductivity superinsulation | mW/(m·K) | 16 |
| Thermal conductivity conventional insulation | mW/(m·K) | 42 |
| Cost of superinsulation | EUR/m$^3$ | 5 000 |
| Cost of conventional insulation | EUR/m$^3$ | 200 |
| Storey height | m | 3.2 |
| Window fraction | dimensionless | 0.5 |
| Equivalent thickness of all non-insulating layers | m | 0.11 |
| Equivalent thermal conductivity of all non-insulating layers | mW/(m·K) | 139 |
| Thickness of superinsulation to reach target U-value | m | 0.065 |
| Thickness of conventional insulation to reach target U-value | m | 0.170 |
| Thickness difference | m | 0.105 |
| Cost according to Eq. (8) to create additional usable space | EUR/m$^2$ | **4 406** |
| Interior façade length, superinsulation | m | 9.65 |
| Interior façade length, conventional insulation | m | 9.44 |
| Gross internal area (including walls etc.), superinsulation | m$^2$ | **93.1** |
| Gross internal area (including walls etc.), conventional insulation | m$^2$ | **89.1** |



**Fig. 11.** Profit in EUR by applying superinsulation for a five-storey example building with a spatial footprint of 10 m by 10 m as a function of real estate price. Green marks for different cities indicate the median real estate price in these cities according to Numbeo.

future. The building geometry parameters, including storey height and window fraction, are determined by economic optimisation (building cost, maximum building size), by architectural style (e.g. large glass facades in office buildings) and by building physical considerations (for example, target values of optimal solar gains influence window area). Since conventional insulation materials are well established in the building market for a significant time, drastic changes in their cost or thermal performance are also unlikely in the near future. Similarly, the thermal performance of high quality superinsulating materials at their low-conductivity end is close to the theoretical optimum, so that also this variable can be assumed to be fairly fixed.

### 6.1. Superinsulation price development

The different superinsulation materials are at different points with respect to their market development. Hence, not taking into account any potential and currently unknown technical innovations in the future, their potential for price decreases can be evaluated based on that.

VIPs are a well researched and established product type. However, recent developments of better VIP envelopes and alternative core materials such as glass wool or perlite might allow the creation of cheaper long life VIPs for the building sector [12,48]. This could lead to significant cost reductions which would translate into a reduction of the cost to create additional floor space of similar size according to Eq. (8).

Silica aerogel, on the other hand, is a newer material type in the building industry and there is strong research activity on improving and simplifying the production process of aerogel [13,19,25,54], which could decrease cost. Compared to current manufacturing methods, a reduction of production cost of silica aerogel granules by a factor of two could be possible in the best case. Other superinsulating materials such as aerogel boards or renders can be produced from aerogel granules, so that a more cost-effective production of aerogel granules could result in a variety of cheaper aerogel products. Also, economy of scale effects for this rather new building material are likely to take effect with increased use, leading to further price reductions.

The cost of high-performance, superinsulating PIR foams, may reduce to levels currently seen for standard, medium-performance PIR products. However, it is not guaranteed that all of the technical innovations that enabled PIR to break the 20 mW/(m·K) barrier will remain compatible with environmental regulations with respect to the filler gasses. As a reminder, polyurethane foam's first period as a superinsulator was cut short after the global ban on chlorofluorocarbons [37].

Since the cost to create additional floor space is proportional to the cost of the superinsulation material (plus a constant offset, cf. Eq. (8)), a reduction of the superinsulation material cost translates almost directly to a corresponding reduction in the break-even cost, i.e. the cost to create additional floor space. For, example, for a silica aerogel board with a thermal conductivity of 18 mW/(m·K) a 50% cost reduction – for example due to a new production method – would result in drop of the break-even price, $c_{1m^2}$, from about 10 000 EUR/m$^2$ down to 5 000 EUR/m$^2$ (cf. Fig. 5(a)). For this scenario, the median real estate price of all European cities presented in Fig. 8 and of most Northern American cities shown in Fig. 9 would be above or around the break-even price. For insulation systems based on aerogel granules even lower costs to create floor space would be possible: currently the cost of silica aerogel granules is around 2 500 EUR/m$^3$, corresponding to a $c_{1m^2}$ of roughly >5 000 EUR/m$^2$ according to Fig. 5(a) (taking into account that the granules need to be integrated into an insulation system at a certain cost). If granule prices fell to 1 250 EUR/m$^3$ because of technological improvements, $c_{1m^2}$ would be around 2 500 EUR/m$^2$. Price drops such as these would significantly change the economic feasibility of superinsulation in many areas. Hence, technological developments towards cheaper superinsulation material production will likely be one of the most crucial factors in its application in the future.

### 6.2. Real estate price development

Real estate prices have risen in many larger cities over the last decades, leading to the high prices shown in Section 4.2. It is expected that cities will continue to become more and more popular compared to small towns and villages, leading to a further shortage of housing in cities and urban areas and hence an increase in real estate prices [57]. This continuous increase in housing cost is faster than salary and wage increases, resulting in the ongoing global "urban housing affordability crisis" [61]. In the context of thermal insulation materials, this development favours the use of superinsulation materials, since it allows for a better use of the available space in cities. Also, it lowers the threshold for the economic feasibility of the use of superinsulation materials. That

**Fig. 12.** First new building in Switzerland with aerogel insulation on the whole façade, located in the centre of Zurich. (a) View from the street with aerogel insulation under and next to the windows. (b) Assembly of aerogel façade element with grey aerogel blankets. Images: Jannis Wernery.

**Fig. 13.** Multi-family home in Zurich, Switzerland: (a), (b) during and (c) after the retrofit in 2020 with silica aerogel blankets. The existing render was removed (see detail in (b)), 20 mm of silica aerogel blanket were applied and covered with render again, resulting in the final state as shown in (c) (opposite view of the building). Neither the roof nor the characteristic stone details on the building façade and around the windows had to be modified. Images: AGITEC AG.

means, superinsulation materials are likely to be used more widely in inner city areas in the future.

## 7. Conclusions

In a few building scenarios – namely new buildings with a restricted outer perimeter, upward extensions and energy-efficient retrofits with internal insulation – the use of thermal superinsulation instead of conventional materials creates additional space or saves space that would otherwise be taken up by the construction.

Based on a few basic assumptions, we have derived a simple equation to calculate the cost to create or save additional floor space in building projects by the use of superinsulation materials instead of conventional insulation materials. The equation depends only on the thermal performance and cost of the superinsulation material and the compared conventional insulation material as well as the storey height and the window fraction of the considered building. Interestingly, it does not depend on the thermal resistance or U-value of the whole wall.

By comparing the cost to create the additional space to its financial value, i.e. the real estate price of the building location, one can determine if the use of superinsulation materials is economically recommended or not for a given building project. To aid this deci-

sion, the distribution of real estate prices for a number of cities globally were presented.

With the derived equation and the presented real estate prices, planners and building owners may now easily estimate if the use of superinsulation would create a financial value for a specific building project by inserting the parameter values of the project into the equation and comparing the calculated cost with the actual real estate price. Such an estimation can be the basis for a more detailed cost evaluation, maybe taking into account more parameters of the construction as well as precise real estate cost values for the specific location within the city. Also, financial effects such as future discounting of the real estate value should be taken into account to allow for a more precise analysis. With that, different scenarios for the management of the building may be considered, such as an immediate sale of the real estate after the construction process or the use as rental property.

Currently, many cities already offer a strong financial incentive to use thermal superinsulation in order to create more usable space in building projects. Furthermore, with new technological improvements in the production of superinsulation materials – both for vacuum insulation panels and silica aerogel materials – a moderate to significant reduction of the cost of these materials is likely to occur in the next decade. During the same timeframe, a further increase in real-estate cost is expected. Combined, the decreasing cost of superinsulation and the increased real estate

price will make the use of superinsulation materials financially viable in many more locations than today, creating a disproportionally larger market. This may in turn create an economy of scale in the production processes, leading to a further drop in price. Superinsulation materials may thus play a larger role in the urban densification expected for the future.

## CRediT authorship contribution statement

**Jannis Wernery:** Conceptualization, Methodology, Formal analysis, Investigation, Resources, Visualization, Writing – original draft. **Francisco Mancebo:** Investigation, Resources, Visualization. **Wim J. Malfait:** Conceptualization, Methodology, Resources, Writing – original draft, Writing - review & editing. **Michael O'Connor:** Resources, Writing - review & editing. **Bjørn Petter Jelle:** Methodology, Formal analysis, Visualization, Writing – original draft, Writing - review & editing.

## 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.

## Acknowledgements

## References

[1] T. Abergel, B. Dean, J. Dulac, I. Hamilton, 2018 Global Status Report – Towards a zero-emission, efficient and resilient buildings and construction sector. International Energy Agency (IEA), for the Global Alliance for Buildings and Construction, 2018.

[2] Aerogel Particles [WWW Document], 2021. Cabot Corp. URL https://www.cabotcorp.com/solutions/products-plus/aerogel/particles (accessed 3.18.21).

[3] F. Asdrubali, F. D'Alessandro, S. Schiavoni, A review of unconventional sustainable building insulation materials, Sustain. Mater. Technol. 4 (2015) 1–17, https://doi.org/10.1016/j.susmat.2015.05.002.

[4] R. Baetens, B.P. Jelle, A. Gustavsen, Aerogel insulation for building applications: A state-of-the-art review, Energy Build. 43 (2011) 761–769, https://doi.org/10.1016/j.enbuild.2010.12.012.

[5] Bay Area Census [WWW Document], 2010. Cities. URL http://www.bayareacensus.ca.gov/cities/cities.htm (accessed 1.29.21).

[6] U. Berardi, The impact of aging and environmental conditions on the effective thermal conductivity of several foam materials, Energy 182 (2019) 777–794, https://doi.org/10.1016/j.energy.2019.06.022.

[7] D. Bozsaky, Nature-based thermal insulation materials from renewable resources – A state-of-the-art review, Slovak J. Civ. Eng. 27 (2019) 52–59, https://doi.org/10.2478/sjce-2019-0008.

[8] R. Brandner, G. Flatscher, A. Ringhofer, G. Schickhofer, A. Thiel, Cross laminated timber (CLT): overview and development, Eur. J. Wood Wood Prod. 74 (2016) 331–351, https://doi.org/10.1007/s00107-015-0999-5.

[9] C. Buratti, E. Moretti, Glazing systems with silica aerogel for energy savings in buildings, Appl. Energy 98 (2012) 396–403, https://doi.org/10.1016/j.apenergy.2012.03.062.

[10] Buratti, C., Moretti, E., Belloni, E., 2016. Nanogel Windows for Energy Building Efficiency, in: Torgal, F.P., Buratti, C., Kalaiselvam, S., Granqvist, C.-G., Ivanov, V. (Eds.), Nano and Biotech Based Materials for Energy Building Efficiency. Springer International Publishing, pp. 41–69. https://doi.org/10.1007/978-3-319-27505-5_3.

[11] CALOSTAT® Product Information – Evonik Industries [WWW Document], 2021. URL https://www.calostat.com/en/product-information (accessed 3 March 21).

[12] B. Chang, L. Zhong, M. Akinc, Low cost composites for vacuum insulation core material, Vacuum 131 (2016) 120–126, https://doi.org/10.1016/j.vacuum.2016.05.027.

[13] M. de Fátima Júlio, L.M. Ilharco, Hydrophobic granular silica-based aerogels obtained from ambient pressure monoliths, Materialia 9 (2020), https://doi.org/10.1016/j.mtla.2019.100527 100527.

[14] DIN EN 13501-1:2019-05, Klassifizierung von Bauprodukten und Bauarten zu ihrem Brandverhalten_- Teil_1: Klassifizierung mit den Ergebnissen aus den Prüfungen zum Brandverhalten von Bauprodukten; Deutsche Fassung EN_13501-1:2018 (Engl.: "Fire classification of construction products and building elements – Part 1: Classification using data from reaction to fire tests; German version EN 13501-1:2018"), 2019. Beuth Verlag GmbH, Berlin, Germany. https://doi.org/10.31030/2870379.

[15] Ebert, H.-P., 2013. High-Performance Insulation Materials, in: Pacheco Torgal, F., Mistretta, M., Kaklauskas, A., Granqvist, C.G., Cabeza, L.F. (Eds.), Nearly Zero Energy Building Refurbishment: A Multidisciplinary Approach. Springer, London, pp. 457–481. https://doi.org/10.1007/978-1-4471-5523-2_17.

[16] ESTV, 2021. Jahresmittelkurse [WWW Document]. Eidgenöss. Steuerverwaltung. URL https://www.estv.admin.ch/estv/de/home/direkte-bundessteuer/wehrpflichtersatzabgabe/dienstleistungen/jahresmittelkurse.html (accessed 17 January 2021).

[17] S. Gaan, S. Liang, H. Mispreuve, H. Perler, R. Naescher, M. Neisius, Flame retardant flexible polyurethane foams from novel DOPO-phosphonamidate additives, Polym. Degrad. Stab. 113 (2015) 180–188, https://doi.org/10.1016/j.polymdegradstab.2015.01.007.

[18] M. Ganobjak, S. Brunner, J. Wernery, Aerogel materials for heritage buildings: Materials, properties and case studies, J. Cult. Herit. 42 (2020) 81–98, https://doi.org/10.1016/j.culher.2019.09.007.

[19] R. Garrido, J.D. Silvestre, I. Flores-Colen, M.F. de Júlio, M. Pedroso, Economic assessment of the production of subcritically dried silica-based aerogels, J. Non-Cryst. Solids 516 (2019) 26–34, https://doi.org/10.1016/j.jnoncrysol.2019.04.016.

[20] K. Ghazi Wakili, B. Binder, M. Zimmermann, Ch. Tanner, Efficiency verification of a combination of high performance and conventional insulation layers in retrofitting a 130-year old building, Energy Build. 82 (2014) 237–242, https://doi.org/10.1016/j.enbuild.2014.06.050.

[21] K. Ghazi Wakili, Th. Stahl, E. Heiduk, M. Schuss, R. Vonbank, U. Pont, C. Sustr, D. Wolosiuk, A. Mahdavi, High Performance Aerogel Containing Plaster for Historic Buildings with Structured Façades, in: Energy Procedia, 6th International Building Physics Conference, IBPC, 2015, https://doi.org/10.1016/j.egypro.2015.11.027.

[22] Global Property Guide, 2020. Investment Analysis of French Real Estate Market [WWW Document]. Glob. Prop. Guide. URL https://www.globalpropertyguide.com/Europe/France (accessed 1.19.21).

[23] M. Gonçalves, N. Simões, C. Serra, I. Flores-Colen, A review of the challenges posed by the use of vacuum panels in external insulation finishing systems, Appl. Energy 257 (2020), https://doi.org/10.1016/j.apenergy.2019.114028 114028.

[24] Heinemann, U., Adl-Zarrabi, B., Brunner, S., Foray, G., Johansson, P., Kono, J., Kücükpinar, E., Milow, B., Quenard, D., Sprengard, C., Wallbaum, H., Yrieix, B., 2020. Annex 65 Long-Term Performance of Super-Insulating-Materials in Building Components and Systems. Report of Subtask I: State of the Art and Case Studies (No. EBC Annex 65).

[25] L. Huber, S. Zhao, W.J. Malfait, S. Vares, M.M. Koebel, Fast and Minimal-Solvent Production of Superinsulating Silica Aerogel Granulate, Angew. Chem. Int. Ed. 4753–4756 (2017), https://doi.org/10.1002/anie.201700836.

[26] N. Hüsing, U. Schubert, Aerogels—Airy Materials: Chemistry, Structure, and Properties, Angew. Chem. Int. Ed. 37 (1998) 22–45, https://doi.org/10.1002/(SICI)1521-3773(19980202)37:1/2<22::AID-ANIE22>3.0.CO;2-I.

[27] ISO, 6946:2017 Building components and building elements — Thermal resistance and thermal transmittance —, Calculation methods (2017).

[28] S. Iswar, S. Galmarini, L. Bonanomi, J. Wernery, E. Roumeli, S. Nimalshantha, A. M. Ben Ishai, M. Lattuada, M.M. Koebel, W.J. Malfait, Dense and strong, but superinsulating silica aerogel, Acta Mater. 213 (2021), https://doi.org/10.1016/j.actamat.2021.116959 116959.

[29] B.P. Jelle, Traditional, state-of-the-art and future thermal building insulation materials and solutions – Properties, requirements and possibilities, Energy Build. 43 (2011) 2549–2563, https://doi.org/10.1016/j.enbuild.2011.05.015.

[30] B.P. Jelle, T. Gao, Aerogel systems for miscellaneous building applications - Experimental investigations, Translucent Silica Aerogel – Properties, Preparation and Applications, Nova Science Publishers, 2019.

[31] B.P. Jelle, T. Gao, Experimental Investigations of Miscellaneous Aerogel Systems Intended for Application in Building Envelopes. Proc. 13th Conf, Adv. Build. Ski. ABS 2018 (2018) 503–512.

[32] B.P. Jelle, A. Gustavsen, R. Baetens, The path to the high performance thermal building insulation materials and solutions of tomorrow, J. Build. Phys. 34 (2010) 99–123, https://doi.org/10.1177/1744259110372782.

[33] B.P. Jelle, S.E. Kalnæs, Nanotech Based Vacuum Insulation Panels for Building Applications, in: F. Pacheco Torgal, C. Buratti, S. Kalaiselvam, C.-G. Granqvist, V. Ivanov (Eds.), Nano and Biotech Based Materials for Energy Building Efficiency, Springer International Publishing, Cham, 2016, pp. 167–214, https://doi.org/10.1007/978-3-319-27505-5_7.

[34] B.P. Jelle, S.A. Mofid, T. Gao, M. Grandcolas, M. Sletnes, E. Sagvolden, Nano insulation materials exploiting the Knudsen effect, IOP Conf. Ser. Mater. Sci. Eng. 634 (2019), https://doi.org/10.1088/1757-899X/634/1/012003 012003.

[35] S.E. Kalnæs, B.P. Jelle, Vacuum insulation panel products: A state-of-the-art review and future research pathways, Appl. Energy 116 (2014) 355–375, https://doi.org/10.1016/j.apenergy.2013.11.032.

[36] A.N. Karim, P. Johansson, A.S. Kalagasidis, Super insulation plasters in renovation of buildings in Sweden: energy efficiency and possibilities with new building materials, IOP Conf. Ser. Earth Environ. Sci. 588 (2020), https://doi.org/10.1088/1755-1315/588/4/042050 042050.

[37] P. Kjeldsen, M.H. Jensen, Release of CFC-11 from Disposal of Polyurethane Foam Waste, Environ. Sci. Technol. 35 (2001) 3055–3063, https://doi.org/10.1021/es000194i.

[38] M. Koebel, A. Rigacci, P. Achard, Aerogel-based thermal superinsulation: an overview, J. Sol-Gel Sci. Technol. 63 (2012) 315–339, https://doi.org/10.1007/s10971-012-2792-9.

[39] M.M. Koebel, J. Wernery, W.J. Malfait, Energy in buildings—Policy, materials and solutions, MRS Energy Sustain. 4 (2017), https://doi.org/10.1557/mre.2017.14.

[40] lacounty.gov, 2016. . Cty. Los Angel. URL https://lacounty.gov/government/about-la-county/incorporated-cities/(accessed 29 January 2021).

[41] A. Lamy-Mendes, A.D.R. Pontinha, P. Alves, P. Santos, L. Durães, Progress in silica aerogel-containing materials for buildings' thermal insulation, Constr. Build. Mater. 286 (2021), https://doi.org/10.1016/j.conbuildmat.2021.122815 122815.

[42] S.T. McKenna, N. Jones, G. Peck, K. Dickens, W. Pawelec, S. Oradei, S. Harris, A.A. Stec, T.R. Hull, Fire behaviour of modern façade materials – Understanding the Grenfell Tower fire, J. Hazard. Mater. 368 (2019) 115–123, https://doi.org/10.1016/j.jhazmat.2018.12.077.

[43] E. Moretti, M. Zinzi, F. Merli, C. Buratti, Optical, thermal, and energy performance of advanced polycarbonate systems with granular aerogel, Energy Build. 166 (2018) 407–417, https://doi.org/10.1016/j.enbuild.2018.01.057.

[44] Numbeo, 2021. Numbeo [WWW Document]. Cost Living. URL https://www.numbeo.com/cost-of-living/(accessed 18 January 2021).

[45] Orsini, F., Marrone, P., Asdrubali, F., Roncone, M., Grazieschi, G., 2020. Aerogel insulation in building energy retrofit. Performance testing and cost analysis on a case study in Rome. Energy Rep., The 7th International Conference on Energy and Environment Research—"Driving Energy and Environment in 2020 Towards A Sustainable Future" 6, 56–61. https://doi.org/10.1016/j.egyr.2020.10.045.

[46] M. Pedroso, I. Flores-Colen, J.D. Silvestre, M. Glória Gomes, L. Silva, L. Ilharco, Physical, mechanical, and microstructural characterisation of an innovative thermal insulating render incorporating silica aerogel, Energy Build. 211 (2020), https://doi.org/10.1016/j.enbuild.2020.109793 109793.

[47] PropertyData, 2021. Property Market Analytics – PropertyData [WWW Document]. URL https://propertydata.co.uk/(accessed 8 April 2021).

[48] S. Resalati, T. Okoroafor, P. Henshall, N. Simões, M. Gonçalves, M. Alam, Comparative life cycle assessment of different vacuum insulation panel core materials using a cradle to gate approach, Build. Environ. 188 (2021), https://doi.org/10.1016/j.buildenv.2020.107501 107501.

[49] Schwarz Architekten, 2021. Wohnhaus Hohlstrasse 100, Zürich. Schwarz Archit. URL https://www.schwarz-architekten.com/project/apartment-und-buerogebaeude-hohlstrasse-100-zuerich/(accessed 13 April 2021).

[50] N. Simões, M. Gonçalves, C. Serra, S. Resalati, Can vacuum insulation panels be cost-effective when applied in building façades?, Build. Environ. 107602 (2021), https://doi.org/10.1016/j.buildenv.2021.107602.

[51] Spaceloft Insulation for Building and Construction [WWW Document], 2021. Aspen Aerogels Ind. Aerogel Insul. URL/markets/building-and-construction/ (accessed 8 April 2021).

[52] Stadt Zürich, 2021. Bodenpreise und Wohnflächenpreise – Stadt Zürich [WWW Document]. URL https://www.stadt-zuerich.ch/prd/de/index/statistik/publikationen-angebote/datenbanken-anwendungen/bodenpreise.html (accessed 8 April 2021).

[53] Statistique Genève, 2021. Statistiques cantonales – République et canton de Genève [WWW Document]. URL https://www.ge.ch/statistique/domaines/05/05_05/tableaux.asp (accessed 8 April 2021).

[54] A. Stojanovic, S. Paz Comesaña, D. Rentsch, M.M. Koebel, W.J. Malfait, Ambient pressure drying of silica aerogels after hydrophobization with mono-, di- and tri-functional silanes and mixtures thereof, Microporous Mesoporous Mater. 284 (2019) 289–295, https://doi.org/10.1016/j.micromeso.2019.04.038.

[55] swisspor – saving energy | swissporPIR Premium Plus [WWW Document], 2021. URL https://www.swisspor.ch/index.php?section=datasheet&cmd=productPage&id=586 (accessed 26 February 2021).

[56] swisspor – saving energy | swissporVIP [WWW Document], 2021. URL https://www.swisspor.ch/index.php?section=datasheet&cmd=productPage&id=235 (accessed 26 February 2021).

[57] van Doorn, L., Arnold, A., Rapoport, E., 2019. In the Age of Cities: The Impact of Urbanisation on House Prices and Affordability, in: Nijskens, R., Lohuis, M., Hilbers, P., Heeringa, W. (Eds.), Hot Property: The Housing Market in Major Cities. Springer International Publishing, Cham, pp. 3–13. https://doi.org/10.1007/978-3-030-11674-3_1

[58] Wernery, J., Ben-Ishai, A., Binder, B., Brunner, S., 2017. Aerobrick — An aerogel-filled insulating brick. Energy Procedia, Sustainability in Energy and Buildings 2017: Proceedings of the Ninth KES International Conference, Chania, Greece, 5-7 July 2017 134, 490–498. https://doi.org/10.1016/j.egypro.2017.09.607.

[59] J. Wernery, S. Brunner, B. Weber, C. Knuth, M.M. Koebel, Superinsulation Materials for Energy-Efficient Train Envelopes, Appl. Sci. 11 (2021) 2939, https://doi.org/10.3390/app11072939.

[60] J. Wernery, A. Rigacci, P. Achard, M.M. Koebel, Aerogels for Superinsulation – Properties, Products and Applications, Aerogel Handbook – in Press, Accepted Manuscript. Springer, 2021.

[61] S. Wetzstein, The global urban housing affordability crisis, Urban Stud. 54 (2017) 3159–3177, https://doi.org/10.1177/0042098017711649.