Title: **Designing a High-Performance Sustainable Megatall**

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Subjects: Building Case Study
Sustainability/Green/Energy

Keywords: Code Compliance
Energy Efficiency
Megatall
Passive Design
Sustainability

Publication Date: 2014

Original Publication: Ping An Finance Center: In Detail

Paper Type:
1. Book chapter/Part chapter
2. Journal paper
3. **Conference proceeding**
4. Unpublished conference paper
5. Magazine article
6. Unpublished

Designing a High-Performance Sustainable Megatall

设计高性能可持续巨型高层建筑

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This chapter summarizes the characteristics of high-rise development and related considerations on building energy during design. The chapter introduces the Shenzhen Ping An Finance Center as a showcase of how a high-performance sustainable building can be achieved. Starting from local energy code compliance, and proceeding to adoption of passive strategies and an active energy-efficient system, the overall annual building energy cost savings is about 18% compared with the baseline of ASHRAE Standard 90.1.

本文总结了高层建筑发展的特点和对建筑设计上的节能考虑。文中还介绍了施工中的项目——深圳平安金融中心，展示了实现高性能可持续建筑的典范。从当地能源规范设计，到采用被动策略，以至利用主动式节能系统，与ASHRAE标准90.1基线相比，整体年建筑能耗成本大约节省18%。

Introduction

China is a country containing a high proportion of the world's high-rise building developments. The Council on Tall Buildings and Urban Habitat states that "Asia now contains 56.8% (342) of the world's 200-meter-plus buildings and 57.5% of the global population. China, with 200 buildings at the 200-meter-plus level, has nearly seven million citizens for every 200-meter-plus building."[1] In this circumstance, cities grow towards the sustainable vertical urbanism model. However, that model causes another issue: greater energy demands and energy use intensity in the development due to the transportation and resource needs of its occupants.

As members of a sustainability design consultancy, that has built over 70 successful high-rise developments world wide, the authors have proposed various energy conservation strategies and innovative ideas for high-performance sustainable buildings with the object of reducing carbon emissions and mitigating global warming impact. This chapter provides a definition for a "high-performance sustainable building" and demonstrates how a high-performance building was achieved for the Ping An Finance Center (Figure 2.18).

Defining "High-Performance Sustainable Building"

The United States Department of Energy defines the principles of High-Performance and Sustainable Buildings (HPSB)[2] as follows:

- Employ integrated design principles with aesthetic, sustainability and comfort;
- Optimize energy performance
- Protect and conserve water
- Enhance indoor environmental quality
- Reduce the environmental impact of materials

[1] Council on Tall Buildings and Urban Habitat (2011), Tall & Urban – An Analysis of Global Population and Tall Buildings.
[2] United States Department of Energy (2011), High Performance Sustainable Building, technical guideline, DOE G 413.3-6A

引言

中国是全球拥有较多高层建筑开发项目的国家。CTBUH[1]指出，亚洲现在拥有全球56.8% (342所) 200米以上的建筑和全球人口的57.5%。以中国拥有200所200米以上的建筑大楼计算，平均每700万居民对应一座高层。在这种情况下，城市发展将朝向可持续性垂直城市化模式。然而，这种模式会导致另一个问题: 垂直交通与居民对资源的需求会导致更大的能源采用和能源开发需要。

作为一个可持续发展的设计顾问公司，Arup在世界各地建造了超过70所成功的高层建筑，积极提出各种节能减排的策略和创新理念以减少碳排放并减缓全球变暖的步伐。本文提出对"高性能可持续建筑"的定义，并演示了如何在深圳市最高的综合性商业建筑——平安金融中心实现高效能建筑 (见图2.18) 。

界定"高性能可持续建筑"

美国能源部[2]界定高性能和可持续建筑 (HPSB) 的原则规定如下:

- 与审美性，可持续性和舒适性运用一体化设计原则;
- 优化能源运用;
- 保护和节约用水;

To achieve exemplary levels of sustainability addressing these green initiatives is critical, since no single discipline alone or any green building certification system can apply sufficient measures to deliver this level of sustainability. As illustrated in Figure 2.19, the three primary characteristics of High-Performance Sustainable Buildings are:

- Quantifiable – Every aspect of environmental performance is monitored throughout the building life-cycle. This ranges from computational modeling during the concept and design stages, the specifications and implementation during the construction stages, and measurement and verification during the operation stage.
- Integral – No single discipline can provide all aspects of exemplary environmental performance. Hence the design of High-Performance Buildings is an integrated design process, where the performance goals are agreed upon and all the teams are aware of their responsibilities during each stage of the building life cycle.
- Visual – To achieve the cross-team exemplary performance described above, it is necessary to develop effective means of communication to achieve environmental performance. This is achieved through Building Environmental Modeling, which analyzes the various aspects, and then presents them a three-dimensional visual platform using computer modeling tools.

Sustainability Plan for the PAFC

The design and planning of the project commenced in 2008, and the construction work began in 2010. The design of the building has included various sustainability strategies, which are described in this

Figure 2.18 Rendering of Ping An Finance Center (source: KPF)
图2.18 平安金融中心效果图 (来源: KPF)

- 提高室内环境质量;
- 降低材料对环境的影响。

没有单一技术或任何绿色建筑认证体系能直接地体现高性能和可持续建筑，为了实现可持续发展的模范项目，这些环保措施是非常重要的。如图2.19所示，高性能可持续建筑的三个主要特征为:

- 量化——在整个建筑生命周期监控各个方面的环保性能。这包括从设计概念阶段中的计算模型，到施工阶段中对设计的详述与实施，以至在运营阶段上利用计算机建模进行量化计算。
- 完整性——没有单一技术能直接在所有环境影响方面体现及保证高效能表现。因此，高性能建筑设计需要一个综合性的设计流程，令所有团队意识到自己在建筑生命周期各个阶段上的责任。
- 视觉——实现上述的高效能表现，有效建立团队间良好沟通是必要的。通过三维建筑模型作为可视化平台，分析各个方面环境影响。

Figure 2.19 High performance sustainable building concept (Source: Arup)
图 2.19 高性能可持续建筑概念(来源: 奥雅纳)

chapter and have been incorporated into the site planning, architectural design, M&E design, landscape, and lighting design. PAFC aims to achieve the US Green Building Certification System – Leadership in Energy and Environment Design (LEED)[3] Gold rating, making it the first megatall building to obtain this certification in China.

Key Considerations and Challenges of PAFC's Sustainability Planning

Several design considerations and challenges have been faced by achieving a high-performance sustainable building level in this megatall tower:

Extreme Design Conditions for Megatall Buildings
One of the most critical issues for a megatall building is the design of a vertical transportation system with a vertical distance over 600 meters long. The optimized handling capacity and interval period during normal operation should be maintained for a Grade A office building. Another design consideration for megatall buildings is the high sun exposure on higher floors. In this respect, high-performance building envelope design should be considered to minimize the solar gain to the building.

Unique and Iconic Architectural Design
The iconic stone and glass tower with a large central atrium forming a large amphitheatre-like sun-lit space has been proposed by the architect (Figure 2.20). It will improve daylight penetration in the tower's office and retail areas. However, it will also increase the solar heat gain. With the well integrated architectural design features, the tower's chevron-shaped stone will act as vertical shading to reduce the solar heat gain. Proper glazing selection and façade design, for the podium terrace, will aid in maintaining an optimum balance between solar heat gain and daylight penetration in PAFC.

Advanced Vertical Transportation System

One major challenge for a megatall building is to achieve a vertical transportation system that is able to effectively provide for the demands of the many thousands of random journeys required by the building's occupants. This is in addition to performing on a daily basis within a supertall building with a vertical distance of over 600 meters. The key objective of PAFC is to provide the most efficient vertical transportation system with an optimized handling capacity and interval period during normal operation. Planning of lift zoning at PAFC was the key initial step for the lift system. The client, architect and the system design team were involved in the decision process for the lift planning. The tower's multi-zone layout was conductive to separating the passengers into multiple destination groups (Figure 2.21). A more efficient

[3] U.S. Green Building Council, Leadership in Energy and Environment Design (LEED), reference guide for Core and Shell Version 2.0

平安金融中心的可持续化方案

该项目的设计和规划于2008年开始，，并于2010年7月开始动工兴建。该建筑从选址规划，建筑设计，机电设计，景观和灯光设计上整合各种可持续性设计。平安金融中心旨在达到美国绿色建筑认证体系——能源与环境设计 (LEED) [3]金级认证，并将成为中国第一个获得这个奖项的超高层商业建筑。

平安金融中心可持续化方案的主要设计考虑与挑战

要实现高性能可持续性的超高层塔楼主要针对以下几个设计考虑和挑战:

巨型高层建筑的极端设计条件
平安金融中心超高层建筑项目中其中一个较关键的问题在与垂直距离超过600米长的垂直运输系统设计。甲级写字楼需要在正常垂直运输系统运行时间保持理想的垂直运输运载能力和时隔。同时，超高层建筑项目因不受周围环境及建築物的遮挡而导致办公室高楼层区域有较高的太阳辐射量。在这方面，应考虑设计高性能的围护结构以尽量减少建筑物的制冷量。

独特及标志性的建筑设计
在以石材和玻璃为材料的标志性的塔楼中，建筑师提出了一个庞大的圆形剧场般的大型中央中庭设计概念，可以为中庭空间提供充足的采光 (见图2.20) 。这将改善写字楼及零售区的日光射入量。但中庭设计概念也同时增加了太阳光热量的获得。随着建筑一体化的设计——独特形状的石材将作为垂直遮阳，以减少室内太阳得热量。适当的玻璃选择和裙楼幕墙立面设计将平衡室内太阳得热和日光渗透量。

先进的垂直运输系统

超高层建筑其中一个主要挑战在于实现良好的垂直运输系统，并能够有效地满足数千使用者在超过600米高的超高层建筑中每天所需的随机行程的要求。平安金融中心项目的主要目标是为使用者在正常运行情况下提供最高效的垂直运输系统，以达到理想的垂直运输运载能力和时隔。良好的电梯分区是在平安金融中心的电梯系统规划中的关键一步。业主、建筑师和系统设计团队都参与电梯规划及分区的决策过

Figure 2.20 Rendering of amphitheatre-like sun-lit podium atrium (Source: KPF)
图2.20 裙楼内充满阳光的圆形大型中庭效果图 (来源: KPF)

route is obtained by avoiding frequent stopping, which causes long waiting periods for the lift system. Each sub-zone is served by four to six double-deck lifts with traveling speed of 3.5 to 6m/s. Use of high speed double-deck lifts enhances the handling capacity and shortens the travelling time for each journey. In particular, two high-speed lifts of 10m/s are provided to serve the observation deck, which is sufficient to cater to the transportation of high visitor densities running over the 660-meter vertical distance. The overall interval period for each zone is maintained within 30 seconds, which complies with the international standards of lift design.

High-Performance Integrated Façade Design

The iconic stone and glass tower has a unique design which enhances the transparency and daylight harvesting for the building. However, CTBUH[4] has noted that the increased façade transparency causes a reduction in the envelope insulation, which increases the heat loss and heat gain. With the integration of sustainable concepts into the architectural design in PAFC, the chevron-shaped stone verticals (Figure 2.22)

程。本项目共划分7个约有8 到14层的电梯服务区，连同一个观景台，通过分区可以有效地识别并划分不同乘客 (见图2.21) ，从而设计一个更有效的垂直运输系统，避免系统过频繁地停车，造成较长的时隔。每个子区域将由4到6台双层升降机以每秒3.5到6 米的移动速度服务各区域层。使用高速双层升降机有效提升处理能力，缩短行车时间。同时本项目提供两台每秒10米的高速升降机，以服务观景台，这足以在660米的垂直距离中满足高密度乘客的运输量。每个区域的时隔保持在30秒范围内，即符合电梯设计的国际标准。

高性能一立面设计

标志性的石材设计和玻璃塔的独特设计有助增强建筑物的透光度和建筑内的日光利用。然而，世界高层建筑与都市人居学会[4]指出，高透度的幕墙设计减少维护结构的隔热功能，并增加了热损失和得热量。平安金融中心项目具有良好的可持续发展设计一体化的概念，每个外立面的特色垂直石材 (见图2.22) 不仅提供了一个独特的建筑外形，同时也达到外遮阳的效果。本项目利用动态热模型计算评估外遮阳一年四季的性能 (见图2.23) 。项目显著减少太阳得热量后，所需的空调系统能耗也随之减少。再者，在裙楼内庞大的圆形大型中庭设计中选择具有良好热工性能的玻璃类型及不透明墙体，在太阳得热和中庭采光效果上取得平衡。整体围护结构的热工性能比当地节能标准要求高出约20%。

改善室内环境质量

平安金融中心具有较高的人员密度。随着进一步考虑到深圳市的空气污染情况，作为中国高性能可持续建筑的典范，良好的室内环境质量十分重要。在过渡季节，平安金融中心高层区域有较低的室外环境温度，空调系统十分适合采用全新风供应，提供最大限度的干净和新鲜的室外空气量到办公空间，同时减少回风量作室内循环。这有效减少室内交叉污染，并提高了室内空气质量。本项目采用流体动力学模拟计算根据幕墙上不同的风压分布，分析适当的新风位置 (见图2.24及2.25) 。本项目的空调系统新风量设计与当地的设计标准相比增加了30%，这增加了室内空间的氧含量，并提高使用者的工作效率。空调系统亦使用较高性能的过滤器有助过滤室外空气的颗粒。

[4] Council on Tall Buildings and Urban Habitat, (2008) Tall Buildings in Numbers – An Overview of Historical Factors Affecting Tall Building Energy Consumption, CTBUH Journal, Issue III

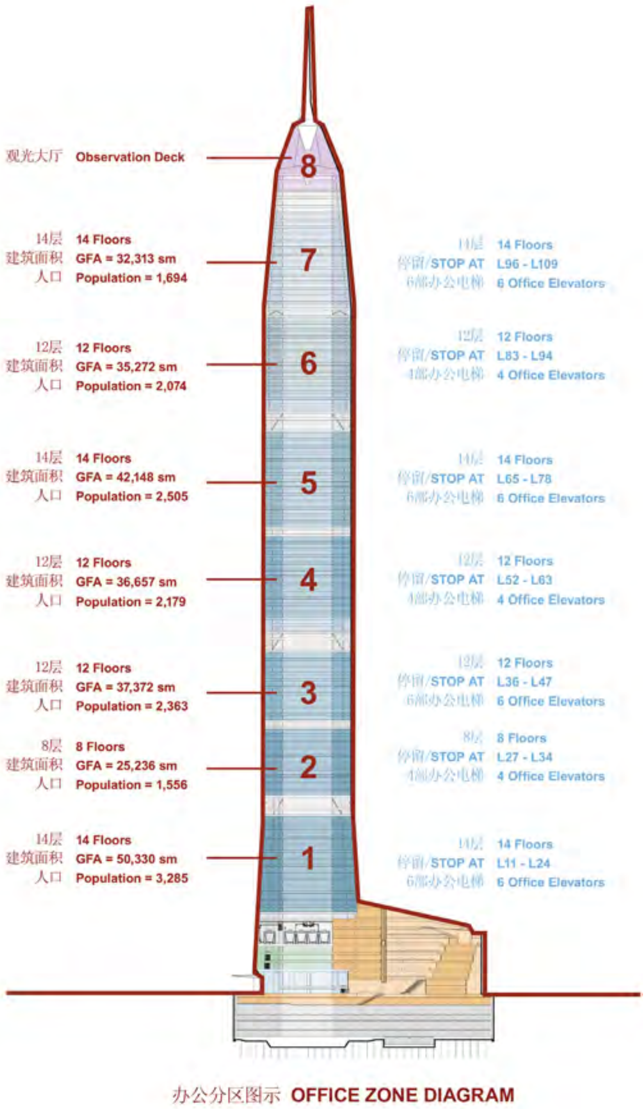

Figure 2.21 Zoning of vertical transportation system (Source: KPF)
图2.21 平安金融中心竖向交通系统区域划分 (来源: KPF)

are introduced in each elevation, which not only provide a unique architectural feature to the building, but also provide functional external shading. The dynamic thermal model is applied to evaluate the performance of external shading throughout the year (Figure 2.23). A significant reduction in solar heat gain of the tower is obtained, which reduces the energy consumption required for the air conditioning systems. Further, for the large amphitheatre-like, sun-lit space at the podium's atrium, the selection of the glazing system was optimized. This achieved excellent thermal properties in external opaque elements and fenestrations, which balance the solar heat gain and daylight penetration in the atrium. The overall façade performance is approximately 20% higher than the local code requires.

Indoor Environmental Quality Improvement

PAFC has a high occupancy density. With further consideration of air pollution in Shenzhen city, good indoor environmental quality should be maintained as an exemplar of a high-performance sustainable building in China. With suitable lower ambient temperatures in the higher zones of PAFC during the transition period, full outdoor fresh air supply has been integrated into the air conditioning system, which maximizes the clean and fresh outside air volume, serving office spaces with limited recirculation. It also minimizes the cross-contamination and enhances the indoor air quality effectively. Computational fluid dynamic (CFD) analysis has been applied to evaluate the appropriate location for full fresh air supply under different wind pressures acting on the building envelope (Figure 2.24 & 2.25). A 30% increase in fresh air rate compared with the local design standard is provided, which increases the oxygen content to the indoor space and enhances occupant productivity. Higher-performance filtration systems have also been adopted into the air conditioning system, which filter the particulate matters from the outside air.

其他低能耗建筑节能设计策略

符合当地环境设计和节能标准

本项目主要根据两个建筑节能标准，包括 (1) 中国建筑节能设计规范GB50189-2005[5]和 (2) 深圳市建筑节能设计标准SZJG 29-2009[6]。这两个节能标准都考虑了围护结构性能、空调系统、电器及照明系统的效能。同时平安金融中心需要达到美国LEED认证体系金级认证，并符合ASHRAE标准90.1——建筑物能源标准 (除低层住宅建筑) [7]。

被动式设计策略

高反射材料和屋顶绿化

高层建筑屋面部分的太阳得热量较高，屋面保温使用非常重要。使用高太阳辐射能反射的材料 (SRI> 78) 可反射大部分太阳辐射到室外。安装约2500平方米的绿化屋顶也可减少吸收太阳辐射量，尽量降低屋顶表面温度以减少空调空间的冷负荷，同时亦减少城市热岛效应对周围环境的影响。

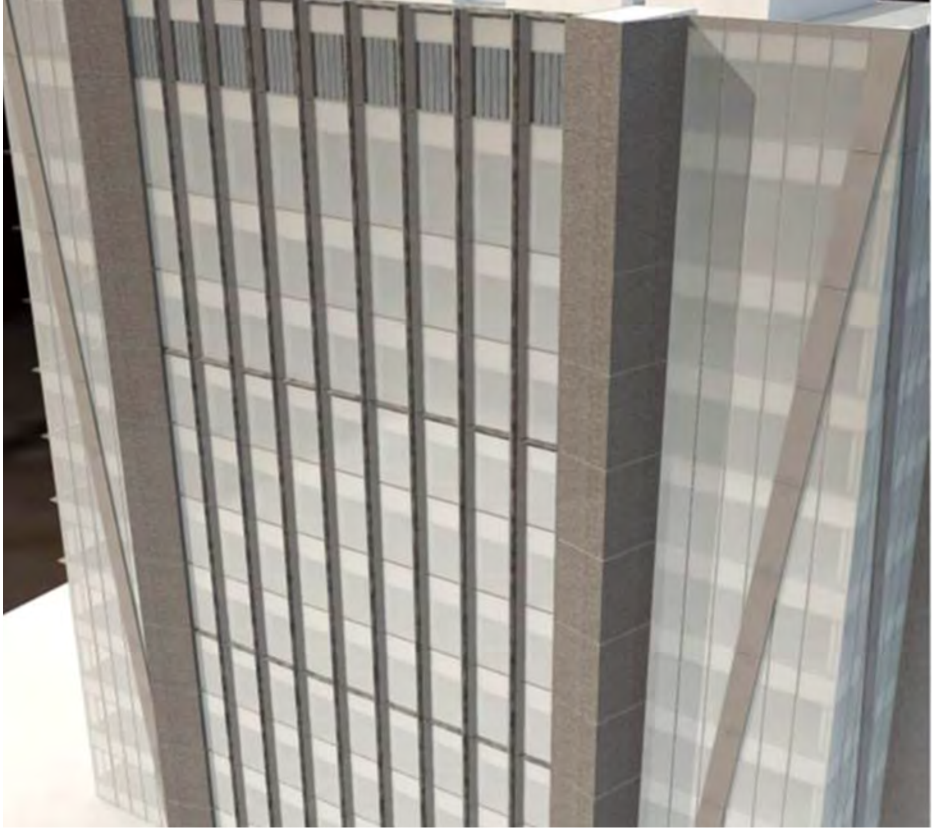

Figure 2.22 Façade model – chevron-shaped stone verticals (Source: KPF)
图2.22 平安金融中心立面模型——特色垂直石材 (来源: KPF)

Other Low-Energy Design Strategies

Compliance with local context and best practices

There are two building energy efficiency local standards applicable to this work. (1) China Energy Efficient Building Design Code – GB50189-2005[5] and (2) the local design standard for energy efficiency code in Shenzhen – SZJG 29-2009.[6] Both local codes consider the energy performance of the building envelope, air conditioning system and the electrical and lighting system. This is in addition to the goal of obtaining the US LEED Certification System Gold rating, and complying with the ASHRAE Standard 90.1 – Energy Standard for Buildings Except Low-Rise Residential Buildings.[7]

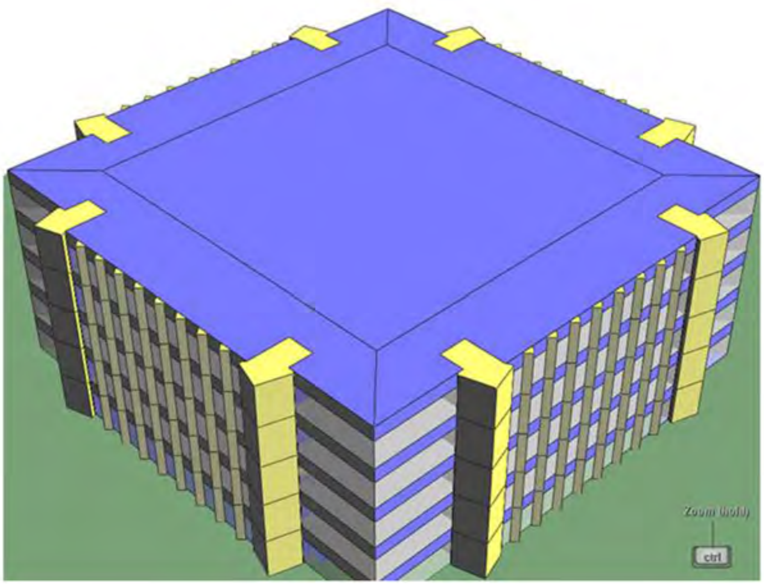

Figure 2.23 Dynamic thermal model for envelope shading study. (Source: Arup)
图2.23 外围护结构遮阳研究 动态热模型 (来源: 奥雅纳)

主动式节能和节约能源成本的系统

自然采光与日照传感器的应用

利用周围建筑物和场地地形的三维模型，通过日光模拟计算，分析超高层建筑与周围建筑物的遮挡的影响。利用低热透射率和高可见光透射率的玻璃将提供足够的可见光进入建筑物，同时减少太阳得热负荷。在足够日光的前提下，使用光电传感器加上可调光的照明设备减少人工照明能耗。

低照明功率密度

在指定的照明功能区采用独立工作台灯照明。保持相对较低的工作照度有效降低照明能耗而不影响室内照明表现。应用简洁而高效的室外照明设计有助于进一步降低照明能耗。

热回收系统

预冷新风机组 (PAUS) 配置热回收轮有助回收排气作预冷新风作用，从而减少建筑物冷却负荷。

通风量控制

在办公室及商业区应用二氧化碳监控系统。空气处理设备 (AHU) 和预冷新风机组 (PAUS) 能够根据二氧化碳浓度调节室外新风量。这显著减少通风风机和处理新风的能耗。

冰蓄冷系统

考虑到节省能源成本，本项目利用40000冷吨的冰蓄冷系统，利用深圳市较大的日夜电价差节约电费成本。

结论 : 整体节能成果

利用建筑能耗模拟计算，平安金融中心的总年能耗与典型的商业建筑相比节约约46%。与ASHRAE / IESNA标准90.1-2004的附录G评定的基准建筑性能进行比较，每年的建筑能耗节省约18%。平安金融中心的能耗流程图见图2.26。其中有27%的节能百分比都来自于满足当地能源规范设计，这意味着现有建筑节能规范在节能策略上已提供了一个清晰和优秀的设计方向。另

[5] Ministry of Construction, Design standard for energy efficiency of public buildings, Beijing, China Architecture and Building Press, GB50189 (2005)
[6] Construction Bureau of Shenzhen Municipality, Design standard for energy efficiency of public buildings, Design Guideline for Shenzhen – SZJG 29-2009
[7] ASHRAE Standard, "Energy Standard for building Except Low-rise Residential buildings," 90.1-2004

Passive Design Strategies

High Solar Reflectance Materials and Green Roof Space

With high solar heat gain at the building roof level, the roof insulation of PAFC is important for reduction envelope heat gain. Podium roofs covered by high solar reflectance materials (of SRI >78) can reflect a large portion of solar radiation. Also, applying 2,500 m^2 of greenery at podium roof level can also reduce the solar absorption and roof surface temperature, minimizing the cooling load in conditioned spaces, thus to reducing the urban heat island effect on the surroundings.

Active Energy Efficient and Energy Cost Saving System

Use of Natural Lighting with daylight sensors application

By the adoption of a daylight simulation tool, with a three-dimensional model at the surrounding buildings and site topography model, it is evaluated that few shadowing impacts are obtained for this ultra high-rise development, thereby enabling daylight penetration into the building. Low-emissivity and high-visibility light transmittance glazing is applied to allow sufficient visible light entering the building, reducing the unwanted heat gain at the same time. Photo-sensor and dimmable lighting devices are used to reduce energy consumption when there is sufficient daylight.

Low Lighting Power Density

The task lighting approach has been adopted to provide specified illumination to electric functional areas. Relatively low background illumination levels reduce the lighting energy consumption without degrading the functional performance of interior lighting. A concise external lighting design with a high-efficiency lighting application is used, helping to further lower the lighting energy use.

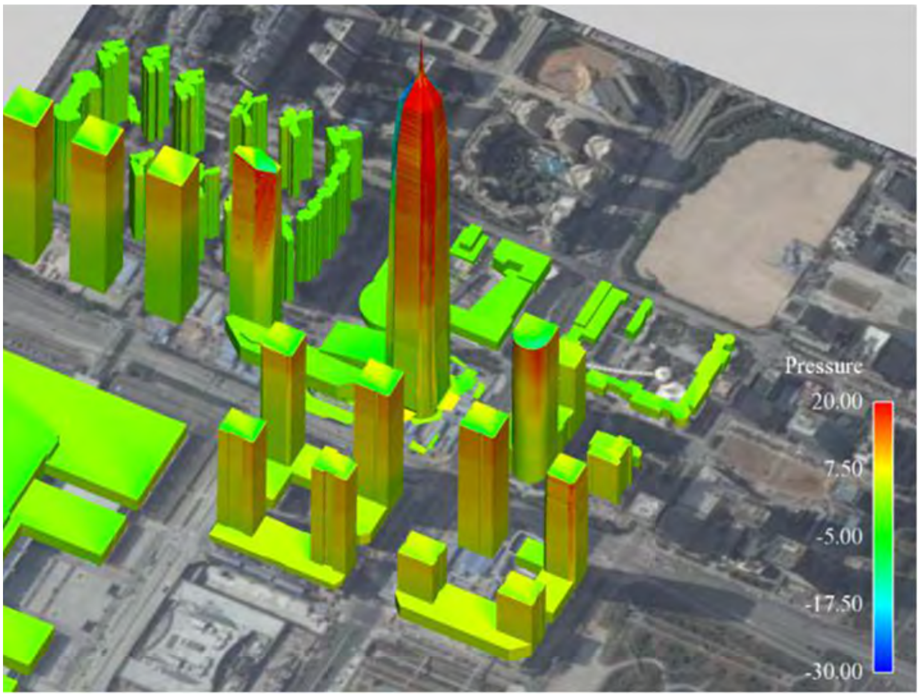

Figure 2.24 Computational fluid dynamic analysis – wind pressure at building façade (Source: Arup)
图2.24 平安金融中心 电脑模拟流线动态分析——建筑立面风压 (来源: 奥雅纳)

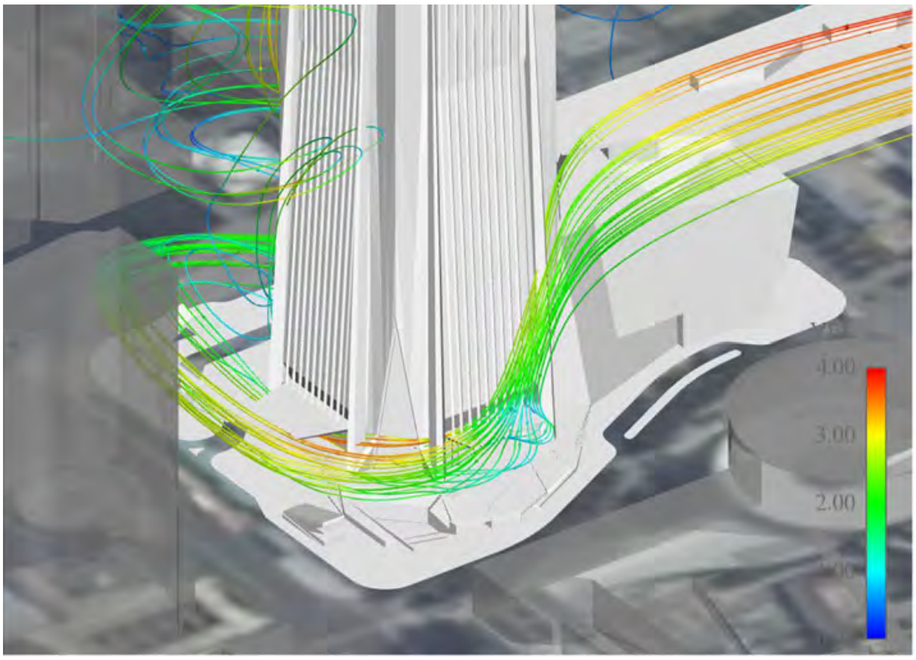

Figure 2.25 Wind velocity streamline diagram at podium (Source: Arup)
图2.25 平安金融中心裙房风速流线分析图 (来源: 奥雅纳)

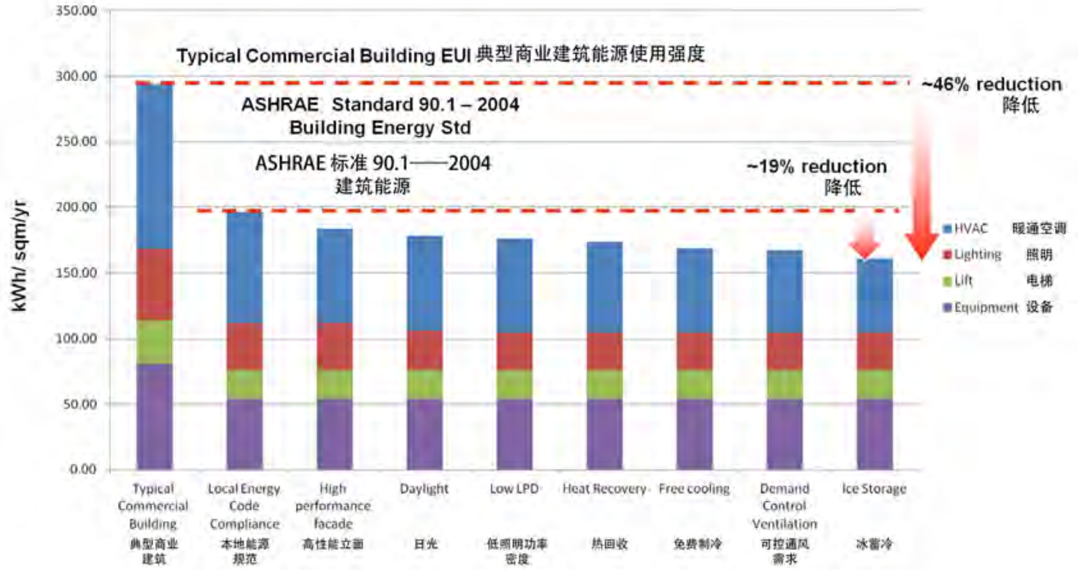

Figure 2.26 Energy flow diagram (Source: Sai Yau Cheng)
图2.26 平安金融中心能源流分析图 (来源: 郑世有)

Heat Recovery Systems

Primary Air Units (PAUs) are fitted with total enthalpy recovery wheels. The unused energy stored in the exhaust air is recovered to pre-cool the incoming fresh air, so as to reduce the building's cooling load.

Demand Control Ventilation

A CO_2 monitoring system is applied in office and retail floor spaces. The Air Handling Units (AHUs) and PAUs are able to adjust the outdoor air flow according to CO_2 concentration. These provide significant energy savings in both ventilation-fan systems and fresh air-conditioning treatment.

Ice Storage System

Considering the annual energy cost savings, the ice storage system with a capacity of 40,000 tons/hr is applied in the AC system, obtaining higher electricity cost savings from the large variation in electricity tariffs between day and night time.

Conclusion: Overall Energy Savings Achievement

A whole-building energy simulation has been conducted, resulting in around 46% annual building energy savings, compared with a typical commercial building. In addition, an annual building energy cost savings of 18% has been achieved compared with the baseline building performance rating method in Appendix G of ASHRAE/IESNA Standard 90.1-2004 (without addenda). The energy flow diagram of PAFC is shown in Figure 2.26. It is estimated that 27% of the energy reduction achieved, compared with a typical commercial building, has come from compliance with the local energy code design. This means that the local building energy efficiency code already provides a clear and excellent design direction on the energy conservation approach. A further 6% energy savings was achieved from the adoption of passive design strategies, including a high-performance façade and greenery solutions. The remaining 13% of building energy budget savings achieved are provided by active systems, including free cooling, lower lighting power density design, daylight penetration, heat recovery, demand control ventilation and thermal storage design.

有6%的节能是来自于被动式设计策略，包括高性能外墙和绿化方案。建筑节能预算节省的其余13%则由主动式节能系统提供，包括外气通风，低照明功率密度设计，采光利用，热回收，通风量控制和冰蓄冷系统。