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Embodied Carbon and High-Rise
隐含碳排放与高层建筑

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Philip Oldfield博士为诺丁汉大学建筑环境工程系的一名讲师，其主要职责是教授硕士生高层建筑可持续发展（理论），并负责主持与高层建筑设计相关的设计研讨会等。加入诺丁汉大学之前，Philip先生也曾任教于芝加哥、威尼斯和新加坡等城市的大学。除此之外Philip Oldfield先生为“世界高层都市建筑学会”（Council on Tall Buildings and Urban Habitat简称CTBUH）的研究、学术和研究生工作小组的联合主席，并且他也是世界高层建筑协会季刊（CTBUH Journal）编委会的成员之一。

Abstract

This paper examines the significance of embodied energy and carbon in tall buildings. It presents the life-cycle carbon analysis (including both operational and embodied emissions) of a 40 storey building in London, UK. The results demonstrate that embodied emissions account for a third of the building's total carbon footprint, with the structure, building services and finishes being the main contributors. It suggests that due to increasing energy efficiency and stricter building regulations the role of embodied carbon is likely to become more significant in the coming years. It also shows how embodied carbon is a vital consideration in meeting the short-term carbon reduction targets set by many countries and recommended by many bodies worldwide. It concludes by presenting a number of strategies for reducing embodied carbon in tall buildings, under the key headings of reduce, recycle and retrofit.

Keywords: Tall Buildings, Embodied Carbon, Life Cycle Analysis, Sustainability, Materials

摘要

本文通过英国伦敦一栋四十层高楼在生命周期中的碳指数分析（包括运营产生的排放量和隐含排放量），考察了高层建筑隐含能耗与隐含碳排放的重要意义。结果表明：该建筑碳足迹总量的三分之一来自隐含排放，而建筑的结构、建筑服务功能空间和建筑饰面为隐含排放的主因。由于增长能效和更加严格的建筑法规，未来几年内，人们可能更重视隐含碳排放的作用。本文还展示了为许多全球性机构推荐的隐含碳排放。作为一个重要的考虑因素，满足众多国家短期内减少碳排放的目标。以降低、回收和改造为关键课题，本文总结出一系列策略来降低高层建筑中的隐含碳排放。

关键词：高层建筑 隐含碳排放 生命周期分析 可持续发展 材料

Introduction

It is well known that the built environment is a key contributor to global greenhouse gas emissions with buildings accountable for 30 – 40% of all primary energy used worldwide (UNEP, 2007) and carbon dioxide emissions from buildings increasing at an annual rate of two percent between 1971 and 2004 (Levine et al., 2007). In light of this, attention has turned towards the environmental impact of tall buildings, which are still seen by many as inherently unsustainable (Roaf, Crichton & Nicol, 2005) and frenzied research has – and continues to be – undertaken in order to reduce their impact on the environment.

Much of this research undertaken to date has focused on reducing the environmental impacts associated with the operation of tall buildings – that is reducing the energy required for (and emissions released from) activities such as space conditioning, lighting, equipment operation, water supply and water heating that occur on a day-to-day basis. Whilst these advancements are vital for creating more sustainable high-rise, they are in themselves not enough. Like all buildings, tall buildings utilize energy and generate emissions not only during their operations, but across their entire life cycle, from the

引言

众所周知， 环境设计对于全球温室气体的排放是一个重要的因素，因为建筑占所有主要能源使用的30%至40%（联合国环境规划署，2007年数据United Nations Environment Program，简称UNEP），而自1971年至2004年期间，建筑物的二氧化碳排放量以每年百分之二的速度递增（Levine等人于2007年的数据结论）。鉴于此，人们的注意力已经转向高层建筑的对环境造成的影响，很多人认为其本质为非可持续发展的（Roaf，Crichton & Nicol，2005年），也有很多执着的研究人员开始着手或持续以来致力于减少高层建筑对于环境的影响。

迄今为止，这样开展的大部分研究仅着眼于降低与高层建筑运作系统有关的环境影响，即降低一项活动所需的能源（和这项活动所释放的相应的排放量），诸如空调、灯光照明、设备运作、供水和水加热等日常需求。虽然这些条件对于营造一个更为可持续发展的高层建筑来说至关重要，但单凭这些条件本身显然还难以完成可持续发展的目标。如同所有的建筑一样，高层建筑对能源的利用和排放物的产生不仅存于其运作阶段，而存在于他们的整个“生命周期”中，即从建造时所需原材料的提取，至拆除后对材料的处置与回收。这一完整的过程，涵盖一切与建筑建

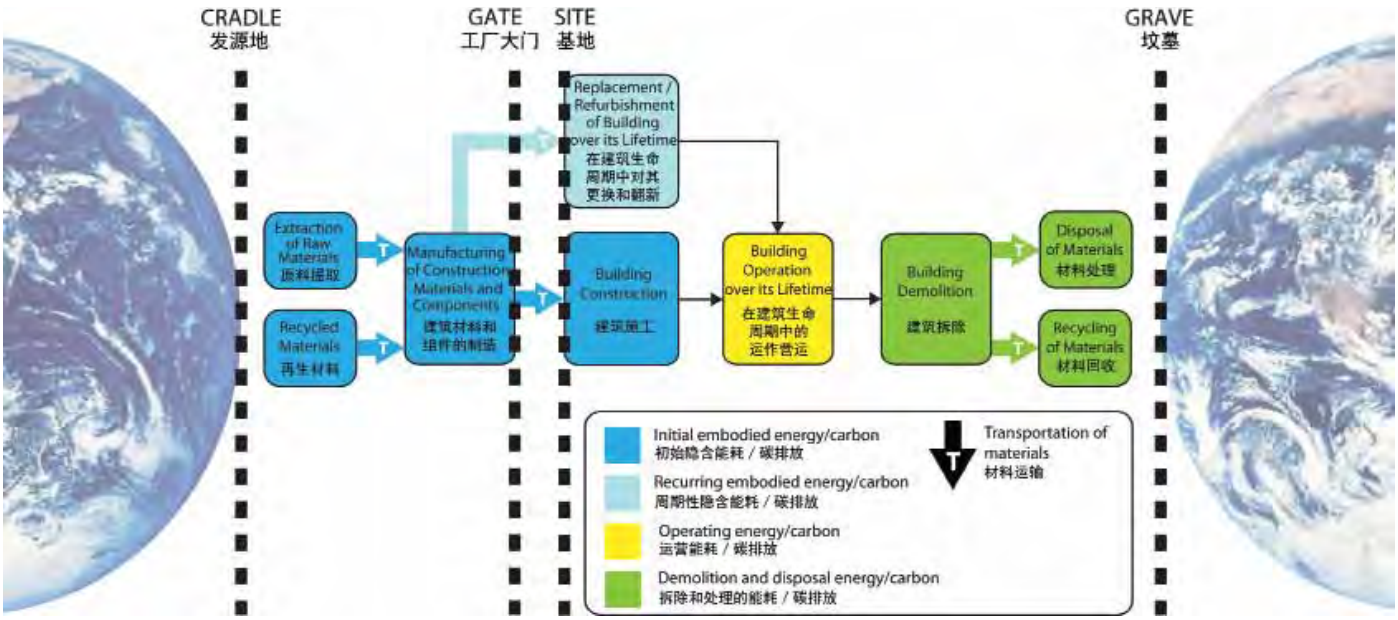

Figure 1. Building life-cycle environmental impacts. (Source: Philip Oldfield)
图1. 建筑生命周期对环境的影响。（来源：Philip Oldfield）

extraction of the raw materials needed for construction, to the disposal and recycling of materials after demolition. This complete boundary, encompassing all the activities related to a building's creation, use and removal is known as cradle-to-grave (see Figure 1).

As outlined in Figure 1, the embodied energy / carbon of a building comprises the energy / carbon required to extract, transport and refine the raw materials (e.g. mining iron ore), manufacture the building components (e.g. creating steel beams) and construct, renovate and maintain the building[1] (Fay et al., 2000). The total embodied energy of a building can be considered the sum of its initial embodied energy and its recurring embodied energy. The former is the energy required in initially creating the building, whilst the latter is the energy required in maintaining, repairing and refurbishing the building over its effective life (Chen et al., 2001).

Most current sustainability thinking is informed by the fact that roughly 20% of a building's total environmental impacts are embodied in the materials with the remaining 80% due to operations (Kestner, 2009), although recent research suggests this is becoming closer to 40% embodied and 60% operational for an average building (Sturgis & Roberts, 2010). However, there is still debate regarding the relative importance of embodied energy in the built environment, with figures for embodied energy in office buildings found to range from equivalent to 3.1 years (Scheuer et al., 2003) to 40 years (Treloar et al., 2001) of operating energy.

Tall Buildings and Embodied Energy

One of the many criticisms leveled at tall buildings is the high quantities of structure and materials required to support, clad and service them, coupled with energy intensive construction at height. A well known study by Treloar et al. (2001) examining initial embodied energy in five office buildings in Melbourne, Australia – 3, 7, 15, 42

造、使用和移除的有关活动，也是所谓的“从摇篮至坟墓”（见图1）的整个过程。

如图1所示，建筑的隐含能耗和碳排放包括了对原材料本身的提取、运输和提炼（如开采铁矿石），生产建筑物构件（如制造钢梁），以及施工、改造与建筑维护所需的能耗和碳排放[1]（Fay等人，2000年）。总建筑隐含能耗可视为初始隐含能耗与其持续产生隐含能耗的总和。前者是在最初建造建筑时所需的能耗，而后者则是在建筑服务生命中用来维护、修缮和翻新建筑所需要的能耗（Chen等人，2001年）。

目前，大多数可持续发展认为建筑总体环境影响大约20%来自于隐含能耗，其余80%来自于实际使用能耗（Kestner，2009年），当然近期也有研究表明：对于一个普通建筑的总体环境影响，隐含能耗将近40%，而使用能耗则占60%（Sturgis与Roberts，2010年）。然而，隐含能耗对于建筑环境的重要性仍存有争议，就一个办公楼的隐含能耗数据来说，其范围自相当于3.1年的实际使用能耗（Scheuer等，2003年）至相当于40年的实际使用能耗（Treloar等，2001年）不等。

高层建筑与隐含能耗

在许多以高层建筑为矛头的批判中，有一条是针对高层建筑需要大量的结构和材料来支撑、围合并且服务高层建筑，加之在高度上的能源密集型建设。Treloar等人（2001年）做过一个非常著名的研究，即在澳大利亚的墨尔本选择了五个办公楼进行初始隐含能耗的测试，其建筑高度分别为3层、7层、15层、42层和52层。实验表明：两栋高层建筑较两栋低层建筑的单元建筑总面积约多出60%的隐含能耗（见图2）。这一结果致使Treloar（以及许多建筑界的人士）提出：如有可能则应减少使用高层建筑的方案（Treloar等人,2001年）。然而，笔者驳斥这种观点，并认为该表象仅仅是对围绕着隐含能耗和高层建筑问题的一种简单化和间或性不准确的写照[2]。例如，改变用于比较高层建筑和低层建筑的隐含能耗的功能单元因素，则会引发大相径庭的结果。Norman

[1] It is worth noting that some definitions of embodied energy include the energy associated with the building's demolition and disposal. However, within the scope of this paper, demolition and disposal energy is categorized separately. This approach is consistent with the majority of published embodied energy studies and definitions.
[1]值得注意的是，有些隐含能耗的定义包括了建筑在被拆除和处置阶段所需要消耗的能源。然而，本文将侧重于将拆除和处置能耗分离出来并单独归类，从而与主流出版物对隐含能耗的研究和定义保持一致。

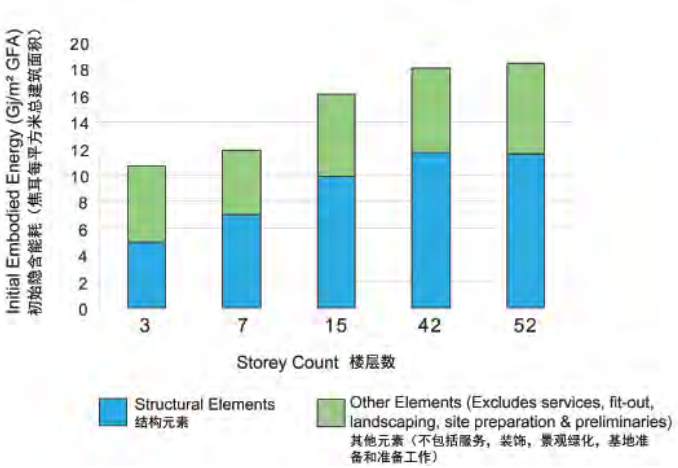

Figure 2. Embodied energy of five buildings in Melbourne, Australia. (Source: Philip Oldfield, data from Treloar et al., 2001)
图2. 澳大利亚墨尔本五座建筑的隐含能耗。（来源：Philip Oldfield，数据来源于Treloar等人2001年的研究）

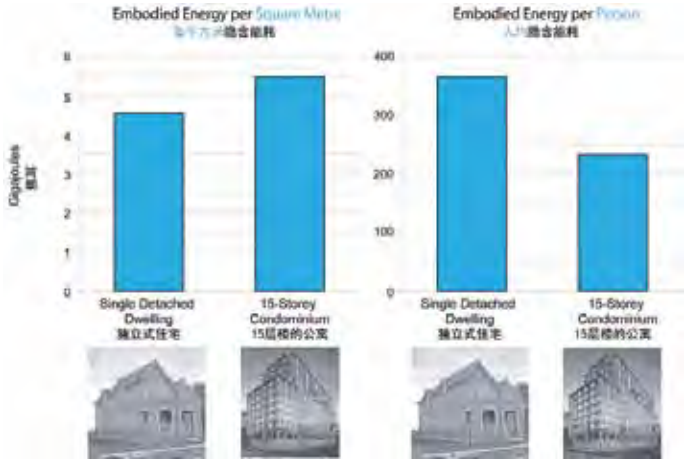

Figure 3. Embodied energy comparison of detached suburban dwellings and 15-storey condominiums, in Toronto, Canada. (Source: Philip Oldfield, data from Normal et al., 2006)
图3. 加拿大多伦多独立郊区住宅与15层公寓的隐含能耗比较。（来源：Philip Oldfield，数据来源于2006年Normal等人的研究）

and 52 stories in height – shows the two high-rise buildings have approximately 60% more embodied energy per unit gross floor area than the two low-rise buildings (see Figure 2). This has led Treloar (and many others in the architectural community) to suggest alternatives to tall buildings should be sought where possible (Treloar et al., 2001). However, the author disputes this point of view, and suggests that it presents a simplistic and at times inaccurate portrayal of the issues surrounding embodied energy and tall buildings. For example, changes to the functional unit[2] used to compare the embodied energy of high-rise and low-rise buildings can significantly influence the results. A study by Norman et al. (2006) compares the embodied energy of detached suburban dwellings with that of 15 storey condominiums in Toronto, Canada. The findings, presented in Figure 3, show that when compared per unit floor area, the high-rise condominiums do indeed have greater embodied energy, but when compared per person the condominiums have 33% less embodied energy than the low-rise dwellings. This fact is due to high-rise apartments accommodating more residents per unit floor area than detached, low-rise dwellings.

However, the issue of embodied energy and high-rise is not simply a case of being better or worse than low-rise construction, and there are a variety of advantages and disadvantages to building tall in terms of embodied energy. These are outlined in Table 1 below.

Tall Buildings and Embodied Energy / Carbon: Advantages 高层建筑和隐含能耗 / 碳排放：优势	Tall Buildings and Embodied Energy / Carbon: Disadvantages 高层建筑和隐含能耗 / 碳排放：劣势
Residential high-rise typically accommodates more occupants per unit area than single-detached housing, which can result in reduced embodied energy per resident 高层住宅通常比单一的独立式住宅容纳更多的居民，这样的直接结果是人均隐含能耗的降低。	Increased height means increased structural material requirements to provide resistance to wind and lateral loads 高度的增加意味着对结构材料需求量的增加，来抵抗风荷载和横向荷载。
Increased density of cities can reduce infrastructure requirements, thus saving materials for road construction, water and waste supplies, etc. 城市密度的增加降低了对基础设施的需求，从而为道路建设，给水和废物回收等提供了物质资源。	Construction at height requires lifting materials often hundreds of metres into the sky (energy requirements for craning, pumping concrete, etc) 高空施工往往需要把材料提到几百米的高空。（对吊拉材料和泵送混凝土的能量需求）
Repetition of floor plates, facade and other elements allows for prefabrication, re-use of formwork, etc. 重复的楼板，幕墙立面和一些建筑配件有机会预制和对模具的再次利用。	Tall building construction often requires specialist materials / components which may not be available locally 高层建筑的施工往往需要特种材料 / 组件，很有可能在当地无法取得。
Tall buildings are generally refurbished or renovated rather than demolished and replaced with entirely new constructions 高层建筑通常是翻新或返修，而不是整体建筑的完全拆除和替换。	Reduced net-to-gross efficiencies as compared to low-rise (e.g. more materials needed for less usable space) 和地层建筑相比需要减少净 / 毛面积效率（例如，高层建筑可能需要更多的材料来建造较少使用到的空间。）
	Due to greater wind speeds at height, natural ventilation strategies often require additional materials such as double-skin facades 由于高空较大风速的影响，自然通风策略往往需要额外材料的帮助，比如双层幕墙立面。
	Limited opportunities for timber frame construction which has reduced embodied energy as compared to steel or concrete systems - see Cole & Kernan (1996) 非常有限的机会使用木质框架结构，因为较钢结构或是混凝土结构而言，木结构往往具有更低的隐含能耗——见Cole & Kerman (1996)

Table 1. Environmental advantages and disadvantages of tall buildings from an embodied energy / carbon standpoint. (Source: Philip Oldfield)
表1. 高层建筑以隐含能耗 / 碳排放为立足点的环境优劣势。（来源：Philip Oldfield）

Case Study: 30 St. Mary Axe, London

To further examine the importance of embodied energy / carbon in tall buildings, a life cycle carbon analysis of the 180 meter-tall 30 St Mary Axe building in London (often referred to as the Swiss Re Building, or the "Gherkin" – see Figure 4) is presented.

Methodology

The scope of this analysis is cradle-to-end of life, encompassing all CO_2 emissions until the end of the building's effective life, but excluding demolition / disposal of materials. The analysis boundary includes

[2] The purpose of a 'functional unit' within a life cycle or embodied energy / carbon analysis is to present a reference to which the inputs and outputs can be related (ISO, 1997). This allows for two, or more, completely different products, services or buildings, to be compared on equal footing.
[2] 对生命周期或者隐含能耗 / 碳排放分析中的"功能单元"进行分析的目的，旨在表明输入条件和结果实为相关联的（ISO，1997年）。这可供两个或者两个以上完全不同的产品、服务或者建筑于平等的基础上进行比较。

Figure 4. St Mary Axe, London. (Source: Philip Oldfield)
图4. 圣玛丽艾克斯30号大楼，伦敦 （来源：Philip Oldfield）

all major architectural elements, but excludes fit-out, furniture and the embodied carbon of local infrastructure and landscaping. The analysis is taken over a 50-year period from 2004, when the tower was completed, to 2054.

When comparing operational and embodied carbon most studies use what is defined as a 'static model' for determining life-cycle operational emissions. That is, the studies assume that operating emissions will be the same for each year into the future (Jones, 2011). However, this is simply not the case as the carbon intensity of electricity is changing, and more often than not decreasing, as countries embrace 'greener' power generation strategies on a national scale. For example, The UK, like many countries, is undertaking a significant decarbonization of its electricity network in order to meet the ambitious greenhouse gas reduction targets set by the government. The UK Climate Change Act sets a target of an 80% reduction in national greenhouse gas emissions by 2050, and a 26% reduction by 2020 against a 1990 baseline (UK Parliament, 2008) with similar targets existing in many countries around the world.

To meet these targets, there will need to be a shift in electricity generation from fossil fuels to nuclear, renewable technologies and carbon capture systems. The result is the carbon intensity of electricity in the UK is estimated to reduce significantly in the coming decades. For example, in the year 2004 (when 30 St Mary Axe opened) the carbon intensity of UK electricity was 0.539kgCO_2/kWh (Committee on Climate Change, 2010a). By 2050, this will have decreased to an estimated 0.038kgCO_2/kWh (Committee on Climate Change, 2010b), a 14-fold reduction. This is illustrated in more detail in Figure 5.

The life cycle analysis presented here then, acknowledges this changing carbon intensity of electricity supply, and factors it into the calculations. The methodology for determining the operating emissions over the 50 year life-cycle first takes the annual energy

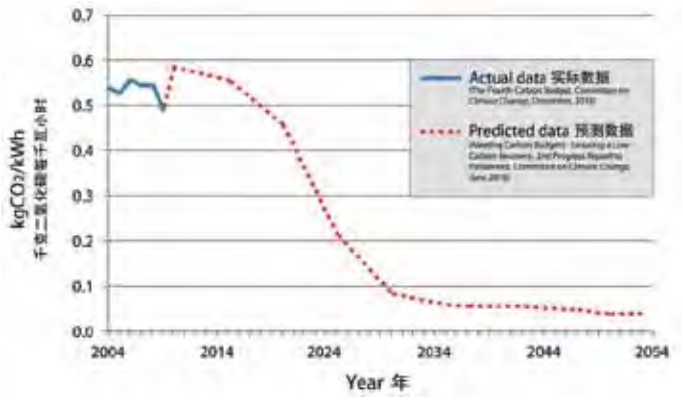

Figure 5. CO2 intensity of UK electricity, 2004 – 2054. (Source: Philip Oldfield, data from Committee on Climate Change, 2010a & 2010b. Figures for 2051 – 2054 assumed to be the same as 2050).
图5. 英国电力在2004年至2054年间的二氧化碳排放强度。（来源：Philip Oldfield，数据来源于气候变化委员会，2010a和2010b。2051至2054年的数据被视为与2050年相同。）

等人（2006年）进行的一项研究以加拿大多伦多的一栋独立式的郊区住宅和一栋15层的公寓进行比较研究。结果显示，如图3所示，以单位面积进行比较时，高层公寓确实具有更大的隐含能耗，但以人均为单位进行比较时，高层公寓相对低层住宅却少了33%的隐含能耗。这实际上是由于相较于独立式的住宅，高层公寓可以容纳更多的居民比率。

然而，隐含能耗和高层建筑的问题较低层建筑，并非简单的争论好与坏的问题，根据隐含能耗，其中蕴藏着各种各样的优劣势。参见下表1。

案例分析：伦敦圣玛丽艾克斯30号大楼

为了进一步研究隐含能耗和碳排放在高层建筑中的重要性，我们对180米高位于伦敦的圣玛丽艾克斯30号大楼（通常被叫做瑞士再保大楼，或者“歌金”——参见图4）的生命周期碳排放数据进行分析。

方法

这一分析范围将从“摇篮到生命结束”，即在该建筑有效服务寿命中包括所有的二氧化碳排放，但是不包涵材料的拆除和处置阶段所产生的碳排放量。这一分析的界限将包括所有主要的建筑元素，但是不包涵装修、家具和场地基础设施还有环境美化的隐含碳排放。该分析将会涵盖自2004年该高层建筑完工以来跨度为50年的周期，直至2054年。

当比较运营过程中的碳排放和隐含碳排放的时候，大部分研究是采用了一种被定义为“静态模型”的方式来确定生命周期中所使用过程中的排放量。也就是说，研究本身假定了其使用过程中的排放量在未来的每一年中都是固定不变的（Jones，2011年），然而实际可能并不是这样。因为电力的碳强度正在变化，更多的情况可能并不是衰减；同样因为在国家范畴内，绿色发电策略正在被大力推行和拥护。例如英国，同其他许多国家一样， 正在开展一种以电力系统脱碳化的独特技术，旨在满足政府所提出的以满足温室气体的大量减排目标。英国气候变化法案设定的目标是在2050年之前实现温室气体减排80%，在2020年之前实现减排26%，而这则是相对1990年的底线而言的（英国议会，2008），而这一目标与当今全球许多国家所制定的减排目标是相类似的。

为了实现这些目标，我们需要把电力生产从原有的石化燃料向核能、可再生能源技术和碳获取系统进行转变。其结果很有可能体现在英国未来的数十年间电力生产的碳强度将显著减少。例如，在2004年（圣玛丽艾克斯30号大楼完工运作之初），英国电力的碳强度为0.539千克二氧化碳 / 千瓦时（气候变化委员

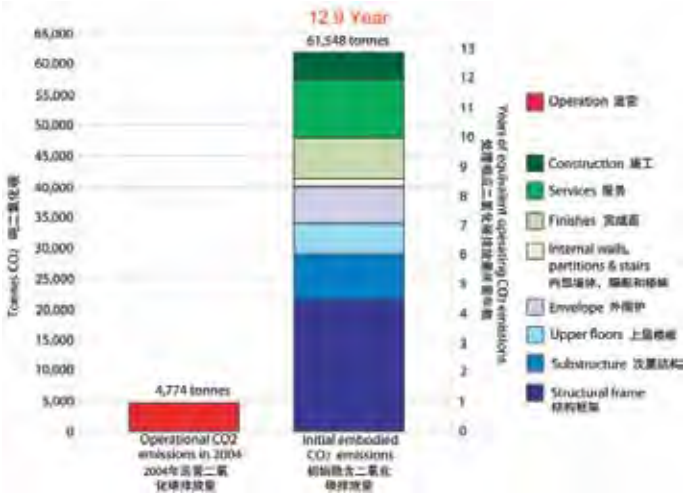

Figure 6. Comparison between 30 St Mary Axe initial embodied carbon and operational carbon for the year 2004. (Source: Philip Oldfield)
图6. 比较2004年圣玛丽艾克斯30号大楼的初始隐含碳排放和运营碳排放。（来源：Philip Oldfield

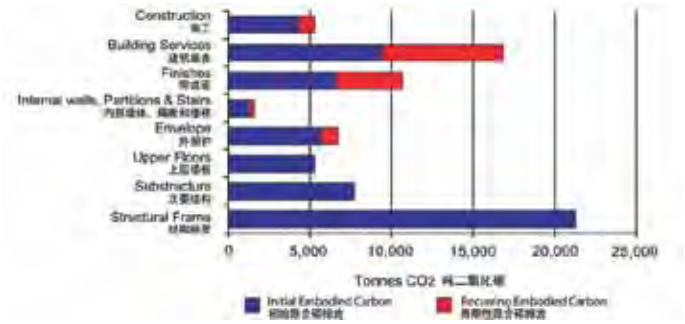

Figure 7. 30 St Mary Axe total embodied carbon by building element, including recurring embodied carbon over a 50 year life cycle. (Source: Philip Oldfield)
图7. 圣玛丽艾克斯30号大楼建筑构件的总体隐含碳排放，包括50年生命周期中周期性的隐含碳排放。（来源：Philip Oldfield）

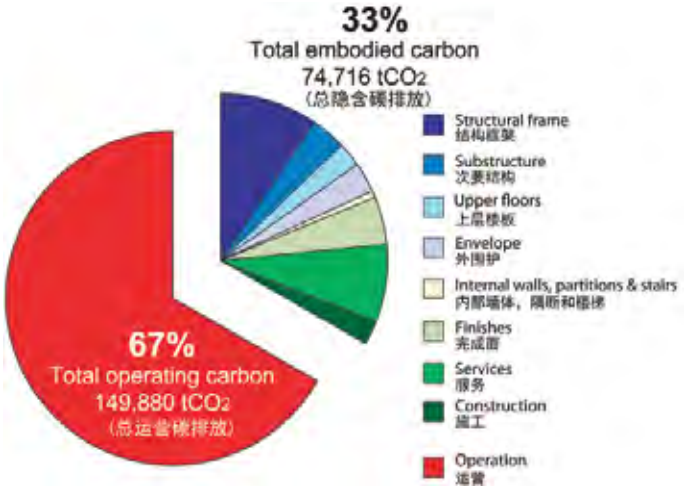

Figure 8. 30 St Mary Axe total life-cycle carbon emissions over a 50 years (Source: Philip Oldfield)
图8. 圣玛丽艾克斯30号大楼在50年生命周期中的总体碳排放量。（来源：Philip Oldfield）

requirements of the building from CIBSE benchmark data. These are listed as 95kWh/m^{2}GFA electrical energy requirements and 120kWh/m^{2}GFA gas requirements for an air-conditioned office building (Field, 2008). The carbon intensity of gas will stay the same throughout the building's life at 0.19kgCO_2/kWh, while the carbon intensity of the electrical energy component will vary as outlined previously.

The methodology for determining the building's embodied carbon consists of firstly calculating building material quantities from published sources and from estimations by the author from drawings. Wastage of materials through manufacturing and construction are also factored in. Material quantities are then multiplied by embodied carbon data for the UK context taken from the Inventory of Carbon and Energy (Hammond & Jones, 2008a) to give the embodied carbon within a cradle-to-gate framework (e.g. all CO_2 emissions up until the materials reach the factory gate). The emissions from the transportation of materials are determined by firstly locating the factories where components were assembled from published data, calculating the distance to the site, and then determining the emissions using the carbon intensity of freight transportation taken from DEFRA, 2008. The carbon impact of construction is assumed as 7.5% of cradle-to-site embodied emissions based on research by Scheuer et al., 2003. The recurring embodied carbon - the emissions caused by repair, maintenance and refurbishment over the building's lifetime – are taken from a similar study on an office building by Davis Langdon (2009). An overview of this methodology, along with a full list of building characteristics, assumptions and data sources is outlined in Table 2.

Results

The results of the life cycle carbon analysis of 30 St Mary Axe are shown in Figures 6 – 8. The initial embodied carbon is 61,548 tons of CO_2, or 955kgCO_2/m^{2}GFA as shown in Figure 6. As expected this is higher than values in low-rise buildings. For example, Hammond & Jones 2008b found the embodied carbon of low-rise residential dwellings in the UK to be 403kgCO_2/m^{2}GFA on average (58% lower than this study), while Davis Langdon found the initial embodied carbon of an eight story office building in the UK to be 764kgCO_2/m^{2}GFA (20% lower than this study). Also corresponding with previous research, it is the structural elements (structural frame, substructure and upper floors) which make the largest contribution to 30 St Mary Axe's embodied emissions being

会，2010a）。直至2050年，这一数据将降低一个估计值约为0.038千克二氧化碳／千瓦时（气候变化委员会，2010b），减少了近14倍。详见图5。

在这里所介绍的生命周期分析是承认这种电力供应系统碳强度的变化和对其计算的影响。要衡量一个五十年以上的周命周期运营排放量的方法，首先是按照CIBSE的基准数据来获取建筑每年的能源需求量。而对于一个使用空调的办公楼来说这些数据已经被罗列出来了：95千瓦时／平方米总建筑面积的电能需求和120千瓦时／平方米总建筑面积的气需求（Field 2008）。气的碳排放强度在整个建筑的生命过程中将稳定在0.19公斤二氧化碳／千瓦时不变，而电能组件的碳排放强度将会如之前概括的一样起伏变化，这也在图4中所呈现。

要衡量一个建筑隐含碳排放的方法首先是要通过公布的资料来源和设计师图纸的评估来计算所需要的材料数量。整个制造过程和施工过程中所产生的材料浪费也应该被考虑在内。材料数量再乘以隐含碳排放数值，这个数值来自碳和能源清单（Hammond & Jones，2008a）为了英国当地环境而给予从材料新生至工厂门口被工厂加工之前隐含碳排放量的数值（例如，所有二氧化碳的排放量直到这个材料抵达工厂大门前的总和）。衡量运输材料的排放量首先是从公布的数据中确定组装组件工厂的位置，计算它到基地之间的距离，然后按照《DEFRA，2008》来计算货运过程中碳排放强度的排放量。基于《Scheuer et al.，2003》所做的研

30 St Mary Axe Characteristics 圣玛丽艾克斯30号大楼特性		Sources 来源
Gross Floor Area 高层住宅通常比单一的独立式住宅容纳更多的居民，这样的直接结果是人均隐含能耗的降低。	64,469m²	Powell, 2006
Façade 城市密度的增加降低了对基础设施的需求，从而为道路建设，给水和废物回收等提供了物质资源。	24,000m² Double-skin glazed curtain walling 24,000m² 双层玻璃幕墙	Powell, 2006
Operational Carbon Emissions 重复的楼板，幕墙立面和一些建筑配件有机会预制和对模具的再次利用。	95kWh/m²GFA electrical energy requirements and 120kWh/m²GFA gas requirements 95千瓦时每平方米（总建筑面积）的电能需求和 120千瓦时每平方米（总建筑面积）的天然气需求	Taken from the benchmark data presented in Field, 2008. The carbon intensity of gas is 0.19kgCO2/kWh (Field, 2008), whilst the changing carbon intensity of electricity is outlined in Figure 4 在2008年Field的研究报告中采样的基准数据为： 气体的碳强度是0.19千克二氧化碳每千瓦时（Field，2008），而电力的碳强度变化在图四中有所概括。
Building Material Quantities 高层建筑通常是翻新或返修，而不是整体建筑的完全拆除和替换。	Various 各类	Weight of building structural steel and foundations from Powell, 2006. Steel decking data taken from Richard Lees Steel Decking, 2009. Weight of facade materials courtesy of an estimate from Viracon / Harmon Inc. Figures for internal walls, partitions, stairs, finishes and building services taken from a study in Davis Langdon, 2009. In some instances material quantities are estimated by the author from drawings 取自Powell,2006研究，建筑结构钢和基础的重量。取自Richard，2009年槽型钢装饰，钢板的数据指标。取自Viracon / Harmon公司，对幕墙材料重量的积极评估。Davis Langdon在2009年的研究，内部墙体，分隔墙，楼梯，饰面和建筑服务的数据。在某些情况下，笔者可从图纸本身大致估量所需材料的数量。
Material Wastage Factors	Various 各类	Chen et al., 2001
Embodied carbon Of Materials (Cradle-To-Gate)	Various 各类	Hammond & Jones, 2008a
Recurring Embodied Carbon Of Materials	Various 各类	Annualised figures for recurring embodied carbon taken from a study in Davis Langdon, 2009 取自Davis Langdon 2009年的研究，定期隐含碳排放的年度数据。
Material Locations	Structural Steel - The Hague / Brussels; Facade - Aesch, Switzerland; Concrete – assumed as 50km 结构钢材 – 海牙 / 布鲁塞尔；立面幕墙 – Aesch，瑞士；混凝土 – 大约50公里距离。	Locations as per the completed building, taken from Powell, 2006 取自Powell，2006年研究，位于每个建成建筑。
Emissions from Freight Transportation	0.132KgCO2/tkm	DEFRA, 2008
Construction Emissions	Assumed as 7.5% of cradle-to-site embodied emissions 假定为从材料生产到现场的隐含排放量的7.5%.	Estimates in the literature suggest energy from construction is between 1.2 – 10% of the embodied energy of materials (Scheuer et al., 2003). A figure of 7.5% was chosen to acknowledge the generally large energies needed for construction at height. 评估表明，施工中产生的能耗是材料隐含能耗的1.2%到10%之间（Scheuer 等人.，2003）。 而7.5%则是被公认的一个通常高层建筑建设所需大量能耗的数值。

Table 2. Environmental advantages and disadvantages of tall buildings from an embodied energy / carbon standpoint. (Source: Philip Oldfield)
表2. 高层建筑以隐含能耗 / 碳排放为立足点的环境优劣势。 （来源：Philip Oldfield）

responsible for 56% of the initial embodied carbon.

The recurring embodied carbon is shown in Figure 7. The building has a recurring embodied carbon of 13,168 tonnes of CO_2, or 204kgCO_2/m²GFA, with recurring emissions contributing 17.6% of total embodied carbon. It can also be seen that whilst the structural elements are the greatest contributor to initial embodied carbon, building services and finishes also have a significant environmental impact due to their regular refurbishment and maintenance.

The total life-cycle carbon emissions of the building over a 50 year life span stands at 224,596 tons of CO_2, or approx 3.5 tons of CO_2 per meter gross floor area (see Figure 8). The total embodied carbon of the building stands at 74,716 tons of CO_2, or 1,159kgCO_2/m²GFA, which equates to 33% of the total life-cycle carbon emissions. This value is higher than older studies, such as those by Suzuki and Oka (1998), who suggest embodied carbon in multi-story buildings in Japan contributes on average 22% of total life-cycle emissions, but lower than recent suggestions by Sturgis & Roberts (2010), who note that embodied carbon can contribute up to 45% of total life-cycle emissions in modern office buildings.

The Growing Importance of Embodied Carbon

Whilst the study above suggests that reducing tall building operational emissions has the best potential for improving their environmental performance, it is clear embodied emissions are not insignificant and

究，施工工程的二氧化碳排放影响被视为从原料生产到工程基地的隐含排放量的7.5%。定期的隐含碳排放——建筑整个生命过程中维修，维护和翻新等原因所产生的排放量——来源于一个相似的《Davis Langdon （2009）》对一个办公楼建筑研究数据结果。纵观这个方法和一个完整的建筑特性，假设和数据来源的列表在表2中有具体的概括。

结论

圣玛丽艾克斯30号大楼生命周期碳排放的分析结果呈现在图6至图8中。图6所展示的是初始隐含碳排放是61548吨二氧化碳，即955公斤二氧化碳 / 平方米总建筑面积。正如预料中的，这一数值相对低层建筑也是较高的。例如，Hammond & Jones 2008b，他们发现在英国的低层住宅住房的隐含碳排放平均是403公斤二氧化碳 / 平方米总建筑面积（比该案例要低58%），而Davis Langdon则发现英国的一座八层办公楼的初始隐含碳排放达到了764公斤二氧化碳 / 平方米总建筑面积（比该案例低20%）。同时与之前的研究相一致的是结构体（结构框架、副结构和上层楼板）占了圣玛丽艾克斯30号大楼初始隐含碳排放绝大因素约为总数的56%。

持续性隐含碳排放如图7所示。该大楼大约有13168吨二氧化碳的持续隐含碳排放，即为204千克二氧化碳 / 平方米总建筑面积，还有持续性排放量约为总隐含碳排放的17.6%。同时我们也可以看到，虽然结构体在整个初始隐含碳排放中占有绝大部分比重，建筑服务阶段和室内外的最终完成面同样也对周边环境影响起到了不可忽视的作用，因为我们需要对建筑定期地进行翻新和维护。

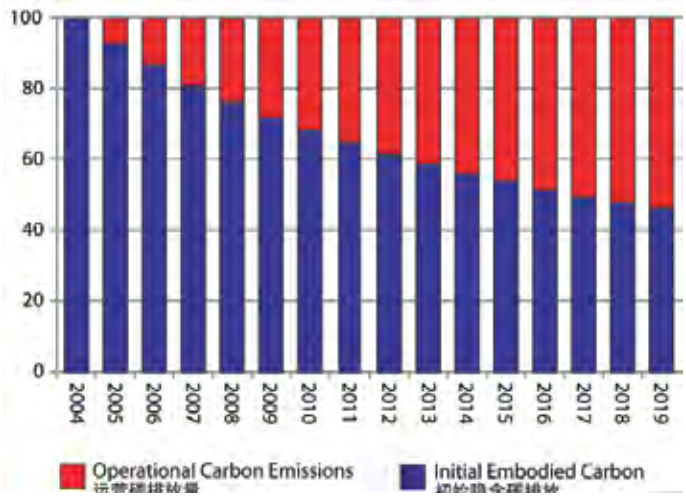

Figure 9. 30 St Mary Axe initial embodied carbon and operating carbon emissions 2004 – 2020. (Source: Philip Oldfield)

图9. 圣玛丽艾克斯30号大楼在2004年至2020年间初始隐含碳排放和运营过程中的碳排放量。（来源：Philip Oldfield）

strategies to reduce embodied carbon – particularly to the structural elements, services and finishes – will have a positive impact on tall building sustainability. In addition, the author suggests that embodied emissions will actually play a more significant role in the future for the following reasons;

Short Term Carbon Reduction Targets

Over the next decade, it is clear that vast anthropogenic green house gas emission reductions will have to occur globally in order to reduce the impacts of climate change. The Intergovernmental Panel on Climate Change (IPCC), for example, states that for low and medium CO_2 concentration stabilization levels, developed countries as a group would need to reduce their emissions by 2020 on the order of 10% to 40% below 1990 levels (Levine et al., 2007). Any reduction to a recently completed tall building's embodied carbon would be made in this short-term future, long before the building is even occupied, whilst operational savings may take many years to accumulate. Looking at the 30 St Mary Axe study in Figure 9, by 2020 46% of the total carbon emissions of the building will be due to its initial embodied carbon. For a tall building completed today, this figure would be much higher.

Increasing Energy Efficiency

The life-cycle carbon analysis of 30 St Mary Axe presented here assumes operational emissions typical of a recently completed office building. However, due to increased environmental awareness, stricter building regulations and technological advances operational emissions are likely to reduce significantly in the coming years. In tall buildings we are already seeing completed and under construction towers that claim to have large reductions in operating energy requirements as compared to the norm. For example, the Bank of America Tower, New York will use 50% less energy than the norm (Fox, 2008) and the Pearl River Tower, Guangzhou 58% less than the norm (Frachette & Gilchrist, 2008). It is clear that such examples will become more typical in the future, and as they do, embodied emissions will play a much greater role in the tall building life-cycle environmental impacts.

Strategies for Reducing Embodied Carbon in High-Rise

As a conclusion to this work, the author outlines below a number of strategies to reduce embodied energy / carbon in high-rise under the headings of reduce, recycle and retrofit.

该建筑生命周期为 50年寿命时间中总的碳排放量高达224596吨二氧化碳，即为建筑总面积中每平方米3.5吨（见图8）。建筑的隐含碳排放则是74716吨二氧化碳，即为建筑总面积中每平方米1159千克二氧化碳，相当于总生命周期中碳排放量的33%。这个数值高于一些相对较旧的研究，就像Suzuki and Oka（1998）等人所提出的，在日本的多层建筑的隐含碳排放平均维持在总体生命周期排放量的22%，但是这依然低于Sturgis & Roberts (2010)所提出的数值，他们指出现代办公楼建筑的隐含碳排放可以高到总体生命周期排放量的45%。

隐含碳排放重要性的日益增加

虽然上述研究表明降低高层建筑运营过程中的排放量对改善其周边环境有最好的表现效果，但是隐含排放量也并非是微不足道的，战略上也需要降低隐含碳排放——特别是结构构件，服务过程和内外饰面——将会对高层建筑的可持续发展产生非常积极的作用。此外，笔者也认为隐含排放量在未来将扮演更为重要的角色，原因如下：

短期碳减排目标

在未来十年中，大量人为产生的温室气体排放量的削减将在全球范围内产生，并且明显会降低对气候变化的影响。政府气候变化专门委员会（IPCC）对相应条例也有所规定，例如，其指出为了达到稳定的中低二氧化碳浓度水平，发达国家作为一个群体，则需要在2020年之前将其排放量降低至1990年排放量10%至40%的水平（Levine等人，2007）。任何已建成高层建筑对隐含碳排放的削减只是短期性的，远在这栋建筑被完全使用其功能之前，同时运营过程中产生的碳排放的削减则可能需要很多年的积累。纵观圣玛丽艾克斯30号大楼如图9，在2020年之前，46%该建筑的碳排放量直接是由初始隐含碳排放构成的。

提高能源效率

对圣玛丽艾克斯30号大楼生命周期碳排放量的分析中，认为其运营时产生的排放量是一座现代已建成办公大楼的典型特征。然而，由于环保意识的增加，更严格的建筑法规和技术进步使得在运营时产生的排放量有可能在未来的几年中显著减少。在许多高层建筑中，一些已建或者在建的塔楼已经宣布，相比较规范要求其运营时对能源需求已经大量地削减。例如，纽约的美国银行大厦将使用比标准少50%的能源（Fox，2008），广州的珠江大厦只用了标准能源需求的58%（Frachette & Gilchrist，2008）。很显然，这样的例子在未来会变得更为普遍，就像他们所做的那样，隐含排放量将在高层建筑整个生命周期环境影响中起到更大的作用。

降低高层建筑隐含碳排放的策略

作为这项工作的一个总结，在一系列降低高层建筑隐含能耗／碳排放的策略中，笔者概括成为三个小标题：降低、循环再生和改造。

降低

很显然，减少高层建筑材料的数量将对隐含碳排放有积极影响，特别是诸如结构材料，服务和饰面。定期地开展高层建筑设计，诸如结构优化和结构防火工程，不仅能减少隐含碳排放还能降低成本。追求高层建筑的被动设计策略同样也可以减少隐含碳排放。例如位于波恩的德国邮政大楼，该建筑采用了双层幕墙系统，内部使用了过渡中庭来帮助建筑在没有中央设备系统的情况下，仍然能做到自然通风。同时，我们也清楚地认识到，隐含碳排放和排放量的控制成本相当于建造多一层大于7000平方米的建筑幕墙立面，所以其意义既有环境方面的优势与又有经济上的优势。这些措施包括取消所有竖向通风管道和去除整个设备层，以

Reduce

It is obvious that reducing the quantities of materials used in tall buildings will have a beneficial impact on their embodied carbon, especially in terms of structural materials, services and finishes. Strategies such as structural optimization and structural fire engineering are routinely undertaken on high-rise designs to achieve just that, reducing embodied carbon but also decreasing cost. Pursuing passive design strategies in high-rise can also reduce embodied carbon. The Deutsche Post Tower in Bonn, for example, utilizes a double-skin facade with internal atria which allows for the building to be naturally ventilated without a central mechanical system. Whilst there is quite clearly an embodied carbon and economic cost for creating an additional layer of skin over 7,000m^2 of building facade, there are also environmental and economic advantages. These include the elimination of all vertical air distribution shafts and the removal of an entire mechanical floor saving materials required for technical building equipment, and 1,000m^2 of rentable floor space (Jahn et al., 2004).

Recycle

A further strategy to reduce embodied carbon in tall buildings is to use recycled materials in place of virgin / non-recycled materials. In particular, recycled metals (steel, aluminum, copper, etc) and cement replacements in concrete such as fly ash or blast furnace slag, can have a significantly reduced embodied carbon as compared to their virgin / non-recycled content equivalents.

Retrofit

The upgrading and retrofitting of existing structures can also be used to reduce embodied carbon requirements over a tall building's lifetime. Whilst many construction elements such as facade, services, finishes, etc, need regular replacement, a tall building's structure may last for hundreds of years, allowing for a building to be upgraded or improved, without the need for total demolition and replacement at a greater environmental cost. Many high profile tall buildings including Taipei 101, Taipei, the Empire State Building, New York and Willis Tower, Chicago are following such a route, improving their environmental performance without demolishing the entire building and starting again.

While this is a strategy used across all typologies, tall buildings do have an inherent advantage in this case. Whereas low-rise buildings are regularly pulled down and replaced, tall buildings are very rarely demolished due to their iconic stature in cities and the high investment that goes into every project – both financially and professionally. As shown in Table 3, very few tall buildings have actually ever been demolished. In fact, there have been 727 tall buildings of 200m or greater in height and 2,573 of 150m or greater in height constructed globally as of September, 2011. Of these only one building 200m or taller has been demolished[3], and only five 150m or taller demolished. So, while the construction of a tall building may be a significant carbon investment, their long life-cycles are beneficial in terms of embodied energy / carbon.

及节省技术上建筑设备所需要用到的所有材料，这些节省下来的1000平方米空间可以成为额外出租空间（Jahn 等人， 2004）。

循环再生

进一步的降低高层建筑隐含碳排放的策略是用可再生材料来替换新生或不可再生材料。特别是可再生金属（如钢，铝，铜等）和水泥代替混凝土，如粉煤灰或者高炉矿渣，如果与等量的新生或不可生材料相比较的话，使用可再生材料可以显著降低隐含碳排放。

改造

高层建筑寿命周期中，可以通过对现有结构的升级与改造来降低隐含碳排放的要求。虽然许多工程元件诸如幕墙、服务、饰面等需要定期更新，通常一个高层建筑的结构可以持续数百年，应允许建筑本身的升级或改进，没有因完全推倒或替换带来更大的对环境成本的消耗。许多备受瞩目的摩天大楼包括台北101、纽约的帝国大厦、芝加哥威利斯大楼都遵循了这样的原则，整个建筑不拆除，而是再次开始修缮其对环境的良好表现。

虽然这个战略适用于各种建筑形式，但是高层建筑在这种情况下便具有了先天优势。而低层建筑通常是推倒更换的，无论是从经济方面还是专业角度高层建筑则很少被拆除原因有以下两点，一是这些高层建筑本身在城市中的标志性意义，二是每一个项目的巨额投资。如表3所示，只有极少数的高层建筑实际上是被拆除的。事实上，直至2011年9月全球已建成的高层建筑中，有727栋高度是在200米或者200米以上，有2573栋高度是在150米以上。在这之中，200米以上的大楼被拆毁的只有一座[3]，而150米以上被拆毁的也只有五座。所以，建造一个高层建筑，可能会消耗相当大的碳排放，就整个建筑生命周期来看，建造高层建筑可能就隐含能耗和碳排放这个主题来说对人类更有益。

Rank 排名	Name 名称	City 城市	Completed 完成年份	Demolished 拆除年份	Height (m) 高度（米）
1	Torre de la Escollera 防汛大厦	Cartagena 卡塔赫纳	unknown 未知	2007	206
2	Singer Building 胜家大楼	New York City 纽约	**1908**	**1968**	**187**
3	Morrison Hotel 莫里森酒店	Chicago 芝加哥	1925	1965	**160**
4	Deutsche Bank 德意志银行	New York 纽约	1974	ongoing 正在进行	158
5	One Meridian Plaza 子午线广场	Philadelphia 费城	1972	1999	150
6	City Investing Building 城市投资大厦	New York 纽约	1908	1968	148
7	The Ritz-Carlton 丽思卡尔顿酒店	Hong Kong 香港	**1993**	2009	142
8	Hennessy Centre 轩尼诗中心	Hong Kong 香港	1983	2008	140
9	Ardmore Park Old Block 1 雅茂园旧座 1	Singapore 新加坡	1978	unknown 未知	137
10	Ardmore Park Old Block 2 雅茂园旧座 2	Singapore 新加坡	1978	unknown 未知	137

Table 3. World's ten tallest buildings ever demolished, as of September 2011. Note: the list does not include World Trade Centers 1, 2 & 7 as these were destroyed, rather than demolished. (Source: Philip Oldfield, data from CTBUH 2011)
表3. 截止2011年9月，全球10大被拆除的高层建筑。注：列表中不包括世贸中心1，2和7，因为他们是被摧毁的而不是被拆除的。（来源：Philip Oldfield 数据来源于2011年高层建筑和都市住宅委员会）

[3] Calculations by author, with initial data taken from CTBUH, 2011.
[3] 笔者计算，来源于2011年高层建筑和都市住宅委员会的初始数据。

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