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A "Fabric-First" Approach to Sustainable Tall Building Design

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Abstract

This research suggests the most effective way for improving energy efficiency in tall buildings is a "fabric-first" approach. This involves optimizing the performance of the building form and envelope as a first priority, with additional technologies a secondary consideration. The paper explores a specific fabric-first energy standard known as "Passivhaus". Buildings that meet this standard typically use 75% less heating and cooling. The results show tall buildings have an intrinsic advantage in achieving Passivhaus performance, as compared to low-rise buildings, due to their compact form, minimizing heat loss. This means high-rises can meet Passivhaus energy standards with double-glazing and moderate levels of insulation, as compared to other typologies where triple-glazing and super-insulation are commonplace. However, the author also suggests that designers need to develop strategies to minimize overheating in Passivhaus high-rises, and reduce the quantity of glazing typical in high-rise residential buildings, to improve their energy efficiency.

Keywords: Energy consumption, Fabric first, Façade, Passivhaus, Sustainability

1. Introduction

One of the primary criticisms of contemporary tall buildings is that they are perceived to use much more energy, both in day-to-day operations, and in the materials needed for their construction, than do low- and mid-rise buildings. While there is a general lack of studies comparing energy use between low- and high-rise typologies, there is some empirical evidence to support this. For example, a study by Leung and Ray (2013) compared the delivered energy consumption of more than 700 office buildings in New York. They found that, on average, taller buildings have higher energy demands. Myors et al. (2005) studied more than 3,500 dwellings in Sydney, Australia, and found high-rise housing had the highest energy-related greenhouse gas (GHG) emissions per person – over twice that of townhouses and villas.

While the sustainable credentials of building tall are perhaps best considered on an urban scale – creating dense, compact cities, with efficient use of public transportation to reduce urban carbon emissions (Pramati and Oldfield, 2015) – there is still an urgent need to improve the energy efficiency of high-rises at the building scale. This is particularly pressing given the projected growth in global population and urbanization, which will likely see an increasing number of people living and working in tall buildings.

To combat this, many tower designs are now looking at incorporating the latest technologies in order to reduce their delivered energy requirements. A trend emerging in contemporary tall buildings is the integration of low- or zero-carbon energy generation technologies (Oldfield, Trabucco and Wood, 2009). These include building integrated wind turbines and photovoltaic panels. The Heron Tower in London (see Fig. 1), for example, generates 2.5%



Figure 1. Heron Tower, London. South-facing photovoltaic integrated facade generating 2.5% of building electricity (Source: Philip Oldfield).

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of its electricity demand from a vast south-facing array of photovoltaic panels (Construction Manager, 2010).

While such developments are clearly valuable, few towers have seen on-site generation achieve more than 10% of the building's energy needs. With this in mind, this research suggests an alternative approach to improving energy efficiency in tall buildings – a "fabric-first" approach. This strategy suggests the cheapest and most effective way for improving energy efficiency is to maximize the performance of the building form and envelope as a first priority, with additional technologies an important, but secondary, consideration in the design process.

This research focuses on a specific fabric-first concept known as "Passivhaus." It explores the opportunities and challenges for achieving Passivhaus performance in tall buildings in cold and temperate climates.

2. Passivhaus: A "Fabric-First" Approach

Passivhaus is a building concept in which thermal comfort is achieved to a maximum extent through a high-performance building fabric, including the use of super-insulation to minimize heat loss, and harnessing solar energy and internal heat gains for free heating. It is the fastest-growing energy performance standard in the world (McLeod et al. 2012) and can result in a 75% reduction in heating and cooling energy requirements, as compared to typical new-build construction. To be considered Passivhaus-compliant, buildings need to achieve less than 15 kWh/m²/annum for heating or cooling and less than 120 kWh/m²/annum for primary energy requirements (Passipedia, 2016). Typically, Passivhaus buildings can be characterized by six factors (see Fig. 2):

1. The use of super-insulation and triple-glazing in a high-performance building envelope, yielding typical building fabric U-values of less than 0.15 W/m^{2}K for opaque elements, and 0.85 W/m^{2}K for glazing (McLeod et al., 2011).
2. The use of mechanical ventilation with heat recovery (MVHR)
3. Careful exploitation of solar gain for passive winter heating requirements
4. A high degree of airtightness, with an upper limit of 0.6 air changes per hour at 50 Pascals pressure, to reduce heat loss by infiltration (McLeod et al., 2011)
5. Minimization of thermal bridges in the building fabric
6. Compactness of form

While the majority of realized Passivhaus buildings remain in Europe or North America, the standard is gaining international appeal, including in China, typified by the recent completion of the five-story Passive House Bruck in Changxing. The RHW.2 office tower in Vienna was certified as the world's first Passivhaus skyscraper in 2013, achieving a heating and cooling demand 80% lower than a conventional tower (Passivehouseplus, 2013). The world's tallest Passivhaus tower is currently under construction in New York, and will on completion contain 26 stories of accommodation and facilities for Cornell University. Yet, despite these projects, the vast majority of the estimated 50,000 completed Passivhaus buildings are low-rise.

3. Passivhaus and Typology: The Importance of Surface-Area-to-Volume Ratio

To identify how a Passivhaus skyscraper might differ in performance from other building types, four typologies – a detached house, terraced house, low-rise apartments and

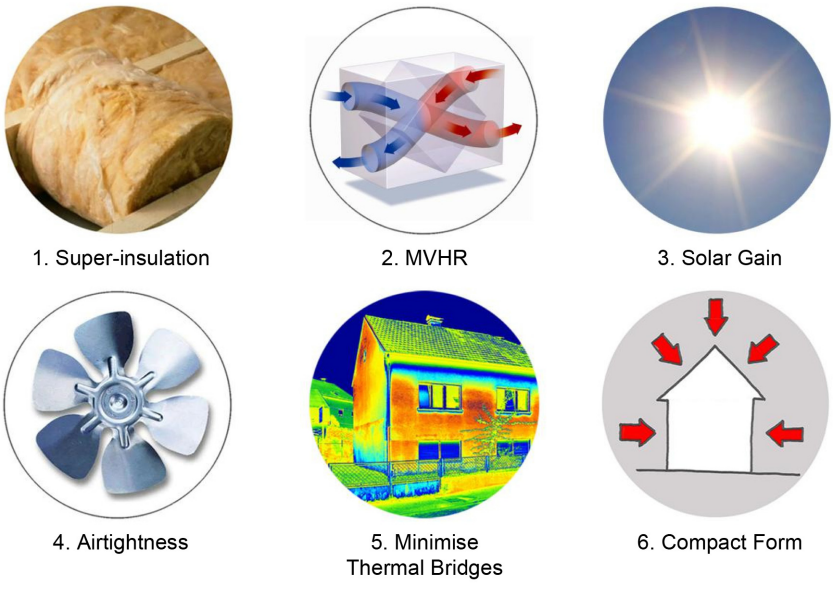


Figure 2. Characteristics of Passivhaus Buildings (Source: Philip Oldfield).

high-rise apartments – have been studied, and their annual heat demand determined by the Passive House Planning Package 2007 (Feist, 2007). This is essentially a series of linked spreadsheets that can determine Passivhaus performance based on the input of key building characteristics (U-values, floor and wall areas, windows, ventilation system efficiencies, etc.). Heat demand is used as the primary metric for comparison in this study, as space heating is the biggest contributor to building energy needs in cold and temperate climates, accounting for 70% of energy use in buildings in Europe (LSE Cities & Eifer, 2014; WBCSD, 2009).

For each building type, two different building envelopes were modeled. The "standard" building fabric is designed to the minimum standards set out in UK Building Regulations Part L1A (HM Government, 2016) with typical wall U-values of 0.3 W/m^{2}K and double glazing. The Passivhaus building fabric scenarios used much greater levels of insulation and triple glazing.

The three low-rise typologies are based on as-built Passivhaus buildings. Due to a lack of completed residential Passivhaus towers, the high-rise example is based on a non-Passivhaus building (The Beetham Tower, Manchester, UK) with its mechanical performance and building fabric upgraded. As the study is an examination on the impact of form and typology, all other characteristics of the four scenarios – location, orientation, glazing, shading, ventilation, etc. – are kept the same. A full list of building characteristics and assumptions are outlined in Table 1. An illustration of each of the four buildings, along with their surface-area-to-volume ratios, is outlined in Fig. 3.

Fig. 3 shows the impact form and typology have on building surface-area-to-volume ratio. In this instance, the tall building has almost seven times less surface area per unit volume as compared to the detached typology, and almost four times less than the terraced block. The impact of this on heating energy requirements is profound. Fig. 4 shows the annual heating demand of all four buildings using standard and Passivhaus building fabrics, with all other parameters kept the same. The results show a linear relationship between surface-area-to-volume ratio and annual heat demand – the greater the surface-area-to-volume ratio, the greater the energy required to heat the building.

In this case, the high-rise typology has the lowest heat demand, followed by the low-rise apartments, terraced house and detached house. In fact, even the high-rise building scenario with the standard building fabric of double-glazing and minimum insulation levels achieves Passivhaus compliance, with a heating demand of just 8 kWh/m^2/annum.

These results demonstrate an inherent advantage tall buildings have over other typologies – a low surface-area-to-volume ratio, resulting in reduced heat loss and thus lower space heating requirements. Such results are consistent with other studies in the field. A study comparing heating demand of different typologies in London, Paris, Berlin and Istanbul found that compact and tall buildings had the greatest heat-energy efficiency at the neighborhood scale, while detached housing had the lowest (LSE Cities & Eifer, 2014).

This provides a multitude of opportunities to the Passivhaus skyscraper designer. Firstly, architects will have more freedom to explore different high-rise forms, shapes and geometries and still achieve Passivhaus performance. On the flip side, designers of detached Passivhaus buildings are far more restricted to maintaining compact building forms in order to reduce heat losses (McLeod et al., 2011). In the example in Fig. 4, even the detached house with a high-performance building fabric does not meet Passivhaus heating requirements, and would require additional insulation, or a change in shape, orientation or glazing to reduce heating demands to below 15 kWh/m^2/annum.

A further advantage of tall buildings is that they can

Table 1. Building characteristics (Source: Philip Oldfield with data from HM Government, 2016, Qiu, 2011 and Feist, 2007)

Characteristics	Detached House	Terraced House	Low-Rise Apartments	High-Rise Apartments
Building	Camden Passivhaus	Hannover-Kronsberg Passivhaus	Lodenareal Passivhaus	Beetham Tower
Floors	2	2	6	47
Surface area to volume ratio	1.091 m^2/m^3	0.639 m^2/m^3	0.302 m^2/m^3	0.163 m^2/m^3
Location	All modelled in Manchester, England			
Orientation	All modelled as north / south orientated			
Standard Fabric	Wall U-Value = 0.3 W/m^{2}K, Floor U-Value = 0.25 W/m^{2}K, Roof U-Value = 0.2 W/m^{2}K, Glazing U-Value = 2-2.2 W/m^{2}K			
Passivhaus Fabric	Wall U-Value = 0.138 W/m^{2}K, Floor U-Value = 0.131 W/m^{2}K, Roof U-Value = 0.108 W/m^{2}K, Glazing U-Value = 0.78 W/m^{2}K			
Glazing	All buildings modelled with the same window areas on each facade. South Facade = 42%, North Facade = 21%, West Facade = 2%, East Facade = 2%. (Feist, 2007).			
Shading	No shading from surrounding buildings is considered.			
Ventilation	All buildings modelled with the same ventilation system with a heat recovery efficiency of 83% and an electrical efficiency of 0.4 Wh/m^3			



Figure 3. Four building types and their surface area to volume ratios. (Source: Philip Oldfield)

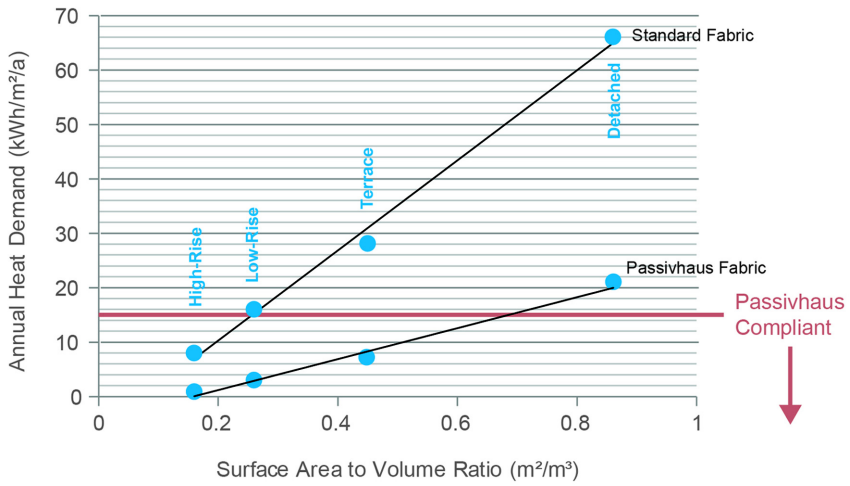


Figure 4. Relationship between compactness (surface area to volume ratio) and the annual heat demand of four buildings modeled. (Source: Philip Oldfield)

meet Passivhaus performance levels with thinner insulation and lower performance glazing systems as compared to other typologies. This could potentially make the concept of a Passivhaus skyscraper more economically viable. In addition, it can mean simpler detailing and construction, reduced weight and therefore reduced embodied energy requirements.

4. Façade Design

To further explore the opportunities and challenges for Passivhaus performance in tall buildings, 10 additional iterations of the high-rise apartment example outlined previously in Table 1 have been modeled using the Passivhaus Planning Package (PHPP), the energy balance and

planning tool. Each scenario presents a different combination of glazing, insulation, ventilation and shading systems. Scenarios 1-3 are made up of the standard building fabric as per the minimum prescribed by UK Building Regulation Part L, but each with a different window area of the façade – 75%, 50% or 30%. Scenarios 4-6 use a façade with typical Passivhaus characteristics and again different windows areas. Scenarios 7-9 use a Passivhaus façade, but with the addition of shading elements and summer and nighttime ventilation to reduce overheating. Finally, a tenth scenario was determined to identify the minimum acceptable building fabric characteristics necessary to achieve Passivhaus compliance of 15 kWh/m²/annum heating demand. A full list of characteristics for each scenario is outlined in Table 2.

Fig. 5 presents the results of the annual heat demand and frequency of overheating for each of the 10 scenarios.

The first thing to notice is the challenge of overheating. According to Lewis (2014), 5-10% of overheating is considered "acceptable," with 2-5% considered "good" performance. Of the scenarios modeled, only 8, 9 and 10 were found to overheat less than 10%. Scenario 4, with a high performance envelope and 75% of the façade area dedicated to windows was found to overheat for 45% of the time (but did not include summer or nighttime ventilation strategies for cooling).

This presents the "flip-side" to a low surface-area-to-volume ratio: while reduced areas of façade facilitate less heat loss in the winter, a compact form also means it can be more difficult to expel unwanted interior heat in the summer months. A reduced façade area can mean fewer openings to facilitate ventilation and less surface area to expel internal heat gains from hot water pipes, people and machinery.

These results are consistent with empirical studies. For example, a national study of summertime temperatures in UK dwellings found 68% of living rooms and 74% of bedrooms in flats overheated. This is compared against only 28% of living rooms and 48% of bedrooms in terraced housing, and 21% / 36% respectively in detached dwellings (Beizaee et al., 2013). This should raise concern, especially considering increasing global temperatures. The period 2011 to 2015 has been the warmest on record (World Meteorological Association, 2015), with projections suggesting this trend will increase across the 21st century. Overheating can have significant and deadly health consequences; the 2003 heat wave in Europe, for example, led to 14,947 deaths in France over just two weeks (Poumadere et al. 2005).

Particular emphasis in the design of Passivhaus skyscrapers then should be given to reducing overheating and providing opportunities for the design to adapt to increasing global temperatures. In the scenarios modeled, overheating was significantly reduced by the addition of solar shading along with summertime and nighttime purge ventilation. The exposed nature of tall buildings, along with increased wind speeds at height, can provide greater access to natural ventilation, as compared to low-rise buildings within a dense urban setting. However, higher wind speeds can mean tall buildings suffer a wide variety of wind pressures, which can cause ventilation control difficulties and limit the opportunity for opening large windows at height (Etheridge & Ford, 2008). An alternative is, of course, mechanical cooling systems, but at an additional energy cost.

A second point of discussion is the impact of window area. The scenarios with 75% of the façade made up of windows (S1, S4 and S7) were found to have the highest heat demands and highest frequency of overheating. Scenario 7, for example, included a high performance façade, shading systems and summer and nighttime ventilation strategies, but was still found to overheat almost 19% of the time. This is a figure that would be deemed "catastrophic" (Lewis, 2014).

Table 2. Facade Scenarios for PHPP analysis (Source: Philip Oldfield)

Scenario	Glazing	Wall U-value (W/m^2K)	Window area of façade (%)	Summer + Night ventilation	Shading systems
1	Double	0.3	75	None	None
2	Double	0.3	50	None	None
3	Double	0.3	30	None	None
4	Triple	0.138	75	None	None
5	Triple	0.138	50	None	None
6	Triple	0.138	30	None	None
7	Triple	0.138	75	Yes	800 mm balconies on south, east and west
8	Triple	0.138	50	Yes	800 mm balconies on south, east and west
9	Triple	0.138	30	Yes	800 mm balconies on south, east and west
10	Double with 30 mm air gap	0.18	50	Yes	800 mm balconies on south, east and west

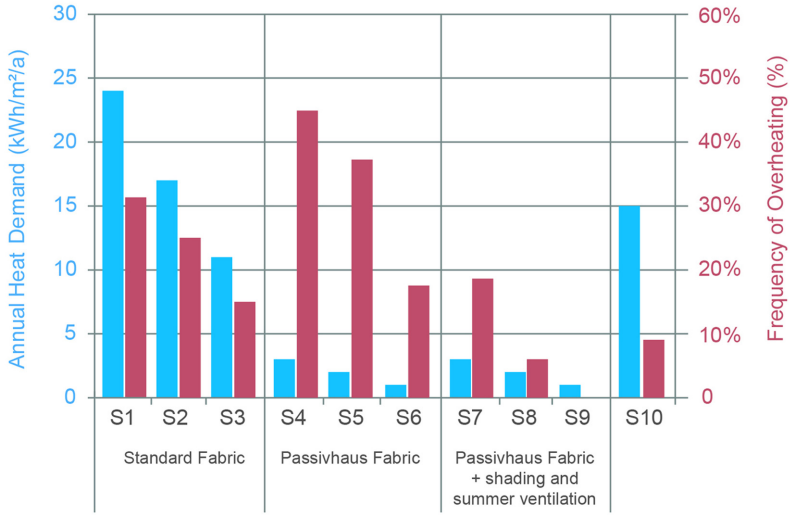


Figure 5. Annual heat demand and frequency of overheating for ten scenarios outlined in Table 2. (Source: Philip Oldfield)

The scenarios with a significantly reduced window area of 30% (S3, S6, and S9) were the best-performing, with the lowest heat demand and frequency of overheating. However, such a small percentage of glazing would likely be deemed commercially unviable for residential high-rises, where access to views is considered a unique selling point. In addition, such significantly reduced glazing would have a negative impact on daylighting levels, and likely the health and well-being of the occupants (see Fig. 6).

Given this, the most promising scenarios considered were those with 50% window area, as this provides a reasonable balance between thermal performance, daylighting and view. To further explore this option, a tenth scenario (S10) was modeled to identify the minimum building fabric that would result in Passivhaus performance with 50% window area. It was found that a low heating energy demand (15 kWh/m^2/a) and acceptable frequency of overheating (9%) could be achieved with a lower façade performance as compared to "typical" Passivhaus buildings. In this instance, the use of double glazing with an increased air gap (30 mm) and an opaque U-value of 0.18 W/m^{2}K (achieved with 210 mm insulation) was ade-

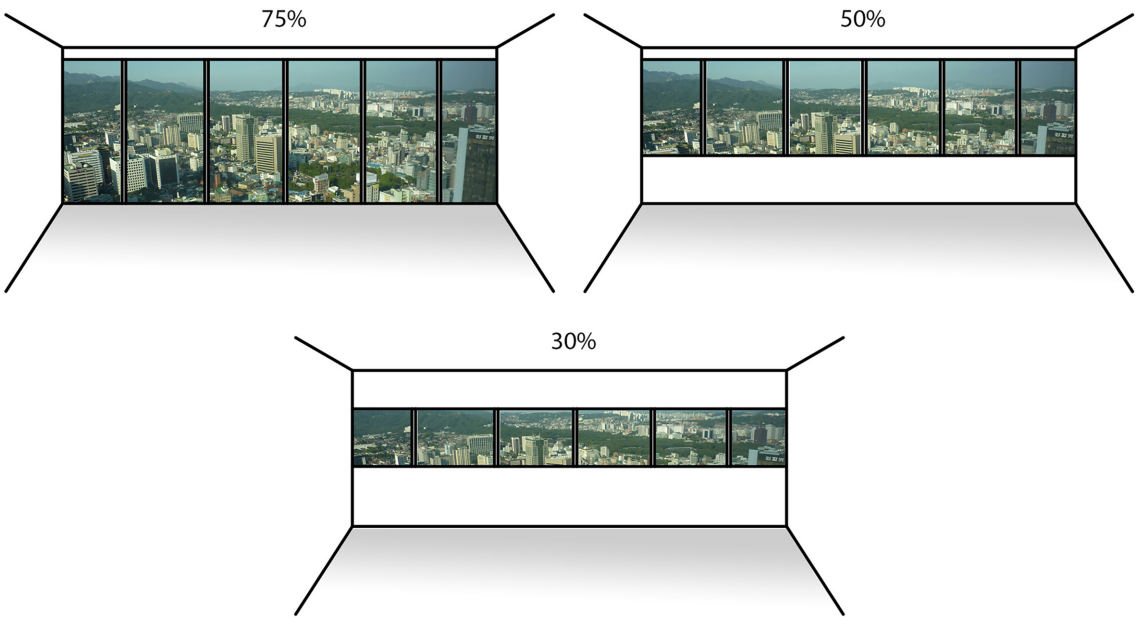


Figure 6. Internal perspective and impact on view of alternative façade window areas. (Source: Philip Oldfield)

quate to meet Passivhaus performance. In typical low-rise examples, the use of triple glazing and opaque fabric U-values of less than 0.15 W/m^{2}K (250 mm of insulation as a minimum) are common.

5. Conclusions: Opportunities and Challenges for Fabric-First Skyscrapers

This research explores the opportunities and challenges for achieving Passivhaus performance in skyscraper design, in cold and temperate climates. Three main findings are highlighted for designers following such a "fabric-first" approach:

5.1. Impact of SA/V ratio

High-rise buildings have an intrinsic advantage in achieving Passivhaus performance. Their compact form and efficient surface-area-to-volume ratio results in a reduced heating demand in temperate climates, as compared to other residential typologies. Whereas low-rise buildings typically require a triple glazed façade and super-insulation to meet Passivhaus requirements, high-rise buildings can achieve the same performance with a thinner façade fabric and double glazing. This could generate a number of potential advantages.

5.2. Cost

Façade is the most expensive element cost in a typical residential tower (Barton & Watts, 2013), and so the need for a complex and high-performance building envelope could make a Passivhaus skyscraper financially unviable, or at least unattractive to developers. The ability to meet Passivhaus requirements with a more "traditional" façade build-up and double-glazing could make a fabric-first approach far more achievable from a cost perspective.

5.3. Constructability

Passivhaus performance requires careful façade detailing, to eliminate all thermal bridging (see Figs. 7 and 8). One challenge that thicker insulation envelopes face is they can require complex and expensive structural solutions, which can lead to increased thermal bridging. This in itself can require additional insulation and cost to resolve (Burrell, 2015). Thinner insulation can overcome this, by reducing the complexity of the façade detailing.

5.4. Embodied carbon

A notable criticism of tall buildings is that they typic-

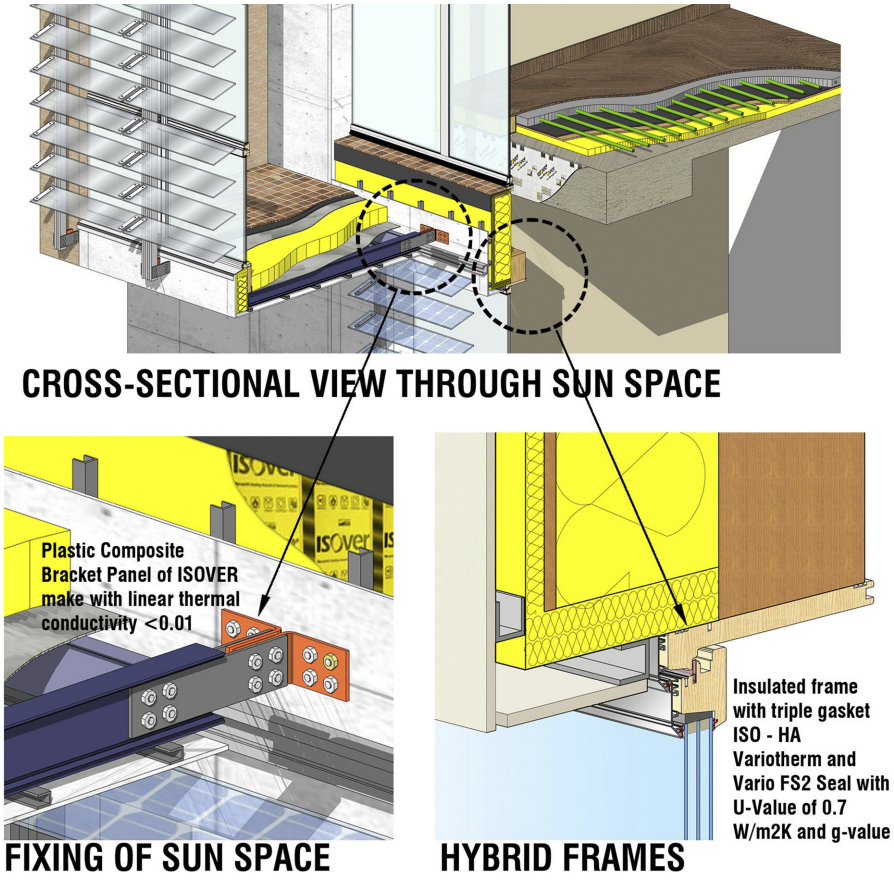


Figure 7. Detailing to eliminate thermal bridges in a Passivhaus skyscraper design. (Source: A. Modi, S. Modi and L. Qiu / University of Nottingham)

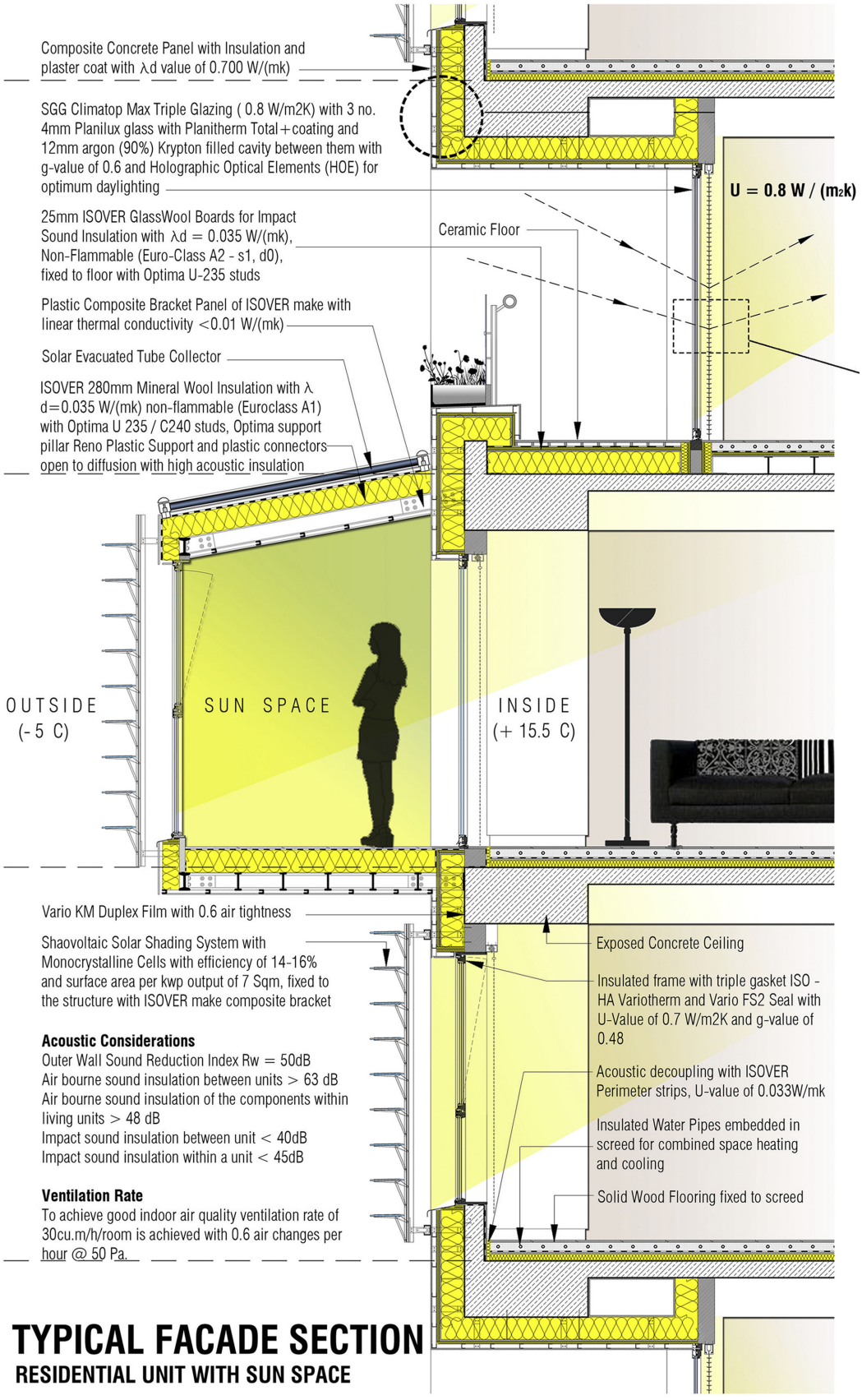


Figure 8. Façade cross-section for a Passivhaus skyscraper design. (Source: A. Modi, S. Modi and L. Qiu / University of Nottingham)

ally require much greater material quantities, and therefore have a greater embodied carbon than low-rise buildings (Oldfield, 2012). Being able to achieve Passivhaus performance with a thinner façade would mean fewer building materials, and reduced embodied carbon as compared to traditional Passivhaus façade construction.

5.5. Overheating

Designers of Passivhaus and fabric-first tall buildings should give particular care to avoid summer overheating, due to the high levels of insulation and airtight façade construction, even in cold climates. Consideration should be given to increasing global temperatures and the fact that occupants will have to adapt to warmer summertime temperatures in the future. Overheating can have significant health and mortality implications, so strategies to foster free cooling through natural ventilation should be maximized. At the same time, the management of internal heat gains – for example, by insulating hot water pipes – is considered vital.

5.6. Glazing

The design of fabric-first skyscrapers should carefully balance occupants’ needs for light, view and the thermal performance of the façade, through choosing appropriate levels of glazing. This research demonstrates that with 75% of the façade dedicated to windows, it is extremely difficult to avoid overheating in the summer months. At the same time, a significantly reduced percentage of façade glazing is considered commercially unviable in high-rise residential schemes. This research suggests a more appropriate level of façade glazing for future projects is closer to 50%, though this should be optimized for climate, context and orientation. In reality, architects and designers need to do more to make lower façade glazing ratios more attractive, for example, by framing specific views, providing an interesting mixture of solid wall and transparency, etc.

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