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Energy Performance and Sustainability of High-Rise Buildings

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Abstract:
This study is to examine methods of enhancing energy efficiency and self-sustainability of tall buildings. The current levels of energy consumption of high-rise buildings were investigated. The alternative methods of producing onsite energy that can be harnessed from tall buildings were reviewed. The amount of solar energy that can be harnessed from PV panels installed on the roof and the south façade of a testbed building in New York was estimated. Comparing the quantities of renewable energy produced from and the energy demand of the building, the energy self-sufficiency of the building was analyzed. It was found that, with current technology, onsite solar systems can meet only a small fraction, less than 4.2%, of the building's energy demand. From this study, it was concluded that energy self-sufficiency of tall buildings must be approached by enhancing the energy efficiency of various building systems of tall buildings.
Keywords: Building Energy Performance; High-Rise Buildings; Building Integrated Photovoltaics; Energy Self-Sufficiency

1. Introduction

Incorporating renewable energy technologies, today it is very practicable to build energy-autonomous small-scale buildings (Voss et. al. 2012, Aeleni et. al. 2014, Wang et. al. 2019**;** Amen, 2021; Aziz Amen, 2022; Amen et al., 2023; Amen & Nia, 2020). Solar, wind and geothermal energy technologies are the most technologically feasible for building application (NREL 2002, Del Sol 2010, Larsen 2013, GCCE 2018). As these onsite renewable energy technologies make use of natural energy flows that are available at a specific location, and their technical feasibility and efficiencies depend on the particular physical, geological and climatic contexts of a building site. As such it is critical for building designers to assess the technical feasibility of each renewable technology as an onsite energy production alternative.

Wind Technology: The availability of wind at a location is, first, affected by its macro-climatic context, i.e., the geographic location on earth and elevation above the sea level. The NREL (National Renewable Energy Laboratory) developed Wind Resource Maps, long-term statistical wind data, are a useful resource for predicting the availability of wind energy at a location in the U.S. At low altitude, below 10 meter above the ground surface, the regions of the world having sufficient year-round reliable wind speeds to start up and operate wind turbines are confined to mountainous regions with high elevation, for instance the Rocky Mountain regions in the U.S., or open coastal strips along Lake Michigan. Other than these limited regions, most inland regions of the continental U.S. are not suited wind energy production. Practically speaking, most inland locations of the world are not suitable for producing wind energy from wind turbines. The wind energy is more available at higher altitude above the surface. To take advantage of high-speed winds at high altitude, the recent wind turbines have been taller with wide span blades.

Wind Energy Production from Buildings: Even in regions where sufficient and reliable winds are available, producing wind energy from building-integrated wind turbines faces multiple challenges. First and foremost, a building itself becomes an obstruction that either blocks or disturbs winds blowing onto the turbines (Wilson, 2009). Thus, installing wind turbines on the roof is the only viable option for wind turbine integration with a building. Even wind turbines installed on the roof are affected by the roof itself and adjacent buildings. For this reason, rooftop wind turbines need to be elevated high above the roof surface to utilize higher speed wind. Next, the constantly changing speed and direction of air flows around a building make building-integrated wind turbines inefficient for energy production. Vertical axis wind turbines can better utilize such turbulent winds. Still, a building itself functions as a wind obstructor, and reduces wind speed on building-integrated wind turbines. As such building integrated wind turbines far less efficient than those freestanding in an open terrain. Because of these problems, building integrated wind technology is not a viable onsite energy production alternative. Handful of tall buildings with building-integrated wind turbines, such as Pearl River Tower in China and Bahrain World Trade Center, have been built. But they have not been able to serve as models for future buildings to follow suit. Many publications describe about the nature and the predicted or simulated energy production from building integrated wind systems. But the actual measured performance data of the Bahrain World Trade Center are unrevealed, and parties who have access to the building's wind system performance data, the building owner and the building manager, are not eager to disclose them. The architects who designed the buildings are awarded no merit in conducting the post occupancy evaluation of the buildings and their wind systems that they designed. As such the actual performance of building-integrated wind systems remains in the dark.

Geothermal Energy: Geothermal energy is onsite energy production technology that harnesses the heat contained in the Earth's crust. Using the heat exchanger tubes that are buried in the ground, heat stored in soil or water is conducted to the fluid running in the tubes. Incorporating a heat pump, the heat harness from the ground is then used for space heating in the winter and cooling in the summer. To harness geothermal energy for the space heating and cooling of a medium

size single family home, a substantial length of the tube is required. In order to harness one ton (12,000 Btus/hour) or 3.5kW of cooling effect, about a 150-180 m long tube is required (Buschur's Refrigeration Heating and Cooling, 2022). An average single-family home in the U.S. requires about 1/4 to 3/4 acre of land is required for trenches. Geothermal heat pump systems can contribute to a significant portion of the energy demand for heating or cooling single-family homes or low-rise buildings with a sufficient lot size. But for high-rise buildings, geothermal energy can contribute to a very small fraction of their energy demand (Goldman Copeland Consulting Engineers, 2018). The contribution of geothermal energy to the energy self-sufficiency of tall buildings is marginal.
Based on the preliminary assessment of the appropriateness and feasibility of wind, geothermal and solar technology, it was determined in this study that solar technology is the onsite energy technology that is technically feasible as an onsite energy alternative for high-rise buildings. By incorporating solar panels on the roof or on the walls, buildings can now be energy producers. As renewable technologies become increasingly cheaper and feasible for building application, such energy producing buildings can be expanded to near zero-energy, or even energy surplus (Thomas 2008). However, is it possible to achieve large-scale zero-energy buildings or skyscrapers by incorporating solar? This study examines this question about the prospect of zero energy high-rise buildings that employ building integrated photovoltaic (BIPV) systems.

2. Research Objectives and Methods

The principal objectives of this study are threefold:

1) to examine energy consumption of tall buildings in cold climates,
2) to evaluate the feasibility of a zero-energy skyscraper employing building integrated PV technology, and
3) to examine how much solar energy can contribute to the building's energy self-sufficiency.

Through this feasibility analysis, this study intends to identify strategic directions the building industry must move forward to attain zero-energy or near zero-energy skyscrapers in the future. In order to assess the feasibility of a zero-energy building, two quantities of building energy are necessary: 1) the energy consumption of the building, and 2) the amount of energy that can be produced from it onsite. The energy consumption data of a test-bed skyscraper was calculated by using a computer energy simulation program, eQuest (Hirsh 2007). In order to check the validity of eQuest, we gathered actual energy consumption data of nine existing skyscrapers in New York. Then, the simulated energy consumption data and the actual energy consumption data were compared. Upon confirming its validity, the energy simulation program was used in conducting two sets of parametric analyses of the test skyscraper: one with alternative glazing materials in the windows and the other with different HVAC system layouts to examine how alternative glazing materials and HVAC systems increase the building energy self-sufficiency. The amount of energy production from the building skin was calculated by PVWatts (NREL 2022), a program developed by the National Renewable Energy Laboratory.

3. Skyscraper Energy Consumption

The test-bed skyscraper is a 30-story 45m wide, 30m deep and 108m high office tower located in New York. The total floor area is 40,500 m^2, 1350 m^2 for each floor. The floor-to-floor height of the building is 3.9m, and the floor-to-ceiling height 2.7m. The test skyscraper's facade consists of 2.7m single pane PPG glass and 1.2m high opaque spandrel walls. The window-to-wall ratio of all four walls of the building is 0.69. The opaque exterior wall is assembled with 2x4 16" o.c. metal stud construction with insulation in between studs. The heat source of the building is gas-fired boilers, and the cooling source water chillers. The air distribution system is a multi-zone with hot water reheat system. Lighting load is 7.5 W/m^2, and task lighting 4.0W/m^2, and plug loads 15W/m^2.

3.1 Energy Consumption of the Test Skyscraper

Employing energy analysis program eQuest, the energy consumption of the test skyscraper was simulated, and its energy performance was analyzed in terms of 1) annual energy consumption by end use, and 2) monthly energy consumption by end use. The annual gas energy consumption is 6375 MWh, which amounts to 54.8% of the building's total building energy consumption, and the annual electricity consumption is 5266 MWh, 45.2% of the building's total energy consumption.

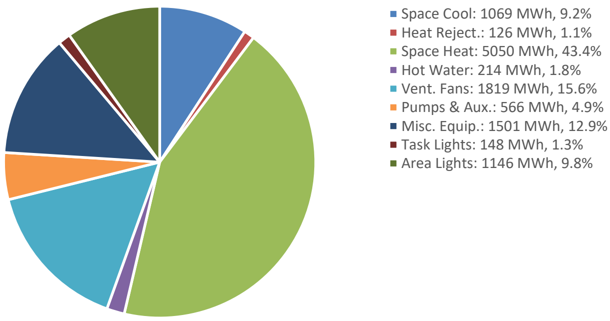

Figure 1. Annual Energy Consumption by End Use.

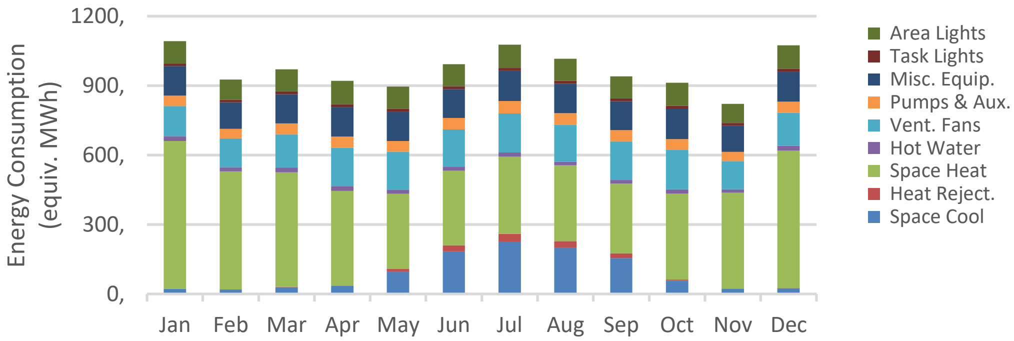

Figure 2. Monthly Energy Consumption of the Test Building.

4. Energy Consumption of Existing Skyscrapers

To validate if the computer simulation provides reasonable results, we gathered the energy consumption data of nine skyscrapers in the City of New York and compared them with the simulation results. The energy use intensities (EUI), the annual building energy consumption per unit floor area, of the nine buildings are shown in Table 1.

Table 1. Energy use intensity of skyscrapers in New York.

Building Name	Floor Area (m^2)	Year Built	Total EUI (kWh/m^2)	Gas (kWh/m^2)	Electricity (kWh/m^2)
4 World Financial	193,688	1986	260.8	60.6	200.2
New York Times	117,740	2007	448.4	234.6	213.8
Marine Midland	106,067	1967	418.2	236.4	181.7
Citi Corp Center	170,565	1976	399.6	235.8	163.8
Four Time Square	152,665	1999	283.8	73.4	210.4
Hearst Tower	80855	2006	270.3	84.0	186.3
Lever House	20397	1952	426.0	105.3	320.7
Chrysler	96218	1929	183.9	35.2	148.7
Seagram	78906	1958	570.2	271.0	299.2
Average			362.4	148.5	213.9
Test Building			**309.1**	**139.7**	**169.4**

The annual energy use intensity of the nine skyscrapers ranges from 183.9 (the Chrysler Building built in 1929) to 570.2 kWh/m^2 (the Seagram Building built in 1958). It is interesting that a building built in 1929 is about three time more energy efficient than one built in 1958, which is a period when the international-style glass towers were a dominant trend. Buildings built after Year 2000 are not necessary more energy efficient than ones built before. The New York Times Building built in 2006, the newest building among the nine sample skyscrapers, is energy intensive with a EUI of 448.4 kWh/m^2. The EUIs of the nine skyscrapers in New York range from 183.9 to 448.4 kWh/m^2, with the average of 362.3 kWh/m^2, while the EUI of the test skyscraper is 309 kWh/m^2. Five of the nine sample buildings consumed more energy than the simulated building, and four less. With this comparison result, we adopted eQuest as the energy simulation tool for this study.

4.1. Complexity of Assessing Building Energy Efficiency

A building's energy performance is affected by a range of factors related to climate, building attributes and building use patterns. First, a building's energy consumption is climate dependent. Though the climate of a region is statistically stable and predictable, the actual weather conditions of a building site are deviant from the long-term statistical means. As such, the actual energy consumption of a building in a particular year is variant as well. The "weather-normalized" energy consumption of a building's take into account the deviation of weather conditions year-by-year.

For a given set of physical attributes of a building, its energy performance varies significantly with user behavior, building use patterns, and occupancy schedule. For these reasons, a building that consumes more energy is not necessarily an energy-inefficient building. Although there is a general correlation that buildings that consume more energy are less energy-efficient, theoretically one cannot make a determination that buildings with high energy use intensities are less energy-efficient. This complexity of the correlation between energy consumption and energy efficiency is a factor that needs to be considered in evaluating buildings' energy performance.

Aside from climate and building use patterns, a range of architectural and system features of a building affect its energy performance. In the design process, architects and building designers determine those architectural and systems features. Physical variables of a building that influence building energy performance can be categorized into three categories: 1) building form, 2) building skin and 3) building systems. The key variables of Category 1 (building form) include building orientation and the shape of building mass. Category 2 (building skin) variables include window size, window-to-wall ratio, thermal and optical properties of glass and walls. Category 3 (building systems) variables include building's system attributes associated with lights and HVAC (heating, ventilating and air-conditioning) equipment. Of these architectural and system variables that contribute to building energy performance, it is of particular interest to architects and building designers to examine the relationship between energy performance (consumption) and building skin design of the nine skyscrapers listed in Table 1.

Four of the nine skyscrapers, the Seagram Building (1958), the Marine Midland Building (1967), Lever House (1952) and the Hearst Tower (2006) are all glass towers. And their energy use intensities are highest of the nine sample buildings. Particularly, with an EUI of 570.2 kWh/m^2, the energy consumption of the Seagram Building is the highest of them all, and Lever House is the third highest. Designed by Mies van der Rohe in 1958, the Seagram Building epitomizes international style minimalistic glass towers, as well as an icon of energy inefficient building (See Figure 3-a). It was originally cladded with single-pane glass, which was one of the main reasons for its high energy consumption. The building was later renovated with higher efficiency glass. Though lower, Lever House building built in 1952 cladded with glass on its entire facades shows similarly high energy use intensity (See Figure 3-b). On the other hand, the Hearst Tower, another all-glass skyscraper, designed by the Norman Forster Associates and built in 2006 (See Figure 4-a), consumes low levels of energy. With an EUI of 270.3 kWh/m^2, the building can be regarded as one of the most energy efficient buildings among the sample buildings. This indicates that glass skin is not solely responsible for high energy consumption of tall buildings. Naturally glass towers glazed with modern higher performance glass will be more energy efficient than ones with single pane glass.

The most energy efficient building among the nine sample skyscrapers is the Chrysler Building built in 1929 (See Figure 4-b). It is the oldest building among the sample buildings. The fact that the oldest building is the most energy efficient building is very intriguing. In the absence of the data on the building's systems and construction materials, it is impossible to diagnose why this century-old art-deco landmark of New York is energy efficient. But based solely on visual inspection of the facade, it is evident that the Chrysler Building has smaller window size, i.e., low window-to-wall ratio. Because windows have low thermal insulation values, they lose heat far more than walls with higher insulation values. In the summer, windows bring in solar heat gain that increases to the cooling energy operating air-conditioning equipment. Thus, based on this thermodynamic principle, buildings with smaller window size and higher opaque wall fractions are more energy efficient. Yet, the real practical question is whether the architectural practitioners and building owners are willing to change the course of skyscraper facade design from all glass to more energy efficient alternatives that are more thermally and visually advantageous and sustainable. As glass symbolize modernity, glass is attractive to skyscraper designers who are propensity to design a building that represent modernity. Additionally architectural glass is more energy efficient by incorporating low-emissivity coatings and gas-filling. Incorporating these technologies, modern glass is far more energy efficient than old single pane glass. Yet alternative facade designs that have lower fractions of glass and higher opaque portion will make them more energy efficient and environmentally sustainable.

(a) (b)

Figure 3. (a) the Chrysler Building built in 1929 with a low window to wall ratio and (b) the Seagram Building built in 1958 with a high window to wall ratio and a minimalistic façade design. The energy use intensity of the Chrysler building is far lower than that of the Seagram Building.

5. Renewable Energy Production from the Building

Building integrated photovoltaic (BIPV) was the onsite energy production technology employed in this study. Using PVWatts, electricity that can be generated from the solar panels integrated with the test skyscraper's roof and south façade was calculated (see Figure 5). The rooftop PV panels produced the maximum solar energy in July and August and minimum in December. On the other hand, the south wall panels generated the maximum in February and minimum in June. This suggests a strategy for solar energy generation from buildings: when a building needs more electricity in winter, solar panels should be installed on the south façade; when more electricity is needed in summer, PV panels should be installed on the roof. The synchronization of onsite energy generation and energy consumption will reduce the need and size of energy storage for electricity generated onsite (Tronchin et. al. 2018).

6. Energy Self-Sufficiency and Path Toward Zero Energy Skyscrapers

The energy self-sufficiency of a building, S_e, is defined as the ratio of the electricity generated from its PV system, E_{solar}, to its total energy consumption, E_b, as:

$$S_e = E_{solar} / E_b \quad (1)$$

On an annual basis, the test-bed building's electricity self-sufficiency is 4.2%, i.e., the building can generate only 4.2% of its own energy consumption from the building integrated solar panels. In order to increase its energy self-sufficiency, the building's energy consumption must be reduced. The strategies for reducing energy consumption of tall buildings can be classified in three categories. Category 1 strategy is to improve the energy efficiency of building skin including the walls, roof, and windows. The insulation of building skins will keep heat in the building,
reducing heating energy in the winter. In the summer, an insulated building skin will prevent conductive heat gain and reduce energy consumption from cooling the building. Category 2 strategy is to incorporate high efficiency building systems, such as HVAC (heating, ventilating and air conditioning) and lighting. Category 3 strategy is to use energy

efficient appliances. A significant fraction of building energy consumption is attributed to the use of electrical appliances such as computers, monitors, printers, microwave ovens, refrigerators, etc. But the selection of electrical appliances to be used in buildings is usually made by the IT and facility managers after the building is designed, not by the architect who designed the building.

(a) (b)

Figure 4. (a) the Hearst Tower built in 2006 with all glass façade and (b) the New York Times Building built in 2007 with glass façade with exterior shading screens. These two skyscrapers show new expressive trends in façade designs of recent tall buildings.

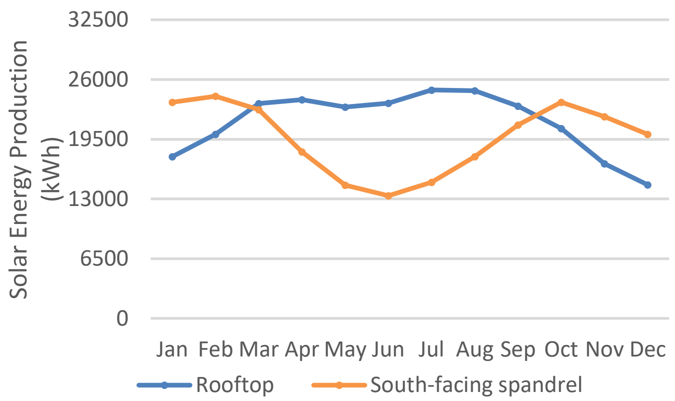

Figure 5. Monthly Electricity Generated from Solar Panels.

To evaluate the impact of different glazing materials on the test skyscraper's energy efficiency, a parametric analysis was conducted on a variety of glazing materials that can be used in the windows (see Figure 6). The Southwall triple glass was identified to be the most energy efficient. When it was used on all four façades, the energy self-sufficiency of the skyscraper increased to 6.1%.

Upon identifying the most energy efficient glass type, the next parametric analysis was performed on building HVAC system type. It was found that variable air volume (VAV) air distribution systems is the most energy efficient (see figure

7). With the combined installation of the Southwall triple glass and VAV air distribution for the HVAC system, the energy self-sufficiency of the test skyscraper increased to 10%.

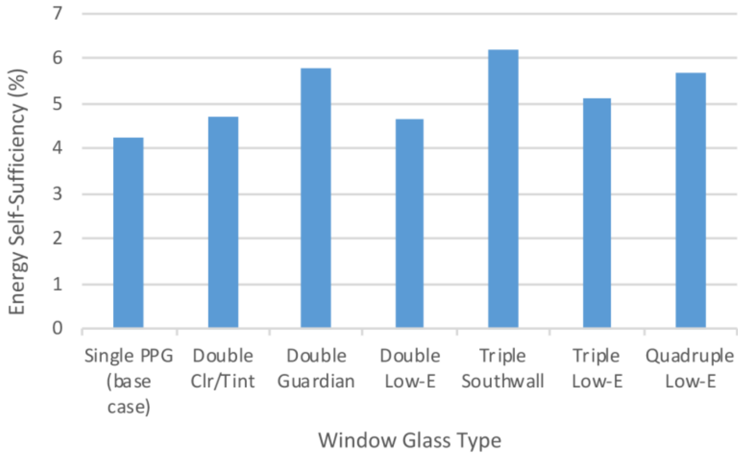

Figure 6. Energy Self-Sufficiency of The Test Building with Alternative Glass.

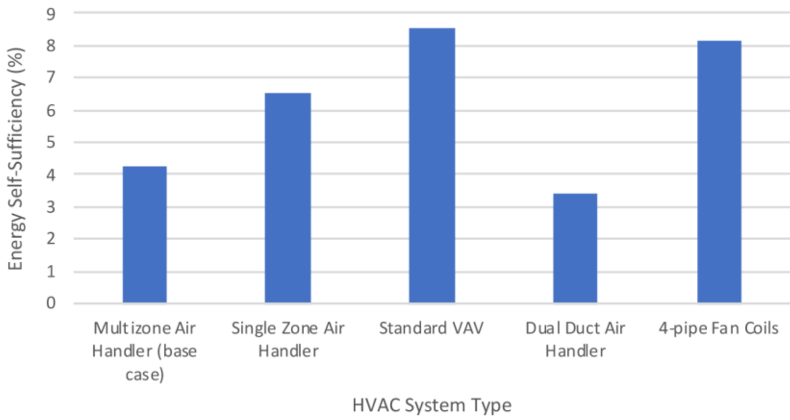

Figure 7. Energy Self-Sufficiency of The Test Building with Alternative HVAC systems.

7. Conclusions and Future Directions

This feasibility study revealed that the onsite building integrated solar system can provide only a small fraction, 4.2%, of the test skyscraper's energy consumption. In addition to solar, other renewable technologies for producing onsite energy such as geothermal or wind could be incorporated to further increase its energy self-sufficiency. Yet, those other onsite energy production alternatives will contribute to meeting only a marginal fraction of energy demand of tall buildings. Supply-side approaches to zero energy skyscrapers, i.e., attempting to produce more onsite renewable energy, will be futile to attain the tall buildings 'zero-energy goal. From the parametric study, it was found that the combination of two methods of improving the energy efficiency of skyscrapers, use of high-performance windows and VAV (variable air volume) HVAC system, increases the energy self-sufficiency of the test skyscraper significantly, from 4.2% to 10.1%. Yet, it still falls far short from total energy self-sufficiency. In order to attain zero-energy or near zero-energy, if they are ever possible, It is apparent that a drastic reduction of the current level of energy consumption is required for moving toward energy autonomy of skyscrapers.

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Conflict of Interests

The authors declare no conflict of interest.

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