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Title: **Towards Resource Generative Skyscrapers**

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Subjects: Architectural/Design
Building Case Study
Façade Design
Structural Engineering
Sustainability/Green/Energy

Keywords: Energy Efficiency
Parametric Design
Performance Based Design
Renewable Energy
Sustainability

Publication Date: 2016

Original Publication: Cities to Megacities: Shaping Dense Vertical Urbanism

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 Unpublished conference paper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 Unpublished

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Towards Resource Generative Skyscrapers
趋向资源生成的摩天大楼

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Abstract | 摘要

Rapid urbanization, resource depletion, and limited land are further increasing the need for skyscrapers in city centers; therefore, it is imperative to enhance tall building performance efficiency and generative capability. Potential performance improvements can be explored using parametric multi-objective optimization aided by evaluation tools, such as computational fluid dynamics and energy analysis software, to visualize and explore skyscrapers' multi-resource, multi-system generative potential. An optimization-centered, software-based design platform can potentially enable the simultaneous exploration of multiple strategies for the decreased consumption and large-scale production of multiple resources. Resource Generative Skyscrapers (RGS) are proposed as a possible solution to further explore and optimize the generative potentials of skyscrapers. RGS can be optimized with waste energy harvesting capabilities by capitalizing on passive features of integrated renewable systems. This paper describes various resource generation technologies suitable for a synergetic integration within RGS typology, and the software tools that can facilitate exploration of their optimal use.

Keywords: Energy efficiency, Multi-objective optimization, Parametric Design, Performance Based Design, Renewable Energy, Resource generation

城市中心的快速城市化，资源枯竭，以及有限的土地只会增加对摩天大楼的需求，这将继续定义现代城市的构架。资源可生型摩天大楼（RGS）是一个可行的解决方案，通过进一步探索和优化摩天大楼的生产潜力，从而解决城市中心的显著的资源枯竭问题。通过利用空中能源和集成有源可再生能源系统的被动特性，RGS可以对浪费的能量和收集能力进行优化。此外，RGS可以战略性地定位在人口密集的城市中心。通过紧凑城市这个概念，并通过共定位资源的生产和消耗，RGS可具有有效的影响力半径。这个半径可以包含当地收获基本资源（能源，食品，水和土地），继而缓解从城市的边远地区运输资源的需求。另外，通过扩大RGS类型高楼影响的区域，紧凑的配套基础设施的和交通系统能够及时地把所需基础设施及时地从公共转向给私人（RGS）区域。

关键词：能源效率、多目标优化、参数化设计、性能设计、可再生能源、资源生成

Introduction

The Necessity of Tall Buildings

High-rise buildings emerged in the mid-1960s as a principal architectural typology to address the growing need for increased density in city centers (Ko, et al., 2008). This architectural solution aimed to provide maximum usable space from the least possible amount of land in order to accommodate the ever-increasing urban population. The population living in urban areas during the 1960s was close to one billion (about 30 percent of the planet's three billion people), whereas current projections for 2050 predict an urban population of about six billion – about two-thirds of the over nine billion people that will be living on the planet in the future (UN, 2014). The population surge and expanding urbanization have played a key role in the continued boom of skyscraper construction during the past decade. Skyscrapers' urban expansion, in both numbers and heights, is projected

引言

高层建筑的必然性

高层建筑在20世纪60年代成为一个主要的建筑类型，它解决了随着城市中心人口不断增长的密度而增长的空间需求（Ko, et al., 2008）。这种建筑解决方案的目的在于用尽可能少的土地提供最大化的可用空间，以容纳不断增加的城市人口。20世纪60年代生活在城市地区的人口接近十亿，而目前对于2050年的城市人口预计约为六十亿，超过了那时生活在这个星球的九十亿人口的三分之二（UN，2014）。在过去数十年中，这种人口的激增和不断扩大的城市化对摩天大楼建设的持续繁荣起了关键作用，随着对摩天大楼在数量和高度上的预测，沙特阿拉伯吉达的Burj Al-Mamlakah已经达到了约1000米（Weismantle & Stochetti，2013）。

to reach even higher – approximately 1,000 meters in the case of the under construction Burj Al-Mamlakah in Jeddah, Saudi Arabia (Weismantle & Stochetti, 2013).

The Problem

Unfortunately, the casualty of rapid urban expansion is an inevitable and oftentimes dramatic depletion of the city's resources. As cities grow to accommodate the an increasing population, the expansion overtakes adjacent areas used for resource production, such as agricultural land. Moreover, strained farmland yields are regularly subjected to further losses due to transportation, with agricultural losses reaching 30 percent in Europe and North America (Gustavsson & Cederberg, 2011). Similarly, substantial losses occur in energy transmission. A typical power plant source is only 30 to 35 percent efficient by the time energy reaches the building (Frechette & Gilchrist, 2008). Consequently, it seems imperative to re-examine the modern city's resource generation and distribution systems. Greater emphasis on local production within a city center is vital to decrease excessive transportation losses and increase the potential of open areas and parks.

Pros and Cons

Critics opposing the tall building typology remain convinced of its ineffectiveness (Roaf, et al., 2009), despite its apparent necessity – particularly in a densified clustered setting – to limit land use and accommodate increased population and growing urbanization. Criticism against this "urban evil" highlight concerns, such as increased costs from requiring special construction equipment and expertise, in addition to the subsequent operational and maintenance costs (Ali & Al-Kodmany, 2012), straining infrastructure and transportation systems, overshadowing of surroundings, consumption of large amounts of energy (Al-kodmany, 2012), and decreased usable floor efficiency (60 to 70 percent) relative to low- or mid-rise buildings (Watts & Langdon, 2010); however, critics emphasize these drawbacks without offering a viable alternative to address overpopulation and escalating urban densities. Hence, skyscraper construction continues to thrive, with more skyscrapers completed in the previous decade than any previous period in history (Al-kodmany, 2012). A dramatic change in use has recently occurred in many newly constructed skyscrapers, with an increase in hotel, residential, and mixed-use functions by six percent, 16 percent, and 28 percent, respectively. On the other hand, the office function skyscraper – which used to dominate skyscraper developments – has decreased by 50 percent (Wood, 2015).

The driving forces for this skyscraper boom are well beyond merely offering a solution for high urban densities. Supporters of skyscrapers cite many advantages, such as urban regeneration (Nordenson & Riley, 2003), lesser land consumption (Wood, 2013), preservation of open spaces (Al-Kodmany & Ali, 2013), and financial practicality due to extreme land prices in city centers (Al-kodmany, 2012). The most important advantage, however, is the ability to create more compact urban living in city centers. Compact city development have proven successful in cities such as Hong Kong (Newman, 1996) by decreasing driving distances and consequently reducing transportation carbon emissions. By applying this concept in North America, driving distances can be decreased by up to 40 percent (Ewing, et al., 2008).

Untapped Potential

Despite the criticism of high resource consumption, tall buildings remain the most feasible design solution in densely populated conurbations (Cichy, 2012), as a single supertall building in a clustered high-rise city consumes approximately seven percent of land relative to the dense courtyard typology, and one percent of land relative to a typical urban house, even when housing the same number of people (Drew, et al., 2015). The immense advantages that skyscrapers possess over other architectural typologies can be further enhanced by improving their performance efficiency and generative capabilities. Potential performance improvements can be explored using multi-objective optimization (MOO) aided by parametric design tools (Ashour & Kolarevic, 2015). Evaluation tools such as computational fluid dynamics (CFD) (Malkawi, et al., 2004) and EnergyPlus® (Ellis & Torcellini, 2005) can be used with MOO to explore skyscrapers' generative potential. Using these software tools a designer can visualize and explore multi-resource, multi-system generation optimization. An optimization-centerd, software-based design platform can potentially enable the simultaneous exploration of multiple strategies for decreased consumption and the large-scale production of multiple resources, such as energy, food, water, and land. Furthermore, this platform can aid in exploring the feasibility of harnessing sky-sourced energy with increased building heights due to variations in temperature lapse rates, airflow, stack effect patterns, air moisture,

问题

不幸的是，快速的城市扩张引起的意外事故不可避免并时常戏剧性地耗竭城市资源。随着城市的发展以适应不断增长的人口，城市扩张占据了用于生产资源的邻近地区，如农业用地。此外，紧张的农业用地经常受到因运输而产生的进一步损失，这种农业损失在欧洲和北美达到了30%（Gustavsson&Cederberg，2011）。同样，大量的损失也发生在能量传输方面：一个典型的发电厂能量到达用户的效率只有30–35%（Frechette & Gilchrist，2008）。因此，重审现代城市的发电资源和配电系统势在必行。注重市中心内的当地生产对减少过度的运输损耗和增加潜在的开放区域、公园是至关重要的。

优点和缺点

反对高层建筑类型的评论家则认为它们具有无效性（Roaf，et al.，2009），尽管其对于限制土地利用和适应不断增加的人口与城市化具有明显的必要性（特别是在密集成群的环境里）。一些“罪恶都市”的突出问题被批判：诸如所需特殊施工设备和专业技术的后续运营成本以及维护成本，大量的基础设施和交通系统遮蔽了周围的环境，也消耗了大量能源（Al–kodmany，2012），并且相对中低楼层降低了楼面使用效率（60–70%）（Watts & Langdon，2010）。评论家强调这些缺点并没有提供一个可行的替代方案以解决人口过剩和不断升级的城市密度。因此，摩天大楼的建设持续蓬勃发展，过去的几十年间，摩天大楼的建造多于历史上任何一段时间（Al–kodmany，2012），然而在使用方面发生了巨大的变化：酒店、住宅和多用途功能房分别增加了6%、16%和28%。另一方面，曾经主宰摩天大楼发展的高层写字楼减少则了50%（Wood，2015）。

摩天大楼的驱动力持续繁荣，远远超出仅仅提供高城市密度的解决方案。摩天大楼的支持者举出很多优点，如城市再生（Nordenson & Riley，2003），较小的土地消耗（Wood，2013），开放空间的保留（Al–Kodmany & Ali，2013)和城市中心极端地价的经济实用性（Al–kodmany，2012）。然而，最重要的优势在于其创造更紧凑的城市生活的能力。紧凑型城市发展已经在一些城市成功证明，例如香港（Newman，1996）通过减少驾驶距离，从而减少交通碳排放。如若在北美应用这个理念，驾驶距离可以最多降低40%(Ewing，et al.，2008)。

尚未开发的潜力

尽管资源的高度消耗受到了批判，高层建筑依然是人口密集型大都市的最可行的设计方案（Cichy，2012），作为一个在集群高层城市里的单一超高层建筑，

and density (Leung & Weismantle, 2008). Obviously, the design strategies based on resource generation require further research to improve the potential of future high-rise developments in high-density city centers (Oldfield, et al., 2014).

Resource-Generating Skyscrapers

The city centers' rapid urbanization, resource depletion, and limited land will only increase the need for skyscrapers, which will continue to define the fabric of the modern city. Resource-Generative Skyscrapers (RGS) are a possible solution to further explore and optimize the generative potentials of skyscrapers, and thus address the significant issue of the city centers' resource depletion. RGS can be optimized for waste energy harvesting capabilities by harnessing sky-sourced energy and capitalizing on passive features of integrated active renewable systems. Furthermore, RGS can be strategically positioned in densely populated city centers. Through the concept of compact cities, and by co-locating resources production and consumption, RGS can have an effective radius of influence. This radius can contain locally harvested basic resources (energy, food, water, and land) which can relieve the need for transporting resources from the city's outlying areas. Additionally, by expanding the tall building influence domain in the RGS typology, the supporting compact infrastructure and transportation systems can be developed promptly by shifting the required infrastructure expansion from the public to the private (RGS) domain.

Energy Efficiency in Skyscrapers

Skyscrapers have significant potential to be further optimized for energy efficiency and other environmental considerations via thermodynamics and energy flow analysis, which can guide the typological evolution of skyscrapers (Li, et al., 2015). The R2AG formula for high-performance skyscrapers – Reduction, Reclamation, Absorption, and Generation – is a methodological approach to sustainability used in most skyscrapers for its ability to reduce the building's resource consumption, and then establish a connection to the surrounding natural energy streams prior to adding any costly on-site generation capabilities (Frechette & Gilchrist, 2008).

Reduction

The initial approach for higher efficiency is to reduce the building's consumption. The primary step is capitalizing on the natural assets of daylight, solar radiation, natural ventilation, and more extracted via efficient external single or double-skin envelopes, solar chimnies, wind catchers, etc. (Watts & Langdon, 2010). Subsequently, central mechanical systems – whether water based (chilled beams), or varying flow air systems (VAV) – can be developed accordingly (Parker & Wood, 2013). Water supply and use reduction can be achieved via gravity-induced water supply from water tanks integrated at intermittent levels, coupled with the use of low-flow sanitary fittings and water reclamation. For example, the Commerzbank Tower (1997; Figure 1) located in Frankfurt, Germany, and designed by Foster+Partners, deployed passive strategies that relied on the tower's geometry.; strategies included natural illumination and ventilation through a central atrium spanning the full tower

它占用了能够容纳相同数量人口的密集庭园类型7%的土地，和典型城市房屋1%的土地（Drew，et al.，2015）。高层建筑所具的超过其他建筑类型的巨大优势可以通过改进性能效率和生产能力而进一步增强。潜在的性能改进可以使用多目标优化（MOO）的参数设计工具探索（Ashour & Kolarevic，2015）。评估工具例如计算流体动力学（CFD）（Malkawi，et al.，2004）和EnergyPlus®（Ellis & Torcellini，2005）可以用MOO探索摩天大楼的潜在衍生力。利用这些软件工具，设计人员可以可视化和探索多种资源、多种系统的生成优化。以优化为中心、基于软件的设计平台，可以使多种对策同时进行探索，以减少消耗和大规模生产多种资源，如能源，食品，水和土地。此外，该平台可以帮助探索天空资源（由于气温直减率、气流、烟囱效应模式以及空气的湿度和密度的不同引起的建筑高度增长）利用的可行性。（Leung & Weismantle，2008）。显然，

Figure 1. Commerzbank Tower (Mylius, 2009) (Copyright: CC BY-SA)
图1. 商业银行大厦（Mylius，2009）（来源：CC BY-SA）

height, optimized façade design to allow natural ventilation via operable windows, and a water-based chilled ceiling cooling system (Oldfield, et al., 2009).

Reclamation

The principle of reclamation is to recapture and reuse the injected energy in the building, refraining from introducing newly harvested energy or water into the envelope (Parker & Wood, 2013). Examples of reclamation strategies include air-to-air heat recovery, which can be used to reduce the incoming external air's heating/cooling loads by transferring the exiting high-energy-content air stream to the incoming one. Similarly, the use of a heat exchanger before greywater discharge can extract waste heat for domestic hot water usage. Additionally, reclaimed greywater and rainwater can be treated and used for non-potable water use, such as toilet flushing, cooling tower water make-up, and irrigation of vertical vegetation (Simmonds, 2015). Reclamation can also be applied to cooling coils' condensate water deposit from the cooled/dehumidified external air introduced into skyscrapers (Parker & Wood, 2013). The Pearl River Tower (2011) in Guangzhou, China, which was designed by SOM, successfully employed reclamation strategies such as re-circulated air for the pre-conditioning of outside fresh air prior to distribution (Frechette & Gilchrist, 2008).

Absorbtion

Skyscrapers' inherent footprint and height expose it to abundant energy streams of ground, solar and wind-sourced energy. Absorption technologies include geothermal energy, where tapped ground temperature lags behind air temperature by a range function of depth. By using a heat pump, concentrated heat energy can be extracted by circulating a fluid through buried "ground loops" to address space/water heating demands. Conversely, the system can discharge waste heat back into the ground or water as energy storage to address cooling demands (EnerGuide, 2004). A skyscraper's footprint and surrounding site dictate the use of extraction at deeper boreholes or integration with foundation piles (Parker & Wood, 2013), which is demonstrated in projects such as the Porta Nuova district's four geothermal heat pumps in Milan, Italy, which service Bosco Verticale residential towers, taking advantage of the city's underground aquifer to address the tower's heating/cooling demands simultaneously (Smith, 2015).

While ground source energy is used in a variety of projects, sky-sourced energy – with the exception of solar and wind – has not yet been researched comprehensively (Leung & Weismantle, 2008). Harnessing the full potential of sky-sourced energy – induced by variation in environmental factors along building height – can provide extended opportunities for energy savings and generation. Incorporating these variations as part of skyscraper's early design stages, simulation, and analysis can have a significant impact on the overall building heating/cooling distributions. This is demonstrated in the computational analysis of the Freedom Tower (2014) located in New York and designed by SOM (Figure 2). By accounting for height-induced environmental variations of temperature and wind effect changes only, a 13 percent difference was identified in total annual building cooling/heating energy loads between the ground and top floors of

Figure 2. Freedom Tower, New York (Dolby, 2014) (Copyright: CC BY-SA)
图2. 世界贸易中心一号大楼，纽约(Dolby，2014)（来源：CC BY-SA）

基于资源生产的设计战略要求进一步的研究，以提高在高密度城市中心的未来高层发展潜力（Oldfield, et al., 2014)。

资源可生型摩天大楼

城市中心的快速城市化，资源枯竭，以及有限的土地只会增加对摩天大楼的需求，这将继续定义现代城市的构架。资源可生型摩天大楼（RGS）是一个可行的解决方案，通过进一步探索和优化摩天大楼的生产潜力，从而解决城市中心的显著的资源枯竭问题。通过利用空中能源和集成有源可再生能源系统的被动特性，RGS可以对浪费的能量和收集能力进行优化。此外，RGS可以战略性地定位在人口密集的城市中心。通过紧凑城市这个概念，并通过共定位资源的生产和消耗，RGS可具有有效的影响力半径。这个半径可以包含当地收获基本资源（能源，食品，水和土地），继而缓解从城市的边远地区运输资源的需求。另外，通过扩大RGS类型高楼影响的区域，紧凑的配套基础设施的和交通系统能够及时地把所需基础设施及时地从公共转向给私人（RGS）区域。

摩天大楼的能源效率

摩天大楼具有进一步通过热力学和能量流动分析而优化能源效率和其他环境因素的显著的潜力，从而可以指导摩天大楼类型学的演变（Li, et al., 2015)。对于高性能摩天大楼的R2AG 公式，减量、回收、吸收和生产，是用于大多数摩天大楼可持续发展的方法对策，用以减少资源消耗，然后建立一个周围的自然能量流优先于添加任何昂贵的现场生产能力的连接。(Frechette & Gilchrist, 2008)。

减量

获得更高效率的初始方法是减少建筑物的消耗。第一步为利用自然资产如日光、太阳能辐射、自然通风等，通过高效单层或双层外膜、太阳能烟囱和集风口等提取出来（Watts & Langdon, 2010)。随后，中央机械系统 ，无论是水性（冷却梁）或是空气流动改变系统（VAV）， 可相应开发（Parker & Wood, 2013)。此外，供水和减少使用量可以通过重力感应供水系统在水箱不断集成，加上使用节水卫浴配件和水再利用系统来实现。例如，商业银行大厦（1997年；图1）在德国法兰克福，由Foster 和 Partners设计，部署了对塔楼的几何依靠的被动战略；策略包括通过中央心房横跨整个塔楼高度，应用自然照明和通风，优化外观设计，从而允许经由可操作的窗户自然通风，和水基冷却天花板冷却系统（Oldfield, et al., 2009)。

Figure 3. CIS Solar Tower: a skyscraper covered in solar panels (Mikey, 2010) (Copyright: CC BY-SA)
图3. CIS 太阳能大厦：覆盖太阳能电池板的摩天大楼(Mikey，2010)（来源：CC BY-SA）

the tower. The design team, however, didn't account for variations such as air pressure, density, and moisture, which could have increased the energy loads percentage difference (Simmonds, 2015). Hence, it is clear that multiple opportunities for energy savings and generation can be created by exploiting the environmental effects of height in skyscrapers.

Generation

The integration of renewable energy generation systems requires a rigorous exploration for ideal system configuration, minimized cost, maximized system reliability and financial return, in addition to cooperative agreements with local policies to capitalize on peak time generations (Baños, et al., 2011). Moreover, these parameters are explored in the context of fluctuating environmental influences. The complexity of the integrated systems increases when exploring multiple renewable systems to perform symbiotically (Turrin, et al., 2011). Consequently, few renewables can compete with fossil fuel reliant systems, with an economic viability limited to certain locations, climatic conditions, and a prerequisite of a grid connection (Zangeneh, et al., 2009)

1) Photovoltaics

One of the contending renewables is Photovoltaic (PV) technology, which has immense potential for façade integration in skyscrapers, given the skin area-to-volume ratio. For example, 7,244 PV panels are integrated on the 118-meter-high CIS Tower façade (Figure 3) located in Manchester, UK, and is estimated to generate 180,000 KWh annually (Kareem & Zuo, 2012). Geographic location and climatic conditions, however, result in great differences in PVs efficiency and electrical output. For example, an integrated mono-crystalline PV panel in a skyscraper in London or Moscow can yield 111-119 KWh/m2/year, which is only half of what a similar panel mounted on a project in Delhi, Los Angles, or Cape Town could generate (233 KWh/m2/year) (Al-Kodmany & Ali, 2013). Hence, for competitive renewable energy system integration, a holistic optimization is imperative starting in the early architectural design phase.

2) Combined Heat and Power (CHP)

Another critical onsite energy generation system is Combined Heat and Power (CHP), which couples the generation of electricity with usable heat energy, and Tri-Generation, which is the triple generation of electricity, heat energy, and cooling through an absorption chiller (Parker & Wood, 2013). CHP plants can be bio-fueled by organic waste materials, which is particularly appealing if the building has integrated vertical farming. CHPs can be highly efficient in both electricity and heat energy generation; however, it is a characteristic of CHPs to generate undesirable excess heat energy (Ali & Al-Kodmany, 2012), which requires further design considerations for transfer into energy storage. The Shard (2013) located in London, UK and designed by Renzo Piano, is a clear demonstration of the successful integration of a large-scale CHP plant, capable of generating 1.131 MW

回收

回收的原则是夺回并重新利用注入在建筑的能量，避免引入新收获的能量或水进入系统（Parker & Wood，2013）。回收战略的例子包括空气–空气之间的热回收：通过把排出的高能含量气流转换为进入的气流，从而减少外部进入的空气加热/冷却负荷。同样地，灰水排放前使用热交换机可提取废热作为家用热水。加之再生灰水和雨水可以用为非饮用水，如厕所冲洗、冷却塔水和对垂直植被的灌溉（Simmonds，2015）。此外，滞存在用于冷却/除湿外部空气的冷却线圈中的冷凝水，也可被回收导入大楼中（Parker & Wood，2013）。由SOM设计所设计的中国广州的珠江大厦（2011年），成功地采用了回收战略，如对外界新鲜空气的分配前进行预处理的空气循环设计（Frechette & Gilchrist，2008）。

吸收

摩天大楼固有的占地面积和高度暴露于丰富的地面能量流、太阳能和风能之中。吸收技术包括地热能：地面温度与深度相关并成函数地滞后于空气温度。通过使用热泵，提取掩埋在“接地回路” 流体循环系统中的集中热能，从而满足空间、水加热的需求。相反，该系统能排出废热至地面或排放水作为储能以解决冷却需求（EnerGuide，2004）。摩天大楼的占地面积和周围的场地规定了深层钻孔或建筑物的地基桩的集成（Parker&Wood，2013），这可以体现在项目中，例如位于意大利米兰新门区、服侍于Bosco Verticale住宅塔楼的四大地热泵，以城市的地下含水层的优势，来解决塔楼的加热/冷却需求（Smith，2015）。

虽然地源能量能用在各种项目中，除去太阳能和风能的天源能量却尚未全面的研究(Leung & Weismantle，2008)。利用天源能量的全部潜力，即不同环境因素引起的建筑物的高度，可以为节能和生产提供广大的机会。将这些变化合并为摩天大楼在其设计阶段的一部分，建模和分析可以得出对整体大楼的热/冷分配系统的显著的影响。这已从SOM设计的纽约自由塔的计算分析中得到了展示（图2）。如果只计入高度变化对温度和风效应的影响，地面和塔楼顶部之前的年度建筑物总冷却/加热能量负荷有13%的差异。然而设计团队并没有计入气压、密度和湿度的变化所带来的影响，这些可能进一步增加能量负荷的比例。因此，很显然，对节约能源和生产的多种机会可以通过利用环境和高度对摩天大楼的影响来创建（Simmonds，2015）。

生产

集成可再生能源发电系统需要对理想的系统配置进行严格探索，最小化成本，最大化系统可靠性和财务收益，并且与

of electricity and 1.199 MW of hot water at 85 percent efficiency (ClarkeEnergy, 2012).

3) Wind Power

In recent years, the skyscrapers integrating wind turbine technology have been optimized by pioneering strategies, such as shaping the roof to accelerate ambient winds through an array of multiple wind turbines mounted in ducts and/or designing the building profile to accelerate the ambient winds on fewer, yet larger turbines (EL-Mokadem, et al., 2015). Despite concerns of safety, inefficient energy yields and coverage ratios, skyscrapers optimized for wind power can have increased wind energy output from tapping into high-energy-content winds at high altitudes and the extended benefits of decreased structural wind loading requirements due to the aerodynamic form (Frechette & Gilchrist, 2008).

According to Stankovic et al., the wind turbines output power equation is identified as P-Turbine= CP*1/2*ρAV3 (Stankovic, et al., 2009). The coefficient of performance (CP) relies on the turbine type, which is typically 0.3. Air density (ρ) is directly proportional to the turbine's energy output. Since air density decreases with high altitudes, this factor can be crucial when considering optimum turbine placement along the tower height. Swept area of the blade (A) is critical, as doubling (A) can double the energy output. Velocity (V) is considered to be the most important variable in this equation. According to Terri Boake, wind turbine output is a cube of the utilized wind speed (Boake, 2014). Current research in the computational optimization of blade design promises significant improvements in extracting the kinetic energy from the prevailing winds. Another critical concern in skyscraper's integrated wind turbines is the outdated turbines technology which inhibits the building from fully harnessing the abundant energy stream; however, advancements in the field of CFD allow simulations of aerofoils in the third and fourth dimensions (Figure 4), providing designers with a better understanding of the consequential implications of their designs, such as blade interaction with prevailing winds and better control over the overall integrated wind turbine systems (Stankovic, et al., 2009). The Pearl River Tower demonstrates a successful aerodynamic geometric optimization for improved integrated wind turbines' yields (Tomlinson-II, et al., 2014). Performance-optimization strategies included funneling the ambient winds through four channels – embedded to the mechanical floors to conserve usable space – increasing

本地策略合作，以利用高峰期时间来生产（Baños, et al., 2011）。此外，也对这些参数进行在波动环境影响下的探索。当探索多种可再生系统时，集成系统的变得复杂，以达到共生存的状态。（Turrin, et al., 2011）。因此，很少有可再生能源可以与化石燃料依赖系统竞争，经济可行性限定了某些位置，气候条件和电网连接的先决条件（Zangeneh, et al., 2009）

1）光伏

一个有竞争力的可再生能源的是光伏（PV）技术，根据表面的面积-体积比例，该技术具有应用于在摩天大楼外观一体化的巨大潜力。例如，在英国曼彻斯特，7244块光伏电池板集成在一座118米高的CIS塔楼外墙（图3），据估计每年产生18万千瓦时的电量（Kareem & Zuo, 2012）。然而，地理位置和气候条件导致PV在效率和电量输入方面产生巨大的差异。例如在伦敦或莫斯科，集成单晶硅光伏电池板可以产生111-119千瓦时/平方米/年的电量，在安装相同PV板的情况下，这些电量只有安装在德里、洛杉矶或开普敦城产量的一半（233千瓦时/平方米/年）（Al-Kodmany & Ali, 2013）。因此，对于有竞争力的可再生能源系统集成，全面的优化在早期建筑设计阶段极为重要。

2）热电联产（CHP）

另一个关键就地能源生产系统是热电联产，其耦合了发电、可用热能，还有Tri-generation技术，即通过吸收式制冷机进行三重生产电、热能和冷却（Parker & Wood, 2013）。热电联企业可以用有机废料作为生物燃料，如果建筑集成了垂直农场，热电联产将格外有吸引力。热电联产可以产生高效率的电力和热能，但是，其特征是产生不可萃取的多余热能（Ali & Al-Kodmany, 2012），因此CHP需要进一步设计，以计入转移能量储存。英国伦敦的The Shard建筑，由Renzo Piano设计，是一个大型热电联产企业的成功展示，它能够在85%的效率下产生1.131兆瓦的电力和1.199兆瓦的热水（ClarkeEnergy, 2012）。

3）风力

近年来，摩天大楼集成风力涡轮机技术的已被首创的策略优化，例如通过在管道安装多个风力涡轮机的阵列而成形的屋顶而加速环境风，和/或设计的建筑轮廓，用更少但是更大涡轮机来加速环境风（EL-Mokadem, et al., 2015）。除了安全顾虑，低效的能源产量和覆盖率，对风电进行优化的摩天大楼可以利用在高海拔的高能含量风和减少由于空气动力学而产生的结构风荷载的延伸利益，从而增加风电输出。（Frechette & Gilchrist, 2008）。

根据Stankovic等人，风力涡轮机的输出功率方程为P-汽轮机= CP ＊ 1/2 ＊ρAV3 (Stankovic, et al., 2009)。性能系数取决于涡轮机的类型，通常数值为0.3。空气密度（ρ）与涡轮机能量输出直接成正比。由于空气密度随着海拔的升高而降低，当考虑沿塔楼高放置涡轮机的最佳效果时，这个因素是至关重要的。叶片扫过的面积（A）是这里的重要因素，因为加倍（A）可以增加一倍能量输出。速度（V）在此公式中被看做最重要的变量。根据Terri Boake，风力涡轮机的输出是所用风速数值的立方（Boake, 2014）。目前在叶片设计的计算优化研究中，有望显著改善从恒风中抽取动能。摩天大楼的集成风力涡轮机系统中的另一个关键问题是过时的技术，这抑制了建筑充分利用废气能源流的能力。然而，在CFD领域的进步使得在第三和第四维度的翼型的模拟（图4）为设计者提供一个对自己的设计作品的间接影响力的更好理解，如叶片与恒风的相互作用，以及对于整体风力涡轮机系统的更好的控制。（Stankovic, et al., 2009）。珠江大厦成功展示了对改进集成风力涡轮机生产量进行的空气动力学的几何优化（Tomlinson-II, et al., 2014）。

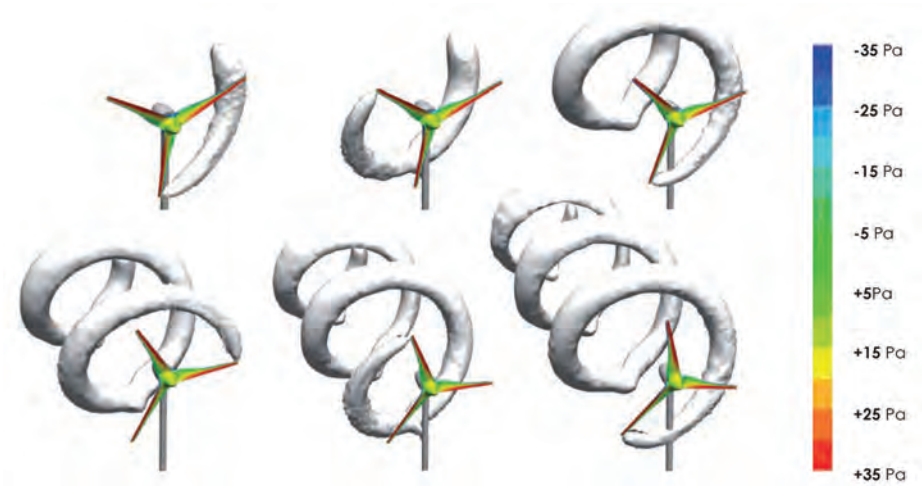

Figure 4. Animated frames of a wind turbine simulation, depicting the pressure on blades and the resulting dynamic movement from tracing smoke from the blades (Stankovic, et al., 2009) (Copyright: CC BY-SA)
图4. 动画模仿风力涡轮机，展示了叶片压力以及叶片示踪烟气的动态运动（Stankovic, et al., 2009）（来源：CC BY-SA）

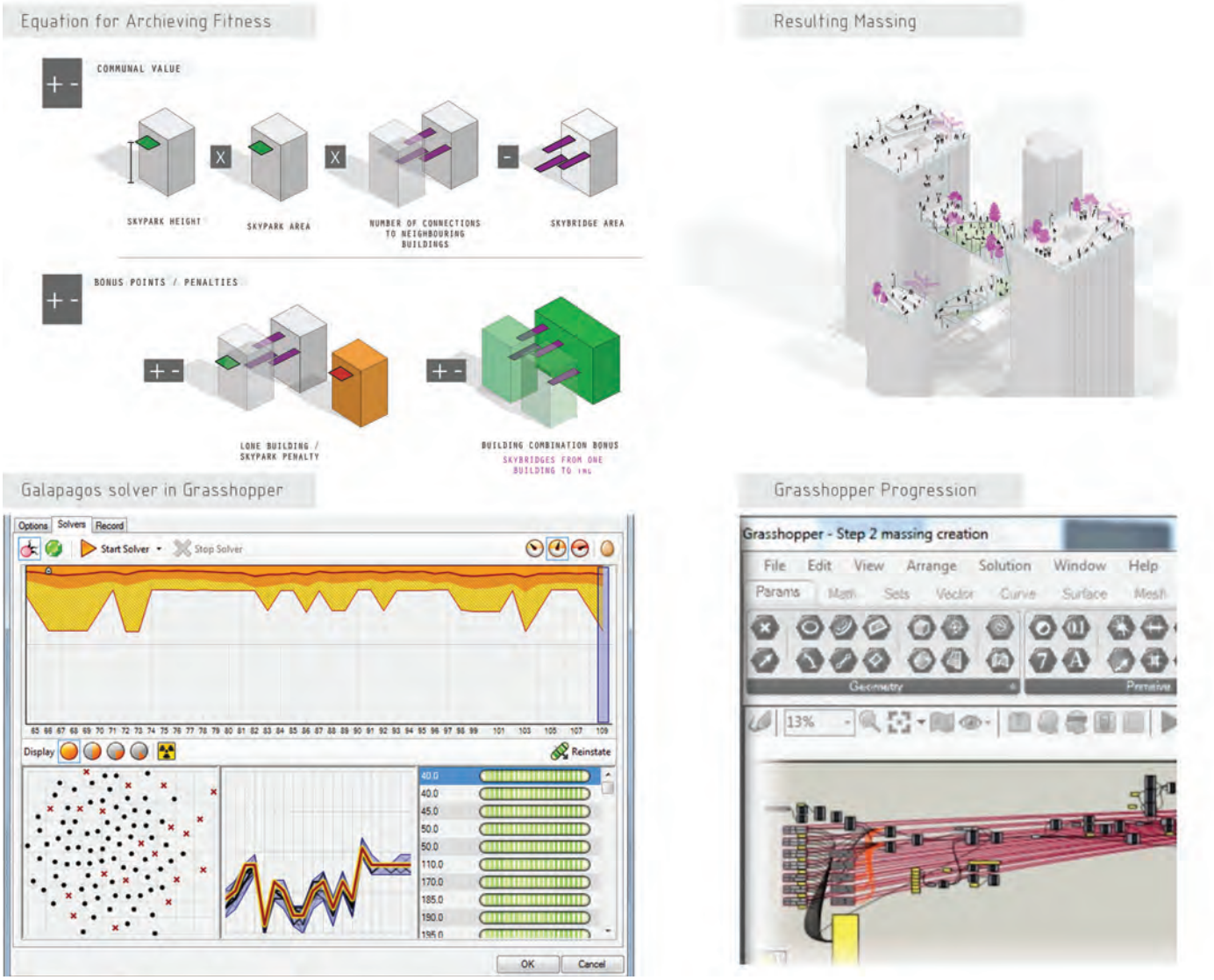

Figure 5. Illustration of using Grasshopper and Galapagos Plugins for form finding based on an identified fitness function (Paul Wintour, 2015) (Copyright: CC BY-SA)
图5. 使用Grasshopper和Galapagos插件探索基于确定适应度函数的形式（Paul Wintour，2015）（来源：CC BY-SA）

the ambient wind speed by a factor of two to 2.5 times (Frechette & Gilchrist, 2008). While wind generation accounts for a relatively small part of total energy consumption, this strategy symbiotically created a more efficient structure, reducing the structural wind loading requirements (Boake, 2014).

Multi-Objective Optimization and Genetic Algorithms

Computational generative systems such as MOO have enabled designers to pursue the concept of form finding rather than form making, which is steered by embedded performance based morphology over time (Kolarevic & Parlac, 2015). To achieve a variety of optimized design solutions based on the embedded design criteria, the MOO process requires first determining the key performative parameters critical for the selected project, and subsequently, computing a balance between various, often conflicting performance parameters (Ashour & Kolarevic, 2015). Genetic algorithms – which can be used as the solution engine in MOO – are part of the population-based algorithmic family. Population-based algorithms have been extensively employed for energy flow optimization through the evaluation of multiple alternatives of generated energy distribution and efficiency protocols (Cai, et al., 2009). Population-based evolutionary algorithms include genetic algorithms, ant colony systems, memetic algorithms, and particle swarm. Genetic algorithms have been particularly successful in the built environment for their inherent cycle-based search technique. By exploring "populations" of design solutions, optimized progression shifts to resulting solutions offspring. Thus, the resulting design outcomes (Figure 5) perform best relative to the predefined design criteria "fitness function" (Baños, et al., 2011).

性能优化策略包括使环境风通过四个漏斗式通道（嵌入到机械层以节约可用空间）来增加2到2.5倍环境风的速度（Frechette & Gilchrist，2008）。虽然风力发电占能源消耗总量的相对较小的一部分，这一战略共生地创造一个更有效的结构，以降低结构风荷载的要求（Boake，2014）。

多目标优化与遗传算法

计算生成系统如MOO激发了设计者追求形式发现，而不是形式制造，通过嵌入性能避免了基于形态随时间推移的概念。(Kolarevic & Parlac，2015)。为了实现各种基于嵌入式设计准则的优化设计方案，MOO过程需要首先确定鉴定所选项目的关键性能参数，接着，计算各种经常发生冲突的性能参数之间的平衡（Ashour & Kolarevic，2015）。遗传算法是基于人口算法中的一种，可以用作解决方案的引擎。通过对生成能量分配和效率协议的多种备选方案的评估，基于人口的算法已经被广泛应用在能量流优化（Cai，et al.，

Other Generative Resources:

Vertical Farming

The generation of agricultural crops through vertical farming can have immense advantages (Despommier, 2010). This method is particularly useful in high-density city centers, where high land prices prevent farming activities in a traditional open land setting. Moreover, because of vertical farming's inherent year-round production, controlled indoor environment and use of NASA's developed dwarf plant agriculture, one acre in a vertical farm can yield the equivalent of four to six acres of traditional open land farming (Despommier, 2009). This margin can increase to 30 times depending on the type of crops produced (Despommier, 2010). Furthermore, this yield is exempt from extra losses due to transportation. Projects such as the Pasona Headquarters (Figure 6) located in the Ginza district of Tokyo, Japan, are examples of this technology's potential (konodesigns, 2010).

It is essential to be mindful of the limited and valuable space available within skyscrapers; therefore, space allocated to integrate generative systems, such as vertical farming, must be rigorously designed. For example, vertical farming can be provided in sky gardens or within a multi-skin façade. For an enhanced system yield, vertical farming requires further optimization

2009)。基于人口的进化算法包括遗传算法，蚁群系统，模因算法和粒子群最佳化演算法。遗传算法在构建基于搜索技术的环境固有周期取得了特别的成功。通过探索设计解决方案的“人口”，优化发展转移，生成后代解决方案。因此，得到的设计成果（图5），相对于预定义的设计标准“适应度函数” 呈现了最佳表现了(Baños，et al.，2011)。

其他资源生成

垂直农场

农作物通过垂直农场生产拥有巨大的优势（Despommier，2010)。这种方法在高密度城市中心尤其有用，因为在这里为了防止传统开放土地上的农耕活动而设置了高地价。而且由于垂直农场固有的全年生产能力，每英亩的垂直农场可以生产相当于传统开放式农耕用地4到6英亩的产量(Despommier，2009)。根据作物的类型，此余量可以增加至30倍（Despommier，2010).此外，这种产量也免除于运输造成的额外损失。例如位于日本东京的银座区得Pasona总部（图6），是这种技术潜力的例子（konodesigns，2010)。

留意摩天大楼中可用的有限且宝贵的空间是至关重要的。因此，分配空间以集成生产系统，如垂直农场必须经过严格设计。例如，垂直农场可以在空中花园或多层玻璃幕墙内提供。为了增强系统的产量，

Figure 6. Pasona Headquarters vertical farming activities on the façade (螺钉, 2011) (Copyright: CC BY-SA)
图6. 保圣那集团总部的立面垂直农场(螺钉，2011)（来源：CC BY-SA）

垂直农业要求经营农业系统进一步优化。这种优化需要灌溉流做成流线型，并且日光从开窗中渗漏进来。（Despommier，2010)，类似地，回收灌溉的输出水流并且痛现场热电联企业生产固体废弃物的潜在能量。

雾气收集

雾气收集是最有前途却尚未研究（特别是在摩天大楼）的集水技术之一。这种特殊的集水取决于大气湿度、密度以及定向风流。这些随高度变化的参数，可以通过CFD分析进行优化（Leung & Weismantle，2008）。这种采用聚丙烯的廉价技术是通过被动压紧处理来集水，而不是主动冷凝（Schemenauer & Cereceda，1994)。雨水收集这种技术已在世界各地的沿海高地经过严格的测试。据非营利组织Fog Quest的小规模雾收集设施（图7）显示了巨大潜力，如在智利，也门，摩洛哥和其他地方一样，一个标准40平米的收集器生产量最高可以达到的2000升/天。然而，生产量很可能全年平均在200升/天（FogQuest，2015）。这些项目证明了在世界各地雾收集作为水资源的可行性。如果这种被动技术使同时容纳雨水收集标准化，它也许会在高层建筑的设计中具有深远的意义。

结论

本文认为，大型资源生产系统的优化整合对下一代的摩天大楼的发展是必不可少的。RGS能够通过使用MOO进化工具和GA评估工具来增强性能改进和生产力的潜能，如CFD和EnergyPlus®。设计人员通过使用这些工具可形象化并探索多资源多系统生成参数优化，如能源，食品，水和土地（见图8）。最初的焦点是通过探索浪费资源收集能力（1）集成有源再生系统的被动特性，（2）利用天空能量，这可以更好的延长能源节约和再生，以及（3）在相对位置情况下，校准最优化的建设足迹和高度范围 ，实现能源消耗和能源再生之间的平衡。

一些高大建筑物进步过程所必需的关键里程碑是协同多系统就地生产的供给，系统能够存储所产生的能量，并给电网一个可靠的，安全的连接的系统，该系统可以通过计算设计探索MOO和GA的辅助工具，在本文中突出显示。这些工具可以通过同时优化摩天大楼外形的其他方面来校准，如日光，热量控制，眩光，观点，隐私和外观一体化太阳能发电，或自然/混合模式通气，形成空气动力学和风力发电或都市农业，热电联产系统的流量，和对周围环境的影响。

of the operational farming system. This optimization needs to streamline the input flow of irrigation, and daylight penetration from fenestration (Despommier, 2010), and similarly, the output flow of recycling irrigation water and the direction of solid waste for potential energy generation via onsite CHP plant.

Fog Harvesting

One of the most promising, yet under-researched (particularly in skyscrapers), water harvesting technologies is fog harvesting. This particular type of water harvesting depends on air moisture, density, and directed wind flow. These parameters – which vary with height – can be optimized via CFD analysis (Leung & Weismantle, 2008). This inexpensive technology uses polypropylene meshes to harvest water through a passive impaction process rather than active condensation (Schemenauer & Cereceda, 1994). This technique of water harvesting has been rigorously tested in various coastal highlands across the world. According to the non-profit organization Fog Quest, small-scale fog harvesting facilities (Figure 7), such as in Chile, Yemen, Morocco, and elsewhere, show great promise, as yields from a standard 40-square-meter collector can reach a maximum of 2,000 L/day. The yields, however, can potentially average to 200 L/day across the year (FogQuest, 2015). These projects prove the viability of fog harvesting as a water source in various locations across the world. If calibrated to simultaneously accommodate rainwater harvesting, this passive technology can potentially be of further significance in the design of tall buildings.

Conclusion

This paper argues for the optimized integration of large-scale resource production systems as essential for the evolution of the next generation of skyscrapers. RGS performance improvements and generative potential can be enhanced using the evolutionary tools of MOO and GA coupled with evaluation tools, such as CFD and EnergyPlus®. Using tools like these, a designer can visualize and explore the multi-resource, multi-system generation optimization of parameters such as energy, food, water, and land (Figure 8). The initial focus must be on waste energy harvesting capabilities by exploring (1) passive features of integrated active renewable systems; (2) the harnessing of sky-sourced energy, which can highlight extended opportunities for energy savings and generation; and (3) calibrations for optimized building footprint and height range – relative to location context – to achieve a balance between energy consumption and generation.

Some of the key milestones essential to the tall building advancement process are the optimization of synergetic, multi-system, on-site generation supplies; systems capable of storing generated energy; and a reliable, secure connection to the grid, which can be explored by the computational design aid tools of MOO and GA highlighted in this paper. These tools can be calibrated to simultaneously optimize other aspects of the skyscraper's performative profile: such as daylighting, heat control, glare, views, privacy, façade integrated solar energy generation or natural/mixed-mode ventilation, form aerodynamics, wind power generation, urban agriculture, CHP system flow, and the impact on the surrounding environment.

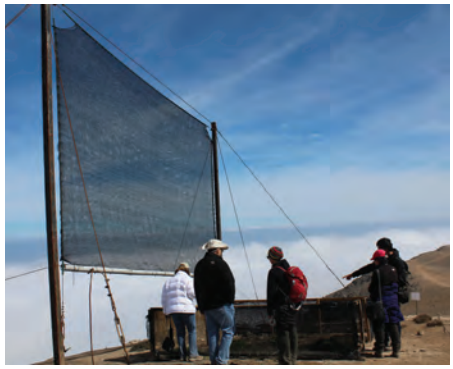

Figure 7. Fog harvesting mesh in Alto Patache, Atacama Desert, Chile (Pontificia Universidad Católica de Chile, 2013) (Copyright: CC BY-SA)
图7. Alto Patache的雾水收集网，阿塔卡马沙漠，智利（智利天主教大学，2013）（来源：CC BY-SA）

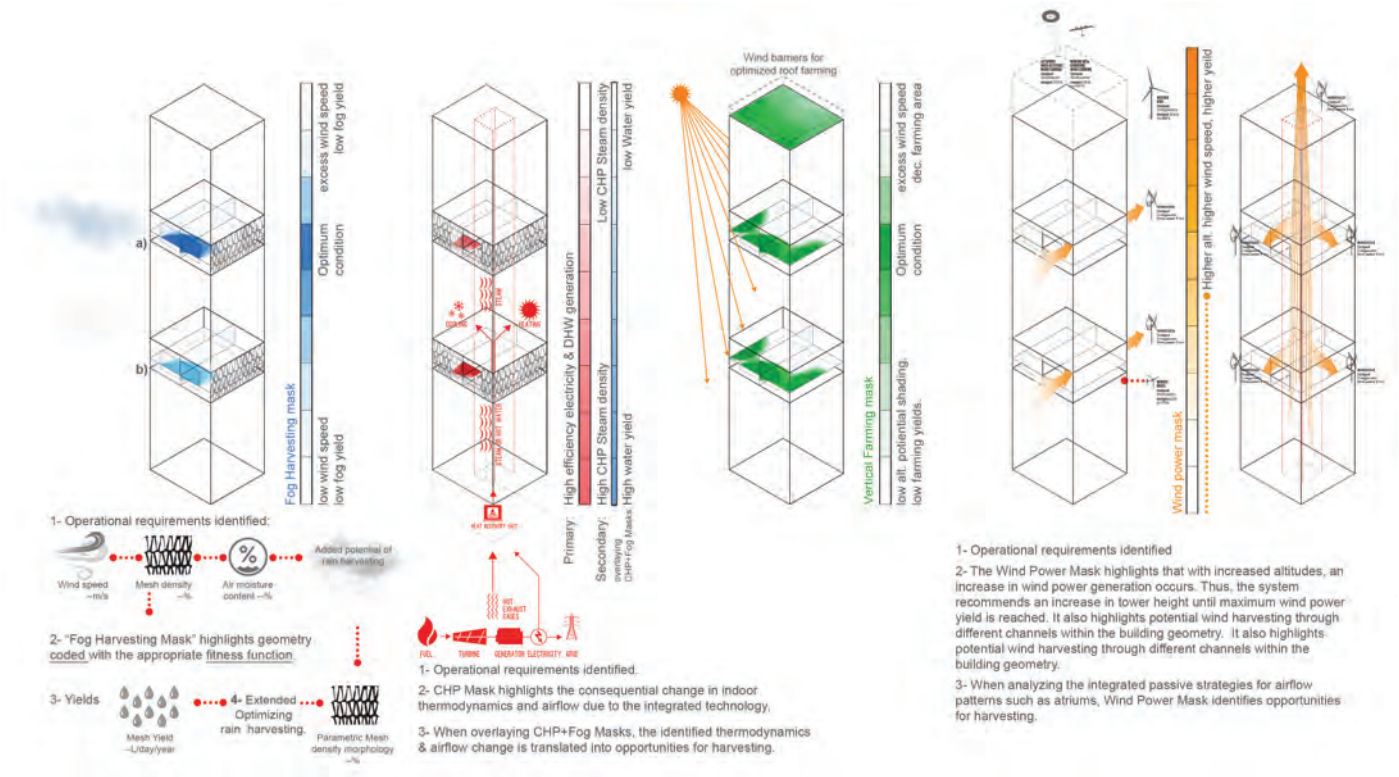

Figure 8. Demonstrating the potential multi-resource, multi-system generation optimization process (Copyright: CC BY-SA)
图8. 阐述了潜在多资源、多系统的生成优化过程（来源：CC BY-SA）

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