Title: **The Environmental Impact of Tall vs Small: A Comparative Study**

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The Environmental Impact of Tall vs Small: A Comparative Study

高层与低层建筑环境影响: 对比研究

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Abstract

The concept of vertical living has been hailed as a solution to control fast growth and urbanization of cities worldwide. As supertall residential projects become more common and sustainability considerations become more necessary, their efficiency has been called into question. How do vertical residential developments compare with suburban homes? What are the environmental advantages and disadvantages of vertical communities? Is there a middle ground? We present the results from an AS+GG study that compares the environmental performance of different housing typologies ranging from a 215 supertall building to single family residences, including several scales in between. Our samples comprise 2,000 residential units per type and include the infrastructure needed to support them. We analyzed land use, energy use, and lifecycle carbon emissions for each typology. The results show that different typologies perform better depending on the parameter being assessed. We discuss these findings; assess overall performance, and present conclusions.

Keywords: Supertall, Energy, Land, Urban Sprawl, Lifecycle Carbon

摘要

垂直生活概念被赞为控制城市快速增长及城市化的解决方案。随着超高层住宅项目变得越来越普遍，考虑可持续变得越来越必要，其效率也越来越受人质疑。垂直住宅项目如何与郊区的住宅相比? 垂直社区有哪些环境优势和劣势? 是否能找到折中的办法? 我们从AS+GG对不同住宅类型 (包含215超高层大楼、单一家庭住宅及介于两者之间不同规模的住宅) 环境性能进行的对比研究中得出了结果。我们为每种类型的住宅选取了两千套作为样品，并包含与其配套的基础设施。我们对每种类型的土地利用、能源利用及生命周期碳排放都进行了分析。 结果显示不同的类型在评估参数的情况下可以获得较高效率。我们对这些结果进行了讨论，评估了整体性能，并最终得出结论。

关键词: 超高层建筑，能源，土地，城市扩张，生命周期碳

Introduction

At the beginning of 2014, the global population stood at over 7.1 billion people (USCB, 2014). The United Nations estimates that the global population will exceed 8 billion by 2025 and almost 11 billion by the turn of the next century (see Figure 1). This will be accompanied by an increase in overall average population density from 51 people per sq. km in 2010 to 60 in 2025 and 147 by 2100 (UN, 2014a).

Urbanization, which is the growth or expansion of urban areas, has recently become the focus of a great deal of attention. In 2010, the global urban population exceeded 50% of the world's population, by 2025 it will reach 58% and by 2050 it will exceed 67% (UN, 2014b). In 1950, when the world's population was a mere 2.5 billion there were 83 cities with over a million people (compared to 12 in 1900). This number has risen to a present day total of more than 520, with 30 cities having more than 10 million and 12 having more than 20 million inhabitants (Brinkhoff, 2014). These

概述

在2014年初，全球人口超过71亿(USCB, 2014). 联合国估测全球人口到2025年将超过80亿，而到下个世纪人口将达到110亿 (见图1) 。与此同时，相伴而来的是2010年平均人口密度由51人/平方公里增长到2025年60人/平方公里，到2100年为147人/平方公里 (UN, 2014a) 。

全球化，即城市地区的增长与扩展，现在已成为人们逐渐关注的焦点。2010年全球城市人口已超过全世界总人口的50%，到2025年该比例将达到58%，2050年将超过67% (UN,2014b) 。1950年世界人口仅250万当时全世界只有83个城市人口过百万 (与1900年仅12个城市相对比) 。而到目前为止此项数据总数已超过520个，其中有30个城市的常住人口超过1千万，12个城市超过2千万 (Brinkhoff, 2014) 。这些惊人的数字促使规划师与政策制定者对城市增长的可持续性提出疑问并尝试想出如何做出最好的规划。

城市化的出现来自于两个途径——农村人口向城市迁移以及自然人口的增长。农村人口向城市迁移是由很多因素共同促成的

staggering numbers are prompting planners and policy-makers alike to ask questions about the sustainability of city growth and try to understand how best it can be planned.

Urbanization occurs as a result of two processes – migration from rural areas and natural population growth. Migration from rural areas may occur as a result of a number of factors. Mechanization of agriculture means that fewer farm laborers are required and therefore there are fewer opportunities for employment on farms and in other agriculture related industries, forcing people to seek employment in urban areas (this phenomenon is known as rural flight). Often, people move to the cities simply for the economic benefits and career opportunities. Furthermore cities tend to have a greater range of education options for parents to choose from for their children as well as better healthcare and social facilities.

There are, however, some negative environmental effects associated with urbanization, the most prevalent known as urban sprawl. Sprawl is a complex socio-economic phenomenon, but one of its defining characteristics is an imbalance between the physical form of a city and the desires and needs of its population. These desires may include specific housing types, neighborhood structure, and the provision of services and/or available recreation space. Consequently, when a population cannot meet all of its needs in one location, it will migrate to other areas to meet those missing needs.

The concept of high density vertical living has been hailed as a solution to control the fast growth and urbanization of cities around the world. As supertall residential projects become more common and sustainability is regarded as a pressing issue for the built environment, the efficiency of such projects is often called into question. How efficient are supertall residential developments versus low-rise single-family residences? What are the environmental, social and economic benefits and/or disadvantages of vertical communities? Is there a middle ground?

This study was undertaken in order to compare the environmental performance of different urban and suburban residential building typologies ranging from supertall buildings graduating down to single-family residences. In all, nine different buildings were designed, divided into four broad categories based on their height and nature: supertall, high-rise, low-rise and single family homes.

Each typology was analyzed against a series of environmental indicators - land use, energy demand, transportation and life cycle carbon emissions.

结果。农业机械化意味着所需更少的劳动力,因而农业及其相关的其他产业所提供就业机会变少，这也迫使人们到城市寻找工作机会(这种现象就是所谓的农村外流)。大多数人搬到城市仅为追寻经济收益和工作机会。此外城市能够为父母在子女教育问题上提供更大范围的教育选择性，且拥有较好的医疗条件和公共设施。

然而伴随城市化的脚步又带来许多负面的环境影响，最为众所周知的是城市的扩张蔓延。蔓延是一种复杂的社会经济现象，但其最显著的特点之一是城市的物质形态与城市人口的愿望及需求之间的不平衡。这些愿望包括特定的住房类型、邻域结构、及服务提供和/或所用娱乐空间。因此，当一个人在一个地方不能满足他的所有需求的时候，他将会迁移到其他地方以满足这些缺失的需求。

高密度的纵向居住概念已被公认为控制城市快速增长与全球城市化进程的解决方案。超高住宅项目变得更加普遍，可持续性被看成是建筑环境的一个紧迫问题，因而这些项目的效能经常遭受质疑。与低层独栋住宅相比超高住宅发展是否真正有效? 垂直社区有哪些环境、社会与经济效益而其弊端又有哪些? 是否存在中间地带?

该项研究对城市与城郊从超高建筑到独栋住宅的不同住宅建筑类型的环境性能进行了对比研究。该研究总共设计了9类不同的建筑，又根据他们的高度与性质分成了四大类: 超高层、高层、低层与独栋家庭住房。

本研究通过一系列的环境指标对每个建筑类型加以分析，这些指标包括土地利用、能源需求、交通及生命周期的碳排放。

研究方法

建筑类型

如上所述，本项研究共设计了9种住宅建筑并将之分为四大类。该研究所设计的每一项都是针对于ASHRAE气候区5 (如芝加哥)，研究还会对其施工能力及遵守《芝加哥建筑规范》与ASHRAE 90.1 (2010)做出测试。

所研究的每个类型的样本大小均为2000户住宅单元，其中包括所需的的基础设施，并创建了9个假设的社区 (见图2)。所房屋的设计主要遵循以下两种截然不同的方法: 第一种为以市场为基础的单元面积 (基于在芝加哥区的公寓与房屋面积的横截面)，在此被

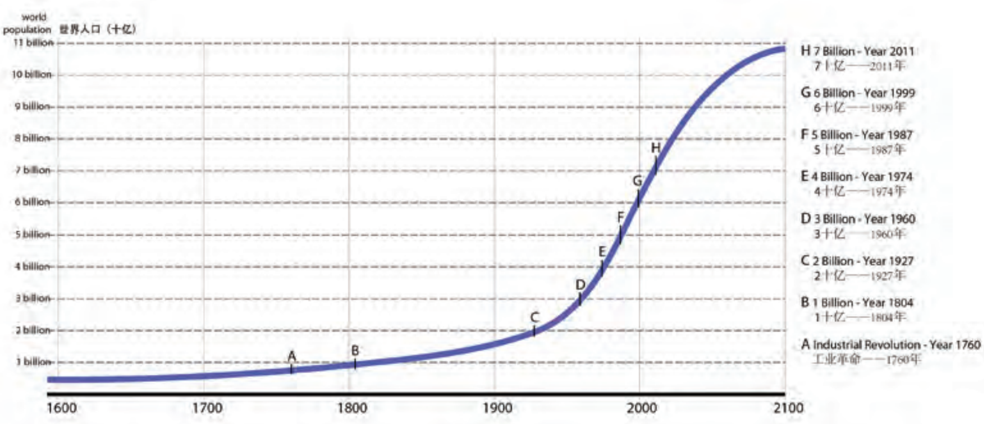

Figure 1. World population growth (Source: UN data)
图1. 世界人口增长图 (来源: 联合国数据)

Methods

Building Typologies

As described above, nine residential buildings were designed within 4 categories as described above. Each was designed for an ASHRAE climate zone 5(such as Chicago) and was tested for constructability and compliance with Chicago's Building Code and ASHRAE 90.1 (2010). Each typology was designed using typical building materials and mechanical systems to allow for a better comparison of the different models.

The sample size for the study of each typology was 2,000 residential units, including the infrastructure needed to support them, creating nine hypothetical communities (see Figure 2). The housing was designed following two distinct approaches: firstly, a market based unit size (based on a cross section of apartment and house sizes within the Chicago area), which was termed T_{base} and secondly on a fixed unit size of 150m^2, termed T_{150} (see Table 1). The two approaches allowed us to make relative comparisons of total energy demand (using T_{base}) and energy use intensity (using T_{150}).

Energy Use

Energy Models were constructed using Design Builder and run in Energy Plus for all the prototypes in the Density Study. This allowed the estimation of overall energy consumption as well as demand profiling for each typology. Buildings were modeled as part of prototype communities, to take into account the effect of overshadowing by neighboring structures, as would be in real life. To eliminate the influence of orientation, the energy models for each prototype were run in four cardinal directions with the mean result being considered for the discussions. These individual results were then extrapolated to represent 2,000 units and the totals have been compared.

Land Use

Communities were built for the T_{base} typologies using ArcGIS. These communities included roads, sidewalks, water, waste water and stormwater distribution networks. The building structures as well as the infrastructure required to support them were included in the community models. Prototypes for each community type were designed based upon GIS data obtained from the City of Chicago and its western suburb of Naperville, IL. Road widths, sidewalks and alleyways were designed according to the relevant Chicago or Naperville code.

Infrastructure falling within the community boundary up to the entrance of each building was included in the GIS model. The infrastructure systems included potable water, stormwater and wastewater networks; electricity and telecommunications were not included.

Lifecycle Carbon

In order to estimate life cycle carbon emissions it was necessary to calculate the embodied carbon for each community. This included above grade infrastructure (roads, sidewalks etc.), utilities infrastructure (potable water, wastewater and stormwater) and the buildings.

For the embodied carbon calculations of the building materials, the most significant (in terms of quantities) components of the constructions were analyzed: structures, building envelopes, insulation and interior partitions. Mechanical systems, wires and tubes, elevators, etc., were not included in the calculations. Quantities were taken from the building models described in the typologies section. The dimensions of the structural components were reviewed by structural engineers, who provided values for concrete strengths and reinforcement steel quantities.

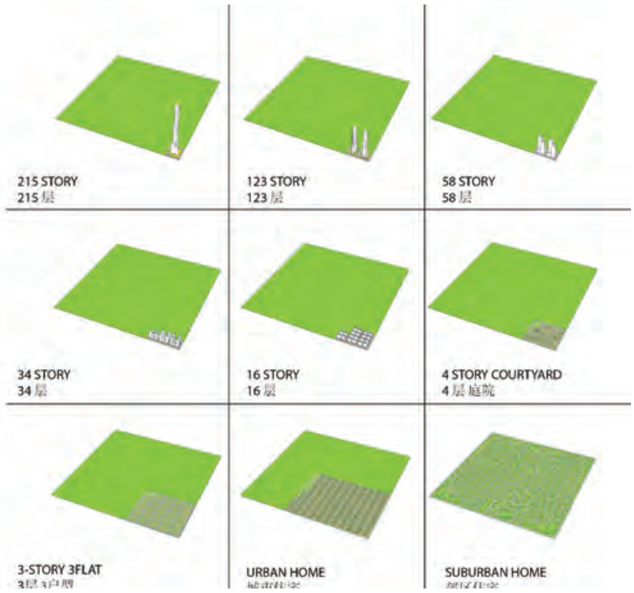

Figure 2. Community prototypes (Source: AS+GG)
图2. 社区类型 (来源: AS+GG)

T_{base} PROTOTYPE 原型	215 STORY 层	123 STORY 层	58 STORY 层	34 STORY 层	16 STORY 层	COURTYARD 庭院	3-FLAT 3户联排	URBAN SF 城市住宅	SUBURBAN SF 郊区住宅
# Buildings 建筑数量	1	2	4	10	20	63	667	2,000	2,000
# Units / Building 每栋户数	2,000	1,000	500	200	100	32	3	1	1
# Storys (Above Grade) 层数（地上）	215	123	58	34	16	4	3	2	2
Building Height (m) 建筑高度	773.0	442.0	208.5	122.5	59.5	14.0	10.5	6.5	8.6
Total Area (m²) 总面积	498,240	258,473	85,511	30,505	17,120	3,833	351	257	287
Total Conditioned Floor Area* (m²) 使用总面积	480,737	248,032	73,696	25,673	14,870	3,833	351	106	233
Net Residential Floor Area (m²) 净住宅面积	299,991	150,069	54,577	18,720	8,859	2,929	267	93	207
Average Unit Floor Area (m²) 每户平均面积	299,991	75,035	13,644	1,872	443	47	0	0	0
Mechanical Floor Area (m²) 设备层面积	34,762	19,618	5,300	1,580	1,844	n/a	n/a	n/a	n/a
Parking Area (m²) 停车面积	44,400	23,600	8,424	4,010	2,106	-	-	41.00	47.80
% Efficiency 效率	75%	75%	84%	89%	84%	86%	93%	100%	100%
Window / Wall Ratio 窗墙比	40.0	40.0	40.0	40.0	40.0	0.1	0.1	0.1	0.1
Parking Spaces Required 所需停车空间	1	1	2	6	11	n/a	n/a	2	2
T_{150} PROTOTYPE 原型	215 STORY 层	123 STORY 层	58 STORY 层	34 STORY 层	16 STORY 层	COURTYARD 庭院	3-FLAT 3户联排	URBAN SF 城市住宅	SUBURBAN SF 郊区住宅
# Buildings 建筑数量	1	2	4	10	20	100	667	2,000	2,000
# Units / Building 每栋户数	2,000	1,000	500	200	100	20	3	1	1
# Storys (Above Grade) 层数（地上）	215	123	65	38	20	4	3	2	2
Building Height (m) 建筑高度	773.0	442.0	229.0	134.5	71.5	14.0	10.5	5.6	8.6
Total Area (m²) 总面积	498,240	258,473	110,184	42,896	24,300	3,833	573	236	235
Total Conditioned Floor Area* (m²) 使用总面积	480,737	248,032	98,392	37,834	21,000	3,833	573	171	177
Net Residential Floor Area (m²) 净住宅面积	299,991	150,069	75,039	30,077	14,980	2,995	450	150	150
Average Unit Floor Area (m²) 每户平均面积	150	150	150	150	150	150	150	150	150
Mechanical Floor Area (m²) 设备层面积	34,762	19,618	6,293	2,108	2,232	n/a	n/a	n/a	n/a
Parking Area (m²) 停车面积	44,400	23,600	8,424	4,010	2,106	-	-	41.00	47.80
% Efficiency 效率	75%	75%	84%	89%	86%	90%	92%	100%	100%
Window / Wall Ratio 窗墙比	40.0	40.0	40.0	40.0	40.0	14.6	9.6	7.0	10.9
Parking Spaces Required 所需停车空间	1,100	550	275	110	55	n/a	n/a	2	2

*Based on energy model %, gross area
根据能量模型百分比，毛面积

Other areas come from Excel area calculations
其他面积来自于Excel面积计算

Table 1. Community design parameters for the T_{base} (market sized units) and T_{150} (150m^2 units) typologies (Source: AS+GG)
表1. T_{base} (市场户型) 和T150 (150m2户型) 社区类型的设计参数 (来源: AS+GG)

称为T_{base}，第二种为拥有固定的150平方米的单元面积，在此被称为T_{150} (见表1)。这两种方法允许我们对于总能源需求 (即用T_{base}) 和能源消耗强度 (即用T_{150}) 做出对比性分析。

能源消耗

在密度研究中文章使用"设计建造" (Design Builder) 建造能源模型并在"能量添加" (Energy Plus) 中运行。这种方法可使我们对每个类型的整体能量消耗及需求状况做出估算。建筑作为原型社区的一部分进行建模，如生活中会出现的，需考虑到邻域结构的遮蔽影响。为减少方向的影响，将每个原型的能量模型在四个主要方向运行，所得出的平均的结果将予以讨论。针对这些单个的结果加以推测进而使之代表2000个单元并对其总数加以对比。

土地利用

使用ArcGIS 建造Tbase 类型社区。这些社区包括道路、人行道、水、污水及雨水分布网络。其建筑结构与所需 之基础设施也被包含在社区模型中。每个社区类型所设计的原型基于GIS数据，其数据来自于芝加哥西部的伊利诺伊州内伯威尔市郊区。根据相关芝加哥或内伯威尔规范设计其路宽、人行道及巷道。

社区中连接每个建筑入口的基础设施都包含在GIS模型中。其基础设施系统包括饮用水、雨水及污水分布网络; 不包括电力与通信。

The emissions factors for infrastructure and buildings were calculated using data from the Athena Institute, Bath ICE and the Concrete Pipeline Systems Association.

Transportation from place of manufacture to construction site was not accounted for in the study.

Results And Discussion

Energy Use

Energy consumption was considered in two ways– Total Energy Demand (TED, kWh/yr) and Energy Use Intensity (EUI, $kWh/m^2/yr$). Figures 3 and 4show the TED and EUI for the T_{base} 2000 unit communities and Figures 5 and 6 show the same data for the T_{150} communities. As the graph shows, the low-rise prototypes had six significant loads affecting their overall consumption: heating, cooling, interior lights, plug loads, fans and water heating. The high-rises had a total of nine loads (the other three being elevators, water pumps and heat rejection). Space heating and domestic water heating were the most energy intensive loads in almost all prototypes. Cooling became more significant in buildings with higher glazing ratios, where overheating occurs in summer.

In judging which of the T_{base} buildings performs best, it is important to consider both EUI and TED as the unit sizes are different. In the T_{150} case, as the units sizes are the same in all typologies, the relationship between EUI and TED is constant.

The courtyard building was the most energy efficient of all the prototypes tested in both scenarios. A series of factors help explain these results: the high density of units, in a configuration where only two walls are exposed to the exterior, as well as a low glazing ratio. This helps contain the space heat in winter and reduce infiltration, as well as keep unwanted summer radiation out. The most significant load in this prototype was domestic water heating, because this value is not associated with environmental factors but with occupancy rates. Despite being a relatively dense prototype (with 32 or 20 units per building), the height still allowed it to operate with a simple system, not needing elevators or water pumping. Although not included in this prototype for the study, a single elevator would be required to allow disabled access up the building.

The high-rises (16 story, 34 story and 58 story) are much more interesting in terms of their performance; when looking at EUI (both scenarios) or TED in the T_{150} ¬scenario the taller the building, the better it performs. Overall their energy consumption is greater than the low rise typologies, because these buildings have the added loads of water pumps and elevators, as well as higher loads for cooling, fans and, compared to some lower prototypes, higher lighting and plug loads as well.

The T_{150} suburban house performs reasonably well, on the other hand the market sized, T_{base} suburban house would appear to perform very well in terms of EUI but because of its size (207m^2 net residential area) the overall energy consumption is high.

In terms of energy use, the supertalls used the most energy out of all the prototypes. There are multiple factors associated with these results. First of all, these buildings depend on a series of spaces that are not residential units but account for around 30% of the total building area. Among these are the mechanical floors, the lobbies and amenities, and parking garages. These spaces are continuously illuminated and conditioned yet are not always occupied.

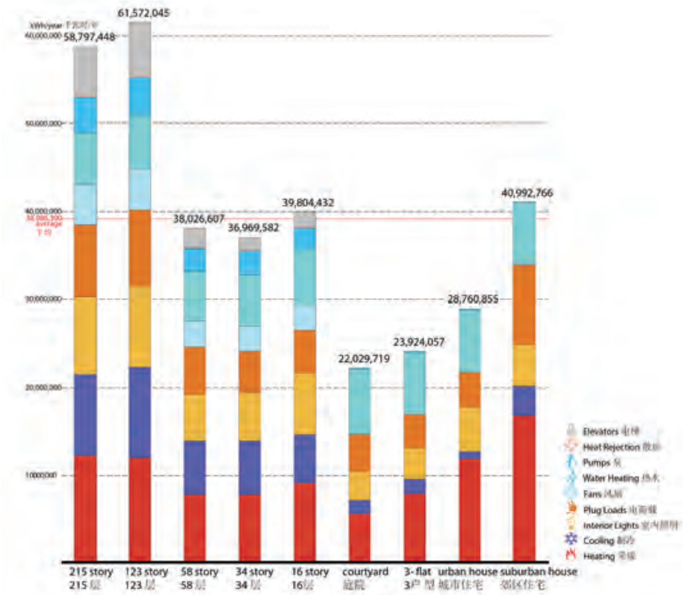

Figure 3. Total Community Energy demand for T_{base} market sized units (Source: AS+GG)
图3 T_{base} 市场户型社区的总能源需求量 (来源: AS+GG)

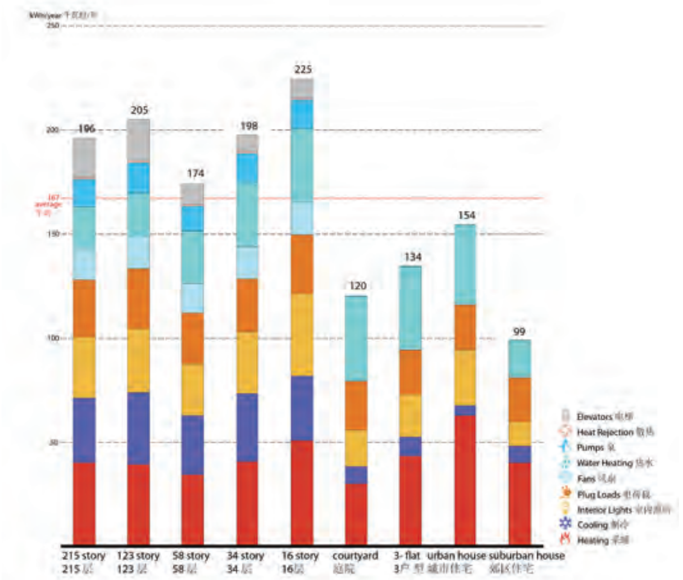

Figure 4. Energy Use Intensity for T_{base} market sized units (Source: AS+GG)
图4 T_{base} 市场户型的能源利用 (来源: AS+GG)

生命周期碳

为估测生命周期碳排放有必要进行每个社区的隐含碳的计算。这包括地面基础设施 (如道路、人行道等) 、公共事业基础设备 (如饮用水、污水与雨水) 及建筑。

建筑材料的隐含碳计算书，研究分析建筑的最主要 (就数量而言) 组成部分: 结构、建筑围护结构、隔离与内部分区、机械系统、电线与管道、电梯等并不包括在计划书中。在类型学章节将对从建筑模型提取的数量予以描述。结构组件的尺寸将由结构工程师审核，他们将提供钢筋混凝土的强度及钢筋数量值。

使用雅典娜学院、Bath ICE及混凝土管道系统协会的数据计算出基础设施及建筑物的排放因素。

从生产到施工地点的运输并不包含在该项研究中。

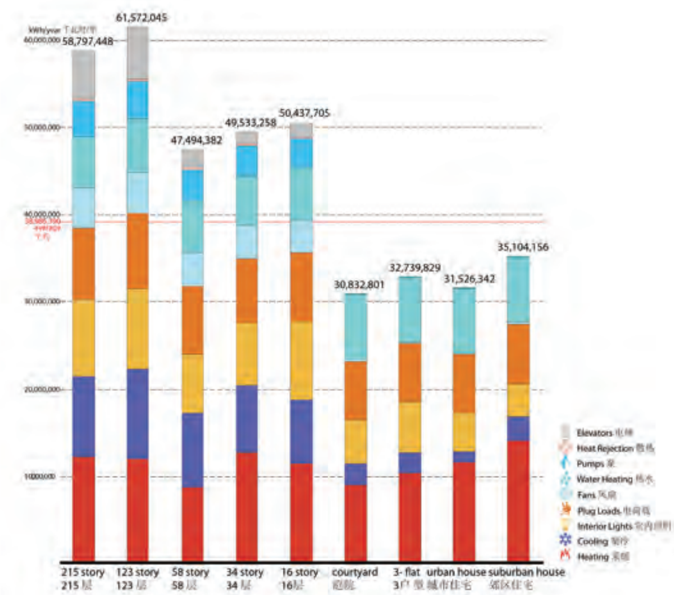

Figure 5. Total Community Energy demand for T_{150}150 m^2 units (Source: AS+GG)
图5. T_{150} (150m^{2}户型) 总能源需求量 (来源: AS+GG)

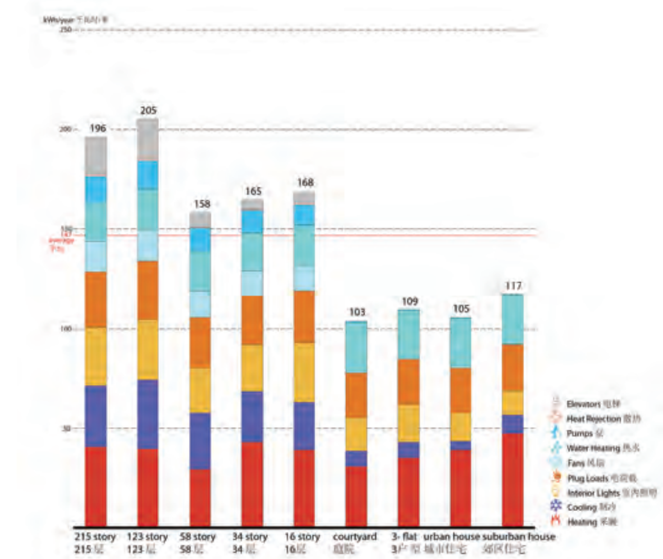

Figure 6. Energy Use Intensity for T_{150}150m^2 units (Source: AS+GG)
图6. T_{150} (150m^{2}户型) 的能源消耗强度 (来源: AS+GG)

结果与分析

能源利用

通过两个方面考虑能源消耗——总能源需求 (TED，kWh/yr) 及能源消耗强度 (EUI, kWh/m^2/yr) 。图3及图4显示的是T_{base} 2000社区的TED及EUI，图5及图6显示的是T_{150}社区的TED及EUI。如图所示，低层建筑原型有六大影响总体能源消耗的主要负荷: 采暖、制冷、室内照明、插头负荷、风机及水加热。高层建筑共有九大负荷 (除低层建筑六大负荷之外的三个负荷为电梯、水泵及散热) 。供暖及生活用水加热几乎是所有原型中能源消耗量最大的负荷。而制冷的能源消耗在窗墙比较高的建筑中占比越来越大，因为这些建筑在夏季会出现过热现象。

在判断哪一个T_{base}建筑性能最佳时，很重要的一点就是考虑EUI及TED两个值，因为建筑的单元规模不同。在T_{150}建筑中，所有原型中的单元规模一致，因而EUI与TED的关系是恒定的。

庭院式建筑是两种测试模式中最为节能的建筑。有一系列的因素可以解释这些结果: 单元密度高、仅两面墙朝外、低窗墙比。这有助于在冬季保持空间内的热量，减少渗透，同时隔离不必要的夏季辐射。这个原型中最重要的负荷为生活用水加热，因为这一数值与环境因素无关，但与居住率有着紧密的联系。尽管这是一个单元较密集的原型 (每栋建筑32或20单元)，但从建筑高度来看，整个大楼还是可以通过一个简单地系统进行运作，而无需电梯或水泵。尽管没有对这种原型进行研究，但该建筑要求配置一部电梯，以满足残疾人出入建筑的需求。

从建筑性能来看，高层 (16层、34层及58层) 建筑则有趣得多; 从T_{150}社区的EUI (两个社区) 或TED来看，建筑越高，性能越好。他们的总体能源消耗比低层建筑要高，因为这些建筑增加了水泵及电梯的负荷，且与较低建筑相比，其制冷及风机负荷更高，同时照明及插头负荷也更高。

T_{150}郊区建筑的性能表现非常好，另一方面，就EUI而言，T_{150}郊区市场户型建筑似乎也表现良好，但是由于规模的原因 (207m^{2}净居住面积)，其总体能源消耗过高。

就能源利用而言，超高层建筑在所有原型中能源利用量最大。与这一结果相关的元素很多。首先，这些建筑有许多非住宅单元的空间，且这些空间约占总建筑面积的30%。这些空间包括机电层、大堂、便利设施及停车库。这些空间都有照明及空调设备，但是无常住人口。

从建筑学来说，与低层建筑原型的大体量围护结构相比，性能较差的建筑通常窗墙比较高。这主要会导致较高的渗透率、冬季的热损失及夏季的不必要吸热。另一个需要考虑的方面为电梯。高效的垂直交通系统对超高层建筑的运作来说特别关键，且电梯约占总能源消耗的10%，相比之下，其他高层建筑的这一比率仅为4%-6%。水泵能源消耗同样显著上升，因为机电系统用水及生活用水需要利用水泵抽送至较高楼层，从而要求更大的功率。

T_{base} PROTOTYPE原型	215 STORY层	123 STORY层	58 STORY层	34 STORY层	16 STORY层	COURTYARD 庭院	3-FLAT 3户联排	URBAN SF 城市住宅	SUBURBAN SF 郊区住宅	SUBURBAN SF 郊区住宅
Number of buildings 建筑数量	1	2	4	10	20	63	667	2,000	2,000	2,001
Total building footprint (m2)建筑总面积	3,177	7,534	16,848	20,050	42,120	60,376	78,039	335,650	394,765	394,766
Total area required (m2)所需总面积	26,896	36,530	36,530	45,508	86,135	173,338	383,178	854,046	2,967,137	2,967,138
Land use as a % of suburban SF 占郊区面积比例	0.91%	1.23%	1.23%	1.53%	2.90%	5.84%	12.91%	28.78%	100.00%	100.00%
Area compared to Suburban SF (m2) 与郊区相比面积	(2,940,241)	(2,930,607)	(2,930,607)	(2,921,629)	(2,881,002)	(2,793,799)	(2,583,959)	(2,113,091)	0	1
PV Power generation , 90% landuse (kWh/yr) 光伏发电量，90%用地量（千瓦时/年）	249,300,094	248,483,237	248,483,237	247,722,001	244,277,279	236,883,423	219,091,300	179,166,873	0	1

Table 2. Land use of T_{base} communities (Source: AS+GG)
表2. T_{base}社区土地利用 (来源: AS+GG)

Architecturally, higher glazing ratios commonly found on these kinds of buildings perform poorly compared to the high mass envelopes of the lower prototypes. This typically translates into higher infiltration rates, heat losses in winter and unwanted heat gain in summer. Another aspect to take into account is elevators. An efficient vertical transportation system is critical for the operation of supertall buildings, and it accounts for around 10% of the total energy consumption, compared to only four to six percent on other high-rises. Pumping energy also raises significantly, since water for mechanical systems and domestic uses needs to be pumped to higher elevations thus requiring more power.

An important aspect that was not accounted for in the study was the auxiliary energy required for the functioning of the smaller buildings. Auxiliary energy is considered to be any additional energy necessary for the operation of the prototypes that is not consumed within the building. Although systems like pumps and elevators are not part of these smaller buildings, other auxiliary systems replace these. For example, water distribution from the utility companies to these buildings at a certain pressure requires electricity. The potable water network in a suburban neighborhood of 2,000 single family homes is over 100 times longer than the one needed to supply one supertall building, resulting in increased auxiliary energy demand. Additionally it could be argued that the elevator energy demand, linking a residential unit almost directly to car-parking, replaces vehicle emissions associated with driving a car around a neighborhood (in the case of the two low-rise typologies).

Land use

The study illustrates the extent to which the land use in lower rise communities is greater than that of high-rise communities; The Tbase suburban community occupies 110 times more land than a supertall tower housing the same number of units (see Table 2).

The land left undeveloped (see Figure 2) in the high-rise and supertall developments could be used to mitigate the effects of the development. In an ideal scenario, the land could be left alone, which would preserve the natural habitat, protect wildlife and water sources and naturally sequester carbon. The land could also be used as farmland to support the demands of the growing population. For the purposes of this study, a scenario where 90% of the additional land is used to generate energy using Photovoltaic panels was considered. The NREL PVWatts calculator was used to estimate annual energy production assuming panel efficiencies of 18%, a Chicago weather profile and taking into account maintenance and shading packing factor. This analysis shows that the land difference between the Suburban Single family home typology is sufficient to meet the energy demands of all the other communities in the study (see Figures 7 and 8). The best performing typology in both the T_{base} and T_{150} scenarios is the 58 (65) story building, where the difference between energy generated on the unused land and energy consumption of the building is the highest, yielding a potential 238GWh and 126GWh of electricity per year in the T_{base} and T_{150} scenarios respectively.

Life cycle carbon emissions

The results of the Embodied Carbon EC analysis for T_{base} are shown in Figure 9. The EC of infrastructure directly correlates with land use. Spatially larger communities have greater lengths of roads and utilities to support the wider distribution of parcels, whereas taller buildings are confined to smaller plots with less external infrastructure. In these, some utilities move inside the buildings whereas other infrastructure (roads and sidewalks) is replaced by elevators and corridors.

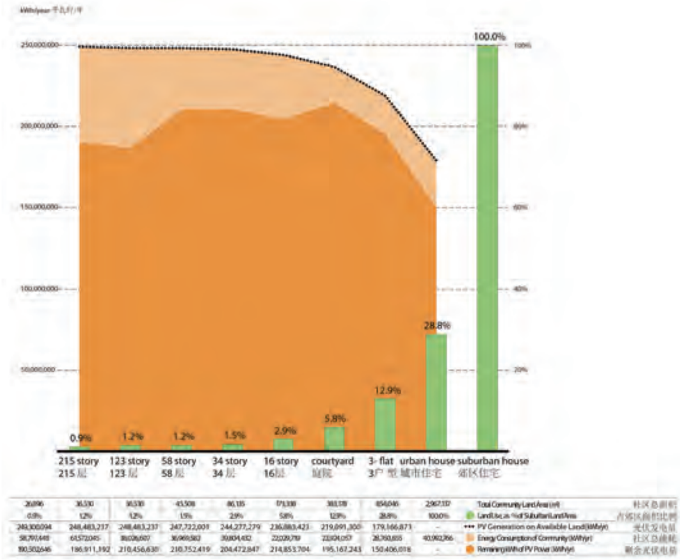

Figure 7. Analysis of land use, energy demand and energy production potential for the T_{base} communities (Source: AS+GG)
图7. T_{base}社区土地利用、能源需求量及能源产出分析 (来源: AS+GG)

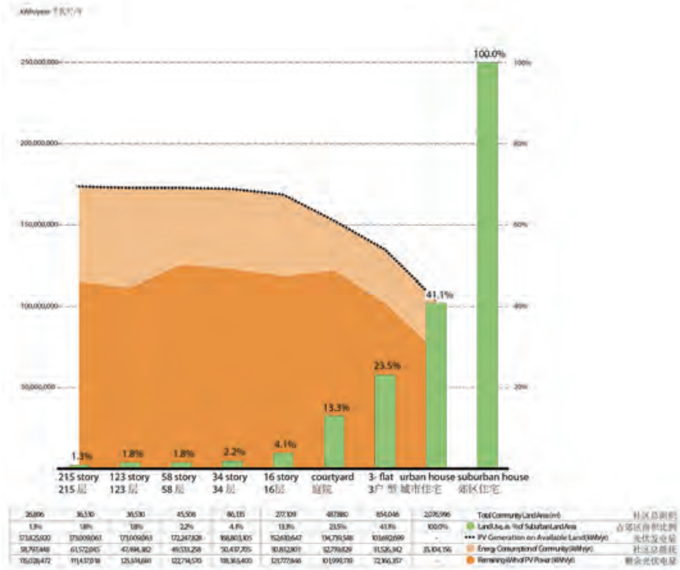

Figure 8. Analysis of land use, energy demand and energy production potential for the T_{150} communities (Source: AS+GG)
图8. T_{150}社区土地利用、能源需求量及能源产出分析 (来源: AS+GG)

未纳入研究的一个重要方面为小型建筑运作所要求的辅助能源。辅助能源是非建筑内消耗的原型运作所必须的任何附加能源。尽管水泵、电梯等系统不是这些小型建筑的一部分，取而代之的是一些其他的辅助系统。如市政公司至这些大楼的特定压力下的配水系统需要电力支持。一个2000户家庭郊区社区的饮用水管网的长度比供应超高层建筑的管网长100多倍，导致必要辅助能源的增加。此外，关于电梯能源需求 (直接连接住宅单元与停车场) 替代开车绕社区 (两个低层建筑原型) 一周的机动车尾气这点上存在争议。

土地利用

研究表明，低层社区比高层社区的土地利用量更大; T_{base}郊区社区比同等单元数量的超高层塔楼所占的土地多110倍(见表二) 。

Regardless of community size (in terms of land area), the EC of buildings accounts for by far the greatest proportion of the communities' overall EC, with infrastructure accounting for only 0.15% in the supertall. However, it becomes more significant in the low rise typologies, rising from 3.7% in the courtyard community to 9.0% in the Suburban single family home community. The 213 story supertall community had a significantly higher embodied carbon than any other typology, primarily due to the amount of concrete and steel within the structure of the building. The typology that performed best in regards to embodied carbon was the 4 story courtyard building community.

The final element of the study was the estimation of lifecycle carbon emissions for the T_{base} community. For this study, a 20 year period was used, as this represents a typical warranty period for photovoltaic systems. Although this is significantly less than the life expectancy of a high-rise building, 20 years is considered an acceptable time period for considering a major re-modelling and was therefore chosen as being appropriate for the purposes of this analysis.

The study included the embodied carbon, the operational carbon emissions and the amount of carbon offset by using the land saved (compared to suburban single family homes) for electricity generation from photovoltaics, as described earlier. This yielded a net relative carbon savings value (see Figure 10) showing that the 58 and 34 story buildings provide the greatest overall net relative carbon saving, followed by the 16 story building and then the courtyard building.

General discussion

The study reveals a number of interesting findings and direction for future study. In both the T_{base} and T_{150} communities, the 4 story courtyard buildings had the lowest energy demand. However, in considering how energy demand across all typologies could be improved, this typology offers the least potential for improvement – the buildings already have a very low window to wall ratio (13.8%) and are well insulated in accordance with ASHRAE 90.1 energy standards. The taller buildings on the other hand offer the most potential for improvement – more efficient mechanical systems, vacancy and daylighting sensors, regenerative braking in the elevators, off peak thermal energy storage in basements, high performance glazing and reduction of the glazing ratios (from 40%) are just a few considerations that could be tested in the future. Moving to land use, when using the land area of the suburban single family home as a baseline, it is obvious that taller buildings will have a smaller footprint allowing the vacant land to be put to good use. For this study, using the vacant land for power generation with photovoltaic was chosen – the study was conservative, assuming 90% of the land was used and that of that 90%, only 45% was covered with 18% efficient PV panels, to account for spacing and maintenance movement etc. Improvements in yield are clearly possible and could be considered as part of a future study. Secondly there are alternative uses for the land – loss of agricultural land, as mentioned in the introduction to the study is a global concern and is something that can be mitigated through building denser housing communities on marginal land. The net effect of using the vacant land for agricultural productivity or even carbon sequestration by natural systems is a subject for a future study.

Embodied carbon and lifecycle carbon emissions conclude this study, but to truly complete, it transportation should be further considered as improved connectivity with public transport and mass transit systems is typically thought of as one of the advantages of denser communities. For the present study, embodied carbon of infrastructure systems largely reflected land use, whereas as the embodied carbon

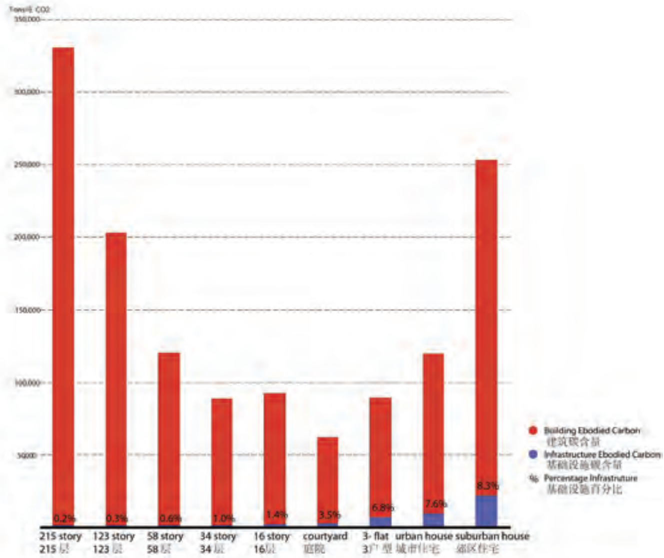

Figure 9. Embodied carbon of buildings and infrastructure for the T_{base} communities (Source: AS+GG)
图9. T_{base}社区建筑物及基础设施隐含碳 (来源: AS+GG)

高层及超高层项目中未开发的土地 (见图2) 可用于减轻项目发展带来的影响。在理想的情况下，可保留未开发的土地，用于保护自然栖息处及野生动物，从而减少碳排放。未开发的土地还可作为农田，以满足不断增长的人口需求。为实现研究目标，考虑一个社区90%的额外土地利用光伏板发电。假设光伏面板效率为18%，同时考虑芝加哥天气状况、维护及遮阳填料因子，采用国家可再生能源实验室PVWatts计算器估算年发电量。该分析表明，郊区独栋户型间的不同土地能够满足该研究 (见图7及图8) 内所有其他社区的能源需求。T_{base} 及 T_{150}社区的最佳建筑性能类型为58 (65)层的建筑，此时未利用土地产生的能量与建筑的能源消耗之差最高，T_{base} 及 T_{150}社区每年各能产生238千兆瓦时及126千兆瓦时的电力。

生命周期碳排放

T_{base}隐含碳分析结果见图9。基础设施的隐含碳同土地利用直接相关。空间较大的社区道路和动力设施路线较长，能够支持在较宽的范围内分布地块; 相对而言，高层建筑地块局限于较小的地块内，外部基础设施较少，部分动线设施设于建筑物内，而其它设施 (道路和人行道) 则被电梯和走廊取代。

无论社区规模大小 (土地面积)，建筑物隐含碳目前占社区总隐含碳的最大比例，超高层建筑的基础设施则仅占0.15%。相比之下，低层建筑的基础设施占比则较大，庭院式社区为3.7%，而郊区独栋社区则达到9.0%。213层的超高社区远高于其它类型社区的碳排放，主要原因在于建筑物内大量使用钢筋混凝土。碳排放表现最好的是4层的庭院式社区。

研究的最后一部分是T_{base}社区生命周期碳排放估算。本研究采用了20年的周期，因为20年是光伏系统的标准保修期。尽管远远小于高层建筑的预计使用年限，20年被认为是主要模型再造的可接受时间。因此本文在分析中选用20年作为合理时期。

研究包括了隐含碳排放，运行碳排放以及光伏发电节约用地带来的碳补偿 (相较于郊区独栋式住家庭住房而言)，如前所述。研究表明，58层和34层建筑的净相对碳储蓄值 (见图10) 最大，其次是16层，接下来是庭院式建筑。

结论

通过研究揭示了今后研究的一些有趣的结论和方向。Tbase和T150两个社区的4层庭院式建筑物的能源需求量都是最低的。但如果

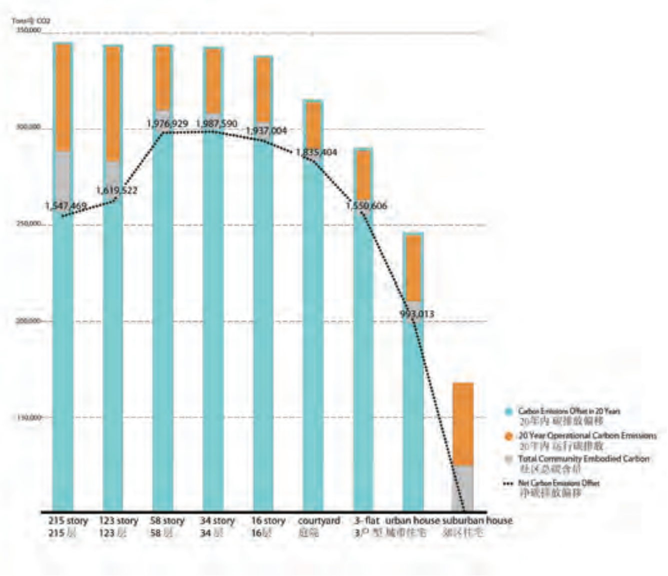

Figure 10. Lifecycle carbon analysis for the T_{base} community (Source: AS+GG)
图10. T_{base}社区生命周期碳排放分析 (来源: AS+GG)

of the buildings largely reflected the height of the individual buildings as far as the courtyard typologies before rising again through to the suburban single family homes. This is largely due to the relationship between structure and gross floor area being greater as buildings get taller. In the lower rise buildings, the choice of construction materials had a greater influence. Operational emissions were converted to CO2e using the grid emissions factor for Illinois. Clearly should the energy grid move over to cleaner forms of energy then operational emissions will become lower and embodied carbon will become more significant. Studying the impact of a reduced carbon grid and the effect of selecting low carbon construction materials is the subject of a future study.

Finally, taking into account operational emissions and potential carbon offsets through onsite energy generation, the communities that perform best overall are the high-rise buildings (58 and 34 story) with the taller buildings performing best.

考虑各类型社区能源需求量的增加方式，庭院式社区的增加潜力最小，因为窗墙比非常低(13.8%)，并且已经按照ASHRAE 90.1节能标准布置了良好的隔热措施。另一方面，较高建筑物的增加潜力最大，因为较高的建筑物拥有更为高效的机械、通风、采光传感器、电梯再生制动和非高峰期间地下室的热能储存，以及高性能的玻璃窗和较小的窗墙比 (40%以下)，这些都可以在今后进一步验证讨论。

至于土地利用，当采用郊区独栋住房作为基线，很明显高层建筑基底较小，因而空地可以更好地加以利用。本研究选择利用空地设置光伏发电。研究保守地假定90%的土地得到利用，在这90%的土地中，仅有45%的部分设置了18%的节能光伏板，因为须考虑到间隙和维护方便。很显然，发电量可以改进，并可以作为今后研究的一部分。其次，土地也可有别的用途---如前文所述，农业耕地流失是国际性关注点，沿用地边沿建造密度更大的住宅社区可以缓和这一问题。利用空地提高农业生产力甚至采用自然系统进行碳回收是今后研究的课题。

研究结论包括隐含碳和生命周期碳排放，但结论如要全面，则须进一步考虑交通，因为公共交通和大运量交通系统的改进被认为是高密度社区的优势之一。对于当前的研究而言，基础设施系统的隐含碳从很大程度上反映了土地利用，而建筑物的隐含碳则从很大程度上反映了建筑单体的高度，包括从庭院式社区到郊区独栋住宅等类型。这主要是因为建筑物越高，建筑结构和总建筑面积之间的关系越密切。低层建筑的施工材料选择影响更大。采用伊利诺斯州的电网排放因素将运行碳排放换算为当量二氧化碳。很显然，电网应采用更为清洁的能源，这样有利于降低运行碳排放量，而隐含碳则会更显著。低碳电网的影响以及低碳施工材料选型是今后研究的课题。

最后，考虑到运行碳排放量和潜在的现场发电带来的碳补偿，总体性能最佳的是高层建筑物 (58层和34层)，较高的建筑物性能最佳。

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