International Journal of High-Rise Buildings
December 2013, Vol 2, No 4, 285-291

International Journal of
High-Rise Buildings
www.ctbuh-korea.org/ijhrb/index.php

Low-energy Tall Buildings? Room for Improvement as Demonstrated by New York City Energy Benchmarking Data

Luke Leung[1]† and Stephen D. Ray[2]

[1]*Director at Skidmore, Owings & Merrill LLP; 224 South Michigan, Chicago, IL 60604, USA*
[2]*Mechanical engineering professional at Skidmore, Owings & Merrill LLP; 224 South Michigan, Chicago, IL 60604, USA*

Abstract

This paper proposes a framework for understanding the energy consumption differences between tall and low-rise buildings. Energy usage data from 706 office buildings in New York illustrates expected correlations from the framework. Notable correlations include: taller buildings tend to use more energy until a plateau at 30~39 floors; tall buildings in Manhattan use 20% more energy than low-rise buildings in Manhattan, while tall buildings outside Manhattan use 4% more energy than low-rise buildings outside Manhattan. Additional correlations are discussed, among which is the trend that the Energy Star program in New York City assigns higher ratings to tall buildings with higher EUIs than low-rise buildings with the same EUI. Since Energy Star is based on regressions of existing buildings, the Energy Star ratings suggest taller buildings have higher EUIs than shorter buildings, which is confirmed by the New York City energy benchmarking data.

Keywords: Energy consumption, Benchmarking data, Energy Star, office buildings, New York, Tall Buildings

1. Introduction

It has been declared, “The age of skyscrapers is at an end. It must now be considered an experimental building typology that has failed. With the arrival of the global economic slump in 2007/08, so began the end of the age of tall buildings.” (Roaf et al., 2009). However, with the increasing migration of people into cities, tall buildings live on. More specifically, 108 buildings with designed heights of at least 300 m are scheduled for construction within the next 5 years (CTBUH, 2013). While tall buildings evoke many debates about sustainability and resource use, this paper will focus primarily on the energy consumption of tall buildings using New York city data publically available through energy benchmarking. Energy use disclosure laws are growing in the United States where nine cities and two states require energy use disclosure for large buildings. These large datasets illuminate potential energy consumption differences between tall and low-rise buildings.

We first propose a framework for understanding the energy consumption differences between tall and low-rise buildings. This framework is then mapped onto city-wide energy consumption data from New York City to discuss differences between tall and low-rise buildings. Finally, correlations between the data and framework are highlighted as well as additional noteworthy trends.

2. Tall Building Energy Consumption Framework

A framework for understanding key differences between the energy consumption of tall and low-rise buildings is proposed. While each component of this framework easily merits a paper of its own, they are only briefly discussed here before the framework is used to describe energy benchmarking data from New York City.

2.1. Elevator energy

Although the energy consumption of elevators is typically negligible in commercial buildings, it is often significant in tall buildings. Depending on height, climate, and program, elevators can consume anywhere from 5~15% of the total building energy in tall buildings (Al-Sharif, 1996; Sachs, 2005; Liu et al., 2010). Tall buildings have higher elevator energy consumptions compared to low-rise buildings, because elevators travel further distances in tall buildings and generally travel at faster speeds.

2.2. Infiltration

Although many energy modelers use constant infiltration rates, they are undoubtedly a function of external conditions (Emmerich and Parsily, 2011). Ng et al. explored this difference by modeling various types of buildings with both an EnergyPlus model that assumed a constant infiltration rate and a CONTAM model that calculated infiltration rates based on dynamic pressure differences, which accounted for changes in external and internal conditions (Ng et al., 2013). They found a 200 and 600% increase in

---

†Corresponding author: Luke Leung
Tel: +312-360-4121, +312-360-4361
E-mail: Luke.Leung@som.com; Stephen.Ray@som.com

total infiltration sensible loads for cooling and heating respectively from using the constant EnergyPlus model to the dynamic CONTAM model, reinforcing the well accepted notion that infiltration rates highly depend on external conditions (Ng et al., 2013). Furthermore, when considering only the effect of wind, they found up to an 800% increase in infiltration rate from 0.1 hr^{-1} at 2 m/s wind speeds to 0.8 hr^{-1} at 8 m/s (Ng et al., 2013).

2.3. Solar gains

Tall buildings are exposed to significant solar radiation because trees and even other buildings rarely cast shadows upon them. In suburban settings, one expects relatively comparable solar exposure per m^2 of façade between a low-rise and tall building because surrounding buildings will offer little shading, though the effect of trees must be considered. In dense urban settings, one expects a more significant difference because low-rise buildings can be significantly, if not entirely, shaded while tall buildings rise above the shadows. While this increased solar exposure to tall buildings in cities increases cooling energy in the summer, one might argue it decreases heating energy in the winter. However, Ellis and Torcellini found a 9.0% net increase in heating and cooling energy due to decreased shading in simulations of the first floor and top floor (at 284 m) of the Freedom Tower (Ellis and Torcellini, 2005). Another related effect is the increased solar gains from reflections off surrounding buildings to tall buildings. This secondary effect is not as substantial as the decreased shading of tall buildings, but these increased reflective solar gains led to a 2.6% increase in heating and cooling energy from the first floor to the top floor of the Freedom Tower (Ellis and Torcellini, 2005).

2.4. Mean radiant loss

For similar reasons tall buildings are exposed to more solar radiation than low-rise buildings in urban environments, they are also exposed to more of the sky from increased sky view factors (SVF). Higher SVFs increase infrared radiation to the sky, which increases heat loss during cold winter nights. Low-rise buildings in urban environments predominately radiate to surrounding buildings at much higher temperatures than the sky, resulting in less heat loss. While infrared radiation to the sky increases heating energy during the winter, it helps lower cooling energy in the summer.

2.5. HVAC pumping

Both the increased solar gains and mean radiant impact HVAC loads, which are important for tall buildings' energy consumption (Ali and Armstrong, 2010; Yeang, 1999). Another factor that can increase HVAC energy in tall buildings is the increased pumping distance required for all the mechanical equipment. Larger distances require larger pressures to overcome, which in turn requires more pumping energy. Additionally, buildings over 35~40 stories typically incur efficiency losses due to heat exchangers in pressure breaks, which are necessary because the chilled-water loop must be divided into two or more separate loops above 35~40 stories to avoid high pressures that can compromise conventional fittings and valves. The heat exchangers in these relays increase the chilled water supply temperature 1~2°C.

2.6. U values

Glazing and façade assembly U-values increase with elevation because of increased external wind speeds. Aware of this significant influence of local wind velocities on U-values, the National Fenestration Reporting Council has specified a standard exterior wind condition of 5.5 m/s for U-value calculations (NFRC, 2010). The commonly used wind profile relationship suggested by ASHRAE predicts local wind velocities as an exponential function of elevation (ASHRAE, 2009). In a dense urban environment, a local wind speed of 5.50 m/s at an elevation of 10 m is predicted to lead to local velocities of 11.6 m/s at an elevation of 300 m (ASHRAE, 2009). These increased wind speeds at higher elevations decrease the boundary layer along the façade and lead to greater heat transfer rates between the building and environment as the floor elevation increases.

2.7. Air properties and quality at different elevations

In addition to changing wind speeds with elevation, other important environmental factors also change. Air temperature drops with elevation, exposing the façade to different outdoor conditions at different elevations (Leung and Weismantle, 2008). An average difference of 1.85°C between 1.5 m and 284 m elevations of the Freedom Tower in New York City have been predicted to decrease heating and cooling energy for upper floors by 2.4% annually (Ellis and Torcellini, 2005). This temperature gradient's effect on annual heating and cooling highly depends on the specific climate under consideration. As cities continue to grow, removing ground-level pollutants through city-scale ventilation becomes more important. Tall buildings help increase the standard deviation of building heights in a city and have been shown to increase pedestrian purging rates and lower ground-level pollutants by increasing both the horizontal and vertical mean flows (Hang and Li, 2010). Aerosols reduce the transmittance of air by absorbing some solar energy (Calinoiu et al., 2013). Calinoiu et al. found a 20% reduction in solar energy for high levels of aerosol (Calinoiu et al., 2013). Water vapor has a significant impact on infrared radiation and is known to decrease with altitude (Calinoiu et al., 2013; Egan 1994). Although average variations in water content with altitude are outside the scope of this paper, two sources of measured New York data confirm what is expected. The National Oceanic and Atmospheric Administration observed a decrease in dew point depression from 3 to 2.4°C with an elevation gain from 8 to 173 m (NOAA, 2013). The University of Wyoming observed a decrease in water mixing ratio of 18% from 10.07 g/kg at 37 m to 8.18 g/kg at 200 m in Upton New York (The University of Wyoming, 2013).

3. New York City Benchmarking Data

In 2009 New York City was the first city in the United States to require large buildings, with gross areas greater than 50,000 ft^2, to publically release energy consumption data by passing New York City Local Law 84. The data analyzed in this paper was collected by the City of New York in 2012 and released in September of 2013 (The City of New York, 2013). Unfortunately, the city does not release any direct measure of building height in their energy benchmarking data. However, the New York City Department of City Planning collects immense data on all buildings and lots in New York through the Primary Land Use Tax Lot Output (PLUTO), including the number of floors of each building (NYCDCP, 2013). They do not collect total elevation, but the total number of floors offers a fairly uniform measure of building height (NYCDCP, 2013). The PLUTO data used in this study was collected between February and May 2013 (NYCDCP, 2013).

The data has been cleaned to remove any building with incomplete data or large outliers, which likely were the result of poor data. While many confounding factors impact building energy consumption, some care is taken to eliminate as many factors as possible. Since all of the data is collected in New York over the same year, the same weather conditions applied to all the buildings. To remove the confounding factor of building use, only office buildings are considered, which are defined as buildings with at least 80% of their total area used as office space. The total number of buildings that meet all these criteria and are thus used in this study is 706. Energy usage is measured using energy usage intensity (EUI) in the units of $kBtu/ft^2/yr$, which is calculated by dividing the entire building site energy in one year by the total floor area.

As shown in Fig. 1, shorter buildings consume less energy on average than taller buildings. While the EUI of buildings from 0~29 floors steadily increases with elevation, a distinct jump is observed at 30~39 floors, after which a plateau is reached for taller buildings. The average EUI of buildings with 10~19 floors increases by 33% as compared to buildings with 30~39 floors. An increase in twenty floors leads to 33% more energy consumption. With the same increase of twenty floors from 30~39 to 50+ floors, the average EUI actually slightly decreases by 3% after reaching the plateau at 30~39 floors. This plateau is consistent with the proposed framework. Above 30~40 floors, the lost chilled-water efficiency from introducing a heat exchanger in a pressure break is already incurred. Sky view factors will also typically not increase with elevation past 30~39 floors, since most buildings of that height are already exposed to a large sky. Wind speeds also do not increase as rapidly at higher elevations. According to ASHRAE, a local wind speed of 5.5 m/s at 40 m (approximately the 10th floor) increases by 27% to 7.0 m/s at 120 m (the 30th floor), while the 7.0 m/s local speed at 120 m only increases by 12% to 7.8 m/s at 200 m (the 50th floor) (ASHRAE 2009). Aerosol levels and moisture content similarly vary less at higher elevations, as they are further away from the pollutant and moisture sources at ground level. While these factors alone do not fully account for the observed trend, they very likely contribute to an explanation. Another factor that may lead to higher EUIs in taller buildings is the fact that many financial institutions with energy dense trading floors and even onsite datacenters typically occupy tall buildings. The fifty five story Bank of American Tower is a well known example of how financial institutions can require large plug loads that significantly impact the total building energy use (Calhoun and Torbert, 2013). Further investigation is required to confirm how systematic these large plug loads are in financial institutions and if the financial institutions in New York City occupy tall buildings.

The 2013 report released by New York City shows newer office buildings consume more energy than older ones (New York City, 2013). This same trend is reproduced in

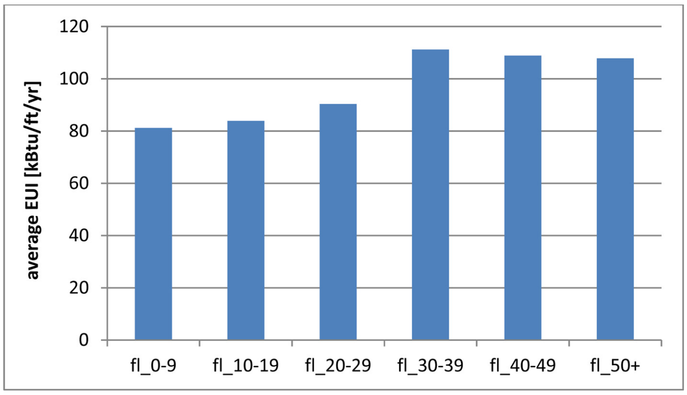

Figure 1. Average EUI in [$kBtu/ft^2/yr$] of all New York office buildings reported by The City of New York as a function of total number of floors.

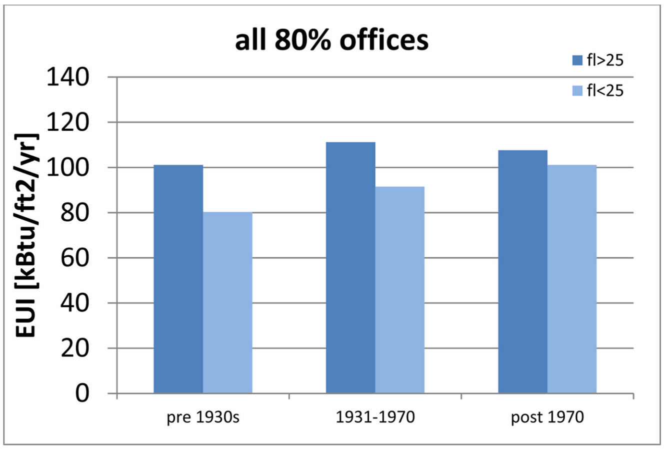

Figure 2. Average EUI in kBtu/ft^2/yr of all office buildings with 80% or more office area as a function of various construction eras in New York subdivided by buildings below and above twenty five floors.

this study for office buildings lower than twenty five floors, as shown in Fig. 2. However, buildings taller than twenty five floors do not follow this trend and those constructed after 1970 have actually, on average, been consuming less energy than those constructed between 1930~1970.

One might think renovations to older buildings would decrease their EUI. The effect of renovations on EUI is shown in Fig. 3. Without renovations, a similar trend to Fig. 2 is observed, though low-rise buildings built between 1931~1970 consume slightly more energy than post 1970 buildings. However, taller buildings that have been majorly renovated diverge from this trend. All renovated buildings taller than twenty five floors, have nearly the same EUI. Furthermore, on average, they consume more energy after renovations. The largest increase in EUI with renovations, 19%, is observed for buildings with twenty five or more floors built before 1930. One possible explanation for the increased EUI is that the renovated space could have attracted more energy intensive tenants.

Multiple components in the proposed framework not only depend on building height, but also the surrounding built environment. Specifically, the mean radiant loss, increased U-value, solar shading, and infiltration highly depend on the surrounding built environment. This effect is investigated in the current study by comparing trends in Manhattan to trends in the other four boroughs of New York: Brooklyn, Queens, the Bronx, and Staten Island. Anyone who has visited Manhattan and any other borough immediately understands the tremendous difference between the relative skylines. A quantitative comparison also helps convey the difference. According to the PLUTO data, the average number of floors for all buildings (not just office) in Manhattan is just over six floors, while the average number of floors in the other boroughs is roughly two floors (NYCDCP, 2013). When considering the office buildings considered in this study, the difference is even larger. Outside of Manhattan, the average height of office buildings is eight floors while the average height is just over twenty one in Manhattan. Consequently low-rise buildings in Manhattan have smaller view factors to the sky, are shaded, and experience lower external wind speeds (thus lower U-values and less infiltration) because of the denser concentration of taller buildings in Manhattan

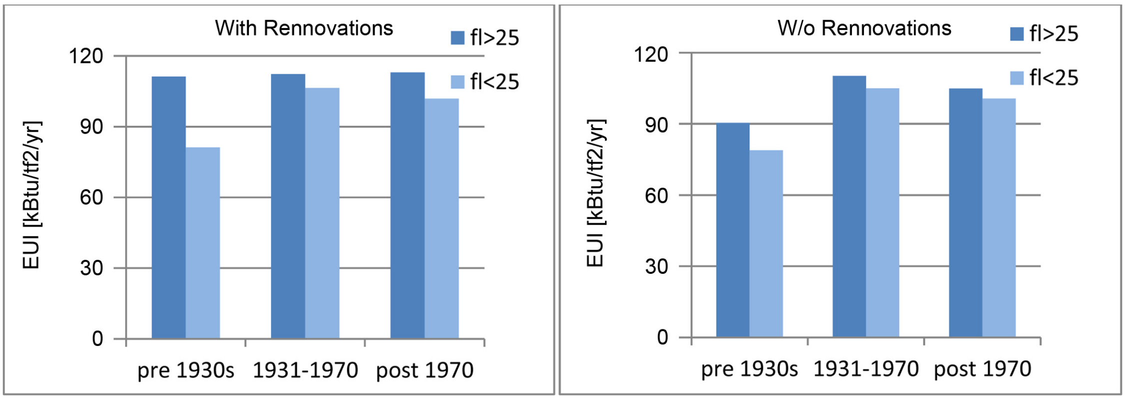

Figure 3. Average EUI in kBtu/ft^2/yr of office buildings with and without renovations as a function of various construction eras in New York subdivided by buildings below and above twenty five floors.

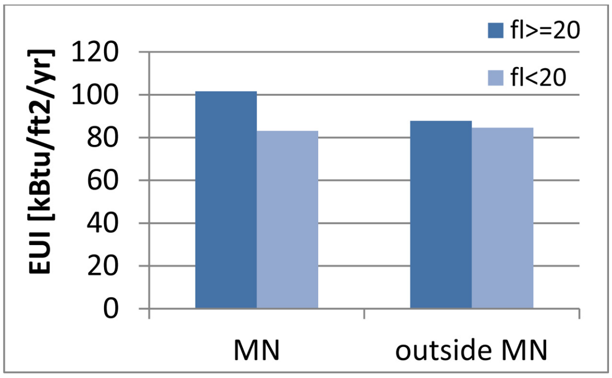

Figure 4. Average EUI of office buildings in Manhattan and outside Manhattan subdivided by buildings with less than and greater than twenty floors.

as compared to other boroughs. Thus, one would expect the difference in EUI between tall and low-rise buildings to be greater in Manhattan. Since many office buildings in Manhattan are concentrated near each other, the average height of Manhattan office buildings in this study (roughly 20 floors) is used as the dividing point between tall and low-rise buildings in Fig. 4.

As expected in the proposed framework, buildings taller than twenty floors outside Manhattan consume nearly the same amount of energy as low-rise buildings, in part, because of the lower concentration of tall surrounding buildings. In Manhattan, however, there is nearly a 20% increase in energy consumption for buildings above twenty floors. These increases of 20% in Manhattan and only a marginal increase outside of Manhattan are in line with the proposed framework. Low-rise and tall buildings outside Manhattan have more similar view factors, wind speeds, and solar shading than low-rise and tall buildings surrounded by tall buildings in Manhattan.

Plotting the EUI as a function of Energy Star rating as shown in Fig. 5 shows a desirable trend for the U.S. Environmental Protection Agency (EPA) that created the program: higher Energy Star ratings are correlated with lower EUIs in New York's office buildings. The program benchmarks the energy efficiency of a specific building against other similar buildings and rates the building on a scale from one to one hundred, with one hundred indicating a high level of comparable energy efficiency. In addition to suggesting higher Energy Star ratings are, on average, identifying more energy efficient buildings, a linear

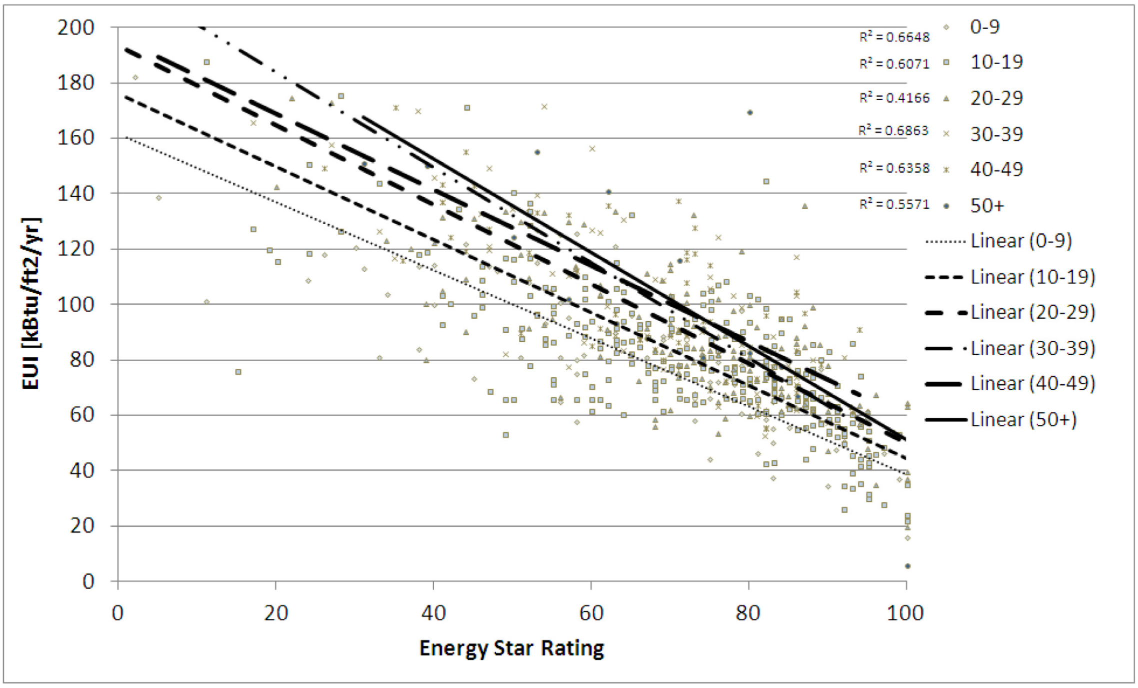

Figure 5. EUI in kBtu/ft2/yr plotted as a function of Energy Star Rating for various building heights with linear regressions fitted to each bin of heights. Symbol and linear fit legends are shown in the figure for each of the six bins.

regression suggests a difference between taller and low-rise buildings. Each subsequently taller bin has a higher average EUI for the same Energy Star rating. Each bin follows this trend except building with 30~39 floors, which deserves further investigation. Another noteworthy characteristic is the similar slope of every linear regression except two bins, 30~39 and greater than 50 floors. These similar slopes suggest the average decrease in EUI with Energy Star Rating is fairly uniform across most building heights. One plausible explanation for the divergence from these similar slopes in the taller buildings is the lack of benchmarking data for large buildings, which is discussed below. More data and further investigation will illuminate stronger conclusions.

An Energy Star context discussion is important to understand the results of the regression between the New York Buildings and Energy Star rating. The relationship used to determine the Energy Star rating for office buildings includes the following variables: natural log of gross area; number of computers per 1,000 square feet; natural log of weekly operating hours; natural log of the number of workers per 1,000 ft^2; heating degree days times percent of the building that is heated; cooling degree days times percent of the building that is cooled (United States, 2013). Note that there is no direct measure of building height, although the gross area could serve as a type of surrogate measure.

Furthermore, note there are also limitations in gross area for the Energy Star algorithm. It is based on regressions of the 2003 Commercial Building Energy Consumption Survey (CBECS) data that predict the energy use of a property. It should be noted that of the 4,859 buildings in CBECS, 95% are less than 50,000 ft^2 and 90% are two-stories or less (United States, 2003). Much of the data are low rise buildings and data above one million ft^2 were determined as inappropriate (EPMI, 2003). Every office building of the 706 considered in this study is larger than 50,000 ft^2 and fifty have more than one million ft^2. These results suggest more buildings above 50,000 ft^2 should be used in the Energy Star rating process and buildings larger than 1 million ft^2 are in fact need to be included in the regression. These larger buildings are often the highest energy consumers in buildings and deserve better benchmarking data for Energy Star ratings.

4. Conclusions

This paper proposes a framework for understanding the energy consumption differences between tall and low-rise buildings. The major components of this framework are: elevator energy, infiltration, solar shading, mean radiant loss, HVAC pump energy, U-values, and air quality. Energy usage data from 706 office buildings in New York illustrates expected correlations from the framework. Notable correlations include: taller buildings tend to use more energy until a plateau at 30~39 floors; tall buildings in Manhattan use 20% more energy than low-rise buildings, while tall buildings outside Manhattan only use 4% more energy. Additional correlations show older New York buildings have lower EUIs, renovations to New York office buildings have led to higher EUIs – up to 19% for tall pre 1930s buildings – and that the Energy Star program in New York assigns higher ratings to tall buildings with higher EUIs than low-rise buildings with the same rating. Since Energy Star is based on regressions of existing buildings, the Energy Star ratings suggest taller buildings have higher EUIs than shorter buildings, which is confirmed by the New York City energy benchmarking data.

References

Al-Sharif, L. (1996). “Lift and escalator energy consumption.” Proc.CIBSE/ASHRAE Joint National Conference, Harrogate, pp. 231~239.

Ali, M. and Armstrong, P. (2010). “Sustainability and the Tall Building: Recent Developments and Future Trends.” AIA Illinois Central Symposium, 2010.

ASHRAE (American Society of Heating, Refrigeration, and Air Conditioning Engineers). (2009). ASHRAE Fundamentals. American Society of Heating, Refrigeration, and Air Conditioning Engineers, Atlanta, GA.

Calhoun, K. and Torbert, R. (2013). “The Bank of America Tower – What Is and What Could Have Been.” Rocky Mountain Institute, published on September 5, 2013.

Calinoiu, D., Paulescu, M., Ionel, I., Stefu, N., Pop, N., Boata, R., Pacurar, A., Gravila, P., Paulescu, E., and Trif-Tordai, G. (2013). “Influence of aerosols pollution on the amount of collectable solar energy.” Energy Conversion and Management, 70, pp. 76~82.

CTBUH (Council on Tall Buildings and Urban Habitat). (2013). “The Skyscraper Center.” Accessed on September 26, 2013, http://skyscrapercenter.com/

Egan, W. (1994). “Radiative Transfer Properties of the Sahara Region.” Remote Sensing Environment, 50, pp. 182~193.

Ellis, P. G. and Torcellini, P. A. (2005). “Simulating Tall Buildings Using EnergyPlus.” Proc. Ninth International Building Performance Simulation Association (IBPSA), Montreal, Quebec.

Emmerich, S. J. and A. K. Persily (2011). “U.S. Commercial Building Airtightness Requirements and Measurements.” Proc. 32nd Air Infiltration and Ventilation Centre Conference, Air Infiltration and Ventilation Centre, Belgium.

EPMI (Energy Performance Measurement Institute). (2003). “2003 CEBCES National Soure Energy Use EUI Percentiles and Mean.” epminst.usz/commercial/CBECS-2003_EUI_pctiles.pdf

Hang, J. and Li, Y. (2010). “Ventilation strategy and air change rates in idealized high-rise compact urban areas.” Building and Environment, 45, pp. 2754~2767.

Leung, L. and Weismantle, P. (2008). “Sky-Sourced Sustainability – How Super Tall Buildings Can Benefit From Height.” Proc. Council on Tall Buildings and Urban Habitat 8th World Congress, Dubai, UAE.

Liu, J., F. Qiao, and L. Chang, (2010). “The hybrid predictive model of elevator system for energy consumption.” Proc.

2010 International Conference on Modeling, Identification and Control, Okayama, Japan.

Ng, L. C., A. Musser, A. K. Persily, and S. J. Emmerich (2013). "Multizone airflow models for calculating infiltration rates in commercial reference buildings." Energy and Buildings, 58, pp. 11~18.

New York City. (2013). "New York City Local Law 84 Benchmarking Report September 2013." A Greener, Greater New York, The City of New York.

NFRC (National Fenestration Rating Council). (2010). "Procedure for Determining Fenestration Product U-factors." National Fenestration Rating Council, Inc. Greenbelt, MD.

NOAA (National Oceanic and Atmospheric Administration). (2013). "Weather Balloon Data." Accessed on September 20, 2013. http://www.ncdc.noaa.gov/data-access/weather-balloon-data

NYCDCP (New York City Department of City Planning). (2013). "BYTES of the BIG APPLE™." Accessed on September 26, 2013. http://www.nyc.gov/html/dcp/html/bytes/applbyte.shtml

Roaf, S., Crichton, D., and Nicol, F. (2009). Adapting Buildings and Cities for Climate Change 2nd Edition. Architectural Press, Oxford, UK.

Sachs, H. M. (2005). "Opportunities for Elevator Energy Efficiency Improvements." Proc. American Council for an Energy-Efficient Economy (ACEEE), Washington, DC.

The City of New York. (2013). "Green Buildings & Energy Efficiency: Benchmarking Scores & Reports." Accessed on September 26, 2013. http://www.nyc.gov/html/gbee/html/plan/ll84_scores.shtml

The University of Wyoming. (2013). "72501 OKX Upton Observations." Accessed on September 29, 2013 http://weather.uwyo.edu/cgi-bin/sounding?region=naconf&TYPE=TEXT%3ALIST&YEAR=2013&MONTH=09&FROM=2900&TO=2900&STNM=72501

United States Energy Information Administration. (2003). "Commercial Buildings Energy Consumption Survey (CBECS)." U.S. Department of Energy, Washington, D.C.

United States Environmental Protection Agency. (2013). "Energy Star Score for Offices in the United States – Technical Reference." U.S. Department of Energy, Washington, D.C.

Yeang, K. (1999). The Green Skyscraper: The Basics for Designing Sustainable Intensive Buildings. Pertel Velag, Munich, Germany.