

Review

Green Retrofitting Skyscrapers: A Review

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Abstract: This paper investigates innovative trends, practices and goals of tall building retrofits while illustrating green design techniques and implementation strategies. The existing building stock is substantially large and represents one of the biggest opportunities to reduce energy waste and curb air pollution and global warming. In terms of tall buildings, many will benefit from retrofits. There are long lists of inefficient all-glass curtain walls, initially promoted by the modernist movement, that are due to retrofit. The all-glass curtain wall buildings rely on artificial ventilation, cooling and heating, and suffer from poor insulation, which collectively make them energy hogs. Recent practices indicate that green retrofit has helped older buildings to increase energy efficiency, optimize building performance, increase tenants' satisfaction and boost economic return while reducing greenhouse gas emission. As such, renovating older buildings could be “greener” than destroying them and rebuilding new ones. While some demolition and replacement may remain a necessity to meet contemporary needs, there are significant opportunities to reduce carbon emission and improve existing buildings' performance by retrofitting them rather than constructing new ones. Practical insight indicates that the confluence of economic and environmental goals is increasingly at the heart of sustainable planning and design.

Keywords: skyscrapers; sustainable design; green retrofit; energy efficiency; building's performance; holistic approach; leadership in energy and environmental design

1. Introduction

Green retrofit could mean different things. Among the prevailing practical views is the one provided by the U.S. Green Building Council (USGBC). It explains that green retrofit is “*any kind of upgrade at an existing building that is wholly or partially occupied to improve energy and environmental performance, reduce water use, and improve the comfort and quality of the space in terms of natural light, air quality, and noise—all done in a way that it is financially beneficial to the owner*” [1]. USGBC continues explaining that then, the building and its equipment must be maintained to sustain these improvements over time. It is important to note that a green retrofit ranges from minor work that involves for example installing new heating, ventilating, and air-conditioning components, mounting solar panels on a roof, or placing a bike rack outside the building; to a major work that involves multiple complex renovations on both the building’s interior spaces and exterior facades. While some buildings may take the retrofit project at once, other buildings may conduct the retrofit in stages by beginning first with changing the entire lighting systems, later, adding window films, and then replacing the Heating, Ventilation and Air Conditioning (HVAC) system, for example.

Today, green retrofitting of buildings is a significant development activity taking place worldwide. Efforts to make buildings more environmentally sustainable have produced hundreds of millions of square feet of greener office space. However, there are remaining tens of billions of square feet in office buildings worldwide that need green retrofit to improve buildings’ performance on energy and sustainability. In the U.S., there are about 5 million commercial buildings consisting of 670 million m² (72 billion ft²) of floor space that are due to green retrofit. Cost-effective retrofit potential remains for over 80% of these buildings, according to USGBC. The council also explains that the 2009 market for major green renovations in the United States was \$2.1 billion a year and that grew to over \$6 billion a year by 2013. Further, it estimates that 2% of existing space is renovated each year, and that 10% of these renovations include state-of-the-art energy efficiency [2].

Researchers and developers view green retrofit as a way to employ the “three R’s” (reduce, reuse, recycle) by extending the life time of the building and saving on the costs of building demolition and acquisition of new building materials. Simply, it makes no sense to demolish a building when it is possible to renovate it into a super sustainable one. At the urban scale, greening tall buildings supports a new global trend for modern cities that aims to grow upward rather outward in their efforts of fighting urban sprawl. Vertical density is increasingly viewed as a critical element in supporting sustainable cities so that travel distances are shortened and providing walkable environments becomes possible. Most importantly, it is viewed that green retrofitting tall buildings is fundamental to combat climate change. Consequently, buildings that define city skylines across many countries or national icons, mainly in western countries, are going green.

2 Retrofit Drivers

2.1. Economics

Many of the city’s buildings are aging and are becoming increasingly inefficient on energy use. Also, the increased costs of utilities coupled with the falling commercial rents in the wake of the 2008 economic crisis forced building owners to search for ways to reduce energy use and waste. Fortunately,

green retrofit projects increasingly make good economic sense, and renovation costs will likely be recouped via energy savings. Further, real estate industry is addressing a new fact that energy efficient buildings command better rents and are increasingly desirable. Once more tenants recognize the potential savings resulting from increased productivity, they demand new and upgraded green buildings. Additionally, the growing green industry is promoting green projects and is making their products and services known to the market. Finally, the greatest potential saving is likely to be gained via the increased workforce productivity facilitated by the healthier workspace. A study explains that if an organization manages to boost employees' productivity by 10%, the resulting saving is likely to equal the cost of renting the space [3–5].

Of course, the economic benefits of retrofitting downtown commercial buildings of major cities—in many cases tall buildings—could permeate to the entire downtown. In the case of advocating the Atlanta Better Buildings Challenge, a voluntary effort based on the Better Building Initiative launched by President Barack Obama to make the country's buildings more energy efficient, Cheryl Strickland, Invest Atlanta's managing director of redevelopment, explained that the program could give downtown a much-needed boost for a strong and competitive central business district is important economically. The relative strength of a city's downtown impacts its ability to attract and retain jobs and tourism, along with the city's overall brand and attractiveness to businesses, residents and visitors. Strickland explained: *“Until market demand for new commercial building is reestablished, one of the best ways to support economic development downtown and the continued revitalization of Atlanta's central business district is to encourage commercial retrofits, renovations and upgrades of the existing building stock. Despite a burst of new building activity over the past decade, there remains a host of aging, obsolete, underutilized and inefficient structures downtown”* [6]. Further, research shows that buildings in the U.S. and Europe that are retrofitted enjoy greater rent values than the ones that are not upgraded [6]. Overall, researchers and developers are optimistic about the future of buildings' green retrofit.

2.2. Environmental

Retrofitting buildings provides clear environmental benefits including reducing energy consumptions, lowering demand on the power grid and decreasing greenhouse gas emission. For example, in New York City, greenhouse gas emission from its 900,000 buildings, more than 5000 of them classified as skyscrapers, constitutes almost 80% of the city's carbon footprint. Another example is the City of Portland. Research shows if Portland were to retrofit buildings that otherwise likely to be demolished over the next 10 years, *“the potential impact reduction would total approximately 231,000 metric tons of CO₂—approximately 15% of their county's total CO₂ reduction targets over the next decade. When scaled up even further to capture the potential for carbon reductions in other parts of the country, particularly those with a higher rate of demolition, the potential for savings could be substantial”* [6,7]. It is often mistakenly assumed that the CO₂-reduction benefits gained by a new, energy efficient building outweigh any negative climate change impacts associated with the construction of that building. Recent research suggested that it requires *“10 to 80 years for a new building that is 30% more efficient than an average-performing existing building to overcome, through efficient operations, the negative climate change impacts related to the construction process”* [7]. Research has documented how reuse and retrofitting for energy efficiency offer the most significant emissions reductions in the categories of

climate change, human health, and resource impact. Further, most climate scientists agree that immediate term action is crucial to staving off the worst impacts of climate change. Therefore, building reuse can avoid unnecessary carbon outlays and help cities achieve their short-term carbon reduction goals. It is suggested that reuse and retrofit are particularly impactful in areas of harsh climate, and in areas in which coal is the dominant energy source, such as the City of Chicago, where coal constitutes 65% of its energy source [7].

2.3. Government

Overall, the government increasingly sees the economic and environmental values of green retrofit. *“Efficiency can save 75% of America’s electricity at lower cost than making it at existing power plants. Helping customers reduce or defer usage when electricity is scarce can also increase distribution equipment’s life and reliability”* [8]. For example, the U.S. government has been providing financial incentives to encourage green retrofit projects through offering tax breaks, credits or grants. The federal stimulus package alone had \$4.5 billion in green building grants. This is in addition to an energy-efficient federal tax deduction that could total up to \$1.80 per square foot in commercial buildings. One of the earliest and ambitious green programs that encouraged retrofitting is the Energy Efficiency Building Retrofit Program launched in 2007 by a former U.S. President William Clinton. The program explored ways to make efficiency retrofit projects more bankable with unsubsidized, commercial lending models applicable in a variety of countries. In 2011, President Obama’s “Better Buildings Initiative” proposed new efforts to improve energy efficiency in commercial buildings across the U.S. The initiative aims at making commercial buildings 20% more energy efficient over the next decade by catalyzing private sector investment through a series of incentives to upgrade buildings. President Obama reasoned that improving the energy efficiency of buildings can create jobs, save money, reduce the country’s dependence on foreign oil and make air cleaner.

2.4. A New Trend

Peer pressure or “Keeping up with the Joneses” has been a driver of skyscrapers’ greening. For example, as the tallest and most famous skyscrapers in the United States, such as the Empire State Building and the Willis Tower (formerly Sears Tower), have already embraced green retrofit, skyscrapers’ owners and investors have been encouraged to follow the trend. Further, some agencies consider locating in “green” buildings a priority. For example, in the case of the Empire State Building, after the retrofit announcement, the Federal Deposit Insurance Corporation (FDIC) committed to a major lease. In addition, Skanska USA, the U.S. division of Swedish construction firm Skanska AB, indicated that energy and sustainability factors were a major part of its decision to relocate in the Empire State Building. *“Many high-profile tenants won’t even consider moving into a property without the U.S. Green Building Council’s Leadership in Energy and Environmental Design (LEED) certification. They may not even know what the certification means, but they demand it nonetheless”* [9,10]. If the public continues to become more energy conscientious, owners will likely provide for that. Four types of tenants are at the forefront in demanding green workplaces:

- The Fortune 500 multinational corporations with corporate sustainability reports;
- The “gazelles”, the new companies that want to recruit the cutting-edge young talent that sees sustainability as a given, not an add-on;
- Government tenants who are pushing the demand because their own policies require such facilities;
- The public sector at large who is increasingly boosting efforts to pass new sustainable development legislation and retrofit public buildings with energy-efficient features [10].

2.5. Structural

Although not related to energy saving, retrofitting existing buildings to withstand potential severe earthquake or wind is essential to save lives and buildings. Recently, the city of Tokyo has embarked on a plan to retrofit skyscrapers in preparation for anticipated major earthquake. The Shinjuku Mitsui Building is a 39-year-old building in downtown Tokyo and is the eighth tallest building. It is a recognizable skyscraper for its height of 205 m (675 ft) and stark black glass [11]. However, it was completed before tuned mass dampers were as common in tall buildings as they are today. Recently, advanced mass dampers have been installed atop of the building. Mass dampers are gigantic pendulum-like counterweights that mitigates the vibration impact by pulling a building’s mass in the opposite direction of the prevailing forces. So when the ground beneath a building’s foundation slides laterally—for example by earthquake or wind forces—the counterweight balances the structure by swaying in the opposite direction, marginally moving the structure with it [11,12]. Mass dampers have saved buildings from severe earthquake damage before. For example, during the 2008 Sichuan Earthquake, the gigantic tuned mass damper inside Taipei 101—the city’s tallest building—effectively swayed to counteract the vibrations. The Shinjuku Mitsui Building’s retrofit project will likely to have a ripple effect worldwide for many tall buildings will benefit from such a retrofit.

Earlier, in 1978, a structural retrofit was carried out to the 59-story Citigroup Center (formerly Citicorp Center) in New York to correct structural flaws that occurred during design and construction process. The engineers computed for wind loads that hit the building straight-on, but failed to compute for quartering wind loads, which hit the building at a 45-degree angle. Further, for cost-saving, the original design’s welded joints were replaced with bolted joints during construction, which were too weak to withstand 113-km/h (70-mi/h) quartering winds [13,14]. The strength of the building was further questioned since the support columns were in the middle not on the corners. This arrangement was made to make room to St. Peter Church located at one of the skyscraper’s corners. However, structural flaws and weakness could result in a catastrophic collapse of the building in a case of a hurricane. An emergency structural retrofit was conducted that involved welding two-inch-thick steel gusset plates over each of the skyscraper’s 200 bolted joints, reinforcing the joints and permanently correcting the problem. The work was carried out secretly at night, almost unknown to the general public. Following the \$8 million retrofit, the entire structure was re-evaluated for safety and the building was found to be safe. Interestingly, Citigroup Center was the first skyscraper in the U.S. to contain a tuned mass damper, “a 410-ton block of concrete housed in the upper floors of the building, floating on a thick film of oil and controlled by an automatic system. The damping system reduces the building’s sway by converting the kinetic energy of swaying into friction” [15]. The skyscraper, built in the wake of the first oil crises

in 1973, has incorporated energy efficiency features including a heat reclamation system, low-brightness lighting and double-deck elevators [16,17].

3. Common Ways to Retrofit Buildings

While there are many ways to retrofit a building, research identifies the most common ones as follows [18–21].

3.1. Lighting

The most common retrofit type that building owners perform is lighting retrofits for many commercial buildings do not have energy efficient lighting, and retrofit practice informs that upgrading lighting fixtures can result in an increase in the lighting level while decreasing energy consumption up to 70%, yielding significant cost saving. Also, lighting retrofits is one of the easiest to conduct entailing little or no interruption to building's daily operation. Here are some options for a lighting retrofit project [3]:

- Change the old fluorescent lighting fixtures into Energy Star benchmarked fixtures, for example, T5 or T8 high bay fixtures;
- Add a timer or occupancy sensor on the fixtures that are only used occasionally, allowing the lights to be turned off automatically when it is not in use;
- Add a dimmer or photo-sensor for the fixtures so that when natural light is available, photo-sensors will adjust the brightness of the fixtures to reduce unnecessary lighting [3].

3.2. Heating, Ventilation and Air Conditioning

Through maintenance and upgrades, the efficiency of the HVAC system can be improved resulting in improving users' comfort and minimizing the negative impact on the environment. To that end, buildings' owners are encouraged to clean the air filters, ventilators, boiler tubes, *etc.* and make sure that all the HVAC equipment is sealed so that heat transfer occurs only when and where it is desired [3].

3.3. Water Systems

Water conservation is important for water is essential to human continuity and many places lack water, particularly potable water. The overarching strategy is to make the building use less water whenever possible and as much as possible. The following specific strategies are helpful to conserve water [3]:

- Upgrade faucets, toilets, or showerheads fixtures that were made before 1992, for the upgrade will result in significant saving on water use. Also, since 1992, the U.S. federal legislation requires that toilet, faucet and showerheads to utilize at most 1.6 gallons per flush (gpf), 2.5 gallons per minute (gpm), and 2.5 gpm, respectively;
- Upgrade to waterless urinal for it uses sealant liquid that has higher buoyancy than urine;
- Consider adding aerators and occupancy sensors on lavatory faucets for they reduce the rate of water flowing through the faucets by mixing water with air while maintaining the pressure of the water;
- Consider reducing water use by recycling it;

- Rainwater can also be captured for irrigation or even to flush toilets and other uses in the building.

3.4. Building Automation System

The building automation system manages all the operation systems including the HVAC system, lighting and the appliances, *etc.* and helps to reduce utility costs and maintenance while improving user comfort. For example, the system can maintain the temperature, air quality, and lighting inside the building based on a given range and preset schedules. In addition, the system can accurately monitor and record energy usage. It also helps to identify and locate a problem if unusual energy use or system failure occurs. Further, the building automation system can be commanded remotely online and allows immediate intervention in emergency cases.

3.5. Insulation

Building's heating and cooling systems consume significant amount of energy. Consequently, reducing the need for heating and cooling will significantly reduce demand on energy. Good insulation helps in this regard by retaining heat in winter and trapping cool air inside in summer. Well insulated windows do help in insulating the building effectively. For example, in case windows covering 15%–25% of the building envelope, they may account for 40%–70% of the total heat loss of the building ([3], p.11). As such, window retrofit could provide significant savings. For example, in the Empire State Building, upgrading insulation of windows alone helped to save \$410,000 per year [13]. There are various ways to enhance insulation of windows:

- Replace existing windows with low U-factor windows and add weather-stripping on windows to prevent air leakage;
- Replace the single pane windows with double pane windows;
- Apply low emissivity coating on the windows to further lower heat transfer between inside and outside [3];
- Pick window frames that have a low U-factor.

Well insulated walls also greatly help in reducing required energy to heat and cool a building. However, an insulation upgrade for walls is uncommon because it is costly. An affordable way to make walls less absorbent of heat is by painting them lighter colors for they reflect light effectively. Further, replacing a single door entrance with a double one (with weather-stripping) is often an affordable and effective insulation measure [3].

3.6. On-Site Energy Generation

Fossil fuel that we heavily rely on today to generate energy is a finite source and it is crucial that we seek alternative sources. Solar PV and solar thermal (more affordable than PV) are increasingly popular. Wind turbines are also becoming available and affordable; which can be incorporated in skyscrapers' retrofit. For example, in the Willis tower retrofit project, wind turbines are planned to be installed to harness wind energy. Geothermal energy could be cheaper than the solar one but are available in limited geographic areas. Ultimately, the right choice of energy renewable adoption depends on the location and

climatic conditions of solar intensity, wind power, humidity, cloudiness and particles in the air each day [3].

3.7. Innovations

Technological and scientific advancement provide planners and architects new ways to improve the environmental performance and energy efficiencies of buildings. For example, lately, 3M (a global innovation company, Minneapolis, MN, USA) has introduced 3M solar film that can be placed on windows to generate energy and to reduce energy needed for cooling building by absorbing more than 90% of infrared light. This thin solar film has started to be available in the market at affordable prices. However, the downside of this film is that it provides only 3%–8% of efficiency during peak intensity, measuring 20% of what conventional solar PV can generate [3]. Another example that highlights technological advancement is the Eco-Skin, a lightweight, transparent textile that can improve a building's insulation and generate electricity by wind or sunlight [3].

4. Green Retrofit Challenges

While energy efficiency and tax deductions do help in paying back the costs of renovations, there are still barriers to retrofitting skyscrapers. Research indicates that the greatest barriers to green retrofit include lacking financial and technical support, tenant's behavior, split-incentives problem, operation and management, and no one template to apply. Historic buildings also provide additional challenges. These challenges are detailed as follows [15,18,22–26].

4.1. Cost-Effectiveness

Proving the cost-benefit equation is key to convince buildings' owners to commit to a green retrofit. To make an investment, an owner wants proven methods and technologies and demands concrete ideas of the return on investment. Often, the energy performance prediction tools are imperfect and every building responds differently. Consequently, there is a sense of lack of confidence about the cost-effectiveness of undertaking a green retrofit. Another potential barrier related to cost-effectiveness could be the amount of time it takes to obtain cost savings from renovations. In many cases, the time needed is several years. Indeed, there are instances where a retrofit is less cost-effective, and a new construction will be more effective and desirable by owners and developers.

4.2. Financial

An owner may be convinced by the presented cost-effective analysis and persuaded by the retrofit's merits but may lack resources. Therefore, securing adequate funds for green retrofit is often a barrier. Buildings' owners are looking for a quick return on investment in two to four years; and for a major retrofit, it is likely going to take longer than that. Further, in urban areas, there is a financial incentive to maximize the use of sites by adding floor spaces to achieve economies of scale and height for views, which translate in increasing rent values. However, these actions are far from being attainable in existing building in urban cores. Also, developers often perceive little economic justification for retaining existing buildings and instead look for developable land rather than retrofitting existing buildings.

Moreover, the environmental costs associated with building construction and demolition are external to developer and are excluded from value-chain analyses. Also, there is uncertainty about the continuity of financial incentives for green retrofit provided by governments and other organizations. The public has been questioning the merit of giving financial aid to retrofit privately-owned buildings. The benefits of green retrofit go directly to the owners and to renters who would pay cheaper utility bills. The direct benefit to the public seems less clear and is hard to gauge. Collectively, these issues encourage developers to favor new construction over retrofitting existing buildings. Consequently, building retrofitting programs have achieved a small market penetration of less than 1% of eligible buildings, according to a recent study by Pike Research [26]. The commercial retrofit market continues to be small compared to its potential.

4.3. Codes and Regulations

Building policies and codes in general form a major obstacle to a building retrofit projects. For example, building codes in the United States have historically favored new construction over retrofit. In the absence of flexible land use regulations and incentives for reuse, older buildings are commonly torn down to make way for larger structures. Energy codes can also sometimes deter building reuse, as they are typically not well-adapted to the unique limitations and opportunities presented by individual buildings. When these issues are added to seismic and ADA requirements, they collectively form the “tipping point” in decisions favoring demolition. Further, bureaucracy of city planning commissions and zoning boards impose additional hurdles. For example, zoning regulations may object adding external insulation, placing solar panels or wind turbines if they exceed a certain height limit, or adding vertical or horizontal shades or screens, allowing reconfiguring building roofs into gardens, placing rooftop greenhouses and the like. Conversely, the city can amend zoning to become conducive to green retrofits. For example, the City of Boston has recently required a green building standard through municipal zoning requirements. By amending one of the articles of the municipal zoning code, the city required that all large-scale projects meet the U.S. Green Building Council’s LEED certification standards [3].

4.4. Split Incentives

Projects are challenged by split-incentives problem, a phenomenon that refers to the fact that a building’s owner pays for building efficiency while tenants reap the rewards. In many instances, building owners delay or avoid making efficiency investments, because their tenants—those paying the utility bills—reap the financial benefits. In turn, tenants are often hesitant to invest in energy upgrades on properties they do not own. Further, allocating saving for increasing efficiency carried by tenants is often difficult due to lacking accurate sub-metering. Motivated by a desire to attract and retain tenants, landlords commonly favor cosmetic retrofits over energy-related renovations. “Green lease” and utility-funded programs are among the prevailing solutions to the split-incentives problem for these programs finance retrofit projects in return of owing part of the energy savings [3].

4.5. Technical Challenges

Overall, required technical expertise on the part of the project team—architects, engineers, building managers, tenants and energy service companies—continue to be lacking. Additionally, retrofit work is often regarded as riskier than constructing new buildings because the process can be less predictable, and many developers fear unforeseen technical challenges once rehabilitation is underway. This perception of risk and fear of the unknown can motivate buildings' owners and developers to demolish buildings even in instances where a retrofit may be less costly and more profitable than new construction.

4.6. Tenants

In some cases, tenants are the most challenging factor. Once tenants reside in a building, an owner needs to obtain their permission to retrofit the building. The owner also should ensure minimum interruption and inconveniences imposed on tenants while the building goes under retrofit. Further, building's systems such as lighting and HVAC should remain functional and operational during a retrofit.

4.7. Operation and Management

In order to guard the sustainability of a retrofit project, building's owners and managers should ensure a match between the provided systems and tenants' behavior. Research and experience confirm that building's performance degrades when there is mismatch between these two. There have been some incidences where buildings that equipped with best technologies perform the worst because of mismanagement. For example, the override feature in a system could be useful to meet temporal needs or respond to an emergency situation. However, it is important that managers reset the system back to normal. Otherwise, tenants may experience discomfort and they will likely blame the new system and equipment, not the improper management of the system.

4.8. No One Template

Due to vast variations of buildings' conditions as well as variations in geography, climate, culture and finance, it is near impossible to develop a work template that developers can use and replicate elsewhere. Developers, architects and engineers need to perform substantial studies before embarking on an effective retrofit. Also, basic familiarity with a region may shed insight on the process. For example, places that enjoy high temperature such as Los Angeles (CA, USA), and Jeddah (Saudi Arabia), buildings may invest in upgrading the cooling system instead of the heating one. For this reason, the USGBC has added regional priority credits in the LEED 2009. Since LEED prevails in countries beyond the U.S., the added category will be valuable [2,24].

4.9. Historic Buildings

Retrofitting older and historic buildings particularly of large scale (the case of tall buildings) face a series of challenges and possible compromises as the design team balances energy performance with a plethora of competing priorities. Environmentalists and preservations often get in conflict when the

appearance of a historic building needs to be changed for the sake of improving building's energy performance. The complications on a project may result from historic preservation standards that often care about retaining historic features, fabric, and character even at the fine-grain scale. Further, some buildings could be treated as "historic" although they do not necessarily acquire a formal recognition of being a historic landmark. For example, when green retrofit was proposed to the Willis Tower (formerly Sears Tower), many voiced objections fearing that changes will may impact its perceived iconic image. Conducting such retrofit would be a challenge for providing environmental benefits while retaining the image of the building unchanged. "*Sears is not yet a historic landmark, of course, but the very idea that its iconic image could be radically altered in the name of environmentalism sent shockwaves coursing throughout Chicago's architectural community*" [24].

4.10. Conducting Retrofit around Tenants' Operations

As mentioned earlier, a common challenge of retrofit is conducting the work without interrupting the daily operations of staff and tenants. Though, there are strategies to address this challenge. For example, developers may not upgrade the entire HVAC system for a tenanted building at once. Instead, inefficient perimeter induction units can be replaced floor-by-floor with quieter and more efficient ones [25,26].

4.11. Security

Finally, some buildings, e.g., government buildings, could require high security and conducting retrofit projects in these buildings would be challenging.

Interestingly, some buildings' retrofit projects may face a combination of the aforementioned challenges. For example, the Dirksen Federal Building completed in 1964 and 330 North Wabash completed in 1973, were recently undergone green retrofit projects that faced many challenges including "*asbestos remediation, historic preservation standards, maintenance of high security levels and, all-glass transparent facades, most of all, conducting work in and around the occupants of an operating courthouse: energy conservation is one priority among many*" [26]. Specifically, the lighting retrofit possibilities were limited because of the desire to preserve the existing historic pattern of the plaster ceiling that contains the luminaries. This issue prevented the project team from increasing lighting efficiency by redistributing light fixture and opted to increase the output of light fixtures instead. This choice has resulted in incurring higher wattages per square foot than the norm today; though, this solution still provided improvement of the existing condition. The renovation of the 330 North Wabash building received Silver certification from LEED for **Existing Buildings: Operation and Management**. Finally, it is important to consider building age and pick the right time for a deep retrofit rather than being motivated by purely government incentives, and a major retrofit must address already existing needs and operational problems. Otherwise, a green retrofit will not be cost-effective.

5. Retrofitting Skyscrapers: Case Studies

5.1. Empire State Building, "*The Green Empire*", New York, NY, USA

The Empire State Building is a 102-story, 381 m (1250 ft) skyscraper located in Midtown Manhattan, New York City. The building's construction was completed in 1931 and remained the tallest building in

the U.S. for almost four decades, until the topping out of the World Trade Center's North Tower in late 1970. With its beautiful Art Deco Style, elegant profile, and distinctive height and history, the building enjoys an important place in the American culture as a symbol of the power of New York. It was named as one of the Seven Wonders of the Modern World by the American Society of Civil Engineers. Its 260,128 m² (2,800,000 ft²) of leasable office space that attracts a wide-range of businesses, drawn by the building's prestige, its unmatched skyline views and convenient location at the center of Manhattan's mass-transit system. Its observatory on the 86th floor attracts between 3.5 million and 4 million visitors yearly. The Empire State Building (ESB) that for long represented a symbol of power of the New York City has become recently also a symbol of "green power efficiencies", or what was nicknamed "the Green Empire" [15,18].

The green retrofit project began in 2009 as part of the Clinton Global Initiative, and in 2010, the 80-years old building underwent an over half billion dollar retrofit, with the goals to transform the building into a more energy efficient and eco-friendly structure. The environmental upgrade of the building is the largest retrofit of its kind to date in the United States. "*It is expected to reduce energy use by more than \$4.4 million annually, cut carbon emissions by 105,000 metric tons over a 15-year period and provide a payback in slightly more than three years*" [27]. Reducing the building's carbon footprint by 105,000 metric tons is equivalent to removing 20,000 cars off the road. In terms of economic feasibility, the expected income stream enhancements included [28]:

- Decreasing capital improvement program costs;
- Decreasing utilities budget due to achieving higher efficiencies in energy and water usage;
- Decreasing building operations budget due to lower maintenance and repair costs;
- Increasing rent and occupancy due to providing higher quality spaces of greater services and amenities; and
- Additional income from new facilities, amenities, and tenant service offerings [28].

Also, an important goal of the project was to make the ESB a green catalyst by changing buildings owners' perception of retrofits as an expense, rather than an opportunity for economic gain. In short, the project is meant to highlight that a green retrofit makes an economic sense. The Empire State Building retrofit program hoped this massive green overhaul will become a beacon for other skyscrapers to follow. "*The \$550 million Empire State ReBuilding program involved development of a groundbreaking transparent, well-documented, replicable energy-efficiency retrofit program that is broadly applicable to all office buildings*" ([15], p. 56). The Empire State Building's retrofit project was carried out in partnership with several organizations summarized in Table 1.

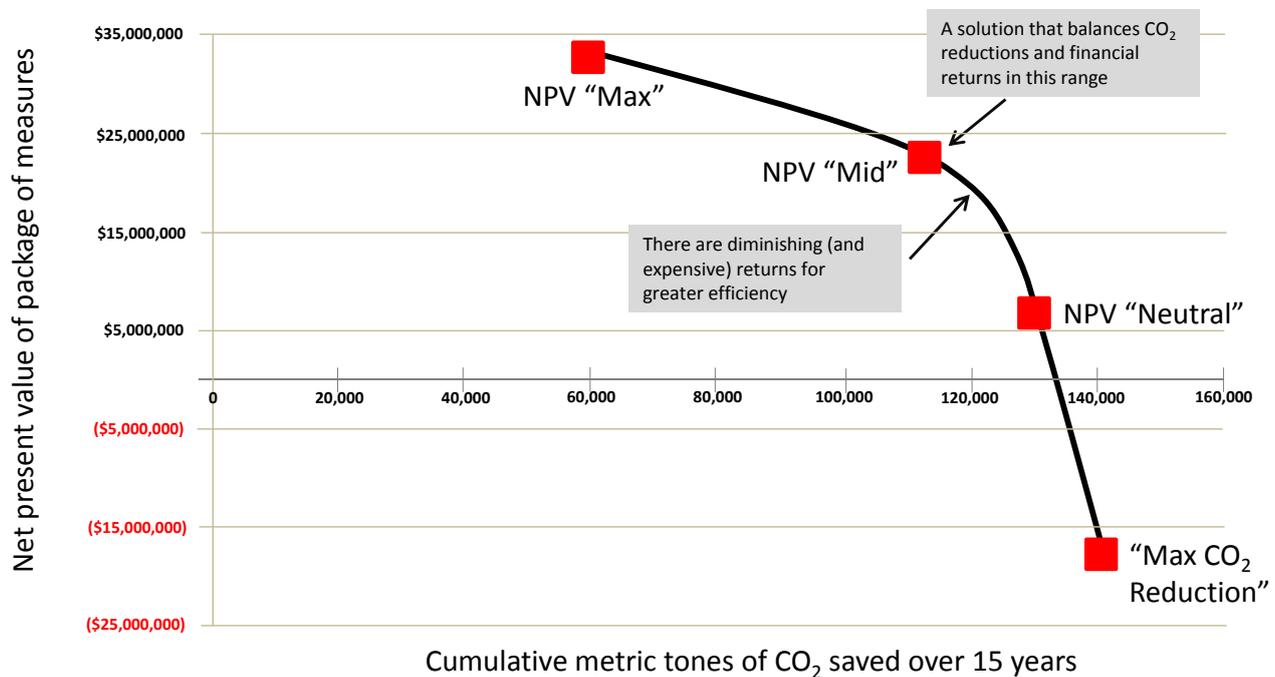
The project team has pursued a systematic multi-phase analytical process, and conducted comprehensive analyses to determine which energy and sustainability strategies could be implemented at the building, and to identify the associated costs, risks and obstacles that might arise for each strategy. Specifically, the project team examined the building's mechanical systems and equipment, computed tenants' energy consumption, and developed a baseline energy benchmark report and a system for gaging energy efficiency. Analyses suggested that the team should pursue a program that "*would reduce energy use and greenhouse gas emissions by 38%, saving 105,000 metric tons of carbon dioxide over the next 15 years*" ([28], p.8). The team's final report noted: "*Achieving an energy reduction greater than 38% appears to be cost-prohibitive. The analysis had examined strategies that could have reduced emissions*

by nearly 45%, out of a theoretical maximum of 55%. A total of 40 energy efficiency ideas were narrowed down to 17 implementable strategies that were later analyzed in depth. Of these, the first 90% of reduced carbon dioxide would also save costs over time by an average \$200 per ton of carbon saved. The last 10%, by contrast, would carry a life cycle cost of more than \$300 per ton of carbon saved” ([28], p. 8) (Figure 1).

Table 1. Organizations that were involved in the Empire State Building’s retrofit project [28].

Organization	Description
<i>The Clinton Climate Initiative (CCI)</i>	It was founded in 2006 with the goal to create and advance solutions to the core issues driving climate change. CCI works with building owners to reduce greenhouse gas emissions from existing buildings.
<i>Jones Lang LaSalle</i>	A global real estate services firm with the industry’s leading sustainability services program.
<i>Rocky Mountain Institute (RMI)</i>	It is a nonprofit organization recognized as a leader in energy-efficient solutions.
<i>Johnson Controls Inc.</i>	A global Fortune 100 company focused on creating effective interior environments, performed the engineering, procurement, and construction work.
<i>Empire State Building Operations</i>	It focuses on ensuring that building’s operations are not disrupted by the retrofit.

Figure 1. Fifteen-Year Net Present Value (NPV) of package vs. cumulative CO₂ savings. The graph demonstrates that the Empire State Building can achieve a high level of CO₂ and energy reduction cost-effectively (Graph by author; redrawn from [28]).



In addition to reducing energy and carbon dioxide emissions, the sustainability program planned to deliver an enhanced environment for tenants including: improved air quality resulting from tenant

demand controlled ventilation, better lighting conditions that coordinate ambient and task lighting; and improved thermal comfort resulting from better windows, the radiative barrier and better controls (Table 2). The upgrade resulted in significant savings [29] (Figures 2 and 3).

Table 2. Summary of key upgraded features of the Empire State Building [3,27–35].

Feature	Detailed Description
<i>Window Light Retrofit</i>	Refurbishment of approximately 6,500 thermopane glass windows, using existing glass and sashes to create triple-glazed insulated panels with new components that dramatically reduce both summer heat load and winter heat loss. This retrofit is estimated to save 11M kBtu of energy per year.
<i>Radiator Insulation Retrofit</i>	Reflective barrier behind each radiator was installed. It is estimated that 6.9M kBtu of energy and \$190 K of utility costs are saved each year as a result of the added insulation behind radiators.
<i>Tenant Lighting, Daylighting and Plug Upgrades</i>	Photo-sensors and dimmable ballasts were installed so that when there is natural sunlight, artificial lighting can be turned on but dimmed to a desired level to reduce unnecessary energy load. Also, plug load occupancy sensors were provided to occupants to plug in their appliances accordingly. These can further cut 13.7M Btu of energy per year [3].
<i>Chiller Plant Retrofit</i>	The tubes, valves, motors <i>etc.</i> of the four chillers are replaced while the shell of it is kept. In addition, the controls, variable speed drives and primary loop bypasses of the chillers are upgraded.
<i>Air Handler Replacements</i>	Over 300 existing air-handling units were replaced with newer units that have higher energy efficiency and better performance, which resulted in reduction of 22.8M Btu of energy per year [3].
<i>Whole-Building Control System Upgrade</i>	The existing building control system was upgraded to optimize HVAC operation, satisfy users' needs as well as provide more detailed sub-metering information. About 20.6M Btu of energy is expected to be saved annually by this retrofit [3].
<i>Ventilation Control Upgrade</i>	A demand control ventilation system has been installed to ensure adequate ventilation by measuring the carbon dioxide concentration in the tenant space. When ambient air is only drawn into the building when needed, about 4.6M Btu of energy used will be trimmed.
<i>Tenant Energy Management Systems</i>	Individualized, web-based power usage systems for each tenant was introduced to allow more efficient management of power usage. Tenants can therefore accurately check their energy use data and obtain sustainability tips to motivate themselves in achieving higher sustainability standards. This tenant energy management program is estimated to further cut the energy use of 6.9M Btu per year, making the totally energy reduction to be 38%.
<i>Green roof</i>	For its total 3,048 m ² (10,000 ft ²) green roof upgrade, the Empire State Building chose to install the Xero Flor Green Roof System for four rooftop areas: 21st floor east 1051 m ² (3,450 ft ²), 21st floor west 1051 m ² (3,450 ft ²), 25th floor northwest 3,048 m ² (1,000 ft ²) and 30th floor west 365 m ² (1,200 ft ²).
<i>Elevators Upgrade</i>	All 68 elevators were upgraded to be 30% more efficient while sending excess energy back to the building's grid.

Figure 2. Empire State Building (ESB) Performance Year 2. Reduction in ESB's 2007 Baseline Electric Utility Costs during Performance Period (Graph by author; redrawn from [29]).

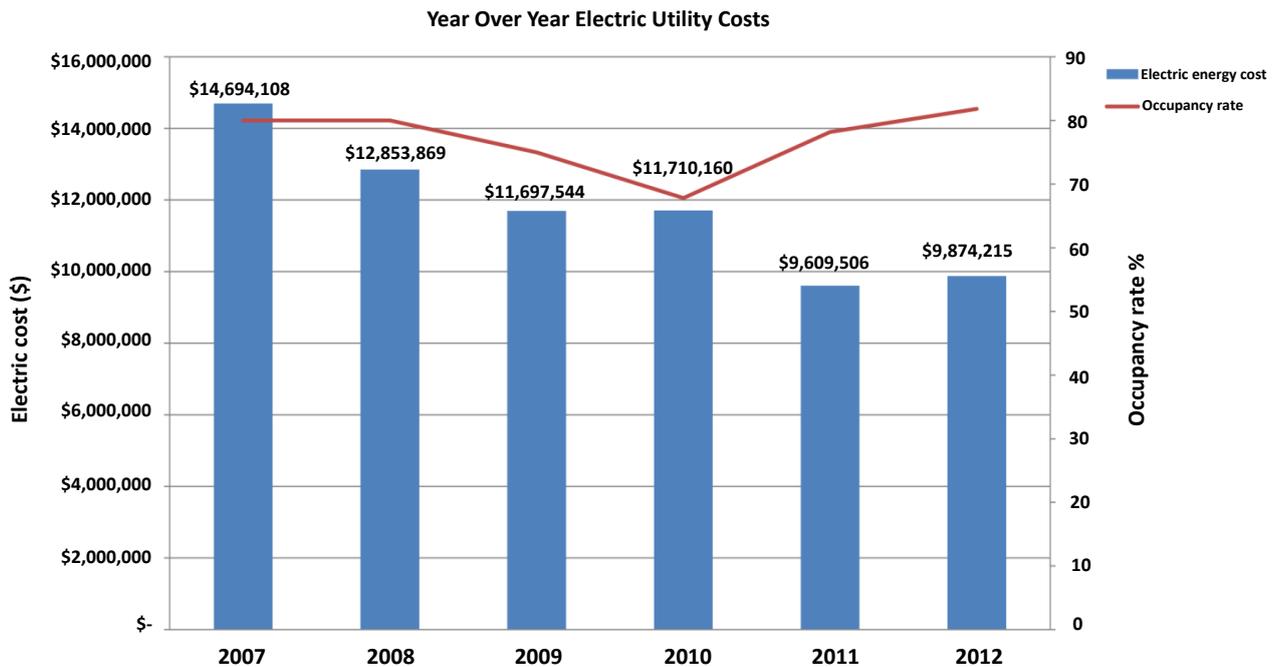
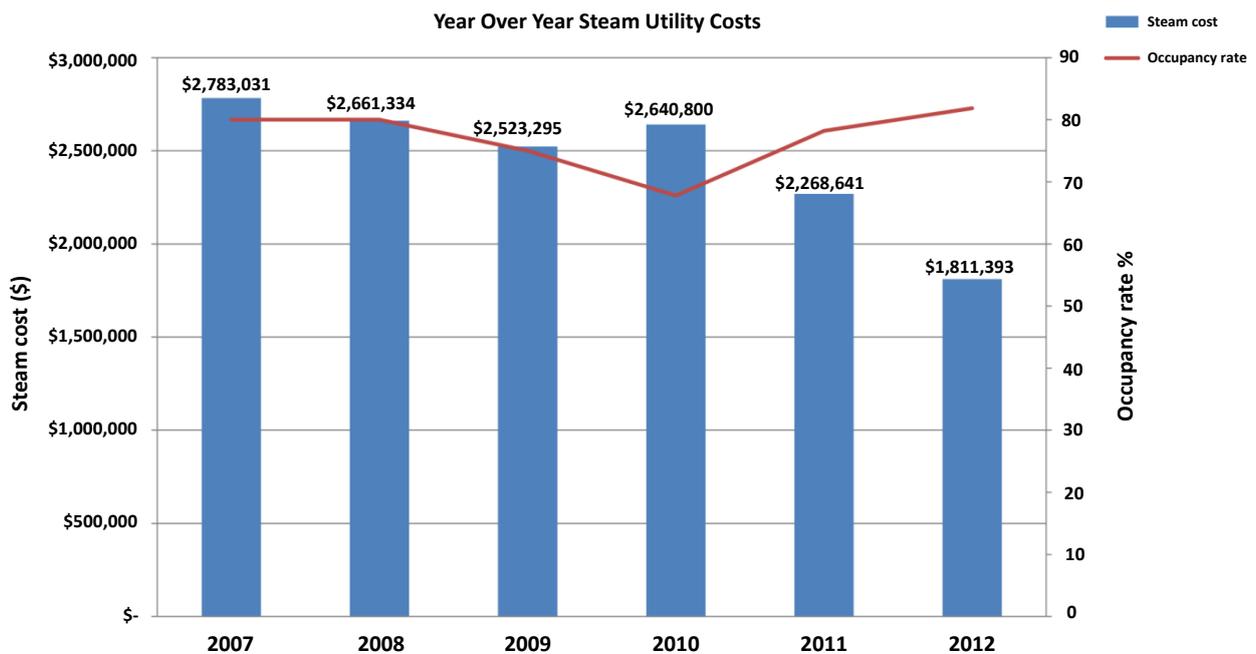


Figure 3. Empire State Building Performance Year 2. Reduction in ESB's 2007 Baseline Steam Utility Costs during Performance Period (Graph by author; redrawn from [29]).



Among the most noteworthy retrofit items were windows and elevators. It is unprecedented that a skyscraper of this scale reuses, rather than replaces, about 96% of its window glass. This choice has saved the building's owner \$2300 per window and avoided the negative environmental impact of transporting new windows from the manufacturing plant and old ones to recycling factories. Also, it is remarkable that the window retrofit happened without disturbing tenants for windows were removed

after office hours and re-installed before most tenants returned to work the next morning. The retrofit was carried by a crew of 35 working in two shifts, refurbishing 75 to 80 windows in a designated workroom [30]. Each night, workers unscrewed windows from their frames, wheeled them to the workroom, and cleaned glass panes after detaching them from their sashes. Later, workers laid a sheath of transparent insulation film between the glass panes (cavity), “*which were resealed and placed for an hour in a 205-degree oven to shrink the film tightly in place*” [30]. Then, workers pumped a mixture of inert gases into cavity for insulation. Finally, they put the panes back in the original sashes, wheeled them back to offices where they were taken from, and remounted them in the window frames from which they were removed. All of this work was carried out before workers returned to work in the following morning [30].

Upgrading the elevator system was also remarkable because the new system saves energy in multiple ways. The employed regenerative system harvests the “waste energy” from braking, of which elevators do frequently. Conventional elevator machinery can lose more than 30 percent of its energy in the form of waste heat, and the new retrofit reduced the loss to only five percent. The new elevator system channels the rest of energy back into the building’s electrical system. The second way of savings is a direct result of the first. In a conventional elevator system, waste heat gathers in the machine room, which then requires substantial air conditioning to prevent overheating. In contrast, the regenerative system does not have this problem because heat has already been captured, harnessed, and channeled to the electrical system as “surplus” power. “*The trick behind the system is a gearless technology based around a permanent magnet AC motor. A gearless machine operating at less than 240 rpm can reach the same speed as a geared machine at 1800 rpm*” [31]. Additional savings are achieved by having the new system’s motor consumes zero energy when the elevator is not in use. Finally, the new elevator system is designed to accommodate high efficiency LED lighting in the cabs. Collectively, the new elevator system results in significant savings that reduce demand on the city power grid.

Further, the building’s owners signed an agreement with Green Mountain Energy to purchase 100% of its power from renewable sources, resulting in a positive ecological impact. “*By purchasing nearly 55 million kilowatt hours of renewable energy each year, nearly 100 million pounds of carbon dioxide will be avoided annually. In New York City terms, that is equivalent to having nearly every house in New York State turning off all their lights for a week, taking approximately 40 million fewer cab rides or planting more than six times the current number of trees in Central Park*” [32]. Most importantly, during the retrofit project, the Empire State Building team engaged tenants in planning discussions and enlightened them about retrofit options to create energy-efficient office spaces that they like and enjoy. For example, one of the tenants designed an open office floor plan to maximize natural light and installed an under-floor ventilation system to bring in fresh air that allowed individual temperature controls for workspaces. Incorporating measures like these at the early stages of the retrofit project added only marginal costs that will likely to be recouped in less than five years [32,33].

In addition to engaging tenants, the retrofit project embraced an integrated process that coalesced efforts of various project teams such as the capital and sustainability teams and facilitated a whole-building retrofit approach. For example, initially, the capital team has assigned a budget to replace the chiller plant. However, the sustainability team found out based on a study it conducted that chiller replacement could be avoided by retrofitting windows on site (a process explained in the previous section), and by just upgrading the existing chiller. Such decision resulted in significant saving for chiller upgrade is far

less expensive than replacing it. The planning and design team also employed energy analyses using DOE-2.2 (eQUEST interface), a building energy simulation tool that allows for comparing sustainable design alternatives [34]. By inputting various parameters including weather data, building geometry, material properties, equipment schedules, system components and the like, the software program estimated energy savings for various design alternatives and individual choices. Once preliminary energy saving estimates for individual measures were provided, the team used the financial model developed for this project to identify the most cost-effective ways to save energy, reduce greenhouse gas emission while providing economic gain. Iterations between these models helped the ESB team to figure out the optimal recommendations.

The green retrofit of the Empire State Building attained the LEED® EBOM (Existing Buildings: Operations and Maintenance) Gold Certification. While the LEED-Gold certification applies to the entire structure as an existing building, specific spaces within the building received LEED-Platinum certification, the highest designation under the USGBC standard for commercial interiors. The building also has earned a score of 90 (out of 100) from the Environmental Protection Agency's "Energy Star" program. Skanska has earned a LEED-Commercial Interiors Platinum rating for its 2200 m² (24,000 ft²) offices on the 32nd floor [3,34]. Critical to the project is using the building as an open laboratory by having all the work and process available for study and replication. This open approach has subsequently attracted the attention of governments and officials including the U.S. Congress, the Obama administration, New York City's Office of Long-Term Planning and Sustainability, cities around the world, and numerous real estate investors, managers and industry groups [2]. The Empire State Building is colloquially called "The World's Most Famous Office Building" and after the green retrofit, the building earned a new title "The World's Most Famous Green Building". This remarkable retrofit fits New York's plan to reduce current carbon emissions by 30% by 2030. It also fits the city's rising green profile. The New York City is considered one of the greenest city in America (per capita) because of its public transit, high density and relatively smaller residences. In conclusion, the retrofit of the Empire State Building offers a stimulating prototype for other skyscrapers, particularly commercial ones that wish to enjoy a sustainable future [34,35].

5.2. Willis Tower, Chicago, IL, USA

The 110-story, 442 m (1451-foot) Willis Tower (formerly Sears Tower, 1973–2009), is a Chicago icon and the second tallest building in the Western Hemisphere after One World Trade Center in New York City. Completed in 1973, the skyscraper is a major tourist attraction in Chicago. Its observation deck attracts over one million people visitors yearly [15,36]. Designed by the firm of Skidmore, Owings, and Merrill, the building enjoys an innovative structural system, developed by structural engineer Fazlur Kahn, and a striking exterior of black aluminum and bronze-toned glass. Willis Tower has recently undergone a long-term green retrofit project by partnering with Smith and Gill architectural firm and Environmental Systems Design, a mechanical engineering firm. The retrofit plan projected "*Willis Tower's base building energy use to be reduced by 80% (equal to 64M kWh annually) and its water use by 24 million gallons annually*" [36]. The cost of the retrofit is estimated at \$350 million.

The greening and modernization plan of the Willis Tower include several features. The major energy savings for this renovation project is replacing the 1973 tower's 16 thousand tinted single-pane windows

with insulated glass [37]. This retrofit measure is crucial to insulate the building from Chicago weather that fluctuates between extreme temperature of cold winter and hot summer. Traditionally, insulated glass involves doubling or tripling the glass panes. However, for the Willis Tower, this option would be inappropriate for that will add substantial load on the curtain wall. Instead, the plan suggested providing the insulation through adding insulating thin-film that will have the insulating properties of a triple-pane glazing while avoiding the heavy weight of triple glass. It is estimated that the re-glazing retrofit will provide effective daylighting and save energy consumption required for cooling and heating the building [36].

Further, the Willis Tower retrofit project suggests upgrading the building's mechanical systems by supplying new gas boilers that utilize fuel cell technologies to generate electricity, heating and cooling with 90% efficiency. The project will also upgrade the building's 104 high-speed elevators and 15 escalators to reduce energy consumption. Further, it will install advanced lighting control systems that automatically dim the lights and adjust to optimal level of brightness when daylight is detected, reducing energy consumption as well. The tower's retrofit will also involve upgrading the building's plumbing system and restrooms by installing low-flow water fixtures on toilets, urinals and faucets; as well as by providing condensation recovery and irrigation systems. Drawing and renderings also show integrating green roof as well as wind turbines and PV panels to harness wind and solar energy.

Similar to the Empire State Building, the Willis Tower is an important national and international landmark skyscraper that will likely inspire other skyscrapers to conduct green retrofits despite the involved initial costs. Chicago Loop alone contains hundreds of skyscrapers that are due to retrofit. Further, retrofit projects may enhance economy by creating jobs; for example, it is estimated that the retrofit project of the Willis Tower will create 3600 jobs [37].

5.3. Taipei 101, Taipei, Taiwan

Taiwan's Taipei 101 skyscraper—the world's tallest building from 2004 to 2010—has recently undergone a major green retrofit that made the tower to successfully earn LEED Platinum certification—the highest level of achievement in the LEED system. A three-year-long green retrofit has enabled the skyscraper to achieve significant savings on electricity and water and to reduce and recycle waste. The retrofit has resulted in reducing annual utility costs by \$700,000 a year and reducing the carbon dioxide emissions by nearly 3000 tons per year; this is equivalent to removing 240 vehicles off the road [38,39]. The tower's retrofit involved upgrading its electrical and mechanical systems of heating, ventilation, and air conditioning units, as well as enhancing its already efficient Siemens Apogee building management system, so that it can carry out more accurate monitoring and analyses of energy consumption. Temperature and humidity sensors were installed on each floor so that they transmit information to the management system which then decides on turning on and off mechanical and lighting equipment. Further, similar to the case of Bank of America Building, the building was equipped with “ice batteries” that make ice at night, when electricity is cheaper, and then melts during the day to cool the building in hot summers. In addition to upgrading these major systems, the retrofit also advanced other important features of the building including the irrigation system and food-waste recycling system. This is significant since the tower houses hundreds of restaurants. Collectively, these enhancements augmented the existing green features of the building including low-E glass and graywater system.

5.4. Adobe System Headquarter Complex, San Jose, CA, USA

Between 2000 and 2006, software maker Adobe engaged in a major retrofit of its headquarters, located in Downtown San Jose, CA, USA. The over 92,903 m² (1,000,000 ft²) complex comprises three commercial high-rise office buildings: West Tower, East Tower, and Almaden Tower, completed in 1996, 1998, and 2003, respectively. These towers rest atop 87,187 m² (938,473 ft²) of parking garage. In 2001, because of experiencing rolling blackouts and spikes in energy prices, the California government asked commercial users to reduce energy usage by 10 percent. In response, Adobe has embarked on a green retrofit projects that earned the building Platinum LEED certification in 2006. The retrofit project resulted in reducing electricity use by 47%, gas use by 42%, and water use by 48%. Adobe's retrofit project cost was about \$1.4 million but it received \$389,000 in rebates and achieved a saving of \$1.2 million a year, translating to a return on investment (ROI) of 121 percent [3,40].

The first step that Adobe took in the upgrade process was identifying utilities and equipment that were overusing energy. For example, the parking garage's exhaust fans were operating unnecessarily 24/7. The retrofit's preliminary study suggested that the fan running time could be reduced to only 3 h during the morning commute and 3 hours during the evening commute—this will suffice to keep air quality above required standards. Another important improvement involved providing a Web-Based Intelligent Building Interface System (IBIS) that monitors and controls building's equipment. The IBIS comprises 30,000 monitoring points and is run by a single software program that would ease the tasks of monitoring building's subsystems by displaying electricity, water, gas, Uninterruptible Power Supply (UPS) systems, data centers and standby generators status in real time. The IBIS also allows adjusting lighting and temperature of the numerous zones of the building individually, floor-by-floor, or the entire building remotely. Further, the IBIS helps in detecting and correcting problems ahead of time, resulting in significant annual savings [3,40].

The building's upgrade also involved implementing water conservation strategies. For example, the retrofit project improved restroom facilities by installing waterless urinals, automated flush valves, faucets, and soap and paper-towel dispensers. Re-landscaping scheme also emphasized using local and drought-tolerant plants to reduce water and maintenance needs, and upgraded the sub-surface drip irrigation system (which is more efficient than the spray irrigation system). Interestingly, Adobe already uses two satellite-based evapo-transpiration (eT) controllers to regulate irrigation by communicating with local weather stations through wireless technology [41]. As such, the system optimally adjusts water flow according to local weather. For example, if the weather forecast predicts rain, the system will delay irrigation. Finally, Adobe has installed a web-based system to control pump-run time for the fountains.

The retrofit project also upgraded chillers by installing an adaptable frequency drive (AFd) which resulted in savings totaling approximately 300,000 kW h (\$39,000) annually [3]. Adobe also employs effective composting and recycling of paper, cardboard, plastic, glass, cans, printer toner, batteries, kitchen grease and the like, which result in diverting up to 95 percent of its solid waste from landfill. Adobe also employs green cleaning methods and materials that reduce health and environmental risks. These green materials are non-toxic, environmentally safe, VOC-compliant and biodegradable. Further, Adobe has encouraged using green transportation means. It installed locked bike cages and provided its employees incentives to use public transport. As a result, about 20% of the employees commute by public transport, compared to 4% in the Silicon Valley [3,41].

5.5. Glastonbury House, London, UK

While there are an increasing number of skyscrapers that embrace green retrofit, there are fewer residential buildings that take this path. As such, the retrofit project of the 23-story Glastonbury House, a residential building in London, UK, provides a good working model for other residential towers. The building has recently undergone a major 17 million dollars retrofit that resulted in 50% in energy saving and 40% in water reduction [3]. The retrofit project involved upgrading bathrooms (dual flush toilets and spray taps were installed to reduce waste of water), replacing light fixtures to increase lighting levels, and improving the heating systems' efficiencies. The project also involved installing renewable energy systems including solar photovoltaic and wind turbines to generate power, and solar water heaters to provide hot water. Further, eco-friendly materials were utilized and recycling was encouraged.

5.6. The Joseph Vance Building, Seattle, WA, USA

After acquiring the 14-story historic Joseph Vance Building in downtown Seattle in 2006, the Rose Smart Growth Investment Fund I, L.P. has embarked on a series of retrofit projects intended to transform the building into "*the leading green and historic class B building in the marketplace*". The 12,400 m² (134,000 ft²) terracotta Vance Building was constructed in 1929 and contains offices over ground-floor retail that had the potential to ignite economic activities and re-energize social and pedestrian life. The purchase was motivated by the company's mission to acquire assets in walkable, mass-transit accessible locations that are ripe for repurposing via green retrofits. It is the company's philosophy that buildings near mass-transit services promote "smart growth" and support the creation of healthy walkable environments that reduce the need for parking lots. The company also holds the belief that destroying to rebuild is not a good use of resources, even if we rebuild in a green fashion. The new owner's goal of retrofitting the Vance Building was to make the building "*the greenest and healthiest historic buildings in the Seattle marketplace....and attractive to current and future tenants who share a commitment to preservation, stewardship of the natural environment, and healthy indoor environments*" ([42], p. 2). Key retrofit strategies included [42,43]:

- Replacing ducted heating systems;
- Recalibrating steam heating system;
- Localizing thermostats; restoring windows to facilitate natural ventilation;
- Adding automated sunshades to reduce heat gain;
- Providing lighting retrofit with automated controls; and adding light shelves and CO₂ sensors;
- Replacing roof with a LEED-approved;
- Replacing water fixture; and
- Providing bike storage and shower facilities.

The historic Vance Building already enjoys a great character and inherent environmentally sensitive features including high ceilings, operable windows and floor plans designed to maximize natural light. The renovation work capitalized on these features by focusing on providing natural ventilation and lighting. Modern technologies implementation was meant to enhance these "vernacular" systems. The project team conceptualized a natural ventilation strategy to meet tenant thermal comfort needs in the summer time. The strategy was backed up with quantitative analysis, temperature monitoring and

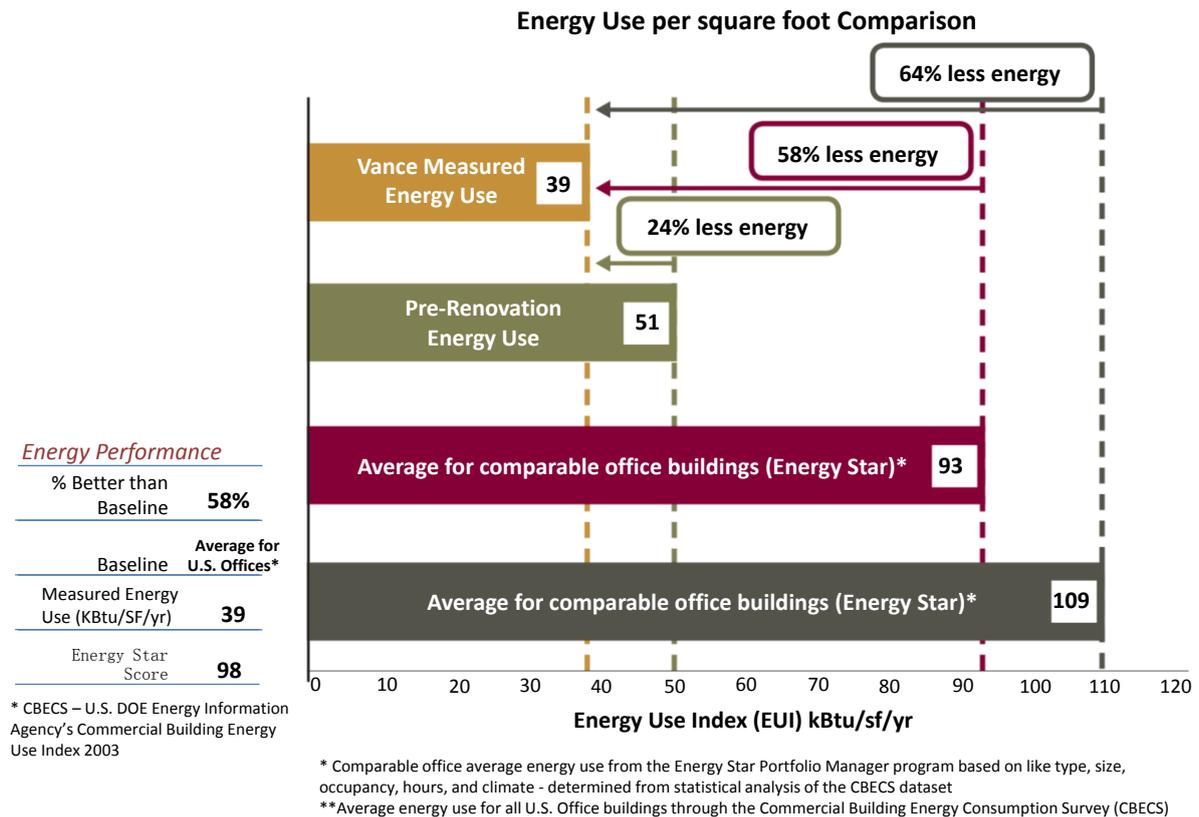
targeted façade solar gain studies. “*The team exposed floor and ceiling slabs, removed drop ceilings, and installed light shelves and MechoShade window shading systems along with ceiling fans and devised an ongoing operations and maintenance plan to decommission cooling units at the end of their useful lives, transitioning office suites to natural ventilation over time*” ([42], p. 3). For economic reasons, the project did not replace the existing steam heating system, which is connected to the Seattle Steam downtown grid, rather it upgraded it. Also, a replacement of the heating system would have involved substantial alteration to the existing structure.

The project also replaced the global thermal control with local controls to enable regulating the steam system at the individual radiator units. This measure will enhance user comfort and improve energy efficiency. Further, the 45-foot building width facilitated natural lighting. This is also augmented by the light shelves on the south and west exposures which reflect sunlight to light-colored ceilings. A lighting retrofit involved replacing inefficient fixtures with T8 and T5 fixtures [43]. Also, occupancy sensors were provided in all common areas and most tenant spaces. Further, the owner has mandated green cleaning and designed a green tenant improvement and operation manual to educate tenants on building green features and to inform about expected behaviors while using the building’s utilities, spaces and amenities.

The building’s energy use prior the retrofit was about 51k Btu/sf/yr, and after the renovation energy use dropped by 24% to just 39k Btu/sf/yr [43]. The building now uses 58% less energy per square foot than the average for offices in the U.S. [43]. The project retrofit has improved the building’s imageability; and consequently, occupancy rate was increased from 68% to 96%, and the building has seen increased rents, tenant retention and net operating income. The building’s acquisition cost was \$23.5 million (\$176/sf); the improvement cost was \$3.5 million (\$26/sf); and the cost of the Tenant Improvements and Leasing Commissions was \$2.26 million (\$17/sf) [43] (Figure 4).

The green retrofit was successful. The building has been dubbed in the press as “ground-zero for the green movement in Seattle”. In 2009, the U.S. Green Building Council (USGBC) awarded the Vance Building LEED for Existing Buildings (EB) Gold certification. The building also achieved an Energy Star rating of 98 (out of 100). This placed the building in the top two percent of office buildings nationally. This retrofit project proves that older buildings can substantially improve their performance, provide significant energy savings and enhance user comfort. A 2010 Post Occupancy Evaluation (POE) has indicated that “77% of building occupants are satisfied with lighting levels. 85% of occupants indicated general satisfaction with the overall building and individual work spaces” ([43], p. 30). The study, conducted by the University of California, Berkeley Center for the Built Environment, also showed that tenants were mostly pleased with the new real-time energy monitoring system that helped them to conserve energy. They were also happy with the provided thermal comfort and acoustic environment.

Figure 4. Gauging energy performance of the retrofitted Joseph Vance Building, Seattle, WA, USA (Diagram by author; redrawn from [43]).



5.7. Hanwha Headquarters, Seoul, Korea

Hanwha is one of the world's leading company that produces environmentally-friendly products including photovoltaic panels. Recently, the company has felt that its 1980s-era headquarters building does not reflect its environmental values and image, and consequently wanted to renovate its building. After soliciting for renovation proposals, Amsterdam's UNStudio's proposal won the bid. The proposal involves replacing the skyscraper's façade of opaque paneling and dark single-pane glass windows with an animated LED one. The new façade also integrate a shading system. Where providing shade to the facade is desirable, the glazing are angled away from direct sunlight; while other places the glazing is purposefully angled to receive direct sunlight. These efforts are coordinated with providing the optimal angles for the introducing PV cells to best harvest sun's energy. The façade will ultimately enjoy 55% transparency which will boost natural daylight provision. Most interestingly, "the pixelated lighting of the façade will reference nature, data processing and energy forms and is designed to become part of the overall Hanwha branding strategy as one of the leading environmental technology companies in the world" [44]. In addition to façade replacement, the renovation project includes remodeling meeting rooms, auditorium and executive areas, incorporating sky gardens and vegetated lobbies, and improving interior climate and air quality. The renovation project also involves incorporating green walls and enhancing outdoor landscaping. These changes will significantly improve the environmental quality and energy performance of the building.

6. Discussions and Concluding Remarks

This paper served as a review of major topics, issues, and case studies related to an emerging and important project concerning green retrofitting skyscrapers. Indeed, the existing building stock of tall buildings is responsible for immense energy consumption and greenhouse gas emission and it is in a dire need to retrofit. *“The existing building stock in some regions accounts for nearly as much energy consumption and carbon emissions as the transportation and industrial sectors combined. Existing buildings represent the greatest opportunity to improve this performance. Early tall building curtain wall applications, not particularly efficient to begin with, are now approaching 40 years of age and more”* [45]. Economically, green retrofit is on demand as property owners and managers become convinced that a greener building now makes financial sense. That is because in recent years environmental retrofits have begun to pay off for owners and tenants alike. Higher-profile companies are seeking out more efficient office space, and new technology at older buildings has started to translate into higher property values, leases and occupancy rates. *“In a good market, we are going to get the best rents for the best tenants, and in a bad market like we have now, we’re going to get tenants when other buildings will not”* ([28], p. 4), according to Anthony E. Malkin who leads a real estate group that owns the Empire State Building. Consequently, buildings that define city skylines across many countries or national icons, mainly in western countries, are going green.

The examined case studies in this paper indicate that green retrofit projects have led to significant benefits to individual buildings and their cities at large. For example, providing energy-efficient windows and installing efficient lighting systems (e.g., a lighting system that dim automatically when not needed) could decrease demand on city grid and reduce greenhouse gas emission. Most skyscrapers enjoy large envelopes, which provide the potential for harnessing solar power. On a city-scale, this could provide quite a boost to the electrical grid. As mentioned, the Willis Tower in Chicago and Hanwha Headquarters in Seoul, South Korea, are expected to embrace this approach as they move toward sustainability. However, the Empire State Building, with its antenna roof, does not. Also, among the common retrofits is swapping buildings’ old HVAC equipment for systems that generate ice during the night to cool the air conditioning in daytime.

While this paper concerned mainly projects that tackled “deep retrofits”, *i.e.*, projects that involved several renovations work to improve the performance of the building; it is important to note that there are numerous green retrofit projects that deal with only a few renovation work. Due to limited needs or restrained budget, a building’s owner may choose a simple retrofit project that yields substantial savings and productivity. For example, recently, the Sheraton Chicago Hotel and Towers installed motion sensing thermostats in every room of the hotel’s 1214 rooms. It is a simple concept but it is resulting in a significant energy saving; it decreased the hotel’s electric bills about \$150,000 per year. The way it works is that rather than keeping all the rooms at a comfortable 22 °C (72 °F) at all times, the introduced motion sensing thermostats retains this ideal temperature only when the rooms are occupied. While the room is unoccupied, the system makes it go into “deep setback” by temporarily deactivating the cooling and heating system. However, once a guest checks in, the thermostat immediately resets the system and reactivates cooling or heating (as required) so that the room’s temperatures becomes comfortable by the time the guest reaches it. When the guest leaves the room (e.g., meeting or shopping) the system goes into “deep setback” by temporarily deactivating heating and cooling system to a threshold so that the system is able

to bring temperature back to ideal within few minutes of the return of the guest. Finally, when the guest checks out, the system goes back into “deep setback” [46].

Other green renovation projects involve incorporating green roofs and walls and sky gardens. These “vertical landscaping” elements aim at improving air quality, ambience, amenity space, visual quality, ecology, storm water management, energy conservation, air cleaning, and mitigating urban heat island effects, to name a few. Green roofs and walls increase energy efficiency (from cooling in the summer and added insulation in the winter), provide longer roof membrane life span, improve fire resistance and sound insulation, increase marketability, and improve the ability to turn wasted roof space into various types of amenity space for building occupants. One early examples of green roof retrofit projects is that of the 11-story City Hall of Chicago, completed in 2001. It was meant to function as a catalyst for other green roof developments since it is visible from over 33 taller buildings in the area. The planting palette provides extensive variety of plants including native prairie and woodland grasses, forbs and shrubs, hardy ornamental perennials and grasses, as well as varieties of trees. An example of a green wall retrofit project is provided by the 18-story Portland’s Edith Green/Wendell Wyatt Federal Building. The proposed 76 m (250 ft) west wall will let plants grow on “fins” or vertical trellises. During spring and summer greeneries will shade the façade and hence will reduce energy required to cool the building. In the winter, the plants will naturally drop their foliage and sunlight will enter the building to warm interior spaces. Captured rainwater from the roof will mainly irrigate the wall and will be supplemented by municipal water when necessary [47,48].

For future retrofit projects, researchers and developers have proposed that tall buildings should include “vertical farms” to supply cities with food. It is argued that cities will need to produce food within to avoid paralyzing congestion, harmful pollution and unaffordable food prices. Urban agriculture is viewed as a solution to these problems by merging production and consumption in one place; and the vertical farm is seen to be most suitable to urban areas where available land is limited and expensive. Luckily, recent advances in greenhouse technologies such as hydroponics, aquaponics and aeroponics have provided a promising future to the vertical farm concept. These high-tech systems represent a paradigm shift in farming and food production by offering suitable and efficient methods for city farming. They also minimize maintenance and maximize yield. As such, incorporating vertical farms into tall buildings will likely be a plausible proposal in the future [46].

In conclusion, if designed and implemented well, retrofitting an existing building could be more cost-effective than building a new facility. Since buildings consume a significant amount of energy and because existing buildings comprise the largest segment of the built environment, it is important to initiate energy conservation retrofits to reduce energy consumption and the cost of heating, cooling and lighting buildings. Careful material selection and efficient design strategies for reuse are critical and can play a major role in minimizing the impacts associated with building renovation and retrofit projects. Cautious retrofits can reduce operational costs and environmental impacts, and can increase building adaptability, durability and resiliency.

However, a successful retrofit requires applying an integrated, whole-building design process during the entire planning and design phase. The integrated project team may discover a fewer design strategies that will meet multiple design objectives and lead to substantial savings, an increase in value of property and longevity, and provide a better, healthier, more comfortable environment for people in which to live, work, and play. Green retrofitting existing buildings constitutes an important and integral part of the

sustainability agenda. It is likely to prevail and become an industry standard in the long-run, with a continued emphasis on the attained economic savings and environmental benefits.

Overall, this paper advocates the notion of retrofitting tall buildings. For sustainability reasons, it encourages developers and buildings' owners to consider retrofitting buildings over demolishing them and constructing new ones. To strengthen the argument, the paper documents examples of buildings of different sizes, heights, conditions, and national significance from various parts of the world that have embraced this path. The paper emphasizes that even a partial retrofit, such as upgrading the lighting or mechanical systems, will be crucial to meet the sustainability challenges facing 21st century cities. Nevertheless, it is important to mention that not all tall buildings are qualified to a retrofit. For example, early curtain wall buildings suffer from too many problems that would make retrofitting them technically difficult and costly. These buildings, which constitute a significant portion of tall buildings in Manhattan for example, lack even the basic code requirements for life safety and handicap accessibility. They also utilize very inefficient mechanical and lighting systems. They often tend to have low floor-to-floor heights and closely-spaced columns that obstruct incoming natural light and hinder views to the outside world. Further, these buildings are not desirable because they fall short to be modern class A office buildings. Importantly, some of these buildings' structural systems are aging and becoming unstable, threatening the lives of their tenants. Collectively, these problems certainly make the retrofit project infeasible for these buildings, and they call to the ultimate choice of demolishing them and building new ones [49].

Conflicts of Interest

The authors declare no conflict of interest.

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