Title: **Solar Glazing for Tall Mixed-Use Buildings: Prospects for Policy and Performance**

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# Solar Glazing for Tall Mixed-Use Buildings: Prospects for Policy and Performance

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## Abstract

*Advancements in photovoltaic systems and associated market trends suggest that vertical installations integrated with building façades will be increasingly competitive for meeting energy demands, while financial incentives and policies at levels influence further the pace of growth and adoption. The study examines 256 tall mixed-use buildings across 49 cities in the United States for their potential to generate solar energy from second generation, thin-film building-integrated photovoltaics in window glazing, while accounting for the effect on building energy performance, and considering state and local policies in determining performance.*

**Keywords:** Energy Policy, Photovoltaics, Solar Energy

This paper summarizes the results of the 2019 CTBUH International Research Seed Funding.

## Introduction

This study examines the potential for Building-Integrated Photovoltaics (BIPV) to cost-effectively improve the energy performance of tall mixed-use buildings in the United States, and the role of policy in enhancing the impact of these technologies. One of the critical elements of a building's green footprint is energy consumption, with the energy demands of tall buildings, exceeding by far those of their low-rise counterparts (UCL 2017). Solar photovoltaic technologies are undergoing rapid changes, allowing for vertical solar installations in building façades (e.g., curtain walls, window glazing) with more competitive prices for energy generation, while the cost of installation and operation is being offset by energy demands. In the United States, the development and proliferation of solar technologies has been advanced by policies at the local, state, and federal levels that incentivize the integration and retrofit of existing structures with solar systems. This study assesses the impact of installing such systems on tall mixed-use buildings, considering the role of policy in determining financial performance.

## Research Framework

This study is based on the data on mixed-use buildings across the United States from the Council on Tall Buildings and Urban Habitat (CTBUH) database (2020). We analyzed the installation potential of second-generation BIPV cells (thin-film solar technologies, such as double-paned windows, which do not create view obstructions) on the side of buildings with the maximum exposure to sunlight (i.e., south-facing). We also assessed associated solar policy financial incentives offered by utilities, cities, states, and the federal government. We find that new solar thin-film technology, in combination with the financial incentives offered, can decrease installation and maintenance cost while allowing for buildings to become more energy-efficient.

## Data and Methodology

Our analysis involved the overlaying of several datasets. The mixed-use buildings, obtained from the CTBUH database were combined with building attributes from the CoStar Group database. Additionally, the building ZIP (postal) codes were used to retrieve solar radiation data and utility rate data from the National Solar Radiation Database (NSRDB) and the OpenEI US Utility Rate Databases. Finally, the renewable energy policies and incentives were downloaded from the Database of State Incentives for Renewables & Efficiency, which archives the most comprehensive renewable policies and incentives in the United States.

Figure 1 shows the procedures used after the initial data collection, which consists of two major parts. The first part simulates solar energy generation and financial impacts of installation of a solar system on south-facing building façades using the initial building dataset as the input. The second part involves cleaning and preparing the policy dataset.

### Measuring Surface Area for Vertical Thin-Film Solar Cells

We assessed 256 tall mixed-use buildings in the CTBUH database across 49 cities throughout the United States (see Table 1). We focused on mixed-use buildings, since studies suggest that energy consumption is often higher than in single-use buildings (Agarwal, Weng & Gupta 2009) and more difficult to predict due to mixed tenancy (Tran et al. 2015), which makes an on-site solar energy generation system a desirable feature.

In this study, we chose thin-film as the solar generation technology, as opposed to standard silicon solar panels. Thin-film solar cells are much lighter, while durable enough to be laminated to windows or any glass surface. They can also be inset between windowpanes (i.e., glazing), which makes the technology an ideal solar generation device for tall buildings with large vertical glass façades. To estimate the total possible surface area for thin-film solar cells on each building, we used the area of each south-facing building façade exposed, unobstructed, to sunlight. Only the south façade is used since most of the irradiation is incoming from south projection angles (Brogren et al. 2003).

The measurement of building surface areas exposed to sunlight is a key challenge. We used Google Earth Pro for initial measurements of all building façade areas and verified the results for each individual building with available 3D models in SketchUp. Figure 2 shows an example of the comparison between Google Earth Pro and SketchUp. The applications are comparable; difference in area measurements between the two software packages is less than four percent.

After measuring the south-facing façade area, we continued to measure the shaded area of each building individually, using Google Earth Pro. The shaded area is a rough estimate that considers the distance between properties and the changing angle of the sun during a day and across the months of the year. Areas estimated to be partially or completely shaded were excluded from the final estimation for the total area available for thin-film solar cells.

Note that building setbacks and width of right-of-way influence the amount of shading, yet the vast majority of the area of south-facing façades in this study remain unobstructed and suitable for solar installation. Table 2 shows the average proportion of shaded area for buildings in

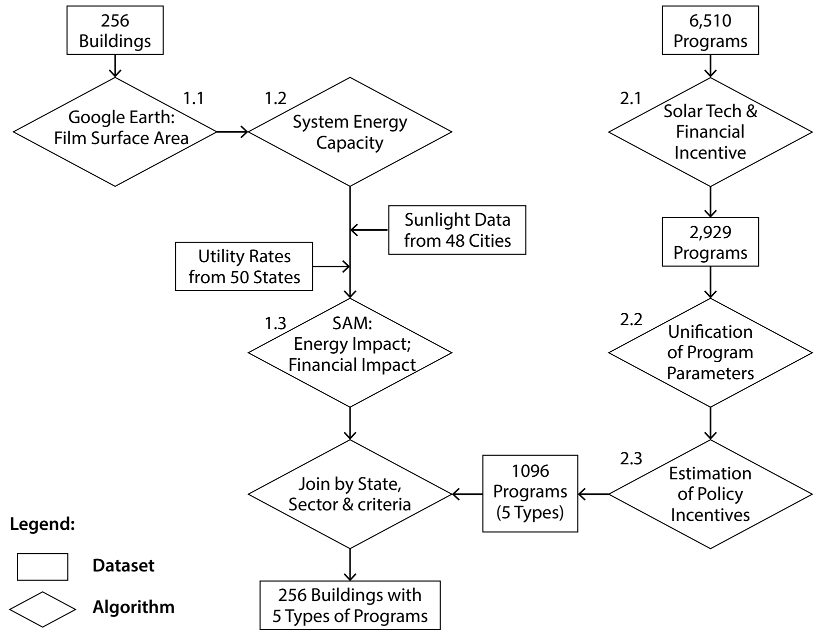



Figure 1. Flow chart of data processing for tall building solar analysis. The numbering system corresponds to the sections of this report.

| City | # | City | # | City | # | City | # | City | # |
|---|---|---|---|---|---|---|---|---|---|
| New York City | 66 | Boston | 5 | Dallas | 2 | Fort Lauderdale | 1 | Raleigh | 1 |
| Chicago | 28 | Philadelphia | 5 | Miami Beach | 2 | Fort Worth | 1 | Sacramento | 1 |
| Las Vegas | 26 | Denver | 4 | Nashville | 2 | Grand Rapids | 1 | San Antonio | 1 |
| Miami | 22 | Baltimore | 3 | Orlando | 2 | Louisville | 1 | South Bend | 1 |
| Atlanta | 10 | Bellevue | 3 | Reno | 2 | Metairie | 1 | St. Petersburg (FL) | 1 |
| Honolulu | 8 | Los Angeles | 3 | San Diego | 2 | Minneapolis | 1 | Sunny Isles Beach | 1 |
| San Francisco | 8 | Pittsburgh | 3 | Arlington | 1 | Niagara Falls (NY) | 1 | Tulsa | 1 |
| Houston | 7 | Austin | 2 | Brooklyn | 1 | Pasadena-TX | 1 | Virginia Beach | 1 |
| Seattle | 7 | Biloxi | 2 | Cabazon | 1 | Phoenix | 1 | White Plains | 1 |
| Atlantic City | 6 | Cleveland | 2 | Cincinnati | 1 | Portland | 1 | | |

Table 1. Building counts by city.

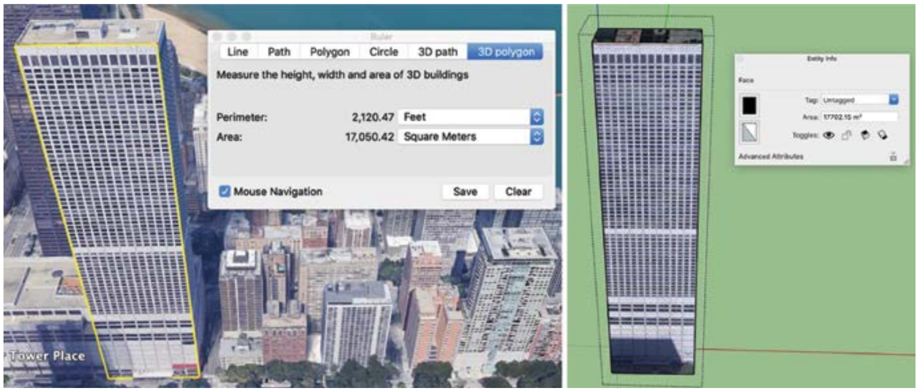
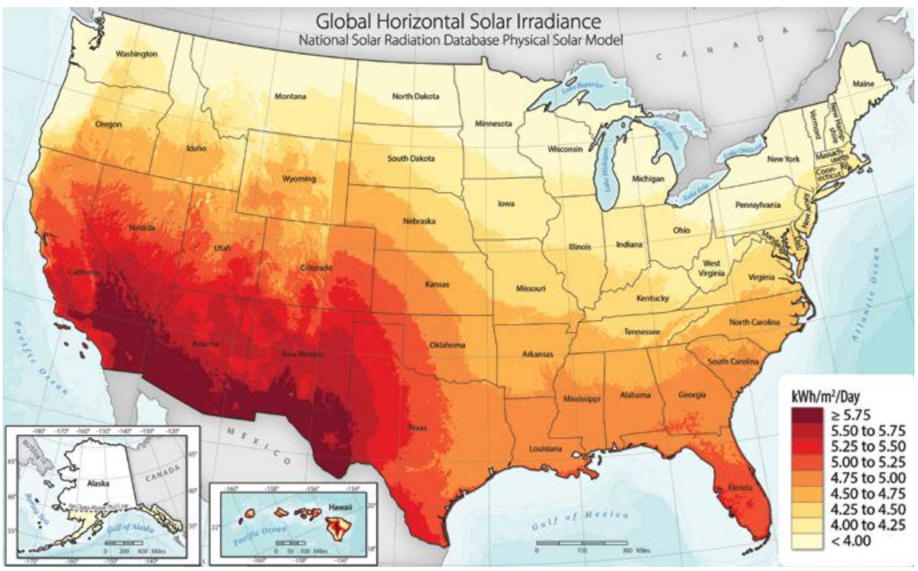



Figure 2. Water Tower Place, Chicago Google Earth Pro initial measurement (left) vs SketchUp measurement for verification (right).




**About the Data**

This map provides annual average daily total solar resource using 1998–2016 data (PSM v3) covering 0.038˚ latitude by 0.038˚ longitude (nominally 4 kilometers by 4 kilometers).

Figure 3. US annual solar global horizontal irradiation. Source: NREL, 2018

this study, according to the city in which they are located. This is to be expected for tall buildings. Even in an urban area as dense as New York City, shading averages less than 30 percent of façades. In Las Vegas, designed with deep setbacks from the right-of-way, shading covers less than 10 percent of the area.

Since thin-film solar cells are commonly attached to, or integrated within windows, we estimated the percentage of window area for buildings with different façade types in SketchUp. Due to a lack of detailed 3D models for some of the buildings in our study, we estimated a percentage for each façade type based on the measurements from the available samples of 3D models. Window area for concrete façades is estimated at 40 percent, and a 100 percent window area is estimated for glass façades.

## Estimation of System Capacity

The capacity (power) of any given solar system is a measure of the size of the system in watts, kilowatts, and so on, which is a reflection of the scale of the system (e.g., number of panels), format (i.e., panels, thin film), type of solar cell (first, second generation), and the density of solar cells in the system (e.g., 300-watt panel).

| | Mean | Std. |
|---|---|---|
| New York City | 0.27 | 0.31 |
| Chicago | 0.17 | 0.28 |
| Las Vegas | 0.08 | 0.18 |
| Miami | 0.22 | 0.28 |
| Atlanta | 0.16 | 0.28 |
| Others | 0.19 | 0.28 |

Table 2. Proportion of shaded area in the top five cities by building count.

To estimate system capacity, we first calculated the total number of solar cells for each building based on our estimates of window area, and then multiplied the derived total number with the capacity of a single solar cell. Information on thin-film solar cells was obtained from the National Renewable Energy Laboratory (NREL) database (2020). In the database, a standard solar cell has the dimension of 1.3 meters by 1 meter and a capacity of 0.4 kWh (kilowatt-hours) per day of electricity (or one kWdc, a kilowatt of direct current).

## Estimation of Energy Generation

After the capacity or power of a system is calculated, several steps of analysis are needed to determine the actual amount of energy or electricity a system can be expected to produce, in watt-hours, kilowatt-hours, and so on, per year and for the designed life of the system. The NREL produced a free modeling system for US solar generation, the System Advisor Model (SAM), that can generate these figures for individual buildings and, with prices for electricity from utilities in the model, can generate estimates of the value of the energy (NREL 2020). SAM is a modeling tool for renewable energy systems, including photovoltaic systems, wind power, and geothermal power generation. In this study, we used SAM to simulate energy and financial impacts of solar systems on tall buildings.

For solar energy generation, the most important determinants are the amount of solar radiation and the design and layout of the system. We first obtained solar radiation data from the National Solar Radiation database based on the location of each

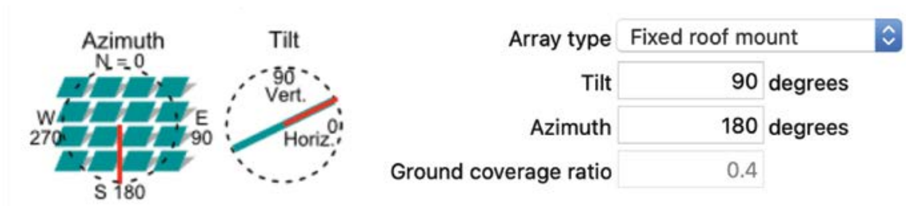



Figure 4. Solar radiation and solar cell orientation and tracking, generated by the NREL SAM system.

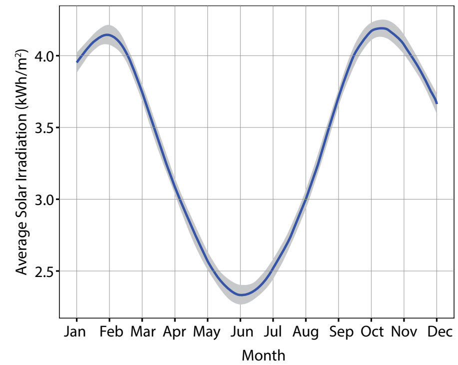



Figure 5. Average solar irradiation (kWh/m$^2$) by month.

building in the study. Figure 3 shows a map of annual average daily solar radiation from National Solar Radiation Database (NSRDB) Physical Solar Model (PSM) accounting for both latitude and cloud cover, across the United States. According to the map, California, Arizona, New Mexico, and Hawaii receive the most daily solar radiation, while Maine, New York, Minnesota, Washington, and Alaska are among the states with the least daily solar radiation.

The estimated solar cells used are on the south-facing façade of each building, which informs the assumption of 90 degrees for the tilt and 180 degrees for the azimuth of each solar system. Figure 4, generated in SAM, shows these settings. SAM does not have a setting for vertical photovoltaic mounts, thus fixed roof-mount settings were altered to be compatible with BIPVs. Based on the solar irradiation inputs and the estimation of system capacity, SAM uses orientation and tracking settings to simulate the total amount of energy generation, as well as energy generation efficiency, through an entire year for each project location.

It is worth noting that because thin films are installed on the vertical façade of buildings (i.e., with a 90-degree tilt), they receive more sunlight from the winter sun than from summer sun. This is because photovoltaics maximize electricity production when placed perpendicular to the angle of the sun. Figure 5 shows the average pattern of global irradiance over time, reflecting how energy received from the sun by the photovoltaic systems changes with seasonal trends for the collection of buildings in this study. Photovoltaics assumed to be installed vertically (on or within windows) on the south-facing façade of buildings are forecasted to receive more sunlight from September to March than in the summer. By contrast, rooftop arrays would be tilted at slight angles, such as 10 percent, and receive maximum irradiation during the summer months.

### System Costs

The total system cost consists of direct capital cost, indirect capital cost, and operation and maintenance cost. The direct capital cost includes the cost of solar modules and inverters, installation labor costs, and installer margin and overhead. The indirect capital costs are those that cannot be identified with a specific piece of equipment or installation service, such as permitting and environmental studies. SAM generates capital cost estimates and allows users to enter operation and maintenance cost estimates at a fixed rate per kilowatt. Actual maintenance costs are very low (e.g., washing of panels, which is the same as window washing in the case of photovoltaic window glazing) and vary based on the lifespan of low-cost components such as wiring and inverters. For this study, no operation and maintenance costs were entered. Instead, the performance of the system was given a 0.3 percent discount rate, applied annually for a lifespan of each solar system set to 25 years, to accommodate warranties and system degradation over time. Note also that SAM does not contain retrofit costs, and if solar film were to be deployed on the buildings included in this dataset, these would be retrofits and would cost more than solar film in new construction.

System costs are also expressed as the levelized cost of energy. The levelized cost of energy is the cost considering capital, operations and maintenance, performance, and fuel (i.e., solar energy) over the 25-year lifespan of the system. It is a measurement used to compare the costs of electricity generated from solar to the cost of providing the same electricity from other sources. If the cost of purchasing electricity from other sources is greater than the levelized cost of providing the electricity with BIPV, the BIPV could be said to generate savings over time, commonly measured on an annual basis. The value of the electricity provided by BIPV can also be shown in the form of a simple payback period, expressed as the number of years of system operation required to pay off the capital costs. Any remaining years in operation would generate net savings.

### Program Selection Based on Technology and Incentive Type

North Carolina State University's NC Clean Energy Technology Center established a database in 1995 of policies that support renewables, such as solar, in the USA (NC CETC, 2020). The Database of State Incentives for Renewables & Efficiency (DSIRE), consists of 14 technology types, including solar, wind, biomass, and other renewable energy technologies; and two program categories: financial incentives and regulatory policy. For this study, we selected financial incentives targeting solar technologies, which reduces the number of programs applicable to our sample of buildings from 6,510 to 2,929.

### Unification of Program Parameters

The financial incentive and regulatory policy programs are implemented by different agencies in various jurisdictions, and therefore the allocation criteria for each vary, usually by units of measurement. We converted and standardized 17 different parameter units into five criteria: total cost (percent of capital cost); system capacity (dollar per kW capacity); energy generation (dollar per kWh electricity generated); surface area (dollar per square meter); and number of units (dollar per cell, or dollar per kWdc). These criteria simplified the process of allocating financial incentives to the 256 buildings studied.

To estimate the financial benefit of incentives, additional calculations were required. For the energy generation category, the amounts of incentives were calculated based on annual electricity generated (i.e., annual energy yield). For other categories, the total amounts were first calculated based on the criteria, and then divided by the lifespan of 25 years to obtain the annual amounts of incentives.

### Estimation of Policy Incentive

The final step of the analysis combines the processed policy dataset with the outputs of building energy and financial performance, to estimate the possible amount of policy incentive awarded to each building. The policy incentives were applied to the buildings by matching the state where each building is located, primary building property type (i.e. commercial or residential), and policy allocation criteria with the corresponding building performance. For example, the Washington State Renewable Energy Cost Recovery Incentive Payment offers tax credits to buildings utilizing solar energy based on kWh, with a US$5,000 maximum for residential buildings and US$25,000 maximum for commercial buildings. Thus, for buildings in Washington State, the amount of the policy incentive was first estimated using the energy generation, or "Dollar per kWh" criteria. Based on the primary building property type, the estimated amount was compared with US$5,000 or US$25,000 for residential and commercial functions respectively, and the lower amount between the estimated amount and the maximum was kept for the final analysis. When multiple policy incentives could be applied to one building, we applied the maximum amount of all potential applicable incentives.

## Results

Results describe the estimated performance characteristics of solar BIPV, as window glazing or similar application of second generation of solar film, for the full collection of 256 tall mixed-use buildings in the study, for the buildings primarily in commercial and residential use, and for the cities that represent the largest number of buildings in this study. Results are separated to differentiate the estimated effects of solar BIPV, with and without the financial incentives provided in policy.

Table 3 summarizes key building characteristics regarding the façade area and height. Out of the 256 US properties designated as mixed-use in the CTBUH skyscraper database, about 65 percent (166 buildings) are defined as primarily residential with hotel (85 buildings, 33 percent of the total), with office (77 buildings, 30 percent) identified as their secondary use. Commercial uses in this study include hotel, office, and "other." Buildings with hotel as the primary use comprise 20 percent (51 buildings) of the total, and another 11 percent (27 buildings) list "office" as their primary use.

Table 4 shows forecasted solar system performance at the building level from SAM for buildings with commercial and residential as primary uses, without the application of financial incentives. The total surface area available for solar BIPV in residential buildings is 33 percent less (40,249 vs. 60,561 square meters on average) than in buildings primarily in commercial use, which reflects, in part, the tendency for tall commercial buildings to be designed with glass façades.

The difference in surface area affects total solar system capacity, energy yield, and related financial savings. With smaller unobstructed south-facing façade areas, solar systems in residential high-rise buildings have capital costs estimated to be 33 percent lower (US$649,097 vs. US$976,673) than those in commercial buildings. The average annual savings due to BIPV energy yield tends to be lower for residential as well. Commercial buildings are estimated to generate 34.7 percent more savings (US$68,558.50 vs. US$50,906.50) based on the statewide utility rate (EIA 2020). However, buildings primarily in residential use tend to use less electricity than their commercial counterparts. As a result, BIPV is forecasted to supply, on average, 12 percent of annual energy use in residential buildings, while about 10 percent is taken up for commercial properties. Similarly, BIPV in primarily residential buildings have a slightly faster payback period, on average, with the standard deviation indicating meaningful differences from building to building.

Nine cities house most of the buildings in this study, and the capacity and performance characteristics of BIPV for the buildings in each city are summarized in Table 5. The capacity to generate energy is realized through the level of irradiation of solar cells, which differs across the United States. Note the comparatively high ratio of energy yield to capacity in Las Vegas, and the considerably lower ratio for Seattle. In terms of financial performance, however, the price of electricity from utilities differs significantly among cities, and this has a direct effect on the benefits estimated to accrue from BIPV systems. While the levelized cost of energy from solar tends to reflect the capacity of the BIPV system, the annual savings made possible by BIPV is more a function of the price one would have to pay to purchase the same electricity from a utility provider. Here, annual savings from BIPV for buildings in Honolulu, Las Vegas, San Francisco, and New York City stand out, due to the relatively high price of electricity charged by utility providers. Seattle, with its municipally-owned electric utility connected to historical investment in publicly-owned hydropower, shows the effect of low prices for electricity paid to utilities. As a result, payback is swift in Honolulu and slow in Seattle.

The next set of tables describes the effects of financial incentives on performance, mainly in the form of changes to the payback period. There is no one-to-one correspondence between the number of incentives and the number of buildings, because each building can qualify for one or more incentives, offered by one or more organizations.

Table 6 summarizes the annual financial incentive opportunities in dollar amounts according to the primary use of the building. The table shows the number of incentives, expected value, and maximum value of incentive awards that a building could receive from qualifying programs. The expected value estimates the average monetary awards a building can receive from all types of incentives assuming the building has an equal chance to qualify for each. The maximum value is the highest monetary award that a building can receive from all qualifying incentives. The monetary awards for each building were then used to calculate the new payback periods with the incentives.

Commercial buildings can qualify for a greater number of incentives and receive higher expected value and maximum value of perceived incentive awards. Even though primarily residential properties receive fewer policy incentives, they qualify for a higher average payoff per kWh (US$14 vs. US$11) and per cell kWdc (US$287 vs. US$220). With the expected value of incentives applied, both residential and commercial buildings on average reduced payback periods by 1.2 years (9 percent) and 1.4 years (9.5 percent), respectively, in the 25-year lifespan of the assets. When the maximum value of incentives was applied, each building type benefited from reductions to payback periods of 3.1 years (23.5 percent) and 3.5 years (24 percent), for residential and commercial, respectively.

Table 7 summarizes the annual financial incentive opportunities in dollar amounts for

| | N | Mean | SD | Min | Max |
|---|---|---|---|---|---|
| Architectural Height (m) | 256 | 150.25 | 50.73 | 100 | 423 |
| South Façade Area ($m^2$) | 256 | 6,068.75 | 4,292.00 | 422.34 | 22,836.39 |
| **Note:** Each observation (N) in the table is a building. **Data Source:** CTBUH | | | | | |

Table 3. Summary statistics of building characteristics.

| | Residential | | | | Commercial | | | |
|---|---|---|---|---|---|---|---|---|
| | N | Mean | Min | Max | N | Mean | Min | Max |
| Total Capacity (kW) | 166 | 415 | 11.3 | 1876.9 | 86 | 625 | 22.6 | 2537.4 |
| Annual Energy Yield (kWh) | 166 | 411,083 | 10,906 | 1,817,809 | 86 | 683,073 | 20,531 | 3,174,416 |
| Levelized Cost of Energy (cents/kWh) | 166 | 9.4 | 7.4 | 11.4 | 86 | 8.9 | 7.4 | 11.2 |
| Annual Savings (US$) | 166 | 50,907 | 1,009 | 299,082 | 86 | 68,559 | 1,946 | 331,819 |
| **Note:** Each observation (N) in the table is a building. | | | | | | | | |

Table 4. Summary statistics of building solar BIPV performance by building primary use.

| | Atlanta (N=10) | Chicago (N=28) | Honolulu (N=8) | Houston (N=7) | Las Vegas (N=26) | Miami (N=22) | New York City (N=66) | San Francisco (N=8) | Seattle (N=7) |
|---|---|---|---|---|---|---|---|---|---|
| **Total System Capacity (kW)** | | | | | | | | | |
| Mean (SD) | 526 (347) | 434 (464) | 332 149) | 436 (188) | 909 (618) | 358 (320) | 398 (406) | 322 (297) | 287 (155) |
| Median [Min, Max] | 415 [93.5, 1040] | 293 [11.3, 1880] | 294 [178, 547] | 410 [135, 716] | 811 [152, 2540] | 223 [32.7, 1230] | 268 [34.4, 1930] | 142 [94.3, 869] | 313 [32.8, 488] |
| **Annual Energy Yield (MWh year 1)** | | | | | | | | | |
| Mean (SD) | 499 (329) | 420 (449) | 277(129) | 393 (169) | 1130 (773) | 333 (296) | 399 (406) | 348 (320) | 242 (131) |
| Median [Min, Max] | 395 [89.1, 981] | 284 [10.9, 1820] | 244 [145, 464] | 373 [121, 651] | 1010 [187, 3170] | 208 [30.2, 1140] | 268 [34.2, 1950] | 155 [103, 942] | 261 [27.7, 413] |
| **Levelized Cost of Energy (cents/kWh)** | | | | | | | | | |
| Mean (SD) | 9.73 (0.0443) | 9.54 (0) | 11.1 (0.265) | 10.3 (0.115) | 7.40 (0.0492) | 9.93 (0.0700) | 9.22 (0.124) | 8.52 (0.0568) | 10.9 (0.0567) |
| Median [Min, Max] | 9.71 [9.69, 9.80] | 9.54 [9.54, 9.54] | 11.1 [10.9, 11.4] | 10.2 [10.2, 10.5] | 7.38 [7.38, 7.51] | 9.97 [9.74, 9.97] | 9.27 [8.95, 9.57] | 8.50 [8.47, 8.60] | 10.9 [10.9, 11.1] |
| **Annual Savings ($1, 000)** | | | | | | | | | |
| Mean (SD) | 52.7 (34.7) | 40.4 (43.1) | 92.7 (43.5) | 28.6 (12.3) | 87.4 (59.6) | 30.6 (27.1) | 73.5 75) | 81.4 (74.6) | 21.6 (11.7) |
| Median [Min, Max] | 41.8 [9.42, 103] | 27.2 [1.05, 175] | 81.3 [48, 155] | 27.1 [8.79, 47.4] | 78.2 [14.4, 245] | 19.1 [2.77, 105] | 49.5 [6.32, 359] | 36.4 [24.2, 219] | 23.2 [2.48, 36.8] |
| **Payback Years** | | | | | | | | | |
| Mean (SD) | 15.6 (0.0994) | 16.8 (0) | 5.65 (0.160) | 23.9 (0.386) | 16.3 (0.146) | 18.3 (0.183) | 8.45 (0.124) | 6.15 (0.0535) | 20.8 (0.151) |
| Median [Min, Max] | 15.6 [15.5, 15.7] | 16.8 [16.8, 16.8] | 5.65 [5.50, 5.80] | 23.6 [23.6, 24.6] | 16.2 [16.2, 16.6] | 18.4 [17.8, 18.4] | 8.50 [8.20, 8.80] | 6.15 [6.10, 6.20] | 20.7 [20.7, 21.1] |

Table 5. Summary statistics of building solar BIPV performance by city.

buildings in the top represented cities in this study. The most favorable locations based on number of incentives are Houston, Miami, and Las Vegas. Incentives in Houston and Miami have the greatest comparative effect on payback period, with reductions of five years or more. Note, too, that expected incentives reduce payback periods to less than six years on average in San Francisco. One could argue that the comparatively minor effect of policies on payback period in Honolulu (which is already at less than six years without incentives), reflects the fact that the differential cost of solar in comparison to utility prices is already a substantial financial incentive.

To understand the factors contributing to the performance of the solar energy systems, we implemented a classification and regression tree (CART) analysis. The CART analysis is a forward-selection modeling approach that selects the variable and cutoff threshold at each step with the strongest association to the outcome and performs a binary split of the data according to that variable. Compared with linear regression, the CART method is especially useful for this type of analysis, because it can perform well with high collinearity between variables.

Figure 6 shows the results of CART analysis along with the variable importance metrics. The variable importance metrics measure the percentage of cumulative model improvements contributed by the variable. A higher percentage indicates that a variable contributes more to the variations in the outcome. Three sets of variables were examined: the energy yield in year one, payback period in years, and reduction to payback period due to policy.

The first model (see Figure 6a) examines how monthly average solar irradiation, building façade area, façade shading percentage, and façade glazing percentage contribute to the total energy yield in year one by the solar energy system. Monthly average solar irradiation is the top and primary predictor of solar energy generation, while the other three variables only contribute a small percentage of the outcome.

The second model (see Figure 6b) examines how electricity rate, monthly average solar irradiation, building façade area, façade shading percentage, and façade glazing percentage jointly contribute to payback period. As the results also show, electricity sell rate and irradiation are the top two predictors for payback period, followed by façade area. Additional analyses run to examine the effect of financial incentives show that all the policy types share similar, meaningful predictive power. Together these analyses emphasize the financial importance of solar irradiation (the geographic location of the building), the current cost of electricity on the electrical grid in the location of the building (electricity rate), and policies that offer financial support for photovoltaics.

| Incentive Type | Residential | | | | | Commercial (Hotel, Office, Other) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | N | Mean | SD | Min | Max | N | Mean | SD | Min | Max |
| Number of qualifying incentives | 164 | 2.77 | 1.13 | 1 | 5 | 83 | 3.17 | 1.57 | 1 | 5 |
| Payback period (year) without incentive | 166 | 13.2 | 5.4 | 5.5 | 24.6 | 86 | 14.6 | 4.8 | 5.5 | 24.1 |
| Payback period (year) with expected incentive | 166 | 12 | 3.6 | 5.3 | 20.6 | 86 | 13.2 | 3.3 | 6.3 | 20.2 |
| Payback period (year) with maximum incentive | 166 | 10.1 | 3.4 | 1.5 | 20.3 | 86 | 11.1 | 3.1 | 2.7 | 14.0 |

Table 6. Annual incentive opportunities (US$) by primary use.

| | Atlanta (N=10) | Chicago (N=28) | Honolulu (N=8) | Houston (N=7) | Las Vegas (N=26) | Miami (N=22) | New York City (N=66) | San Francisco (N=8) | Seattle (N=7) |
|---|---|---|---|---|---|---|---|---|---|
| **Number of qualifying incentives** | | | | | | | | | |
| Mean (SD) | 2.10 (1.45) | 0.857 (1.38) | 3.00 (0) | 5.00 (0) | 4.81 (0.402) | 4.82 (0.588) | 3.00 (0) | 3.88 (0.354) | 3.00 (0) |
| Median [Min, Max] | 3.00 [0, 3.00] | 0 [0, 3.00] | 3.00 [3.00, 3.00] | 5.00 [5.00, 5.00] | 5.00 [4.00, 5.00] | 5.00 [3.00, 5.00] | 3.00 [3.00, 3.00] | 4.00 [3.00, 4.00] | 3.00 [3.00, 3.00] |
| **Payback period (years) without incentive** | | | | | | | | | |
| Mean (SD) | 15.6 (0.0994) | 16.8 (0) | 5.65 (0.160) | 23.9 (0.386) | 16.3 (0.146) | 18.3 (0.183) | 8.45 (0.124) | 6.15 (0.0535) | 20.8 (0.151) |
| Median [Min, Max] | 15.6 [15.5, 15.7] | 16.8 [16.8, 16.8] | 5.65 [5.50, 5.80] | 23.6 [23.6, 24.6] | 16.2 [16.2, 16.6] | 18.4 [17.8, 18.4] | 8.50 [8.20, 8.80] | 6.15 [6.10, 6.20] | 20.7 [20.7, 21.1] |
| **Payback period (year) with expected incentive** | | | | | | | | | |
| Mean (SD) | 15.6 (0.0994) | 16.8 (0) | 5.65 (0.160) | 23.9 (0.386) | 16.3 (0.146) | 18.3 (0.183) | 8.45 (0.124) | 6.15 (0.0535) | 20.8 (0.151) |
| Median [Min, Max] | 15.6 [15.5, 15.7] | 16.8 [16.8, 16.8] | 5.65 [5.50, 5.80] | 23.6 [23.6, 24.6] | 16.2 [16.2, 16.6] | 18.4 [17.8, 18.4] | 8.50 [8.20, 8.80] | 6.15 [6.10, 6.20] | 20.7 [20.7, 21.1] |
| **Payback period (year) with maximum incentive** | | | | | | | | | |
| Mean (SD) | 13.8 (1.24) | 13.7 (0.269) | 5.24 (0.138) | 13.0 (1.38) | 11.3 (1.48) | 7.51 (3.64) | 7.65 (0.262) | 5.27 (0.126) | 12.8 (1.85) |
| Median [Min, Max] | 13.1 [12.9, 15.7] | 13.8 [13.2, 13.8] | 5.24 [5.11, 5.36] | 12.1 [12.1, 15.1] | 11.9 [7.43, 12.5] | 6.87 [1.48, 15.3] | 7.80 [6.97, 7.92] | 5.28 [4.97, 5.35] | 11.4 [11.3, 14.8] |

Table 7. Annual incentive opportunities (US$) by city.

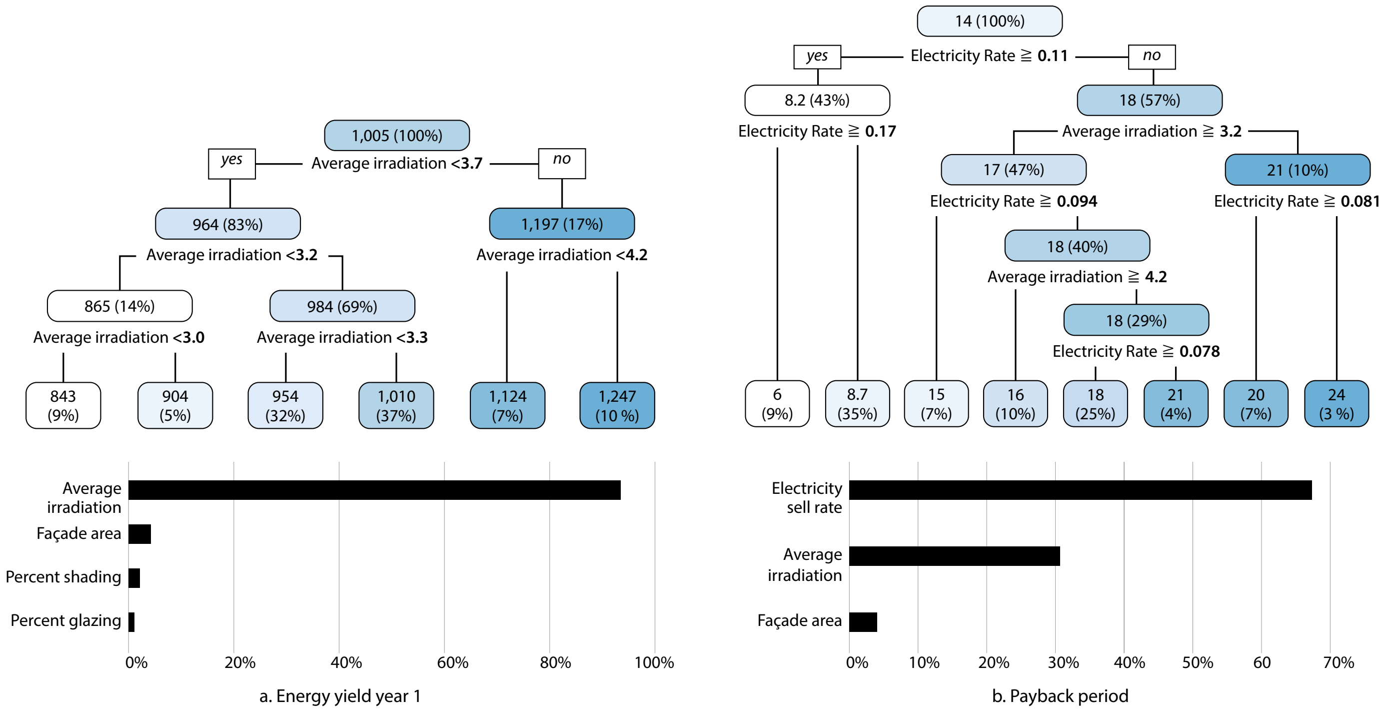



Figure 6. Result of classification and regression tree analysis. Model (a), at left, examines the effect of monthly average solar irradiation, façade area, and glazing percentage on energy yield. Model (b), at right, compares the amount of influence irradiation levels, electricity rates, and façade area have on time to payback of an investment in BIPV panels.

## Conclusions

This research collects and compiles datasets from multiple national databases and estimates the potential energy and financial impact of solar photovoltaic glazing or thin-film laminate systems on mixed-use tall buildings in the United States.

The development of thin-film solar cells has widened the opportunity to install solar systems on the façades of buildings, which has greatly increased potential solar system capacity in urban centers. This study shows that solar systems can cost-effectively generate electricity to meet a meaningful portion of a building's daily consumption. While building designs and density have some impact, solar irradiation has the most predictive power for energy generation.

Secondly, this study demonstrates the financial feasibility of solar systems. Without the support of policy incentives, the average payback period is 13 years for a residential building and 15 years for a commercial building, which is much shorter than the 25-year lifespan of a typical solar system. The length of payback period is influenced by the price to purchase electricity from utilities and by solar irradiation. With the support of policy incentives, these payback periods can be further reduced to an average of 10 years for residential buildings and 11 years for commercial buildings.

These benefits are not equally distributed across the United States, but results show that it is possible for BIPV to be financially beneficial to tall mixed-use buildings in all parts of the country. ■

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