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# Toward Net-Zero Energy Retrofitting: Building-Integrated Photovoltaic Curtainwalls

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## Abstract

With the rapid urbanization and growing energy use intensity in the built environment, the glazed curtainwall has become ever more important in the architectural practice and environmental stewardship. Besides its energy efficiency roles, window has been an important transparent component for daylight penetration and a view-out for occupant satisfaction. In response to the climate crisis caused by the built environment, this research focuses on the study of net-zero energy retrofitting by using a new building integrated photovoltaic (BIPV) curtainwall as a sustainable alternative to conventional window systems. Design variables such as building orientations, climate zones, energy attributes of BIPV curtainwalls, and glazed area were studied, to minimize energy consumption and discomfort hours for three cities representing hot (Miami, FL), mixed (Charlotte, NC), and cold (Minneapolis, MN). Parametric analysis and Pareto solutions are presented to provide a comprehensive explanation of the correlation between design variables and performance objectives for net-zero energy retrofitting applications.

**Keywords:** Building energy efficiency, Building integrated photovoltaic (BIPV) curtainwall, Climate changes, Multi-objective optimization, Sustainable glass buildings

## 1. Introduction

Today's world faces critical problems brought on by climate change, which impact the environment and, consequently, the daily lives of a growing population, with increasing energy needs. Buildings are the primary source of world energy consumption and pollutant emissions. As an additional 2.5 billion of the world's population (two out of three people) will reside in urban settings by 2050 (UN 2018), a high-density built environment with energy-intensive tall buildings is the default expectation. Tall buildings are recognized as having high embodied and operational energy. Environmental imperatives have increased the need for net-zero energy practices for tall buildings. Research data shows that poor-energy-efficiency windows in com-mercial buildings are responsible for more than half of the energy consumed in these buildings. The United States alone has an estimated 5.6 million commercial buildings, equating to $150 billion in energy costs, ,7,000 trillion Btu in energy usage, and 300 metric tons of $CO_2$ emission annually (EIA 2012). High-performance windows that offer renewable energy production and good indoor environments could help to address the worldwide climate crisis and support clean energy practices.

Almost half of all commercial and residential buildings were constructed before 1980. By default, these were built using unsatisfactory energy standards, as the first building energy codes weren't introduced until the 1980s. Low-performing old buildings are responsible for nearly half of the total energy consumption and $CO_2$ emissions (EIA 2012). Therefore, building retrofit is important due to the large ratio of existing buildings to new construction. Building enclosure is one of the key architectural elements in contributing to energy efficiency and occupant comfort, accounting for 20 to 30% of total energy consumption (Galante, Annalisa and Pasetti 2012). Energy-efficient envelope retrofits for commercial buildings are estimated to be able to provide over 3,000 Trillion Btu of annual operational energy reduction, or approximately $70 billion in annual energy bill savings and 161 metric tons of $CO_2$ reduction annually (Fulton et al. 2012). Energy-efficient retrofitting represents a $279 billion investment market that could support more than 3,300,000 jobs (Fulton et al. 2012). Commercial building envelopes are subject to physical and functional obsolescence, due to the limited durability of construction materials. The duration of a retrofitting cycle for a commercial building is typically 25 to 30 years.

Extreme weather events, such as Hurricane Sandy in 2012, are becoming more frequent and can cause critical power interruptions, disrupting the business operations and personal lives of millions of people over large areas and for long periods. Power blackouts from severe weather events and human-induced outages have many negative results, including large financial losses. Microgrids of

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distribution systems nowadays are popular, in that they can supply renewable electricity for local areas. However, microgrids need to integrate into the main electrical grid, which is subject to power intermittency. Solutions to these issues will require innovative approaches to building construction and operation, using renewable power resources such as solar energy. Net-zero energy buildings with on-site power supplies can alleviate the problems associated with power interruptions from the electrical grid. Tall building envelopes are the primary location to capitalize on solar power. A net-zero energy building powered by BIPVs and battery storage could be a solution.

This paper focuses on the discussion of design variables for a new BIPV curtain wall that offers a cost-effective, innovative way to retrofit low-performing building enclosures while producing on-site renewable energy, reducing building energy use, and improving occupant comfort. The authors' system consists of a network of adaptable solar modules that are optimized based on climate data and multi-functional requirements of power production, solar heat gain control, daylight penetration, and views out, depending on façade orientation and climate locations. The "duck curve" is a phenomena where PV production changes the load curve between daytime and night time load demands (Freitas and Brito 2019). The adaptability of the system can mitigate the duck curve issue by deploying higher production capability on windows that face east and west. Conventional BIPVs for window applications include thin-film and crystalline solar cells laminated with glass. They are not climate-responsive, and even more challenged by duck-curve issues in which solar power generation does not align with demand, especially in the early morning or evening, when solar power production is low while demand is high. The existing technology's optical clarity is not truly transparent, often limiting access to daylight and views out, causing occupant dissatisfaction. Monocrystalline or polycrystalline cells are typically used for opaque walls or roof applications, and are not appropriate for window appli-cations due to their opacity.

## 2. State of the Art of Solar Cell Applications

The global power requirement is approximately 15 terawatts (TW). The sun's energy (173,000 TW) can supply this global energy demand in less than one hour. According to the 2019 IEA report, PV solar energy production in 2019 has increased by 22%, accounting for approximately 3% (730TWh) of global electricity generation (Bahar 2017). Prior to the 1970s, the initial applications of PV cells were satellites and special space applications. Most applications between 1965 and 1990 were small-scale niche markets, which led to crucial development and industry standardization of technology. Since 1990, increasing implementation and policy support have re.sulted in massive market deployment. Recently, the global leading solar PV market has spread over the Americas, Europe, and Asia (Binz, Tian and Huenteler 2017). Solar PV can be categorized into two primary applications for the built environment: 1) utility application, and 2) commercial application. The utility PV is a centralized power production facility that directly feeds electricity into the grid. The commercial application, BIPV, integrates PV cells into building rooftops and façades. For the BIPV application, the on-site electricity generated from rooftops or building façades can be consumed directly for the building operation, or be sent as surplus power to the main grid through a net meter.

### 2.1. Cell Technology

There are three types of solar cell technology: crystalline silicon, thin-film, and emerging technologies. Silicon is one of the most predominant materials for solar cells, accounting for 90% of the global market, with an annual growth of approximately 30% (Liu et al. 2020). Silicon technology has two basic solar cell forms: monocrystalline and polycrystalline cells. Currently, monocrystalline and polycrystalline cells have recorded maximum cell efficiencies of 19.8% and 20.4% respectively (Gul, Kotak and Muneer 2016). Thin-film technology uses less or no silicon, and is comprised of 1) amorphous silicon, 2) cadmium telluride/cadmium sulfide, 3) copper indium gallium selenide (CIGS)/copper indium selenide, and 4) gallium arsenide (GaAs). Amorphous silicon is the most developed and commercially available technology. Its highest recorded cell efficiency is 13.8%, whereas other thin film efficiencies range from 5.0 to 9.9% (Gul, Kotak and Muneer 2016). The cadmium-telluride solar cell is one of the more promising materials for thin-film technology, due to its ideal band gap of 1.45eV and long-term stability. Its highest cell efficiency was measured at 17.3%, whereas CIGS cells were measured at 18.8%. A world-record cell efficiency for GaAs was measured at 42.3% but is still in its R&D phase (Gul, Kotak and Muneer 2016). Lastly, new emerging cell technologies could include hybrid cells, carbon nanotube cells, and dye-sensitized solar cells. The hybrid cell combines crystalline and non-crystalline silicon that yields a high ratio of performance to cost. It has a high efficiency rate under low light and high temperature conditions. Its maximum cell efficiency was measured at 25.6%. The carbon nanotube is made of transparent conductors and has a theoretical cell efficiency of 75%. The measured efficiency of a carbon nanotube cell was 15%. The dye-sensitized solar cell is a new material technology designed to overcome low efficiency, production cost, and environmental issues from solar cell materials. This technology utilizes sensitization of a semiconductor such as zinc oxide or titanium dioxide. Its efficiency was recorded at 15% (Gul, Kotak and Muneer 2016).

### 2.2. Financial Incentives

The cost of PV systems has been significantly decreasing due to technology innovation, economies of scale, efficiency enhancements, longevity improvements, and governmental policies. For example, the cost of crystalline cells was \$23/W in 1980, \$1.20/W in 2014, and \$0.39/W in 2018 (Gul, Kotak and Muneer 2016). Additional cost reduction could be achieved through optimization of wafer thickness and efficiency, which is expected to yield a cost of well below \$0.20/W (Liu et al. 2020). Additionally, the prices of PV system components, such as mounting structures, inverters, charge controllers, and electrical components, have significantly decreased, contributing to wide deployment of solar cell technologies. However, financial incentives are only available for the grid-tied system, so it is important that financial support for standalone PV systems also be provided. A slow permitting process is another administrative hurdle when it comes to deployment.

Strong policy support significantly helps the exponential growth of solar PV systems globally. The UN's sustainable development scenario expects world solar PV deployment to rise from 720 TWh in 2019 to 3300 TWh in 2030 (Liu et al. 2020). Governments all over the world are adopting policies and regulations for greenhouse gas emissions reduction and renewable energy increase. California is the leading state in adopting 100% renewable energy supplies by 2045, by mandating PV panels for all new homes and buildings higher than three stories. There are solar-cell policies in the US to support the major growth of solar energy. Net metering is one of the ways to support the wide application of BIPV. Under this policy, the required electricity to operate a building is supplied by the utility grid, and the excess solar power generated from the building site is returned back to the utility grid. The inflow and outflow of electricity is maintained by a specific meter system and the payment of the excess power generation is settled. Ninety-nine percent of PV installations in the US were net-metered (Brown 2013). The majority of PV incentives are for grid-connected installation. Financial incentives for standalone BIPV are important, as they can offer clean and efficient solutions, such as replacing diesel generators with PV systems. A tax-credit policy is another Federal government program that supports BIPVs. Owners of new residential and commercial BIPVs can claim a credit of a certain percentage of the qualified expenditure for a BIPV system.

## 3. BIPV Curtain Wall Retrofitting Application

### 3.1. Energy-Efficient Retrofitting

Both commercial and residential buildings are primary sources of energy consumption and $CO_2$ emissions, especially buildings constructed prior to 1980 with inadequate building energy efficiency. These old buildings are responsible for nearly half of global energy use and $CO_2$ emission. For example, the average energy use intensity (EUI) of houses built prior to 1980 (EUI-200 kWh/$m^2$ or 65 kbtu/$ft^2$) is almost twice of that of newly-built houses (EUI-110 kWh/$m^2$ or 35 kbtu/$ft^2$). Despite energy efficiency improvements for residential buildings, the average energy consumption per household has increased, due to the increase in house size per capita. The average EUI of a commercial building built prior to 1980 is approxi-mately 20% more energy-intensive than the average commercial building constructed after 1980. Energy-efficient retrofit in general is a challenging design and construction process at any scale, often engaging in structural enhancement, HVAC and/or lighting updates, and/or building envelope renovation. The energy attributes and physical characteristics of the building enclosure system affect the HVAC and lighting load, and occupant comfort.

Building envelope retrofitting is one of the more complicated construction undertakings, which has a large impact on aesthetic improvement, user satisfaction, and building energy efficiency. Window improvements, insulation installation, and airtightness enhancement are the most common strategies in façade energy retrofitting (Ardente et al. 2011). Window improvement results in an energy reduction of up to 30% for space cooling and heating (Ascione et al. 2017). Airtight wall assembly can reduce space heating or cooling energy by up to 10% (Suárez et al. 2015). Fully glazed curtain walls have gained popularity for tall buildings, due to their aesthetic quality, daylight provision, and visual connection to the outside. However, they can cause overheating, glare, and occupant discomfort. When it comes to renovation, high-performance curtain walls can make the building more energy-efficient and provide a comfortable indoor environment. Some functional requirements for glazing curtain walls are oppositional, especially between overheating and maximum daylighting. The balance between those opposing functions is important in achieving net-zero energy retrofitting. Façade energy retrofitting has more energy benefits in cold climates, with improved insulation capable of reducing heating energy by 40% (Sarihi et al. 2020). Logistics in material storage and installation are important in envelope retrofitting, as a prolonged renovation period can disturb tenants. Prefabricated curtain wall systems are the preferred option for fast installation and quality control.

### 3.2. BIPV Applications

The first BIPV project was realized for a utility company in Aachen, Germany in 1991, when Pilkington in Germany produced solar modules for BIPV application, with an annual capacity of 5000 $m^2$ in 1993 (Benemann, Chehab and Schaar-Gabriel 2001). There are a few environmental and technical factors affecting conversion efficiency and longevity of the solar cell. Environmental factors such as dust in the air, partial shading, and passing clouds cause power loss. Partial shading is responsible for up to 10% power loss and damage to the cells, by creating hot spots within the system. The premium upfront cost is a financial hurdle for standalone BIPV facades. More contemporary tall buildings adopt fully-glazed curtain walls, due to their aesthetic quality and sustainability. The great challenge for net-zero energy buildings is not only to reduce energy consumption and supply power on demand, but also to provide good thermal and visual comfort for occupants. The premium upfront cost of BIPV curtain walls can be offset by providing energy savings and workplace enhancement during the building-use phase. BIPV curtain walls offer multi-functionalities of thermal insulation, solar heat control, daylighting penetration, glare control, privacy, noise control, fire safety, impact resistance, and view contact with outside, leading to crucial energy reductions and occupant satisfaction. Rooftops have been the most preferred location for PV module installation, due to the highest irradiation reaching the roof surface, as compared to vertical façades. As more tall buildings will be constructed to accommodate growing urban populations, BIPV curtain walls represent a primary location to harness solar energy. BIPV curtain walls, as they convert walls and buildings from energy consumers to energy producers, play an important role in achieving net-zero energy retrofitting, without being tied to the grid and the need for additional transmission lines. Construction schedules and poor workmanship are challenging aspects of retrofitting buildings located in dense urban settings. The BIPV curtain wall is a prefabricated enclosure unit that allows for fast installation and a high level of quality control.

### 3.3. Proposed BIPV Curtain Wall for Energy-Efficient Retrofitting

The BIPV curtain wall proposed in this study incorporates a network of micro-PV cells within a glass window assembly to provide multi-dimensional functionalities and user controllability (see Figure 1). It serves as an energy controller and energy producer, regulating energy transfer between indoors and outdoors while maximizing the conversion of solar radiation to electricity. This innovative technology integrates a dynamic photovoltaic module that is able to track the sun. Capitalizing on the potential of thin-film technology, this system incorporates an adaptable solar module with a durable kinetic mechanism that responds to varying internal and external environmental influences from the sun and from users. The system automatically controls the levels of solar heat gain, daylight transmission, user privacy, glare protection, and unobstructed views to the outside, while allowing users to overrule the operation of the system whenever desired. The current prototype of this adaptable BIPV curtain wall consists of a series of micro-PV shades attached to a circular gear frame for sun tracking. A network of micro-PV shades rotates around a central axis for solar tracking, which is actuated by a centralized servo motor. The Perturb and Observe (P&O) Maximum Power Point Tracking (MPPT) algorithm has been considered to maximize the solar power efficiency. An individual micro-junction box at the micro-PV shades incorporates a bypass diode to maintain stable energy production efficiency when partial shading occurs. Electrical wires and kinetic components are housed in a BIPV curtain wall frame for easy maintenance and longevity. For maximum conversion efficiency and long-term performance, the system is encapsulated within an air cavity between two glazed panes, and the cavity of the system

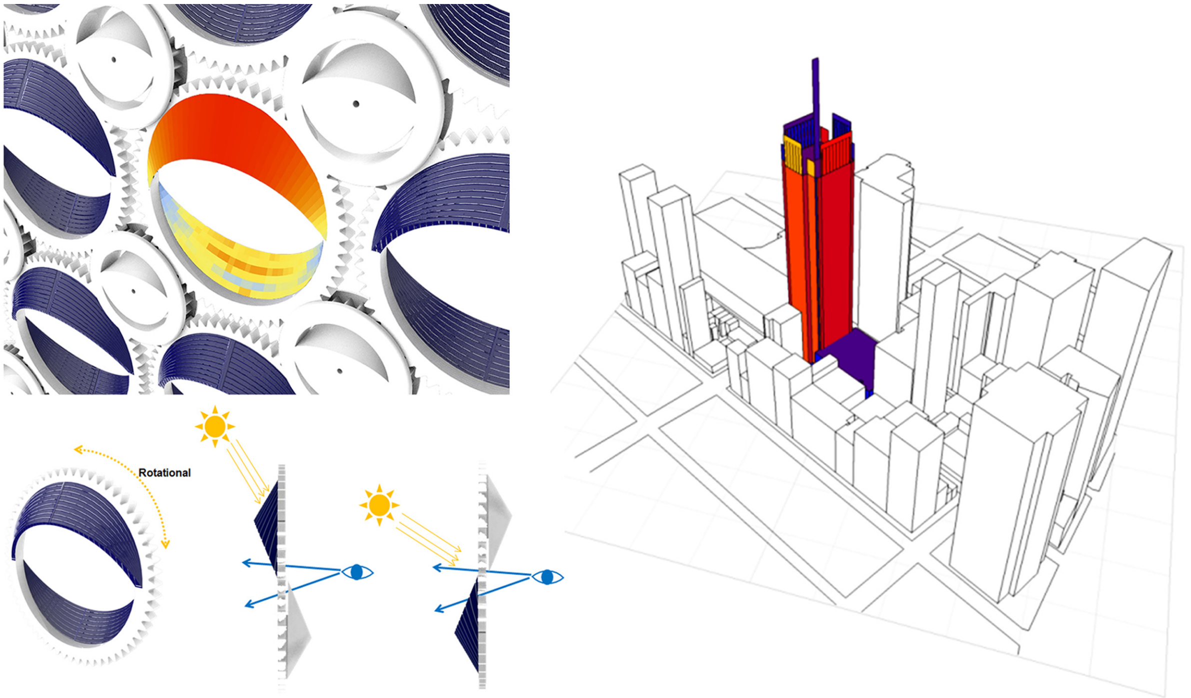

**Figure 1.** Proposed BIPV curtain wall for tall building retrofitting application. It offers multiple functionalities of power production, solar heat regulation, daylighting penetration, and views out. (Source: Authors)

is configured to prevent heat built-up, moisture formation, and UV transmission. The system's on-site solar power generation capabilities reduce the building's energy use and lessen pollutant emissions in the built environment. Preliminary analysis indicated that the proposed BIPV curtain wall increases unit power production by 50 to 100% compared to a conventional BIPV window given the same façade area, depending on seasons and orientations of the building.

Insolation analysis was carried out to determine to what degree the proposed BIPV curtain wall could outperform a traditional BIPV curtain wall in harnessing solar energy. Two analysis models of the BIPV curtain wall and a conventional BIPV window were set up to evaluate energy production potential. The study models utilized a 4.6 m × 4.6 m (15ft × 15ft) system with a southern orientation located in Charlotte. The amount of solar energy reaching both the proposed BIPV curtain wall and a conventional BIPV window was simulated for four days of equinoxes and solstices. The analysis grid size was set at 0.01 m (0.03ft) considering the size and the curved geometry of the micro-PV module. The conversion efficiency of solar cells was assumed to be at 15% for both cases. The analysis results indicated that the proposed BIPV curtain wall outperformed a conventional BIPV window across all seasons. In comparison to a conventional BIPV system, the BIPV curtain wall yielded 45% greater power production during summer seasons, 25% during equinox seasons, and 15% during winter seasons (see Figure 2). This is because the experimental BIPV system accommodates shape optimization and has a sun-tracking mechanism.

## 4. The BIPV Net-Zero-Energy Tall Building

According to the framework of I = f(P, A, T), the environmental impact from the built environment is expected to worsen as building technology advances, GDP per capita grows, and the world population increases. Technical improvements such as highly-insulative building envelopes or energy-efficient HVAC systems have been contributing to EUI reduction. However, with increasing average floor area per capita, technical improvements have not been able to outpace energy consumption. The environmental impact from buildings will be further exacerbated by growing populations and the changing lifestyles of people, such as choosing bigger spaces and more appliances. In addition to these three factors, abnormal weather conditions such as hotter summers and colder winters due to climate change are further increasing environmental impact. Therefore, it is important to adopt net-zero energy building practices in which buildings are extremely energy-efficient and their operational energy is offset by renewable energy resources. To this end, building energy demand should be as low as possible, with passive design strategies and energy-efficient measures. BIPV systems could become a green power source located on-site to supply operational energy.

There are two primary factors that affect building energy consumption and solar power production. One is related to climatic data, especially solar irradiance, cloud coverage, wind, and ambient temperature. The other primary factor is building design variables, including site context (e.g., building orientations and surroundings), building mass (e.g., building-envelope-to-volume ratio, building shape, aspect ratio of floors, building height), building envelope attributes (e.g., window-to-wall ratio (WWR), solar heat gain coefficient (SHGC), visible light transmittance (VLT), U-factor, window shading, R-value

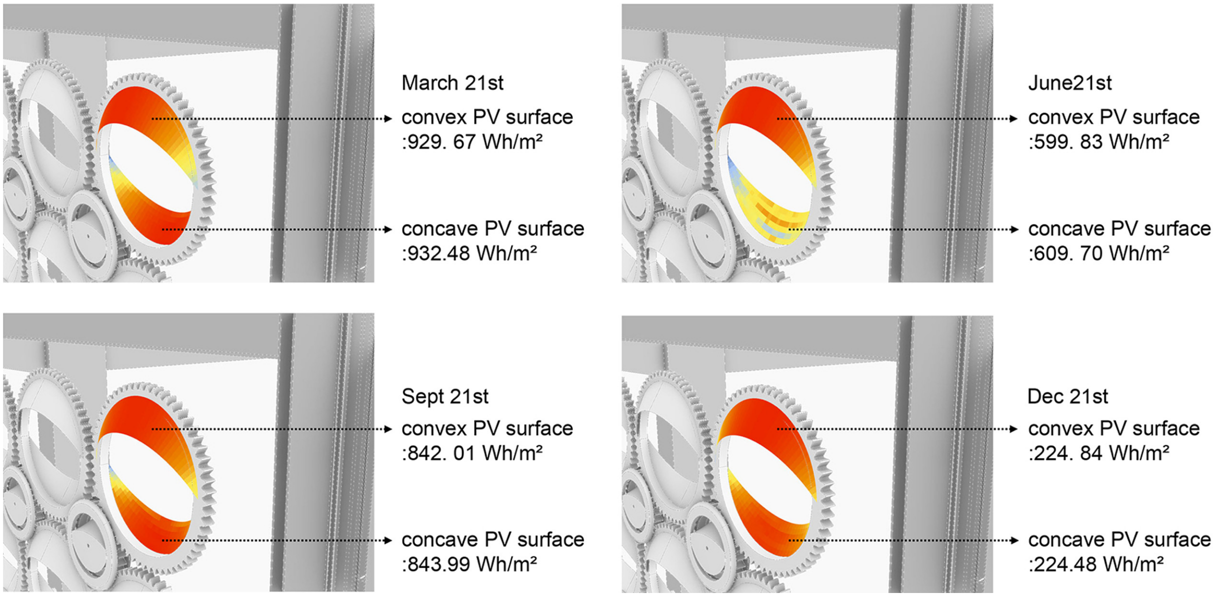

**Figure 2.** Power production potential of the BIPV curtain wall system, as estimated by solar simulations. (Source: Authors)

of opaque wall, airtightness), porosity to the building mass for natural ventilation, and the use of energy efficient building systems such as daylight control, occupancy sensors, plug load management and energy-efficient HVAC systems. Depending on climate zones, certain building design variables are favorable toward augmenting passive design strategies while maximizing solar power production. However, design variables and power production strategies are not always working in the same direction. For example, a south-to-north elongated building mass is good for power production, but it has overheating potential on its eastern and western facades, increasing net energy demand. Advanced glazing technology is available to address such unwanted energy transfer. Low-e coating and the number of air cavities (i.e., double/triple/quadruple glazing) are typical features to improve energy attributes. Chromogenic glass types, such as electrochromic, photochromic, and thermochromic glass, are smart technologies that offer different optical and thermal properties, depending on the climatic conditions or building program needs. Insulative value can be enhanced by introducing aerogel or a vacuum into the air cavity, along with a low-e coating to regulate infrared heat escaping from inside to outside. As contemporary buildings incorporate extensive glazing areas, the glazing surface offers a way to balance heat transfer and power production while providing exterior views and daylight.

### 4.1. Simulation Set-Up

The simulation model was a 20-story office building with 74,322 m$^2$ (800,000ft$^2$) gross floor area, with a 61 m by 61 m (200ft by 200ft) footprint. The locations considered for the simulations were Miami (climate zone 1), Charlotte (climate zone 4), and Minneapolis (climate zone 5) in accordance with ASHRAE 90.1. Our reference model for an existing building was assumed to have 40% WWR enclosed with clear glass. Energy retrofitting simulations were carried out with different design variables, as described in Table 1. Since the primary goal of the energy simulation is to understand the direct impact that retrofitting design variables have on energy savings and occupant comfort, non-design factors affecting energy consumption such as building operation schedule, HVAC system, and plug loads, and so on, were assumed to be constant between the old building and retrofitting building simulations.

Net-zero energy retrofitting requires high-performing building enclosures to act as energy regulators and solar power producers. A series of sensitivity analyses allowed the team to identify important design factors related to building mass and enclosure design for energy-efficient retrofitting. A sensitivity analysis of varying percentages (%) of WWR in relation to energy saving and power production was conducted. The correlation between building orientation, energy efficiency and power production potential was examined. The simulation also considered how different energy attributes from window options impact energy efficiency for retrofitting buildings under varying %WWR in different site locations. In this paper, a noble BIPV integrated curtain wall system, as an alternative to a retrofitted low-energy-efficiency window

**Table 1.** Design variables for net zero energy retrofitting building simulations

| | Design variables for net zero energy retrofitting buildings | Reference old building |
|---|---|---|
| Climate zones in accordance with ASHRAE 90.1 | - 1A Miami FL<br>- 4A Charlotte NC<br>- 6A Minneapolis MN | - 1A Miami FL<br>- 4A Charlotte NC<br>- 6A Minneapolis MN |
| Building orientations Clockwise rotation relative to east-west axis using 1:2 floor aspect ratio | - 0 deg<br>- 45 deg<br>- 90 deg<br>- 135 deg | 0 deg |
| Building aspect ratio | - 1:1<br>- 1:2 | 1:1 |
| % Window-to-wall ratio (%WWR) | 20%-80% at 10% increment | 40% |
| Window attributes | - U-factor-0.57~2.84 W/m$^{2o}$C at 0.57increment (0.1~0.5 Btu/h-ft$^{2\text{-}o}$F at 0.1 increment)<br>- SHGC-0.2~0.6 at 0.1 increment<br>- VLT to SHGC at 1.5 | Single-pane window |
| Solar power production | All facades vs roof<br>15% cell efficiency with inverter and DC storage | none |
| Other simulation settings | Gross floor area: 74,322 m$^2$ (800,000 ft$^2$)<br>Building height: 20 stories; 91 m (300 ft)<br>Operation schedule: office<br>Other enclosure requirements, lighting & HVAC & plug load requirements per ASHRAE 90.1 | |

system, was developed. The study of energy attributes and PV potential from our system can help designers understand the environmental and economic benefits of retrofitting low-performing building envelopes with BIPV curtain walls. Maximum building energy savings and power production potential from the BIPV curtain wall for different climate conditions were studied.

## 4.2. Simulation Data Analysis

While higher %WWR caused overheating problems in Miami, an enlarged glazing surface, up to 80% in Charlotte and Minneapolis, resulted in the lowest energy use, due to energy savings from passive heating. The increase of %WWR in the southern façade reduced EUI overall, while the increase of %WWR in the eastern and western façades yielded higher power production, yet with increasing overheating. The net energy efficiency from the EUI demand and generation favored a southern orientation for all cities. As higher %WWR was recommended for retrofitting scenarios, the SHGC (and VLT) of the BIPV curtain wall played an important role in energy efficiency and thermal comfort in all climates. East- or west-facing buildings produced maximum power production, while high EUI consumption occurred, due to a prolonged intense sun along the east and west sides through the window, causing an increase in cooling load. In this scenario, a BIPV curtain wall with low SHGC was essential to achieve the net-zero-energy building goal from the reduction of cooling load demand. The optimum SHGC for Miami was estimated at SHGC-0.3, whereas both Charlotte and Minneapolis yielded the lowest EUI, with SHGC-0.6. The higher SHGC, from SHGC-0.36 per ASHRAE 90.1 to SHGC-0.6 in Charlotte, for example, reduced fuel consumption by 5% (cooling load increase by 1% and heating load savings by 17%). Passive design strategies, such as natural ventilation and thermal mass, can further reduce EUI. Figure 3 shows correlation studies between energy consumption, building orientations and %WWR for three cities.

Another sensitivity analysis was carried out to understand how the building footprint and height (i.e., vertical surface areas for BIPV curtain walls) correlate with power production in supplying the building EUI demand. For this correlation study, a ratio of building floor area to building façade area was introduced. The analyzed buildings' floor area to façade area ratios were 3:1, 2:1, and 1:1. The analysis revealed that, in general, a building with a 3:1 ratio can offset 20 to 30% of the total EUI demand from the BIPV curtain wall and 10% to 150% of the total EUI from the roof-installed PV, depending on building height. For a 2:1 ratio of building to façade area, BIPV curtain walls can supply approximately 30 to 60% of the total EUI demand, whereas the roof-installed PV can offset the total EUI by <5% to 50%, depending on building height. For a 1:1 ratio of building area to façade area, BIPV curtain walls can supply approximately 40 to 65% of the total EUI demand, whereas the roof PV can offset the total EUI by <1% to 20%, depending on building height. In general, proportions of the energy supply from the

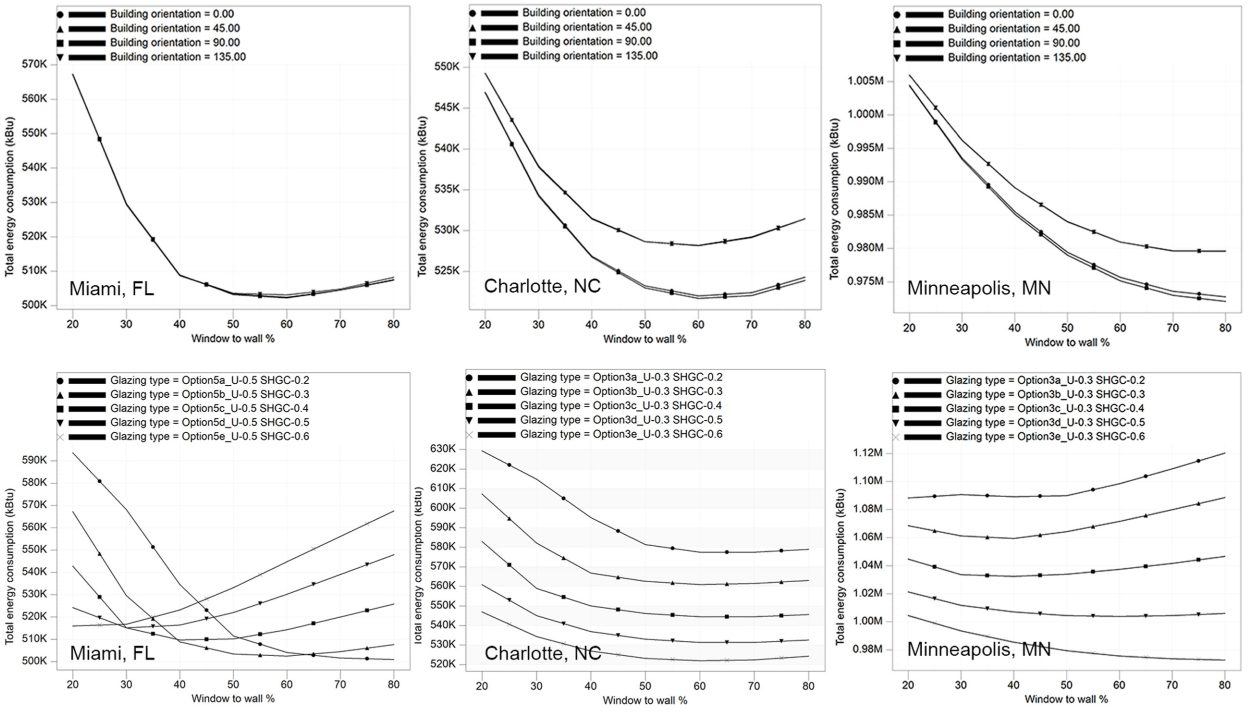

**Figure 3.** Correlation between energy consumption, window-to-wall ratio, and building orientations, depending on three studied climate zones. (Source: Authors)

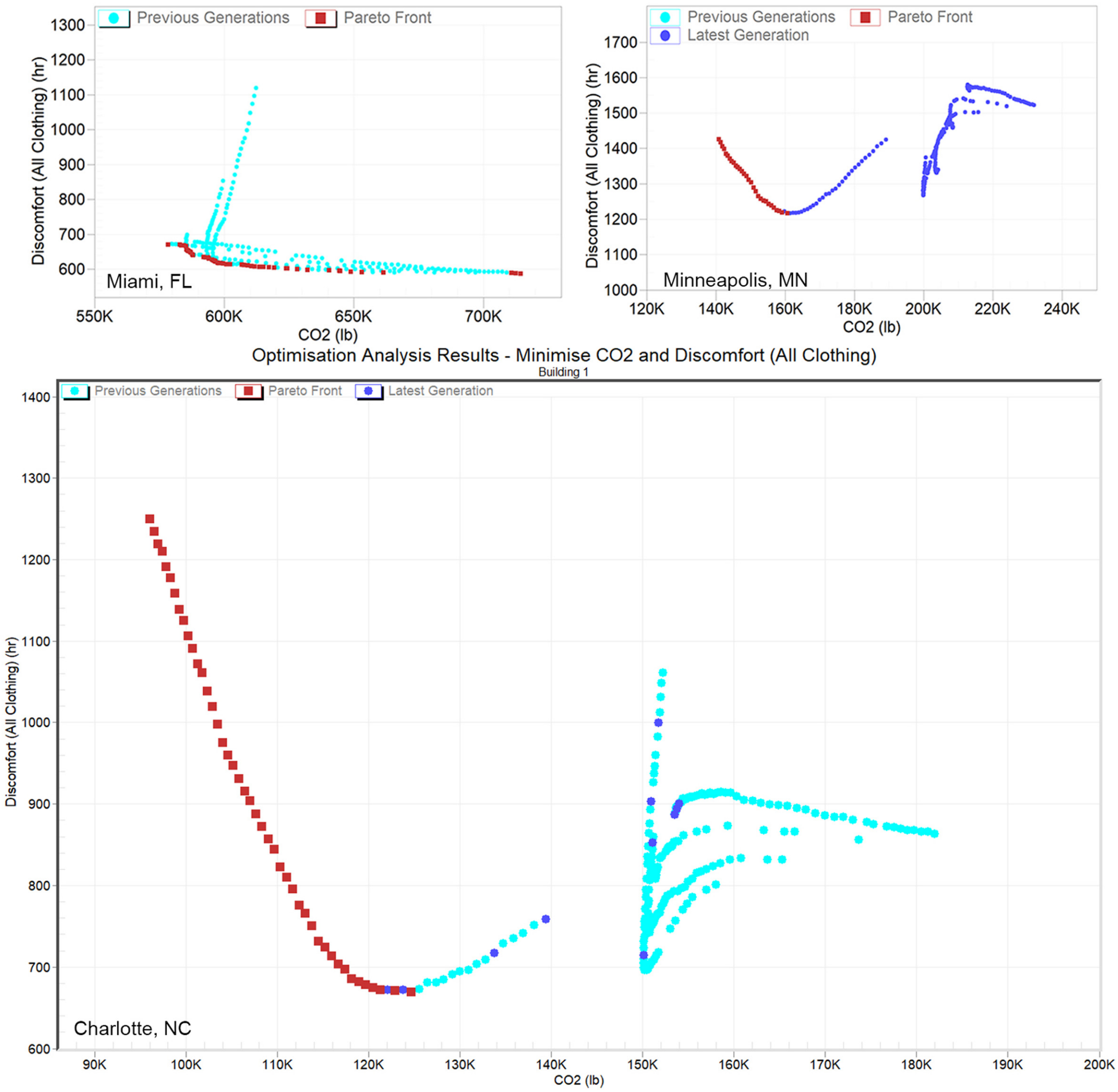

**Figure 4.** Multi-objective optimization to minimize discomfort and carbon emissions. (Source: Authors)

BIPV curtain wall and roof changed as the area ratio differed and building height changed. Buildings with lower area ratios received greater power supply from the BIPV curtain wall. Taller buildings with lower area ratios showed significant EUI reductions from the BIPV curtain wall. With the enhancement of the solar cell's conversion efficiency, the proportion between energy consumption and the power supply could be at 100%, meeting the net-zero energy retrofitting goal.

### 4.3. Multi-Objective Optimization

People spend most of their time indoors. It is important that net-zero energy retrofitting promotes good indoor quality, as it affects work efficiency. Therefore, net-zero energy retrofitting should consider a good indoor environment as a goal alongside energy-efficient measures. There are many microclimatic factors affecting occupant comfort, such as temperature, radiation, humidity, light, air movement, acoustics, and odors. Personal factors such as activity level, physiological factors, and clothing also affect occupant satisfaction. Retrofitting design factors such as %WWR and energy attributes of BIPV curtain walls affect such microclimates. Multi-objective optimization was carried out to understand how glazing area and energy attributes of BIPV curtain walls affect thermal comfort and energy demand. The analysis results indicated that there is a trade-off between thermal comfort and energy savings (See Figure 4). For example, maximizing occupant comfort requires higher energy consumption. The data point of the Pareto Front of optimal solutions that gives the lowest combination of occupant discomfort and energy consumption ($CO_2$ reduction) was identified. The trade-off between occupant comfort and energy use is clear, as is the impact of the design variables, from the glazing area and different glazing types for BIPV curtain walls. The best scenario for winter and summer seasons presents thermal discomfort below 20% (~650 hours). The sensitivity analysis shows that there was no evident reduction of thermal discomfort in Charlotte when glazed areas and SHGC increased. The negative effect was observed in hot climates, where thermal discomfort increases as glazed area and SHGC increase.

## 5. Conclusions

Existing buildings in the US account for almost half of the country's energy use and $CO_2$ emissions. Material deterioration and physical obsolescence of low-performing building enclosures further exacerbate indoor environments that affect occupant health and well-being. It is imperative to decarbonize old, low-performing buildings through energy-efficient retrofitting and a renewable energy supply. This paper discusses potential solutions and challenges for net-zero energy retrofitting with BIPV curtain walls. A key principle of net-zero energy retrofitting is to minimize energy demand and maximize on-site power production. The lower the ratio of gross floor area to building surface area, the more efficiently BIPV curtain walls can fulfill energy demands. The SHGC of BIPV curtain walls has a significant impact on reducing energy use, compared to the U-factor. The Pareto Front from the multi-objective optimization analysis indicates that the enlarged glazed area and higher SHGC of BIPV curtainwalls in Charlotte and Minneapolis do not result in thermal discomfort, while Miami has a negative impact from them. In addition to design variables, upgrading energy end users' lighting and HVAC systems with high-energy-efficiency components is another important strategy for net-zero energy retrofitting. Future work could include experimental field work and lab testing to determine whether the simulations and experimental results provide sufficient alignment. Additional work could include the performance measurements of the proposed BIPV curtain wall to validate simulation results.

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