# International Journal of Smart and Nano Materials

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Published online: 22 Jan 2015.

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# Trombe walls with nanoporous aerogel insulation applied to UK housing refurbishments

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There is an opportunity to improve the efficiency of passive Trombe walls and active solar air collectors by replacing their conventional glass covers with lightweight polycarbonate panels filled with nanoporous aerogel insulation. This study investigates the thermal performance, energy savings, and financial payback period of passive Aerogel Trombe walls applied to the existing UK housing stock. Using parametric modeling, a series of design guidance tables have been generated, providing estimates of the energy savings and overheating risk associated with applying areas of Trombe wall to four different house types across the UK built to six notional construction standards. Calculated energy savings range from 183 kWh/m$^2$/year for an 8 m$^2$ system retrofitted to a solid walled detached house to 62 kWh/m$^2$/year for a 32 m$^2$ system retrofitted to a super insulated flat. Predicted energy savings from Trombe walls up to 24 m$^2$ are found to exceed the energy savings from external insulation across all house types and constructions. Small areas of Trombe wall can provide a useful energy contribution without creating a significant overheating risk. If larger areas are to be installed, then detailed calculations would be recommended to assess and mitigate potential overheating issues.

**Keywords:** silica aerogel; nanoporous insulation; energy harvesting; solar wall; Passivhaus

## 1. Introduction

Silica aerogel is a unique, nanoporous material with the best insulation properties of any solid. It can retain up to four times as much heat as conventional insulation, while being highly translucent to light and solar radiation. Solid monolithic tiles of transparent silica aerogel, produced in laboratories, have been cited as the "holy grail" of future glazing technology because of their unrivalled low thermal conductance and high solar transmission. Alternatively, low cost translucent aerogel granules, produced commercially, achieve similar properties and can be encapsulated and retrofitted to buildings in a variety of applications.

This study investigates the thermal performance, energy savings, and payback period of passive Trombe walls containing aerogel. Trombe walls (visualized in Figure 1) are a type of solar energy harvesting technology invented by Edward Morse in 1881, then later popularized by the French engineer Felix Trombe and architect Jacques Michel in the 1970s [1]. These systems consist of a thermally massive south facing wall (typically

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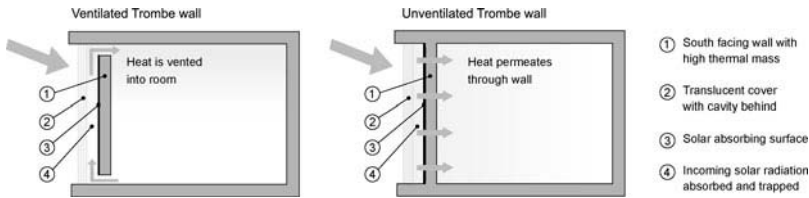*Corresponding author. Email: mark.dowson@burohappold.com

Figure 1.   Ventilated and unventilated Trombe walls.

concrete) painted black and a cover (typically glass) with a cavity behind, which is heated up by incoming solar radiation. This captured heat can either be used straight away by venting the warm air inside or, later, by letting it permeate and warm up the concrete wall so that occupants can benefit from it in the evening.

In Dowson et al. [2], the in-situ performance of a flat plate solar air heater connected to a dwelling's active mechanical ventilation system with heat recovery was carried out. Instead of glass, the cover was a lightweight multiwall polycarbonate panel filled with granular aerogel. During a 7-day in-situ test, peak outlet temperatures up to 45°C were observed inside the collector, preheating the dwellings fresh air supply up to 30°C, facilitating internal temperatures of 21–22°C, without auxiliary heating. Monitoring results were validated to within 5% of predictions. Efficiency calculations for a range of thicknesses were carried out compared to single and double glazing. Findings demonstrated that a 10 mm granular aerogel cover provided the optimum balance between light transmission and heat retention, saving up to 166 kWh/m$^2$/year compared to annual savings of 110 kWh/m$^2$/year for a single glazed collector and 140 kWh/m$^2$/year for a double glazed collector.

As Trombe walls are passive, they do not rely on active mechanical ventilation, thus may be more widely applicable to existing housing in today's market, compared to solar-air collectors. To date, there is limited design guidance available for sizing conventional glazed Trombe walls and no design guidance for sizing Trombe walls containing aerogel insulation. This study aims to fill this knowledge gap through a parametric steady state modeling exercise, providing initial design guidance on the likely energy savings depending on system size and house type, together with potential overheating risk (which the designer must then mitigate through static or movable shading grills to cut high summer sun, combined with passive vents at the top and bottom of the wall).

## 2.   Literature review

### 2.1.   *Trombe walls with translucent insulation*

Several studies investigate the steady state performance, modeling techniques, and in-situ performance of glazed Trombe walls, such as Monsen et al. [3] and Burek and Habeb [4], respectively. By comparison, Peuportier and Michel [5], Athienitis and Ramadan [6], and Suehrcke et al. [7], amongst others, demonstrate that incorporating a translucent insulation material (TIM) into the design, such as glass or plastic honeycombs and flat or corrugated polycarbonate sheets, can provide significant energy savings when retrofitted to residential and commercial properties. For example, in a comparative study of six houses in France, Peuportier and Michel [5] found that honeycomb TIMs can increase the efficiency of conventional solar air collectors and Trombe walls by 25% and 50%, respectively.

A selection of TIM Trombe wall projects has been compiled by Peurortier et al. [8]. Many of these installations were conducted during the 1980s and 1990s by the

Fraunhofer-Institute for Solar Energy Systems in Freiburg, southern Germany, and through the International Energy Agency's Solar Heating and Cooling programme, established in 1977. One project listed by Peurortier et al. [8] is the "Self Sufficient Solar House" in Freiburg. Here, the entire dwelling's heating, electricity, and hot water demand is met through Passivhaus design, photovoltaic panels for electricity generation, and an 80 $m^2$ passive TIM Trombe wall. Trombe wall cavity temperatures up to 70°C and temperature lags of 11 hours were predicted in a simulation study by Stahl et al. [9]. According to the results of a 3-year monitoring study by Voss et al. [10], the property's space heating requirement was found to be almost zero and only necessary in extreme winter periods. The overall solar conversion efficiency of the Trombe wall was 47%, with average internal temperatures ranging from 16 to 28°C. A mechanical shade was recommended to reduce summertime overheating [10].

The world's largest TIM/Trombe wall installation is at Strathclyde University in Glasgow, Scotland [11]. Here, 1040 $m^2$ of translucent insulation applied in glazing and Trombe wall applications has been installed over four separate student accommodation blocks serving 376 students. According to a 3-year monitoring study by Twidell et al. [12], the south facade of the building provides a net energy gain throughout the year, providing up to 20% of the buildings heating even during the mid-winter season. According to monitoring data, the internal temperature in the occupied common rooms was always in the range of 22–26°C in winter. Available internal temperature data for unoccupied bedrooms with no auxiliary heating was not observed to drop below 18°C. Overall student satisfaction was very high (with 91% satisfied or very satisfied). During the summer, peak Trombe wall cavity temperatures of 50°C were observed. Automated roller blinds serve to prevent overheating.

According to Peurortier et al. [8], a well installed Trombe wall incorporating translucent insulation can save heating energy by up to 150 kWh/$m^2$ each heating period. Supporting this, Dolley et al. [13] used a test cell to monitor the thermal performance of a polycarbonate honeycomb TIM system retrofitted to a southern wall. Extrapolating the results, the study predicted that the annual space heating requirement would be reduced by 150 kWh/year in a typical pre-1930s UK solid walled dwelling or 40 kWh/year in a super insulated home for every $m^2$ of TIM installed. Without shading, the hours of overheating (above 27°C) were raised from 4 to 31 for properties with solid walls and from 320 to 784 for super insulated homes.

## 2.2. Drivers and barriers

One of the main advantages of using TIM instead of single or multiple glazed covers is the considerable weight reduction, which can play an important factor in retrofit applications. Despite this, significant implementation of outdoor solar energy systems incorporating TIM has been slow. Platzer and Goetzberger [14] estimated that over 15,000 $m^2$ of TIM had been installed across 85 buildings throughout Germany, Austria, and Switzerland, indicating that the market was promising, but not satisfactory.

Platzer and Goetzberger [14] and Wong et al. [15] claim that commercial uptake of TIMs has been slow because of perceived high-investment costs and small number of payback studies. Peuportier et al. [11] state that production quality must improve to reduce imperfections such as rough or melted edges, which can hinder clarity. In contrast, Kaushika and Sumathy [16] state that considerable progress has been made to improve the quality and reduce the cost of manufacturing translucent insulation. Although capital costs to manufacture a fully functional TIM cladding system with solar control can reach

€ 600–1000/m², TIM glazing systems can have costs as low as € 24/m² [15,16]. On the basis of this lower cost, Wong et al. [15] calculated a 3 to 4 year payback period for an industrial production facility in Salzgitter, Germany, renovated with 7500 m² of TIM glazing costing € 180,000 with annual maintenance costs of € 7200. It is unclear whether these payback periods can be directly transferred to the domestic or commercial sector because of likely differences in design quality. Nonetheless, this payback period is significantly less than solid wall insulation and new double glazing.

Some of the key barriers include a lack of product development guides, imperfections in honeycomb or capillary TIMs, the low working temperatures of plastics, and the potential for overheating when too much solar radiation is absorbed [14,15]. Further to this, Wong et al. [15] state that the high investment cost of TIM, shading devices, and control measures has presented barriers to widespread implementation. Conversely, Wong et al. [15] claim that, with improved design guidance combined with more information on the capital cost and payback periods of TIM in use, there will be increasing evidence to outweigh the barriers currently hindering market growth, especially as fuel prices increase in future, reducing payback periods.

### 2.3.  *Aerogel insulation*

Cutting edge research into TIM products focuses on developing systems using quasi-homogenous silica aerogel insulation [16–20]. This lightweight, nanoporous material is the only known solid with an excellent combination of high solar and light transmittance and low thermal conductance, offering potential to achieve *U*-values as low as 0.1 W/m² K, as well as high solar energy and daylight transmittance of approximately 90% [21,22].

Aerogel is a super insulation material, because its thermal conductivity is lower than still air [23]. The total thermal conductivity of porous insulation depends on the amount of heat transfer through convection in the pores, conduction through the solid and pores, as well as radiation [23,24].

Typically, pores within conventional insulation are over 1 mm wide, allowing gas molecules to move freely and transfer thermal energy by convection [23]. By comparison, pores within aerogel can be as small as 20–40 nm, being smaller than the mean free path of air at 60–100 nm, that is the average distance between air molecules at normal atmospheric pressure [25]. As a result, individual air molecules within the pores have no space to transfer thermal energy by convection [23,26].

Conduction through the solid structure and air molecules within aerogel is also minimal. With little space for convection, air molecules constantly collide with the walls of the pores, suppressing gas conduction [24]. Furthermore, as aerogel only contains 0.1–5% silica and the thermal conductivity of air is very low, heat transfer is minimal [17]. Conduction in the gas will diminish with any decreases in pressure [24]. A vacuum inside the pores results in the best insulating properties. Yokogawa [23] measured thermal conductivities of 0.004 W/m K (ten times better than conventional insulation) using this technique.

The amount of radiative heat transfer through aerogel is dependent on the intensity and wavelength of the thermal radiation, the optical properties of the material, the size and shape of its pores, and the overall thickness [24,26]. At ambient temperature, the nanosized pores and particles provide effective attenuation of infrared thermal radiation because of high levels of absorption and reflection [27]. According to Hartmann et al.

[28], radiative heat transfer at ambient temperature accounts for 10–15% of the total thermal conductivity through aerogel.

The optical and infrared properties of silica aerogel have been well documented [29,30]. It is a TIM that effectively transmits solar light, but blocks thermal infrared radiation [30]. Towards the blue and UV spectral region, absorption is low and transmission levels are reduced because of scattering effects. Transmission levels increase for longer wavelengths of visible light and are high across the near-infrared spectrum, highlighting the materials potential to transmit heat in solar energy applications [26,31].

## 2.4. Aerogel Trombe walls

The potential use of monolithic or granular aerogel applied to passive solar Trombe walls has been discussed by Fricke and Tilotson [30], Fricke et al. [32], Fricke [33,34], Caps and Fricke [35], and Peurortier et al. [8]. This system would consist of a thermally massive black-painted brick wall, over which would be translucent insulation consisting of monolithic or granular silica aerogel between two protective glass panes [34]. Most of the produced heat would be transferred into the house. To prevent overheating, a shading device would be necessary.

There are two examples of large nonevacuated granular Aerogel Trombe walls mentioned in academic literature, both installed on semi-detached houses. However, there is little detailed information regarding the cost, architectural integration, or in-situ thermal performance of these installations. According to Fricke and Tilotson [34], a "convincing example" was a 120 m$^2$ system installed on two-family household in Ardon, Switzerland, in 1989, constructed for a lower cost than conventional insulation. Here, the energy consumption for heating was found to be exceptionally low at about 300 litres of oil per year, equivalent to approximately 3500 kWh/year (compared to the average UK household gas consumption of 16,000 kWh/year [36]). A second example was a 70 m$^2$ system installed in Freiburg-Tiengen, Germany, in 1991. No supporting literature could be found regarding this system.

In 2007, a prototype of an Aerogel Trombe wall was designed and constructed as part of the US Department of Energy's "Solar Decathlon" project: a biennial event challenging teams to design, build, and operate solar powered houses that are cost-effective, energy-efficient, affordable, and attractive. The prototype [37] was designed by W. Colson, Senior Vice President of Hunter Douglas Inc., and was constructed in collaboration with a team of researchers from Massachusetts Institute of Technology, USA, lead by K. Keville.

The south facing aerogel Trombe wall, named the "Hunter Douglas Solar Window," consists of 112 modular acrylic blocks, each containing a 1-inch layer of encapsulated granular aerogel in front of a 2.5 inch layer of encased water. According to a press release from Hunter Douglas [37], this encased water-base thermal mass layer heats up to approximately 100 degrees Fahrenheit (~38°C) on cold sunny days in winter, and the aerogel prevents heat loss to outside, while the interior thermal mass slowly releases its heat to the dwelling over a 24–36 hour period. When the product was used as the sole heating source over the course of two winters, the resultant internal temperature of the dwelling was 21°C for 90% of the time, with some supplemental heat required for the remaining 10%.

Beyond information in press releases, this literature review found no peer reviewed studies or empirical monitoring data evaluating the in-situ performance of this prototype. In 2007, Colson [38] registered the US Patent 8,082,916 "Solar heating blocks" for the

design of the double compartment acrylic blocks, containing water and a translucent insulating material, such as aerogel, for use in assembling solar heating panels in the walls of buildings.

Commenting on monolithic aerogel, modeling by Caps and Fricke [35] found that a Trombe wall containing a 15 mm thick layer of evacuated monolithic silica aerogel between double glazing cover achieves minimal solar heat losses compared to conventional TIM because of its high solar transmission of 50–60% and low *U*-value of 0.5 W/ m$^2$ K. However, Caps and Fricke [35] state that conventional TIMs are technically simpler as the evacuated system would also require a durable vacuum-tight metal rim.

## 3.   Calculation methodology

Duffie and Beckman [39] provide one of the most comprehensive and widely cited resources for predicting the performance of solar energy technologies. According to Duffie and Beckman [39], p. 750, the thermal performance of passive Trombe walls can be calculated using the "Un-Utilizability Design Method" developed by Monsen et al. [3]. The methodology assumes that the fraction of solar energy collected by a Trombe wall converted into useful heat, that is the utilizability, is based upon the actual thermal storage capacity of a building and its Trombe wall, to the ratio of energy that would be dumped in a zero capacitance building that can store no energy. Calculations are done monthly, with a key result being the annual amount of auxiliary energy needed to heat the passively designed building. Building loads are calculated using a simple degree-day method, using the baseline heat loss coefficient of the building calculated by the designer [39].

The methodology assumes that the Trombe wall is unventilated and that heat transfer through the wall is linear. This creates a simple resistance network (shown in the left diagram of Figure 2) to enable straightforward calculation of the net heat transfer through the wall into the indoor spaces. Monsen et al. [3] claim that these assumptions are valid for all reasonable system designs, that is the energy storage of the wall is less than the heating load of a single winter's day. According to Monsen et al. [3], the methodology allows users to parametrically assess a large range of design options, such as cover types, solar absorptance properties, different baseline building heat losses, as well as high and low temperature set-points.

The methodology used in this study is based on the formulas developed by Monsen et al. [3], more recently published by Duffie and Beckman [39]. These formulae are presented in the next section. Note that in several instances, the methodology refers to additional formula to manually calculate figures for monthly average solar irradiance such as ratios of beam and diffuse irradiance as well as estimated cloud-cover dependant on the site latitude/longitude. These solar irradiance formulae are omitted from this methodology,
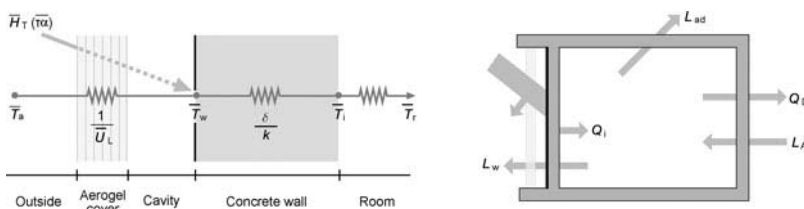


Figure 2.   Monthly average resistance network (right) and energy flows (left).

because the values can also be derived from online climate data, such as NASA's "Surface Meteorology and Solar Energy Data Set," integrated into software such as RETScreen International.

### 3.1. Load calculations

The right diagram of Figure 2 shows the main monthly energy flows considered in the Un-Utilizability Design Method. $L_A$ is the monthly requirement for auxiliary energy for a building with a Trombe wall. $L_w$ is the monthly heat loss through the Trombe wall assuming no solar irradiance is absorbed. $L_{ad}$ is the monthly heat load that occurs with no heat transfer through the Trombe wall. $Q_i$ is the net heat gain through the Trombe wall. $Q_D$ is the energy dump that would occur in a zero capacitance system. Loads $L_{ad}$ and $L_w$ can be determined from Equations (1) and (2), respectively:

$$L_{ad} = (UA)_{ad}(DD) \tag{1}$$

$$L_w = U_w A_r (DD) \tag{2}$$

Here, $(UA)_{ad}$ is the building heat loss coefficient. $DD$ is total monthly degree day hours. $A_r$ and $U_w$ correspond to the area and heat loss coefficient of the Trombe wall. $U_w$ is calculated from Equation (3):

$$U_w = \frac{1}{\frac{1}{\overline{U}_L} + \frac{1}{U_i} + \frac{x}{k}} \tag{3}$$

Here, $\overline{U}_L$ is the average heat loss coefficient from the outer wall surface through the Trombe wall cover to the ambient air. According to Duffie and Beckman [39], it can be conceptually derived in the same way as the front heat loss coefficient for flat plate solar collectors (see Dowson et al. [2]). $U_i$ is the heat transfer coefficient between the inner wall surface and the air in the adjacent room to the Trombe wall. $x$ and $k$ correspond to the thickness and conductivity of the wall.

### 3.2. Net heat transfer through Trombe wall

$Q_n$, the net heat transfer into rooms through the Trombe wall, can be calculated using Equation (4):

$$Q_n = U_k A_r \left(\overline{T}_w - T_r\right) \Delta t N \tag{4}$$

Here, $U_k$ is the conductance from the outer surface of the wall to the room, calculated from Equation (5). $\overline{T}_w$ is the monthly average outer wall temperature, calculated from Equation (6), where $\overline{T}_a$ is the monthly mean ambient temperature. $T_r$ is the room temperature at its low thermostat setting. $N$ represents the number of days in the month. $\Delta t$ is the temperature difference between the outer and inner wall surface, where $\overline{T}_i$, the inner wall surface temperature, is calculated from Equation (7), which assumes linear heat transfer. $\overline{S}$ refers to the monthly average absorbed solar irradiance (see Duffie and Beckman [39], p. 239).

$$U_k = \frac{U_i k}{k + U_i \delta} \tag{5}$$

$$\overline{T}_w = \frac{\overline{S} + \left(U_k T_r + \overline{U}_L \overline{T}_a\right)\Delta t}{\left(U_k + \overline{U}_L\right)\Delta t} \tag{6}$$

$$\overline{T}_i = T_r - \frac{U_L}{U_i}\left(T_r - \overline{T}_w\right) \tag{7}$$

### 3.3.  *Energy dump*

The excess heat that enters a building through its Trombe wall, but does not contribute towards reducing the auxiliary energy load, is referred to as "dumped energy". This concept is visualized in Figure 3, which shows a theoretical operational sequence for a Trombe wall in a zero capacitance building where all solar gain that exceeds the instantaneous auxiliary energy load is dumped. As shown, any incident irradiance below the critical radiation level is useful and any energy above must be dumped. The monthly energy dump that would occur in a zero capacitance system can be calculated from Equation (8):

$$Q_D = \frac{U_k A_r \overline{S} N \overline{\Phi}}{U_L + \overline{U}_k} \tag{8}$$

Here, $\overline{\phi}$ refers to the monthly average daily utilizability, which can be calculated from Equation (9):

$$\overline{\Phi} = \exp\left\{ \left[ a + b\left(\frac{R_n}{\overline{R}}\right) \right] \left[ \overline{X}_c + c\overline{X}_c^{\,2} \right] \right\} \tag{9}$$

where

$$a = 2.943 - 9.271\,\overline{K}_T + 4.031\,\overline{K}_T^{\,2}$$

$$b = -4.345 + 8.853\,\overline{K}_T - 3.602\,\overline{K}_T^{\,2}$$

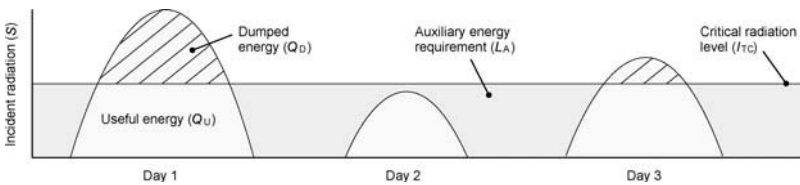$$c = -0.170 - 0.306\,\overline{K}_T + 2.9361\,\overline{K}_T^{\,2}$$



Figure 3.   Dumped, useful and auxiliary energy for a zero capacitance Trombe wall.

$\overline{K}_T$ refers to the average daily clearness index on the Trombe wall surface; $\overline{R}$ is the ratio of the monthly average daily total irradiance on a tilted surface to that on a horizontal surface; $R_n$ is the ratio of irradiance on a tilted surface to that of a horizontal surface at solar noon (see Duffie and Beckman [39], p. 77, p. 109 and p. 136, respectively, for these solar irradiance formulae). $\overline{X}_c$ refers to the monthly average critical irradiance ratio, which can be calculated from Equation (10):

$$\overline{X}_c = \frac{I_{TC}}{r_{t,n} R_n \overline{H}} \tag{10}$$

Here, $\overline{H}$ is the monthly average daily total solar irradiance on a horizontal surface, which can be obtained from meteorological data such as those found in Duffie and Beckman [39], pp. 843–881. $r_{t,n}$ is the ratio of irradiance at solar noon to daily total irradiance on a horizontal surface (see Duffie and Beckman [39], p. 89). $I_{TC}$ refers to the hourly critical irradiance level, which makes the energy dump zero. This is calculated using Equation (11):

$$I_{TC} = \frac{1}{(\overline{\tau\alpha}) A_r} \left[ (UA)_{ad} \left( \frac{U_L}{U_k} + 1 \right) \frac{T_b - \overline{T}_a}{T_r - \overline{T}_a} + U_L A_r \right] (T_r - \overline{T}_a) \tag{11}$$

Here, $T_b$ is the baseline temperature for which degree days were calculated. $(\overline{\tau\alpha})$ is the monthly average transmittance–absorptance product, which can be calculated from Equation (12), where $\overline{H}_T$ is the monthly average daily total solar irradiance on a tilted plane (see Duffie and Beckman [39], p. 109).

$$(\overline{\tau\alpha}) = \frac{\overline{S}}{\overline{H}_T} = \frac{\overline{S}}{\overline{H}.\overline{R}} \tag{12}$$

### 3.4. Storage–dump ratio

The storage dump ratio, $Y$, is the ratio between the theoretical energy dump in a zero capacitance building to the actual storage capacity of the building, $S_b$, and the Trombe wall, $S_w$. It is calculated using Equation (13):

$$Y = \frac{S_b + 0.047(S_w)}{Q_D} \tag{13}$$

The storage capacity of the wall is slightly weighted compared to the building, indicating that heat stored in the building is more effective than heat stored in the Trombe wall. This is because thermal storage in the building or wall raises the temperature of components, leading to increased heat losses; the thermal resistance of the building will generally be greater than that of the wall and also because the temperature difference between the building and ambient air is ordinarily smaller than the temperature difference between the Trombe wall and ambient air [13]. To calculate $S_b$ and $S_w$, Equations (14) and (15) can be used, respectively:

$$S_b = C_b(\Delta T_b) N \tag{14}$$

$$S_\mathrm{w} = \frac{\rho C_\mathrm{p} \delta^2}{2k\Delta t} Q_\mathrm{i} \tag{15}$$

where $C_\mathrm{b}$ and $C_\mathrm{p}$ correspond to the effective thermal storage capacity of the building and specific heat capacity of the wall. $\Delta T_\mathrm{b}$ is the allowable temperature swing between the building's low and high thermostat settings. $\rho$ is the density of the wall. $\Delta t$ refers to the number of seconds in 24 hours (86,400 seconds). $Q_\mathrm{i}$ is the heat gain across the Trombe wall, calculated from Equation (16):

$$Q_\mathrm{i} = \frac{2kA_\mathrm{r}}{\delta}(\Delta T_\mathrm{w})\Delta t N \tag{16}$$

In the above equation, again $\Delta t$ refers to the number of seconds in 24 hours. $\Delta T_\mathrm{w}$ is half of the temperature difference between the inside and outside wall surfaces.

### 3.5. Solar fraction

The solar fraction, that is the proportion of the buildings energy load, which is met by the net energy gain from the Trombe wall, can be calculated from Equation (17):

$$f = \min\{Pf_i + 0.88(1 - P)[1 - \exp(-1.26f_i)], 1\} \tag{17}$$

where

$$P = [1 - \exp(-0.144Y)]^{0.53}$$

where $f_i$ is the fraction of the monthly load supply by solar energy, which can be calculated from Equation (18):

$$f_i = \frac{L_\mathrm{w} + Q_\mathrm{i}}{L_\mathrm{ad} + L_\mathrm{w}} \tag{18}$$

### 3.6. Auxiliary energy requirement

The final step is to calculate the building's auxiliary energy requirement for the month, $L_\mathrm{A}$. This is calculated from Equation (19):

$$L_\mathrm{A} = (L_\mathrm{ad} + L_\mathrm{w})(1 - f) \tag{19}$$

Once $L_\mathrm{A}$ is known, the energy savings, that is the useful energy from the Trombe wall, can be determined by subtracting the auxiliary energy requirement from the building heat load without the Trombe wall, as shown in Equation (20):

$$Q_\mathrm{u} = L_\mathrm{ad} - L_\mathrm{A} \tag{20}$$

### 4. Aerogel Trombe wall parametric modelling

Based on the aforementioned formula, a steady state thermal model was created. The model can generate monthly average figures for a building's heating load, with and without the Trombe wall, the system solar fraction, average cavity temperatures,

critical irradiance levels and net energy gain. Monthly average heat loads and solar fraction can also be evaluated in terms of the actual thermal capacity of the building and Trombe wall or in the theoretical "zero" or "infinite" capacity scenarios.

Understandably, the depth of this tool is limited by the "monthly average" figures it produces. Consequently, detailed information regarding peak temperatures and the time/ day they occur, as well as information regarding thermal lags cannot be assessed. Nonetheless, the flexibility of the input process enables parameters such as different Trombe wall compositions, site locations, areas, and dwelling construction properties, to be promptly compared and evaluated.

Using this tool, the following study consists of a parametric thermal modelling assessment of different Trombe wall areas retrofitted directly to the outside of a range of house types and construction standards. This works builds on an extrapolation study by Dolley et al. [13], who estimated the thermal performance of different translucent honeycomb Trombe wall areas retrofitted to a theoretical detached house, built with solid walls, unfilled cavity walls, to 1976 and 1990 Building Regulations standards as well as to "super-insulation" standards (equivalent to 2010 Building Regulations).

### 4.1. Baseline housing stock performance

The first step in this parametric assessment involved generating representative heat loss parameters for different house types and insulation standards. This was achieved by conducting a series of thermal modeling assessments using IES Virtual Environment, a Building Regulation compliant SAP software. The results of this study are given in Table 1. According to Utley and Shorrock [40], the average heat loss parameter for detached houses, semi-detached houses, terrace houses, and flats in the United Kingdom is 342 W/K, 264 W/K, 235 W/K, and 167 W/K, respectively. Excluding results for the "super-insulated" and 2010 Building Regulations property (as they only represent around 1% of the UK's existing stock), the average heat loss parameter calculated from the SAP assessments was 339 W/K, correlating very well with data from Utley and Shorrock [40].

### 4.2. Data processing and limitations

Figures 4–7 display the predicted annual space heating consumption for each dwelling type and construction standard with 0, 8, 16, 24, or 32 m$^2$ areas of Trombe wall installed on their south facade. In each case, it was assumed in the steady state model that a Trombe wall incorporating a 10 mm granular aerogel cover is retrofitted directly to the outside of the dwelling's existing wall (i.e., brick with/without insulation and a cavity), as opposed to an "optimized" concrete storage wall, which would require more disruptive retrofit works to install.

Results are tabulated using a similar approach to Dolley et al. [13], with figures for predicted annual energy savings given in kWh/year and in kWh/m$^2$/year, whereby m$^2$ refers to the installed area of the Trombe wall (not m$^2$ of floor area). Similarly to Dolley et al. [13], it is assumed that the Trombe wall possesses no shading system or summertime ventilation. Energy dump is given opposed to hours of overheating per year, provided by Dolley et al. [13]. Illustrations beneath each table display the Trombe wall energy savings (per m$^2$ of installed area) and the annual solar fraction (%).

Table 1. Extrapolated heat loss parameters used in parametric modeling.

| Construction type | $U$-value (W/m$^2$ K) and air permeability (m$^3$/m$^2$ h @ 50 Pa) | Extrapolated heat loss parameters (W/K) | | | |
| | | Detached | Semi-detached | Terrace | Flat |
| --- | --- | --- | --- | --- | --- |
| Solid wall | Walls (2.16), Glazing (5.7), Roof (1.7), Ground floor (1.0); Air permeability = 15 | 469 | 362 | 322 | 229 |
| Unfilled cavity wall | Walls (1.24), Glazing (5.7), Roof (1.7), Ground floor (1.0); Air permeability = 15 | 388 | 300 | 267 | 190 |
| 1976 Building Regulations | Walls (0.76), Glazing (5.7), Roof (0.6), Ground floor (1.0); Air permeability = 15 | 292 | 225 | 200 | 142 |
| 1990 Building Regulations | Walls (0.45), Glazing (3.3), Roof (0.25), Ground floor (0.45); Air permeability = 10 | 206 | 159 | 141 | 100 |
| 2010 Building Regulations | Walls (0.25), Glazing (2.0), Roof (0.16), Ground floor (0.25); Air permeability = 10 | 132 | 102 | 90 | 64 |
| Super insulated | Walls (0.15), Glazing (0.8), Roof (0.15), Ground floor (0.15); Air permeability = 1 | 67 | 52 | 46 | 33 |

Note that these preliminary results should only be treated as indicative values, which have not been validated experimentally in this application. It is anticipated that this data could be used as preliminary design guidance to assist designers in sizing Trombe walls, dependent on house type and insulation level. However, at this stage, predicted annual heating load and energy savings for each house type/construction standard are intended solely for comparative purposes, as opposed to providing accurate information.

## 5. Discussion

The preliminary results of the parametric modeling study provide a useful insight into how the performance of the Aerogel Trombe wall may vary when retrofitted to different notional house types and constructions. For example, it is possible to see how utilization and energy savings per m$^2$ reduce as larger areas of Trombe wall are specified and when systems are installed onto more highly insulated buildings. By comparison, as the installed Trombe wall area increases and the property's baseline heating demand reduces, annual solar fractions naturally increase. Evidently, the proportion of useful vs. wasted energy should be taken into account to avoid over sizing a Trombe wall, especially on highly insulated dwellings.

In detached homes, predicted energy savings range from 183 kWh/m$^2$/year for an 8 m$^2$ Trombe wall retrofitted to a solid walled property to 64 kWh/m$^2$/year for a 32 m$^2$ Trombe wall retrofitted to a property built in 2010. Similar findings were observed by Dolley et al. [13] when analyzing a Trombe wall incorporating a 100 mm thick translucent honeycomb cover (with $U$-value of 0.8 W/m$^2$ K and solar transmittance of 48%). Here, energy savings were 153 kWh/m$^2$/year for 8 m$^2$ system installed on a solid-walled detached house compared to 35 kWh/m$^2$/year for a 32 m$^2$ system installed on a detached house built to 2010 Building Regulations. Evidently, figures generated by Dolley et al. [13] are slightly lower than the values calculated in this parametric investigation. This could be because of lower solar transmittance of the 100 mm honeycomb cover compared to the 10 mm granular aerogel cover at 70%.

| Detached | | | Area of Trombe wall installed (m$^2$) | | | | |
|---|---|---|---|---|---|---|---|
| | | | 0 | 8 | 16 | 24 | 32 |
| Solid wall | Annual space heating consumption | kWh/year | 30,431 | 28,968 | 27,700 | 26,647 | 25,655 |
| | Net energy gain from Trombe wall | kWh/year | | 1463 | 2925 | 4388 | 5850 |
| | Useful energy from Trombe wall | kWh/year | | 1463 | 2731 | 3784 | 4776 |
| | Excess energy from Trombe wall | kWh/year | | 0 | 194 | 604 | 1074 |
| | Savings per m$^2$ of Trombe wall | kWh/m$^2$/year | | 183 | 171 | 158 | 149 |
| | Annual solar fraction | % | | 4.8% | 9.0% | 12.4% | 15.7% |
| Unfilled cavity wall | Annual space heating consumption | kWh/year | 25,215 | 23,813 | 22,701 | 21,710 | 20,774 |
| | Net energy gain from Trombe wall | kWh/year | | 1453 | 2906 | 4359 | 5812 |
| | Useful energy from Trombe wall | kWh/year | | 1402 | 2514 | 3505 | 4441 |
| | Excess energy from Trombe wall | kWh/year | | 51 | 392 | 854 | 1371 |
| | Savings per m$^2$ of Trombe wall | kWh/m$^2$/year | | 175 | 157 | 146 | 139 |
| | Annual solar fraction | % | | 5.6% | 10.0% | 13.9% | 17.6% |
| 1976 Building Regulations | Annual space heating consumption | kWh/year | 18,940 | 17,694 | 16,722 | 15,829 | 14,994 |
| | Net energy gain from Trombe wall | kWh/year | | 1361 | 2722 | 4084 | 5445 |
| | Useful energy from Trombe wall | kWh/year | | 1246 | 2219 | 3111 | 3947 |
| | Excess energy from Trombe wall | kWh/year | | 115 | 504 | 973 | 1498 |
| | Savings per m$^2$ of Trombe wall | kWh/m$^2$/year | | 156 | 139 | 130 | 123 |
| | Annual solar fraction | % | | 6.6% | 11.7% | 16.4% | 20.8% |
| 1990 Building Regulations | Annual space heating consumption | kWh/year | 13,348 | 12,312 | 11,505 | 10,754 | 10,058 |
| | Net energy gain from Trombe wall | kWh/year | | 1182 | 2365 | 3547 | 4729 |
| | Useful energy from Trombe wall | kWh/year | | 1036 | 1843 | 2594 | 3290 |
| | Excess energy from Trombe wall | kWh/year | | 146 | 522 | 953 | 1439 |
| | Savings per m$^2$ of Trombe wall | kWh/m$^2$/year | | 130 | 115 | 108 | 103 |
| | Annual solar fraction | % | | 7.8% | 13.8% | 19.4% | 24.7% |
| 2010 Building Regulations | Annual space heating consumption | kWh/year | 8561 | 7785 | 7169 | 6595 | 6069 |
| | Net energy gain from Trombe wall | kWh/year | | 922 | 1845 | 2767 | 3689 |
| | Useful energy from Trombe wall | kWh/year | | 776 | 1392 | 1966 | 2491 |
| | Excess energy from Trombe wall | kWh/year | | 146 | 453 | 801 | 1198 |
| | Savings per m$^2$ of Trombe wall | kWh/m$^2$/year | | 97 | 87 | 82 | 78 |
| | Annual solar fraction | % | | 9.1% | 16.3% | 23.0% | 29.1% |
| Super insulated | Annual space heating consumption | kWh/year | 4358 | 3819 | 3374 | 2986 | 2672 |
| | Net energy gain from Trombe wall | kWh/year | | 683 | 1366 | 2049 | 2732 |
| | Useful energy from Trombe wall | kWh/year | | 539 | 985 | 1373 | 1687 |
| | Excess energy from Trombe wall | kWh/year | | 144 | 381 | 677 | 1046 |
| | Savings per m$^2$ of Trombe wall | kWh/m$^2$/year | | 67 | 62 | 57 | 53 |
| | Annual solar fraction | % | | 12.4% | 22.6% | 31.5% | 38.7% |



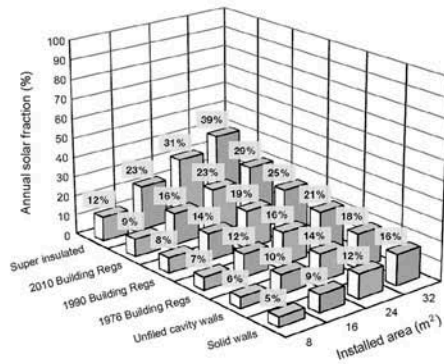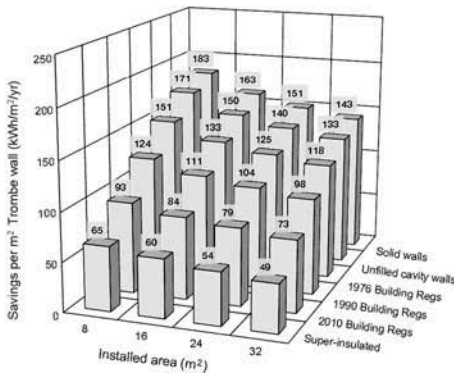Energy savings (per m$^2$ of Trombe wall)
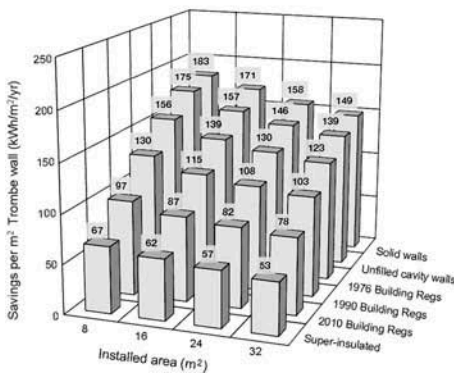
Solar fraction

Figure 4.   Parametric modeling results for Aerogel Trombe walls on detached houses.

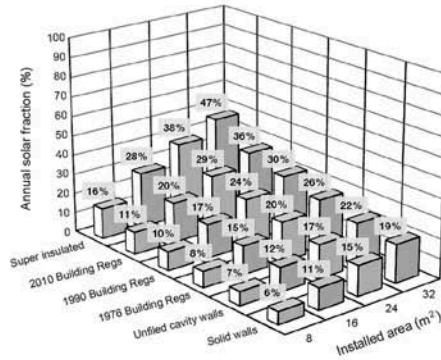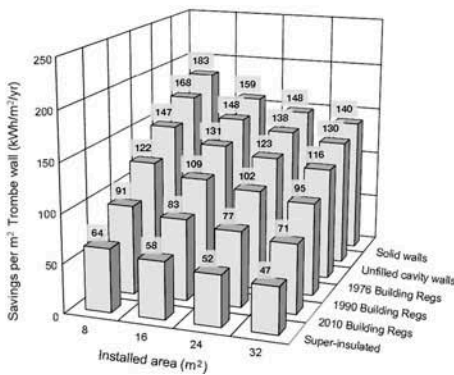| Semi-detached | | | Area of Trombe wall installed (m²) | | | | |
|---|---|---|---|---|---|---|---|
| | | | 0 | 8 | 16 | 24 | 32 |
| Solid wall | Annual space heating consumption | kWh/year | 23,492 | 22,029 | 20,890 | 19,871 | 18,927 |
| | Net energy gain from Trombe wall | kWh/year | | 1463 | 2925 | 4388 | 5850 |
| | Useful energy from Trombe wall | kWh/year | | 1463 | 2602 | 3622 | 4565 |
| | Excess energy from Trombe wall | kWh/year | | 0 | 323 | 766 | 1285 |
| | Savings per m² of Trombe wall | kWh/m²/year | | 183 | 163 | 151 | 143 |
| | Annual solar fraction | % | | 6.2% | 11.1% | 15.4% | 19.4% |
| Unfilled cavity wall | Annual space heating consumption | kWh/year | 19,463 | 18,096 | 17,058 | 16,097 | 15,208 |
| | Net energy gain from Trombe wall | kWh/year | | 1453 | 2906 | 4359 | 5812 |
| | Useful energy from Trombe wall | kWh/year | | 1367 | 2405 | 3366 | 4254 |
| | Excess energy from Trombe wall | kWh/year | | 86 | 501 | 993 | 1558 |
| | Savings per m² of Trombe wall | kWh/m²/year | | 171 | 150 | 140 | 133 |
| | Annual solar fraction | % | | 7.0% | 12.4% | 17.3% | 21.9% |
| 1976 Building Regulations | Annual space heating consumption | kWh/year | 14,627 | 13,423 | 12,494 | 11,633 | 10,844 |
| | Net energy gain from Trombe wall | kWh/year | | 1361 | 2722 | 4084 | 5445 |
| | Useful energy from Trombe wall | kWh/year | | 1204 | 2133 | 2994 | 3783 |
| | Excess energy from Trombe wall | kWh/year | | 157 | 590 | 1089 | 1662 |
| | Savings per m² of Trombe wall | kWh/m²/year | | 151 | 133 | 125 | 118 |
| | Annual solar fraction | % | | 8.2% | 14.6% | 20.5% | 25.9% |
| 1990 Building Regulations | Annual space heating consumption | kWh/year | 10,306 | 9314 | 8528 | 7805 | 7171 |
| | Net energy gain from Trombe wall | kWh/year | | 1182 | 2365 | 3547 | 4729 |
| | Useful energy from Trombe wall | kWh/year | | 992 | 1778 | 2500 | 3135 |
| | Excess energy from Trombe wall | kWh/year | | 191 | 587 | 1047 | 1594 |
| | Savings per m² of Trombe wall | kWh/m²/year | | 124 | 111 | 104 | 98 |
| | Annual solar fraction | % | | 9.6% | 17.3% | 24.3% | 30.4% |
| 2010 Building Regulations | Annual space heating consumption | kWh/year | 6602 | 5858 | 5254 | 4708 | 4256 |
| | Net energy gain from Trombe wall | kWh/year | | 922 | 1845 | 2767 | 3689 |
| | Useful energy from Trombe wall | kWh/year | | 743 | 1348 | 1894 | 2346 |
| | Excess energy from Trombe wall | kWh/year | | 179 | 497 | 873 | 1344 |
| | Savings per m² of Trombe wall | kWh/m²/year | | 93 | 84 | 79 | 73 |
| | Annual solar fraction | % | | 11.3% | 20.4% | 28.7% | 35.5% |
| Super insulated | Annual space heating consumption | kWh/year | 3361 | 2839 | 2408 | 2076 | 1796 |
| | Net energy gain from Trombe wall | kWh/year | | 683 | 1366 | 2049 | 2732 |
| | Useful energy from Trombe wall | kWh/year | | 522 | 952 | 1285 | 1565 |
| | Excess energy from Trombe wall | kWh/year | | 161 | 414 | 764 | 1167 |
| | Savings per m² of Trombe wall | kWh/m²/year | | 65 | 60 | 54 | 49 |
| | Annual solar fraction | % | | 15.5% | 28.3% | 38.2% | 46.6% |



Figure 5.   Parametric modeling results for Aerogel Trombe walls on semi-detached houses.

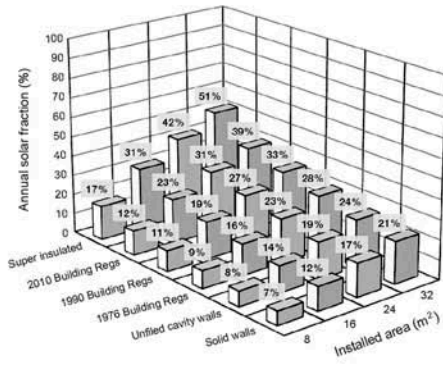| Terrace | | | Area of Trombe wall installed (m$^2$) | | | | |
|---|---|---|---|---|---|---|---|
| | | | 0 | 8 | 16 | 24 | 32 |
| Solid wall | Annual space heating consumption | kWh/year | 20,912 | 19,449 | 18,361 | 17,359 | 16,441 |
| | Net energy gain from Trombe wall | kWh/year | | 1463 | 2925 | 4388 | 5850 |
| | Useful energy from Trombe wall | kWh/year | | 1463 | 2551 | 3553 | 4471 |
| | Excess energy from Trombe wall | kWh/year | | 0 | 374 | 835 | 1379 |
| | Savings per m$^2$ of Trombe wall | kWh/m$^2$/year | | 183 | 159 | 148 | 140 |
| | Annual solar fraction | % | | 7.0% | 12.2% | 17.0% | 21.4% |
| Unfilled cavity wall | Annual space heating consumption | kWh/year | 17,325 | 15,982 | 14,963 | 14,019 | 13,154 |
| | Net energy gain from Trombe wall | kWh/year | | 1453 | 2906 | 4359 | 5812 |
| | Useful energy from Trombe wall | kWh/year | | 1343 | 2362 | 3306 | 4171 |
| | Excess energy from Trombe wall | kWh/year | | 110 | 544 | 1053 | 1642 |
| | Savings per m$^2$ of Trombe wall | kWh/m$^2$/year | | 168 | 148 | 138 | 130 |
| | Annual solar fraction | % | | 7.7% | 13.6% | 19.1% | 24.1% |
| 1976 Building Regulations | Annual space heating consumption | kWh/year | 13,020 | 11,843 | 10,922 | 10,077 | 9320 |
| | Net energy gain from Trombe wall | kWh/year | | 1361 | 2722 | 4084 | 5445 |
| | Useful energy from Trombe wall | kWh/year | | 1177 | 2098 | 2943 | 3700 |
| | Excess energy from Trombe wall | kWh/year | | 184 | 624 | 1141 | 1745 |
| | Savings per m$^2$ of Trombe wall | kWh/m$^2$/year | | 147 | 131 | 123 | 116 |
| | Annual solar fraction | % | | 9.0% | 16.1% | 22.6% | 28.4% |
| 1990 Building Regulations | Annual space heating consumption | kWh/year | 9174 | 8201 | 7422 | 6715 | 6126 |
| | Net energy gain from Trombe wall | kWh/year | | 1182 | 2365 | 3547 | 4729 |
| | Useful energy from Trombe wall | kWh/year | | 972 | 1752 | 2458 | 3048 |
| | Excess energy from Trombe wall | kWh/year | | 210 | 613 | 1089 | 1682 |
| | Savings per m$^2$ of Trombe wall | kWh/m$^2$/year | | 122 | 109 | 102 | 95 |
| | Annual solar fraction | % | | 10.6% | 19.1% | 26.8% | 33.2% |
| 2010 Building Regulations | Annual space heating consumption | kWh/year | 5877 | 5146 | 4547 | 4031 | 3614 |
| | Net energy gain from Trombe wall | kWh/year | | 922 | 1845 | 2767 | 3689 |
| | Useful energy from Trombe wall | kWh/year | | 731 | 1329 | 1846 | 2263 |
| | Excess energy from Trombe wall | kWh/year | | 191 | 515 | 921 | 1427 |
| | Savings per m$^2$ of Trombe wall | kWh/m$^2$/year | | 91 | 83 | 77 | 71 |
| | Annual solar fraction | % | | 12.4% | 22.6% | 31.4% | 38.5% |
| Super insulated | Annual space heating consumption | kWh/year | 2992 | 2476 | 2061 | 1748 | 1479 |
| | Net energy gain from Trombe wall | kWh/year | | 683 | 1366 | 2049 | 2732 |
| | Useful energy from Trombe wall | kWh/year | | 515 | 931 | 1244 | 1513 |
| | Excess energy from Trombe wall | kWh/year | | 168 | 435 | 805 | 1220 |
| | Savings per m$^2$ of Trombe wall | kWh/m$^2$/year | | 64 | 58 | 52 | 47 |
| | Annual solar fraction | % | | 17.2% | 31.1% | 41.6% | 50.6% |



Figure 6.    Parametric modeling results for Aerogel Trombe walls on terrace houses.

| Flats | | | Area of Trombe wall installed (m²) | | | | |
|---|---|---|---|---|---|---|---|
| | | | 0 | 8 | 16 | 24 | 32 |
| Solid wall | Annual space heating consumption | kWh/year | 14,861 | 13,495 | 12,443 | 11,502 | 10,735 |
| | Net energy gain from Trombe wall | kWh/year | | 1463 | 2925 | 4388 | 5850 |
| | Useful energy from Trombe wall | kWh/year | | 1366 | 2418 | 3359 | 4125 |
| | Excess energy from Trombe wall | kWh/year | | 96 | 507 | 1029 | 1725 |
| | Savings per m² of Trombe wall | kWh/m²/year | | 171 | 151 | 140 | 129 |
| | Annual solar fraction | % | | 9.2% | 16.3% | 22.6% | 27.8% |
| Unfilled cavity wall | Annual space heating consumption | kWh/year | 12,312 | 11,054 | 10,064 | 9178 | 8460 |
| | Net energy gain from Trombe wall | kWh/year | | 1453 | 2906 | 4359 | 5812 |
| | Useful energy from Trombe wall | kWh/year | | 1258 | 2248 | 3134 | 3852 |
| | Excess energy from Trombe wall | kWh/year | | 195 | 658 | 1225 | 1960 |
| | Savings per m² of Trombe wall | kWh/m²/year | | 157 | 140 | 131 | 120 |
| | Annual solar fraction | % | | 10.2% | 18.3% | 25.5% | 31.3% |
| 1976 Building Regulations | Annual space heating consumption | kWh/year | 9253 | 8140 | 7249 | 6491 | 5884 |
| | Net energy gain from Trombe wall | kWh/year | | 1361 | 2722 | 4084 | 5445 |
| | Useful energy from Trombe wall | kWh/year | | 1113 | 2004 | 2761 | 3369 |
| | Excess energy from Trombe wall | kWh/year | | 249 | 719 | 1322 | 2076 |
| | Savings per m² of Trombe wall | kWh/m²/year | | 139 | 125 | 115 | 105 |
| | Annual solar fraction | % | | 12.0% | 21.7% | 29.8% | 36.4% |
| 1990 Building Regulations | Annual space heating consumption | kWh/year | 6519 | 5593 | 4842 | 4243 | 3769 |
| | Net energy gain from Trombe wall | kWh/year | | 1182 | 2365 | 3547 | 4729 |
| | Useful energy from Trombe wall | kWh/year | | 926 | 1678 | 2276 | 2750 |
| | Excess energy from Trombe wall | kWh/year | | 256 | 687 | 1271 | 1979 |
| | Savings per m² of Trombe wall | kWh/m²/year | | 116 | 105 | 95 | 86 |
| | Annual solar fraction | % | | 14.2% | 25.7% | 34.9% | 42.2% |
| 2010 Building Regulations | Annual space heating consumption | kWh/year | 4176 | 3475 | 2914 | 2492 | 2132 |
| | Net energy gain from Trombe wall | kWh/year | | 922 | 1845 | 2767 | 3689 |
| | Useful energy from Trombe wall | kWh/year | | 701 | 1262 | 1685 | 2044 |
| | Excess energy from Trombe wall | kWh/year | | 222 | 583 | 1083 | 1645 |
| | Savings per m² of Trombe wall | kWh/m²/year | | 88 | 79 | 70 | 64 |
| | Annual solar fraction | % | | 16.8% | 30.2% | 40.3% | 48.9% |
| Super insulated | Annual space heating consumption | kWh/year | 2126 | 1627 | 1272 | 1002 | 799 |
| | Net energy gain from Trombe wall | kWh/year | | 683 | 1366 | 2049 | 2732 |
| | Useful energy from Trombe wall | kWh/year | | 499 | 854 | 1124 | 1327 |
| | Excess energy from Trombe wall | kWh/year | | 184 | 512 | 926 | 1405 |
| | Savings per m² of Trombe wall | kWh/m²/year | | 62 | 53 | 47 | 41 |
| | Annual solar fraction | % | | 23.5% | 40.2% | 52.8% | 62.4% |
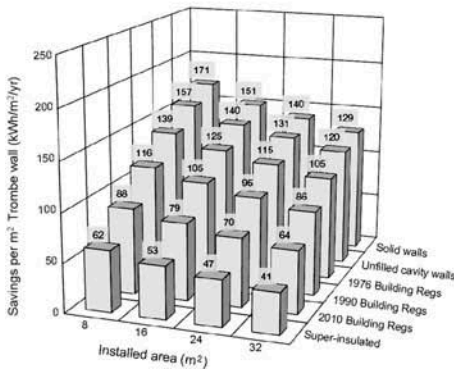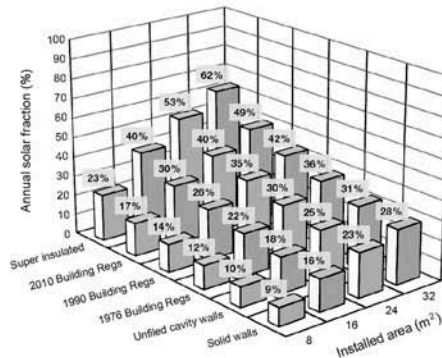


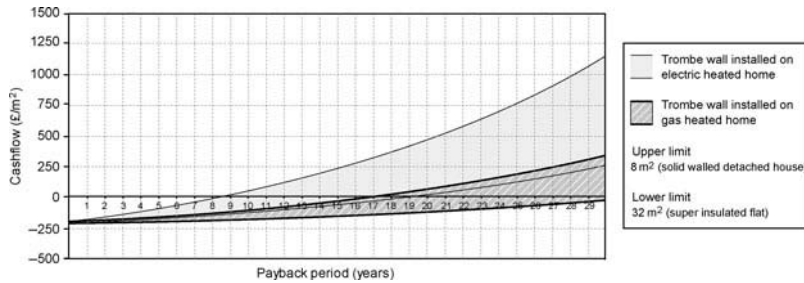Figure 7.    Parametric modeling results for Aerogel Trombe walls on flats.

Figure 8. Payback curve based on energy savings from parametric modeling.

### 5.1. Payback calculation

Figure 8 displays a payback curve based on the energy savings per m$^2$ from all Trombe walls modeled in the parametric assessment. The estimated capital cost of each Trombe wall is taken as £ 220/m$^2$ (assuming £ 100/m$^2$ for the aerogel cover and another £ 120/m$^2$ for the framing and a shading system). The baseline cost of electricity and gas is assumed to be £ 0.12/kWh and £ 0.04/kWh, respectively, with a 6% annual fuel price inflation rate and 2% discount interest rate applied.

The two bands correspond to payback periods for gas and electrically heated homes, respectively. In each case, the upper limit of the band (providing the shortest payback) represents the predicted payback period for 8 m$^2$ Trombe wall on a solid walled detached property. Conversely, the lower limit (providing the longest payback period) represents the predicted payback for 32 m$^2$ of Trombe wall installed on a super insulated flat. All values between these limits represent the paybacks for the remaining house types and Trombe wall areas.

Predicted payback periods for the different Trombe wall installations range from 8 to 19 years in electrically heated homes or 17 to 35 years in gas heated homes. Evidently, the product may only be a viable retrofit option in electric heated homes or gas heated homes with little/no insulation. Countering this, however, as these payback periods are similar to those calculated by Shorrock et al. [41] for external insulation (i.e. greater than 20 years), if a dwelling is being overclad, it may be viable to incorporate a Trombe wall into the design if there is a suitable free area of south facade. Furthermore, if it were assumed that Trombe walls were eligible to the £ 0.085/kWh generation tariff under the governments Renewable Heat Incentive [42], which domestic hot water solar thermal panels currently obtain, then paybacks can be reduced.

### 5.2. External insulation comparison

To investigate if a Trombe wall provides a greater energy saving, per m$^2$, compared to conventional insulation, Figure 9 illustrates the predicted energy savings from the Trombe wall vs. the predicted energy savings through external insulation. The degree-day calculation assumes that the building operates an 18 hour heating schedule on the days when heating is required (i.e., maximizing the need for insulation) and it is assumed that 1 m$^2$ of external wall area is upgraded to a U-value of 0.15 W/m$^2$ K. Upper and lower limits on the Trombe wall energy savings represent the maximum and minimum predicted savings from the detached house and flats, respectively.
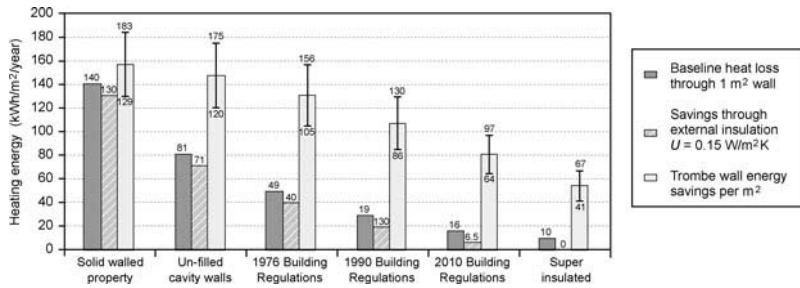
Figure 9.    Energy savings from external insulation vs. energy savings from a Trombe wall.

In all cases (with the exception of 32 m$^2$ of Trombe wall on a solid-walled flat), the Trombe wall energy savings exceed the predicted energy savings through external insulation, indicating that an Aerogel Trombe wall can be used as a stand-alone system or incorporated into an external cladding scheme to enhance its overall benefit. Evidently, as properties are built to better insulation standards, the energy savings from insulation diminish at a greater rate than the predicted Trombe wall energy savings. The greatest potential for increased energy savings is observed within unfilled cavity wall properties and dwellings built to 1976–1990 Building Regulations.

## 6.    Conclusion

This study aimed to serve as a preliminary evaluation into the thermal performance of aerogel applied to passive solar Trombe walls. Preliminary modeling has found that a small area of Trombe wall can provide a useful energy contribution without creating a significant overheating risk. If larger areas are to be installed, then detailed calculations would be recommended to assess the potential overheating issues. Static shading grills to cut high summer sun combined with passive vents at the top and bottom of the wall would be recommended to regulate overheating without active cooling. It is likely that the most appropriate application for Aerogel Trombe walls would be in "deep" retrofits, particularly if incorporated alongside an external cladding scheme to enhance its benefit.

The concept of passive Trombe walls incorporating granular aerogel may prove to be more applicable across the existing UK housing stock, compared to solar air collectors as they do not rely on mechanical ventilation. Preliminary parametric modeling of Aerogel Trombe walls on existing buildings demonstrates that these systems can provide high energy savings, per m$^2$, particularly on older buildings with solid brick walls, comparable to external insulation. In contrast, small Trombe walls areas can provide significant solar fractions, particularly on more insulated dwellings with lower heating requirements.

## Nomenclature

| | |
|---|---|
| $A_r$ | Trombe wall area (m$^2$) |
| $C_b$ | Thermal storage capacity of building (MJ/K) |
| $C_p$ | Specific heat capacity of wall (kJ/kg K) |
| $DD$ | Degree day hours (h K) |
| $f$ | Solar fraction |
| $f_i$ | Fraction of monthly load supply by solar energy |

| | |
|---|---|
| $I_{TC}$ | Hourly critical irradiance level (W/m$^2$) |
| $k$ | Thermal conductivity of wall (W/m K) |
| $K_T$ | Monthly average daily clearness index |
| $L_A$ | Auxiliary energy requirement for the month (GJ) |
| $L_{ad}$ | Monthly building heat load without the Trombe wall (GJ) |
| $L_w$ | Monthly heat loss with zero glazing transmittance (GJ) |
| $N$ | Number of days in a month |
| $R_n$ | Ratio of irradiance on a tilted surface to horizontal surface at noon |
| $\overline{R}$ | Ratio of monthly average daily irradiance on tilted to horizontal surface |
| $r_{tn}$ | Ratio of irradiance at solar noon to daily irradiance on a horizontal surface |
| $\overline{S}$ | Monthly average absorbed solar irradiance (MJ/m$^2$) |
| $S_b$ | Thermal storage capacity of building for a month (GJ) |
| $S_w$ | Thermal storage capacity of Trombe wall for a month (GJ) |
| $\overline{T}_a$ | Monthly average ambient temperature (°C) |
| $T_b$ | Baseline temperature for degree-days (°C) |
| $\Delta T_b$ | Allowable temperature swing between low and high thermostat settings (°C) |
| $\overline{T}_i$ | Monthly average inner wall temperature (°C) |
| $T_r$ | Room temperature at low thermostat setting (°C) |
| $\overline{T}_W$ | Monthly average outer wall temperature (°C) |
| $\Delta T_w$ | Half temperature difference between inside and outside wall (°C) |
| $\Delta t$ | Inner and outer wall temperature difference (°C); seconds in 24 hours |
| $Q_D$ | Energy dump in zero capacitance system (GJ) |
| $Q_i$ | Heat gain across Trombe wall (GJ) |
| $Q_u$ | Useful energy from Trombe wall (GJ) |
| $Q_n$ | Net heat transfer into rooms through Trombe wall (GJ) |
| $(UA)_{ad}$ | Building heat loss coefficient (W/K) |
| $U_i$ | Loss coefficient between inner wall and air inside room (W/m$^2$ K) |
| $U_k$ | Conductance from outer wall to room (W/m$^2$ K) |
| $U_w$ | Trombe wall heat loss coefficient (W/m$^2$ K) |
| $x$ | Wall thickness (m) |
| $X_c$ | Critical irradiance ratio |
| $Y$ | Storage dump ratio |

### Greek Symbols

| | |
|---|---|
| $\rho$ | Density of the wall (kg/m$^3$) |
| $\overline{\phi}$ | Monthly average daily un-utilizability |
| $(\tau\alpha)$ | Transmittance–absorptance product |

### Acknowledgments

ventilation system. The corresponding author would like to thank all those involved in the research as well as the technical reviewers and publishing teams.

## Funding

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