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A “Fabric-First” Approach to Sustainable Tall Building Design

可持续发展的高层建筑设计方法——“构造优先”法

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Abstract | 摘要

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 other 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

该研究提出了提升高层建筑能源效率的最有效方法是“构造优先”法的观点。这种方法以调整建筑的形式和幕墙为首要方式，以附加的技术作第二方式优化建筑性能。这篇文章探究了一种被称为“被动式房屋”的具体的“构造优先”法的能源标准。达到此标准的建筑能够以比普通房屋少75%的制热和制冷能源维持。研究结果显示，与其他低层建筑相比，高层建筑，因其紧凑的形式和最小化的热损耗，在达到“被动式房屋”能效标准上有着本质的优势。这说明高层建筑可以通过双层玻璃和适当程度的保温隔热达到被动式房屋能源标准，与之对比，其他类型的建筑则通常需要三层玻璃和超绝热才能达到。但是，作者也提出设计师需要针对高层被动式房屋中开发最小化过热频率的策略，同时减少尤其是在高层住宅建筑中玻璃幕墙的用量，以提高它们的能源利用效率。

关键词：能耗、构造优先、幕墙、被动式房屋、可持续性

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

简介

当代对于高层建筑的首要批评之一，便是它们能耗太高。与低层和中层建筑相比，不论是在日常运转还是在建造材料方面，高层建筑都需要更多的能源。虽然并没有广泛的研究对高低层建筑之间的能源消耗进行对比，但确有一些实证证据证明这点。例如，Leung and Ray（2013）对比了纽约700多栋办公楼的能源消耗。他们发现，总体上来说，层数更多的建筑对能源的需求更大。Myors et al（2005）对澳大利亚悉尼的3500多栋居民楼进行了研究，发现高层住宅楼的能源相关温室气体人均排放量最高——是联排房屋和别墅的两倍以上。

虽然如果要考虑高层建筑的可持续性，或许最好要放到整个城市的范围内去考虑：它们提高了城市的人口密度和紧凑度，同时能够高效利用公共交通，从而降低了碳排放（Pramati and Oldfield, 2015）。但是提高高层建筑能源效率的需求依旧很急切。考虑到全球人口的预期增长和城市化的发展前景，未来将有越来越多的人在

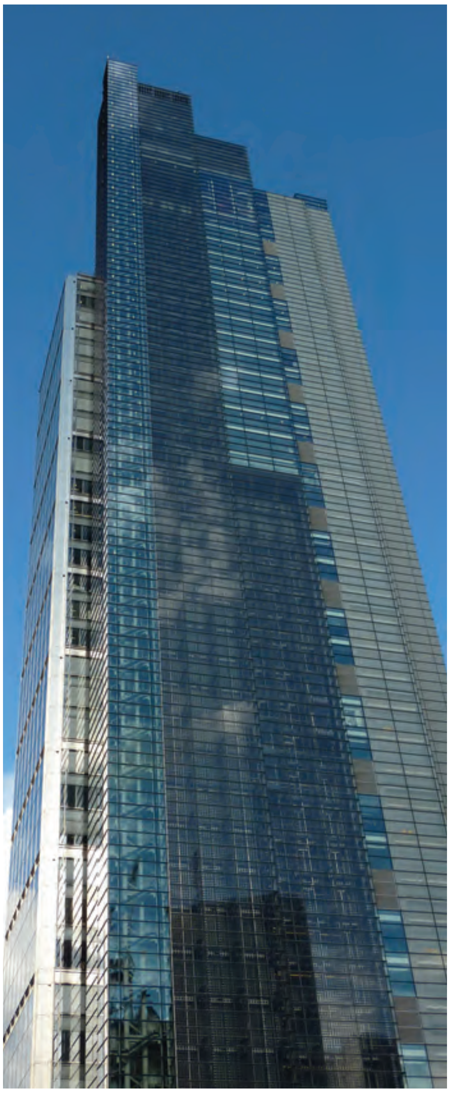

Figure 1. Heron Tower, London. South-facing photovoltaic integrated façade generating 2.5% of building electricity (Source: Philip Oldfield)
图1. 伦敦的苍鹭大厦。朝南的光伏立面满足了建筑2.5%的电能需求（来源：Philip Oldfield）

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 (Figure 1), for example, generates 2.5% 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.

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 new-build construction. To be considered Passivhaus-compliant, buildings need to achieve less than 15kWh/m²/annum for heating or cooling and less than 120kWh/m²/annum for primary energy requirements (Passipedia, 2016). Typically, Passivhaus buildings can be characterized by six factors (Figure 2):

高层建筑中生活和工作，这一需求就显得愈发紧迫。

为了应对这一点，如今许多塔楼的设计都着眼于运用最新科技来减少能源需求。现代高层建筑的一个越来越明显的趋势，就是将低碳和高碳能源生产技术结合起来（Oldfield, Trabucco and Wood, 2009），包括综合利用风力涡轮机和光电板。例如，伦敦的苍鹭大厦（图1）就通过一大片朝南的光电板来满足了自己2.5%的电能需求（Construction Manager, 2010）。

虽然这类进步显然是有价值的，但是很少有塔楼能自行供给10%以上的电力需求。考虑到这点，为了提高高层建筑的能源使用效率，本研究提出了一种替换方法——“构造优先”法。该方法认为，提高能源效率最廉价简便的办法，就是在设计过程中将建筑外形和幕墙的性能优化放在第一位，而将额外的技术设备放在第二位。

本研究以“被动式房屋”（Passivhaus）这种特殊构造优先概念为中心，探讨了在寒冷和温和的气候下，将被动式房屋运用于高层建筑的机遇和挑战。

被动式房屋：一种“构造优先”的方法

在被动式房屋建筑概念中，热舒适的最大化是通过高效能的建筑结构（包括通过高绝热材料将热量流失降到最低），以及利用太阳能和内部热增量等免费热源来实现的。这是世界上发展最快的能源效率标准（McLeod et al, 2012），与新建建筑相比，它能减少75%的制热和制冷能源

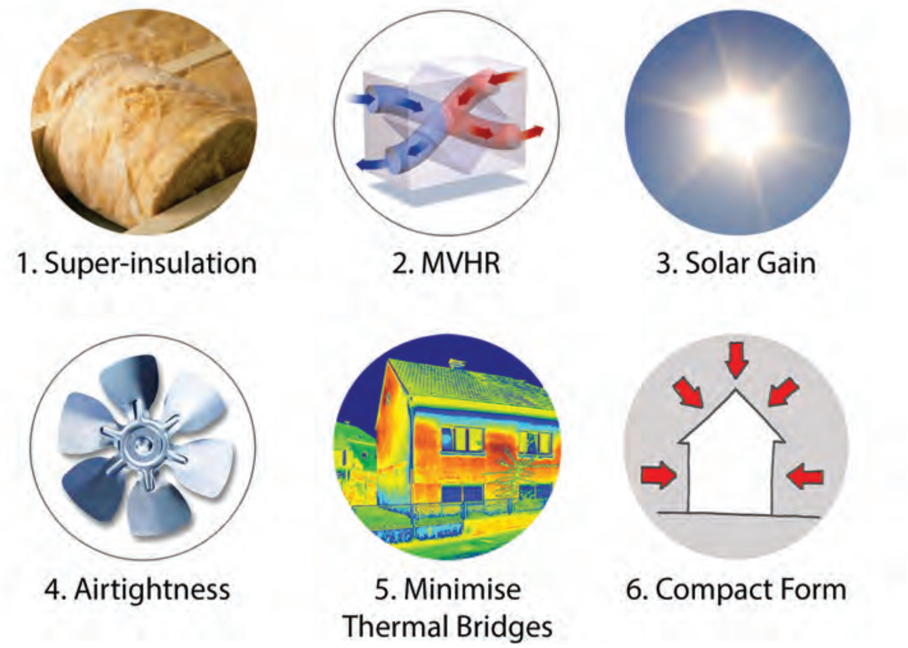

Figure 2. Characteristics of Passivhaus Buildings (Source: Philip Oldfield)
图2. 被动式房屋建筑的特征（来源：Philip Oldfield）

1. The use of super-insulation and triple-glazing in a high-performance building envelope, yielding typical building fabric U-values of less than 0.15W/m²K for opaque elements, and 0.85W/m²K 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 accommodations and facilities for Cornell University. Yet, despite these projects, the vast majority of the estimated 50,000 completed Passivhaus buildings are low-rise.

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, terrace house, low-rise apartments and 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).

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	1.091m²/m³	0.639m²/m³	0.302m²/m³	0.163m²/m³
Location	All modelled in Manchester, England			
Orientation	All modelled as north / south orientated			
Standard Fabric	Wall U-Value = 0.3W/m²K, Floor U-Value = 0.25W/m²K, Roof U-Value = 0.2W/m²K, Glazing U-Value = 2 – 2.2W/m²K.			
Passivhaus Fabric	Wall U-Value = 0.138W/m²K, Floor U-Value = 0.131W/m²K, Roof U-Value = 0.108W/m²K, Glazing U-Value = 0.78W/m²K.			
Glazing	All buildings modelled with the same window areas on each facade. South Facade = 42%, North Facade = 21%, West Facade = 2%, East Facade = 2%. These are taken from the example Passivhaus building outlined in the 2007 Passivhaus Planning Package (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 0.4Wh/m³.			

Figure 3. Building characteristics (Source: Philip Oldfield)
图3. 建筑特征（来源：Philip Oldfield）

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 0.3W/m²K 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 Figure 3. An illustration of each of the four buildings, along with their surface-area-to-volume ratios, is outlined in Figure 4.

Figure 4 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. Figure 5 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

需求。被动式房屋的要求是：制热和制冷耗电少于每年每平方米15千瓦时，一次能源消耗量少于每年每平方米120千瓦时（Passipedia，2016）。通常来说，被动式房屋有以下六个特点（图2）：

1. 在高性能建筑幕墙中使用高绝热材料和三层玻璃，不导热元素的典型建筑构造U值小于0.15W/m²K，玻璃材料的U值小于0.85W/m²K（McLeod等，2011）
2. 使用热回收机械通风系统（MVHR）
3. 小心利用太阳能，以满足冬季被动供暖需求
4. 气密性强，在50帕压力下每小时换气次数不超过0.6次，以减少渗透带来的热量损失（McLeod et al，2011）
5. 尽可能减少建筑结构内的热桥
6. 建筑形态紧凑

虽然大部分建成的被动式房屋位于欧洲或北美，但是这一标准在国际上也越来越受关注，包括中国。最近在浙江长兴完工的五层被动式住宅"Bruck"项目就是典型代表。2013年，位于维也纳的RHW.2 办公塔楼成为世界上第一座被动式摩天大楼。它的制热和制冷能源需求比传统塔楼少80%（Passivehouseplus，2013）。世界上最高的被动式塔楼位于纽约，目前还在建造之中，完工后将达到26层，是康奈尔大学的宿舍和活动空间。然而，虽然目前建成的被动式房屋已有5万栋左右，但除了这些项目之外，大部分都是低层房屋。

Figure 4. Four building types and their surface-area-to-volume ratios (Source: Philip Oldfield)
图4. 4种建筑类型及其表面积体积比（来源：Philip Oldfield）

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 8kWh/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 Figure 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 15kWh/m^2/annum.

A further advantage of tall buildings is that they can meet Passivhaus performance

被动式房屋及房屋类型：表面积体积比的重要性

要确定被动式摩天大楼与其他类型的楼房在性能方面的区别，本研究对四种类型的房屋——独栋住宅、连栋房屋、低层公寓和高层公寓——进行了研究，并根据《2007年被动式房屋计划方案》（Feist, 2007）对各类楼房的年度热需求进行了计算。从本质上来说，这其实是一系列相互联系的电子表格，我们可以通过这些电子表格，以楼房的关键特质（U值、房屋面积、墙壁面积、窗户、通风系统效率等）为基础确定楼房的被动性能。在这项研究中，热需求是主要的对比标准，因为在寒冷和温和的气候下，供暖对能源的需求最大，占欧洲房屋能源消耗的70%（LSE Cities and Eifer, 2014; WBCSD 2009）。

对于每种类型的房屋，本研究对两种不同的幕墙进行了建模。“标准”建筑构造是根据《英国建筑法规L1A部分》（英国政府，2016）的最低标准设计的，其典型墙壁的U值为0.3W/m^{2}K，装有双层玻璃。而被动式建筑的构造方案使用了更高水平的隔热技术和三层玻璃。

三个低层房屋类型以已经竣工的被动式建筑为基础构造。由于缺少已完工的被动式住宅塔楼作为参考，高层房屋类型将以非被动式建筑（英国曼彻斯特的比瑟姆塔）为基础，并对其机械性能和建筑构造进行了改进。由于本项研究的研究课题是建筑外形及类型对建筑的影响，这四类建筑的其他特征——位置、朝向、窗户、遮阴、通风设备等——都是一样的。图3中列出了所有的建筑特征和设想。图4是四种建筑的图解，还标出了每种建筑的表面积体积比。

从图4可看出建筑的外形和类型对表面积体积比的影响。在这个例子中，高层建筑的表面积体积比几乎比独立式楼房小七

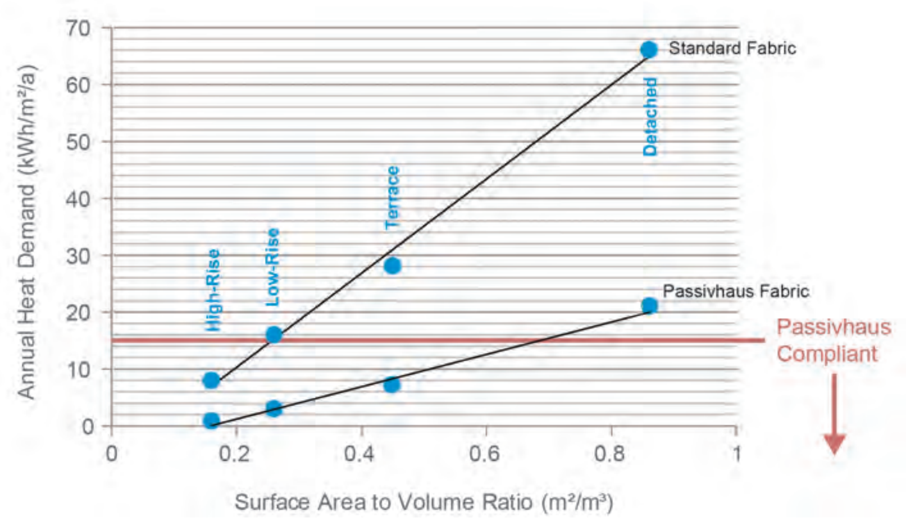

Figure 5. Relationship between compactness (surface-area-to-volume ratio) and the annual heat demand of four buildings modeled in Manchester, UK (Source: Philip Oldfield)
图5. 在英国曼彻斯特的4座代表性建筑的紧凑性（其表面积体积比）和年制热能源需求之间的关系（来源：Philip Oldfield）

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	800mm balconies on south, east and west
8	Triple	0.138	50	Yes	800mm balconies on south, east and west
9	Triple	0.138	30	Yes	800mm balconies on south, east and west
10	Double with 30mm air gap	0.18	50	Yes	800mm balconies on south, east and west

Figure 6. Scenarios for PHPP Analysis (Source: Philip Oldfield)
图6. 用于分析《被动式房屋规划方案》的方案（来源：Philip Oldfield）

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.

Façade Design

To further explore the opportunities and challenges for Passivhaus performance in tall buildings, 10 additional iterations of the high-rise apartment model 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 $15kWh/m^2$/annum heating demand. A full list of characteristics for each scenario is outlined in Figure 6.

Figure 7 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,

倍，比连栋房屋小四倍。这对制热能源需求的影响是深远的。图5显示了在其他参数相同的情况下，四种建筑采用标准和被动式建筑构造时的年制热能源需求。结果显示，表面积体积比和年度热需求之间存在线性关系——表面积体积比越大，建筑就需要越多的能源制热。

在这种情况下，高层建筑类型的热需求最低，其次是低层公寓、连栋房屋和独栋住宅。事实上，即使是使用标准建筑构造，采用双层玻璃和最低隔热水平的高层建筑也符合被动式建筑的标准，制热需求只有每年每平方米8千瓦时。

这些研究结果显示，与其他类型的建筑相比，高层建筑拥有与生俱来的优势——表面积体积比更低，热损失也就更少，对空间制热的需求也就更低。这些结果与同领域类的其他研究相吻合。有一项研究对伦敦、巴黎、柏林和伊斯坦布尔的不同建筑类型的制热需求进行了对比，发现紧凑的高层建筑与周边建筑相比，对制热能源的使用效率最高，独栋住宅则最低（（LSE Cities and Eifer，2014）。

这为被动式摩天大楼的设计师们提供了许多机会。首先，建筑师们将有更大的自由来探索不同的高层建筑样式、外形和几何构造，同时依旧可以实现被动式房屋性能。另一方面，独立的被动式建筑的设计师们则更受拘束，因为他们要维持建筑形态的紧凑以减少热损失（McLeod et al，2011）。在图4的例子中，即使是拥有高性能建筑构造的独栋住宅也没有达到被动式房屋的制热要求，因此需要采取额外的隔热措施，或者改变建筑外形、朝向或窗户，以此将制热需求降低到每年每平方米15千瓦时以下。

与其他类型的建筑相比，高层建筑的另一个优势在于，即使使用更薄的隔热材料和性能更低的窗户系统，它依旧可以达到被

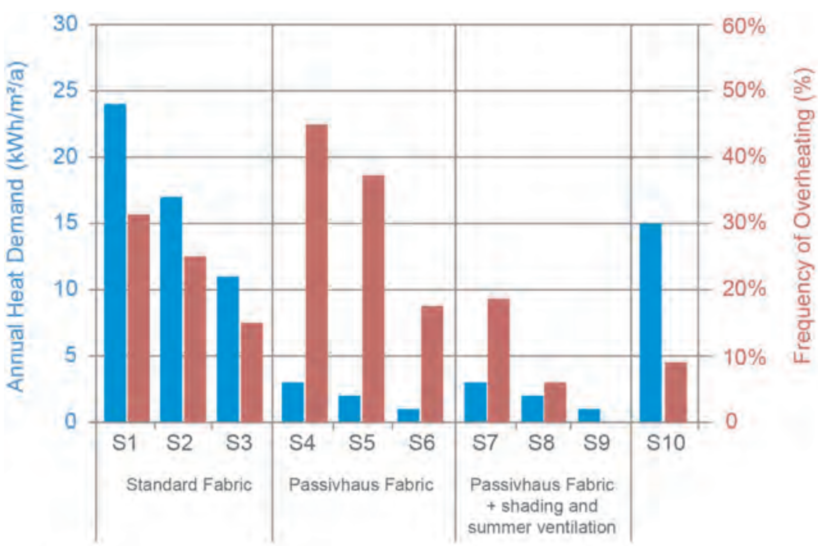

Figure 7. Annual heat demand and frequency of overheating for ten Passivhaus skyscraper design scenarios outlined in Table 2 (Source: Philip Oldfield)
图7. 10个被动式房屋摩天大楼方案的年度热需求和过热频率（来源：Philip Oldfield）

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).

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 (Figure 8).

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 (15kWh/m²/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 (30mm) and an opaque U-value of 0.18W/m²K (achieved with 210mm insulation) was adequate to meet Passivhaus performance. In typical low-rise examples, the use of triple glazing and opaque fabric U-values of less than 0.15W/m²K (250mm of insulation as a minimum) are common.

Conclusions: Opportunities and Challenges for Fabric-First Skyscrapers

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

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.

动式房屋的性能水平。这一点可能让被动式摩天大楼的概念更加经济。此外，这一点还意味着，被动式摩天大楼能采用更加简单的细节设计和建筑方法，降低重量，从而减少施工能耗。

立面设计

为了进一步探索高层建筑在被动式房屋性能方面的机遇与挑战，本研究还将《被动式房屋规划方案》（PHPP）用作能源平衡和规划工具，对表1中概述的高层公寓模型重复进行了10次建模。每种方案都采用了不同的窗户、隔热、通风和遮阴系统。方案1-3都采用《英国建筑法规第L部分》的标准建筑构造，但是每种方案中，立面的窗户占比分别为75%、50%和30%。方案4-6的立面拥有典型的被动式房屋特征，每种方案的窗户占比也不一样。方案7-9采用的是被动式房屋立面，但是增加了额外的遮阴元素以及夏季和夜间通风设备以缓解温度过高的情况。最后，方案10旨在探讨，怎样的建筑构造特征才能达到被动式房屋至多每年每平方米15千瓦时的制热需求。表2列出了各方案的完整特征（图6）。

图7展示了每种方案的年度热需求和过热频率。

第一个引人注意的地方是过热带来的挑战。根据Lewis（2014）的研究，对于过热频率来说，5-10%是“可接受的”，2-5%是“良好的”。在建模的方

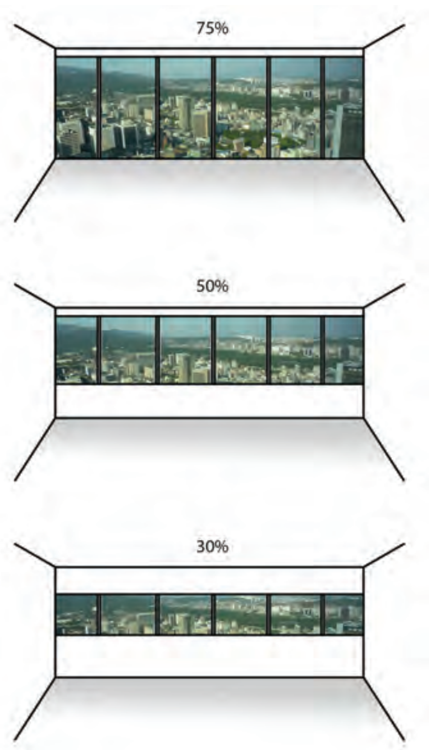

Figure 8. Internal perspective and impact on view of alternative façade window areas (Source: Philip Oldfield)
图8. 内部视角和不同开窗面积对视野的影响（来源：Philip Oldfield）

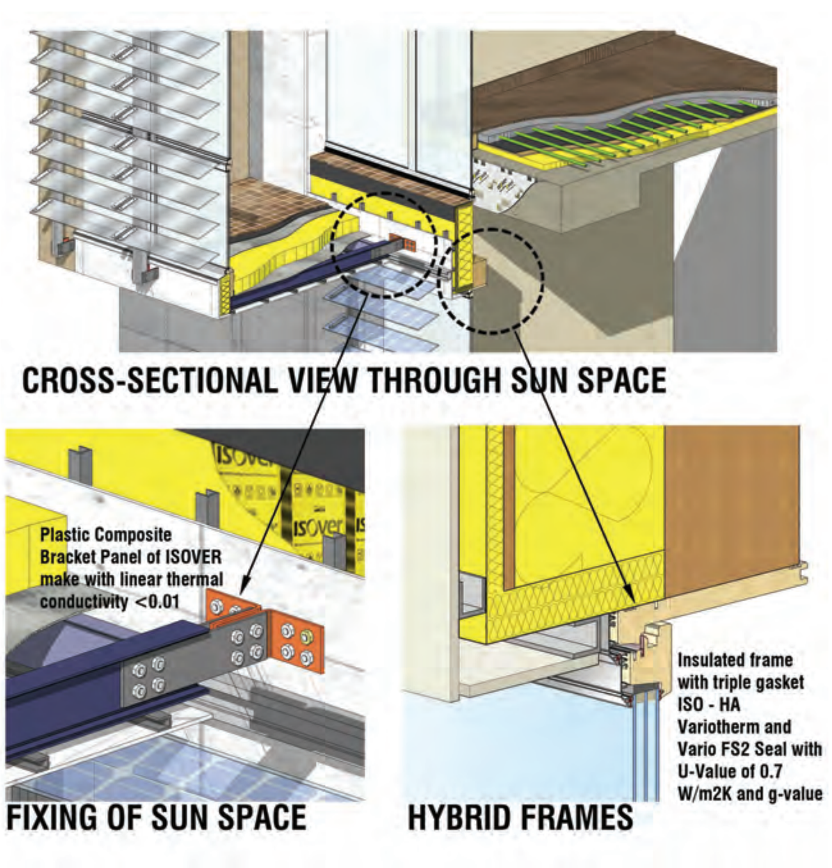

Figure 9. Detailing to eliminate thermal bridges in a Passivhaus skyscraper design (Source: Chuyu Qiu, Ankur Modi and Suruchi Modi / University of Nottingham)
图9. 被动式房屋摩天楼设计中为消除热桥进行的细部设计（来源：Chuyu Qiu, Ankur Modi and Suruchi Modi / University of Nottingham）

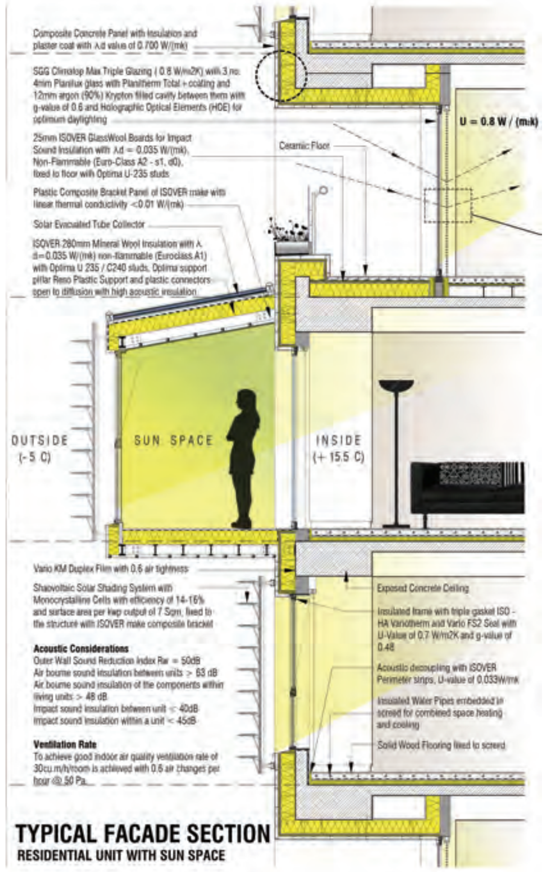

Figure 10. Façade cross-section for a Passivhaus skyscraper design (Source: Chuyu Qiu, Ankur Modi and Suruchi Modi / University of Nottingham)
图10. 被动式房屋摩天楼设计的立面纵剖面（来源：Chuyu Qiu, Ankur Modi and Suruchi Modi / University of Nottingham）

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.

Constructability: Passivhaus performance requires careful façade detailing, to eliminate all thermal bridging (Figures 9 and 10). 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.

Embodied carbon: A notable criticism of tall buildings is that they typically 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.

2. 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.

案中，只有方案8、9和10的过热频率小于10%。方案4拥有高性能的幕墙，75%的立面都装有窗户，但却没有安装夏季或夜间通风设备来进行降温，所以过热频率为45%。

这样，低表面积体积比的“劣势”便显现了出来：虽然立面面积的减少让建筑在冬天的热损失相应减少，但是紧凑的建筑形态也意味着建筑在夏季不易散热。立面面积减少，通风的开口也就相应减少，建筑就拥有更少的表面积来排出来自热水管道、人员和机器设备的热量。

这些结果与实证研究相吻合。例如，一项对英国居民楼的夏季温度的全国性研究表明，在公寓中，有68%的客厅和74%的卧室是过热的。而在连栋房屋中，这两个数字分别是28%和48%，独栋住宅则分别是21%和36%（Beizaee et al, 2013）。这一点值得我们注意，尤其是在全球升温的背景下。2011–2015年是有记录以来最热的一段时期（世界气象组织，2015），而且预计在21世纪，这一趋势还将持续增强。过热问题能导致严重且致命的健康问题；例如，在2003年的欧洲热潮中，仅仅两周内，在法国就有14947人因之丧命（Poumadere et al，2005）。

因此，在被动式摩天大楼的设计中，设计师们应该尤其注意缓解过热状况，让设计能根

3.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.

据全球温度的上升作出相应调整。在建模的方案当中，通过增加遮阳设备和夏季及夜间通风设备，过热状况得到了很大的缓解。与位于人口密集地区的低层建筑相比，高层建筑暴露在空气中的面积比较多，同时高处的风速也更大，所以高层建筑的自然通风性能更强。然而，高风速也意味着高层建筑要承受的风压变化更大，这将带来通风调节方面的困难，限制在高层安装大窗户的可能性（Etheridge and Ford, 2008）。机械降温系统当然是一个替代方案，但这又将带来额外的能源消耗。

第二是窗户面积的影响。那些窗户面积占立面75%的方案（方案1、4和7）拥有最高的热需求和过热频率。例如，方案7拥有高性能的立面、遮阴系统和夏季及夜间通风系统，但过热频率依旧达到19%。这一数字被视为是“灾难性的”（Lewis, 2014）。

窗户占比被减少到30%的方案（方案3、6和9）拥有最佳性能，热需求和过热频率最低。然而，窗户面积占比如此之小，可能会为高层居民楼带来商业上的不便，因为高层的视野是一个特殊的卖点。此外，窗户的占比被大量缩减，还可能为日照水平带来负面影响，从而影响到住户的健康和心情（图8）。

考虑到这一点，最具前途的是窗户面积占比为50%的方案，因为这一比例能实现热力性能和日照以及视野之间的合理平衡。为了进一步探索这一选项，方案10旨在寻找在窗户面积占比为50%的情况下，建筑构造至少要拥有哪些特征才能实现被动式房屋性能。研究发现，较低的制热能源需求（每年每平方米15千瓦时）和可接受的过热频率（9%）能通过低于“典型”被动式房屋的立面性能来实现。在这一情况下，通过气隙增加到30mm的双层玻璃和不导热的0.18W/m²K U值（这一U值是通过210mm隔热材料实现的）足以达到被动式房屋性能。在典型的低层案例中，三层玻璃和小于 0.15W/m²K的不导热的构造U值（隔热材料至少要有250mm）是很常见的。

结论：构造优先摩天大楼面临的机遇和挑战

本研究探究了在寒冷和温和的气候下，在摩天大楼设计中实现被动式房屋性能会遇到怎样的机遇和挑战。以下三项主要研究结果值得使用“构造优先”方法的设计师们进行参考：

1.表面积体积比的影响
在实现被动式房屋性能方面，高层建筑有一个内在优势。与其他类型的住宅楼相比，其紧凑的外形和高效的表面积体积比能在温和气候下减少制热需求。要满足被动式房屋的要求，低层建筑一般需要采取三层玻璃立面和超绝热材料，而高层建筑只需要采取更薄的立面构造和双层玻璃即可。这为高层建筑带来了许多潜在优势。

成本：在典型住宅塔楼中，立面是成本最高的元素（Barton and Watts, 2013）。所以建造复杂高效能的幕墙将让被动式摩天大楼在经济上不可行，或者至少在开发商眼中没有吸引力。而“构造优先”的方法可以通过更加“传统的”立面和双层玻璃达到被动式房屋的要求，从成本方面来看这一方法更加可行。

施工性：要实现被动式房屋的性能，就要对立面进行小心处理，以去除热桥（图9、10）。对于更厚的隔热幕墙来说，一个挑战就在于它们的结构更加复杂，成本更加高昂，这将导致热桥的增加。要解决这一问题，就要增加隔热，加大投入（Burrell, 2015）。更薄的隔热幕墙在建造的时候不用采用这么复杂的立面，也就不会出现这类问题。

隐含碳：对高层建筑的一大批评是它们通常需要更多的建筑材料，因此与低层建筑相比会产生更多的隐含碳（Oldfield, 2012）。与传统被动式立面建筑相比，以更薄的立面实现被动式建筑的性能，意味着建筑材料和隐含碳都能相应减少。

2. 过热
由于采用高水平的隔热措施和密闭的立面，被动式房屋和“构造优先”的高层建筑的设计师们应该尤其注意避免建筑在夏季过热，即使是在寒冷的气候环境下也是如此。设计师们要考虑到全球气温不断升高，未来的居民将要适应更加炎热的夏季温度。温度过高会带来严重的健康问题，甚至致死，所以设计师们应该最大限度地通过自然通风系统来实现自然冷却。与此同时，对内部热增量的控制——例如给热水管绝热——也至关重要。

3. 窗户
在设计构造优先的摩天大楼时，设计师们应该选择合适的窗户面积比例，小心实现住户对光照和视野的需求以及立面热力性能之间的平衡。本项研究显示，如果窗户面积占到立面的75%，那么该建筑在夏季就很容易过热。与此同时，如果窗户面积所占比例过小，高层住宅楼就会在销售上受阻。本研究认为，对于未来的建筑项目来说，50%左右的窗户面积占比更加合适，不过这一数字也要根据气候、环境和朝向进行优化。事实上，建筑师和设计师应该进行更多的工作，让窗户面积占比更低的楼房更加吸引人，例如将坚实的墙壁与透明窗户合理搭配，构造出别致的外观框架，等等。

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