A design-driven approach to integrate high-performance photovoltaics devices on the building façade

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Abstract. To promote sustainable development, the Singapore government has set an aggressive target for PV deployment. However, as a highly urbanized city-state, Singapore has limited land space. Hence, innovative PV deployment is one area where Singapore is actively exploring. In urban environment, Singapore has a lot of vertical building surfaces; building-integrated PV (BIPV) is one of the good options to further increase PV adoption. Using a design-driven approach, this paper explores a different way of integrating PV modules on the building façade, considering the aesthetic as well as the building performance of PV modules.

1. Introduction
Global warming and air pollution have become critical issues in today’s society. As a commitment to reducing greenhouse gas (GHG) emission, Singapore has pledged for an ambitious greenhouse gas emission target of 65 million tons per annum by the year 2030. To achieve the goal, the Singapore government is promoting adoption of solar photovoltaic. By 2020, a total of 350MW of photovoltaic (PV) installed capacity is targeted. Conventional photovoltaic (PV) modules have monotonous blue or dark appearance. Hence, it is difficult to be accepted by architects. Customized PV modules are sometimes used for building application. However, the solution is costly.

For this research, we proposed a design-driven approach to integrate photovoltaics devices (PV devices) on building façades to create a visually dynamic façade design based on the solar potential of the building façade. To maintain a reasonable cost for fabrication, we explored a case study in Singapore where the building façade consists of several types of standardized PV devices. With the help of digital parametric design tools, different types of PV devices can be automatically integrated on the façade according to the solar potential of the façade as well as building function requirements. Supported by high-performance shingled PV modules and ceramic printing technology, the PV device can have a customized color.

2. Literature review
A high-performance façade that integrates passive strategies can have a significant impact on daylighting and shading and create a natural ventilation system. Additionally, a high-performance façade can integrate active strategies such as photovoltaic technology, generating power from renewable
energy and reducing energy consumption during building operations [1]. A building’s façade is the main interface to express building aesthetics, necessitating flexibility of design to encourage architects and other stakeholders to accept but also enhance energy performance [2]. To meet this challenge, a design-driven strategy for enhancing building performance and flexibility of the design was considered simultaneously [3].

Since different PV technologies are used in various building applications, it is necessary to have a systematic approach to classify them. A systematic classification can provide a clear research objective for each level of scale.

- **PV Material**: The PV cell is the basic unit of PV material, which are generally divided into four kinds: monocrystalline silicon, polycrystalline silicon, thin-film silicon, and innovative materials. The related studies focus on power generation efficiency, life cycle, and cost.
- **PV Device**: The PV device consists of different elements (e.g., PV shading device, spandrel panel, glazing window, etc.) forming a complete constructional or functional unit as part of a façade. Research outcomes are normally BIPV products with bi-functional design.
- **PV Façade**: A PV façade system is made up of different transparent or opaque PV and structural components. It can satisfy the basics of technical and functional performance such as air tightness, vision, and insulation. Examples of façade systems are curtain walls, window walls, double skin façades, skylights, etc. PV façades have a great effect on visual aesthetics and urban solar potential.

3. High performance cost-effective PV device

Interestingly, there is a trade-off between cost and visual expression. On one hand, using repetitive PV devices on a façade can reduce the cost of fabrication [4]. On the other hand, visual expression is important to achieve non-apparent repetitive patterns on a building façade [5]. Thus, it is crucial to integrate PV technology into prefabricated building technology in order to create various PV device modular that form a facade system to give architects enough flexibility in design.

This research introduced and explored the latest high-performance color shingled PV modular technology developed by Solar Energy Research Institute of Singapore (SERIS). We used a design-driven approach to integrate PV devices based on building program and solar potential, as described in the following sections.

4. Proposed approach

The proposed approach describes our suggested methodology specifically, interpreting the current SERIS color shingled PV module technology and the strategy to integrate high-performance PV devices on the building façade.

4.1 High Performance Color Shingled PV Module Technology

In order to achieve high efficiency but relatively lower cost, solar cells are packed densely with minimum losses by using in-house shingling PV module technology. Shingling module technology offers high module efficiency by packing more cells into the same area space and reducing resistive losses in cell interconnections. The shingling module manufacturing process is shown in Figure 1a. Through testing the numbers of cell cut and cell overlap, shingling interconnection can provide up to 15% higher module power.

To improve the aesthetics and give more freedom for architects to customize their PV module product, digital ceramic printing on glass technology can be applied to the shingled PV module. Digital ceramic printing offers architectural designers’ chances to print customized patterns, texts, and images on the flat surface of a shingled PV module, which is UV resistant, weather durable, and environmentally friendly. Current research is systematically studying how different design patterns and colors affect PV
module performance. Quantified experiments will be conducted to find out the relationship between different colors, glass transparency degree, and module performance. Ongoing research about colored PV by SERIS is shown in Figure 1b.

Figure 1(a). The shingling module manufacturing process. Source: By Authors. (b). Ongoing colored PV research by SERIS. Source: SERIS.

### 4.2. Pixelation Strategy to Integrate PV Devices

Pixelation aesthetics expression is common in architectural design. The new de Young Museum in Golden Gate Park in San Francisco, designed by Herzog & de Meuron in 2005, is an example of this (Figure 2). Implied in pixel technology is that if the building surface is large enough, the PV device can be a pixel on the image. Based on this thinking, the PV module is standardized to fulfill the needs of efficiency on power generation, while the PV device integrated with prefabricated technology can be designed with various types to satisfy the requirements of building function and visual expression.

To ensure energy generation, the pixelation integration of PV devices should consider the solar potential of a façade. In a highly dense urban scenario like Singapore, the effect of shading from surrounding buildings or trees has a great impact on solar potential. It is vital to obtain a simulation outcome of annual average solar radiance on a building envelope. Currently, the software Rhino (Grasshopper’s plugin for Ladybug’s Honeybee tool) can provide average hourly annual solar radiance on a given surface. The integration of PV devices can then be based on the solar potential map of the building façade. Specifically, areas on the building façade that have more shadows during the year should have less or no PV devices to ensure that shadows have less impact on the performance efficiency of the PV panels. Alternately, areas on the building façade that have few shadows during the year should have more PV devices to ensure high performance efficiency of the PV panels.

Figure 2. Pixel façade of New De Young Museum of Golden Gate Park in San Francisco designed by Herzog & de Meuron. Source: Herzog & de Meuron.

### 5. Case study

#### 5.1 Solar Potential and Pixelation Pattern

A typical office tower (floor plan 50 meters by 30 meters) 33 stories tall with a height of 99 meters, situated in an urban context in Singapore, was chosen as the case study for this research. The façade of the tower was subdivided into a pixilation pattern 2 meters by 9 meters. Through the digital energy
simulation tool Rhino, the annual hourly solar radiation map (kWh/m\(^2\)) was projected on the building façade. Because of the surrounding buildings, the solar potential on the façade was uneven, ranging from 200 kWh/m\(^2\) to 900 kWh/m\(^2\) (Figure 3). The threshold setting for PV panels is varied, depending on the availability of local photovoltaic technology and cost. Normally, the threshold for PV panels should be at least 500 kWh/m\(^2\) for the Singapore scenario. Taking the southern façade as an example, the suitable areas (larger than 500kWh/m\(^2\)) for PV panels were mainly at the top and the middle of the building (Figure 4a). We assumed the zones with PV devices shown in Figure 4b. Using the pixelation strategy, the overall façade was grouped into ten clusters by unifying pixelations with similar solar potential, with each cluster responding to one type of façade device accordingly (Figure 4c).

In Section 5.2, we mainly focused on individual PV devices and non-PV devices studies. In Section 5.3, we explored the pixelation integration method based on both the solar potential map on the façade and building function.

5.2. Individual PV Devices and non-PV Devices Studies
The main purpose of this study was to design various types of individual PV devices and non-PV devices to create a visually dynamic façade design based on the solar potential of the building façade while maintaining a reasonable cost for fabrication.” As discussed in the previous section, the shading by surrounding building had a significant effect on the solar potential of the building in a high-density urban context. The design of PV devices was for areas where the solar potential was larger than the normal threshold 500kWh/m\(^2\), while the non-PV devices were designed for areas where the solar potential was less than 500kWh/m\(^2\). We assumed that a typical office room is 4-meters wide, 8-meters deep, and 3-meters high. The Optimal Base Case was designed with a shading device with a 30-degree tilted panel and 300 mm overhang. The overhanging shading device not only reduced the interior cooling load but also provided space for installing PV panels (Figure 5).
Figure 5. Typical office room and optimal base case with shading device. Source: By Authors.

Starting from the Optimal Base Case, Type A with three variations was generated. With the same tilted angle of 30 degrees while increasing the areas of shading and PV areas, Point A is the control point to enlarge the PV shading device. With the set-up of parametric modeling, the position of point A can be easily modified according to users’ needs (Figure 6). Type B incorporated three different window-wall-ratios (WWR), 40%, 50%, and 60%, which is an important factor influencing indoor cooling load and optical effect. Three variations were also generated for this type by parametric modeling (Figure 7). Type A and Type B with their variations are suitable for areas with high solar potential on the façade, which can function as a typical office room. Furthermore, the simulation outcomes for Type A and B’s building performance can give effective feedback to the geometry set-up and PV integration, forming a design loop to improve building efficiency.

Type C integrated PV panels with multiple levels, which allowed for consideration of indoor vision. Full glazing windows can give a no obstacle view for sky gardens or public spaces in the upper level of a building (Figure 8a). Type D was similar to Type C in geometry, but without PV integration (Figure 8b). Type E had no PV module integration; it was a normal window frame façade system with different heights. The last two types could be fitted on the lower areas of the building, which has less solar potential due to shading by the surrounding buildings and trees (Figure 8c).

Our exploration of PV and non-PV devices established a library of modules. With consideration of the overall solar potential of the façade and the function of the indoor space, various configurations can be generated. This idea of standardization and modulation can be matched with prefabricated building technology, lowering the cost of construction and providing more design freedom to architects.

5.3. Integration PV Devices on the Entire Façade

The main purpose of this section is to illustrate the strategy of integrating PV devices on the entire building façade. The solar irradiation map was divided into ten clusters. Our ten façade clusters can be found in our library of PV devices and non-PV devices, as described in the previous Section 5.2.
With the help of parametric tools, the ten clusters of PV devices were distributed automatically on the façade, showing a dynamic pattern with the consideration of building performance and functions (Figure 9a). Additionally, it was necessary to reflect PV device types and locations visually on an Excel matrix in order to manage the large numbers of prefabricated modules precisely and quickly (Figure 9b). All the PV panels integrated on the devices were shingled PV developed by SERIS to guarantee low cost and high efficiency. Using ceramic digital printing technology, the possible illustration is shown in Figure 9c.

6. Discussion and conclusion
Our research suggests a novel approach for manufacturing shingled color PV modules and an integration strategy for PV devices to create dynamic patterns on a building façade.

Most research in the field focuses on singular PV module design and optimization, neglecting PV device design that bridges the PV module and building façade. PV devices serve dual functions as building components and renewable energy generators. Integration with the building prefabrication industry can have the advantages of savings in intensive manpower, transportation, and installation. Additionally, the combination of the two industries can bring together PV and construction consultants in the early design stage, which is beneficial for designing standardized and modularized prefabricated PV devices.

Our pixelation strategy corresponds with the concept of prefabricated components, dividing the entire building façade into pixel-patterns. The solar potential of a building façade can be mapped on the subdivided pixel-patterns, visually expressing the suitable places to integrate PV devices. The pixel-patterns can then be grouped into clusters according to the pattern’s solar potential. Prefabricated building technology encourages component-driven design; therefore, it is important to form a library consisting of several types of PV devices. Using the library, architects can have more freedom to customize PV devices based on the needs of building performance and function. With the help of parametric design tools, the modularized PV devices can be integrated into the corresponding pixel-patterns...
pattern clusters. The outcome of this design-driven distribution strategy using modularized PV devices presents a dynamic pattern on a building façade based on the building’s solar potential.

![Figure 9](image1.png)

**Figure 9(a)** The outcome of dynamic façade with PV devices. **(b)** Data visualization of PV devices mapping on the façade. **(c)** Colored PV implemented on the entire façade.

Source: By Authors.

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**References**

[1] Sadineni S B, Madala S and Boehm R F 2011 Renewable and Sustainable Energy Reviews. **15** 3617-31
[2] Hachem C 2018 Solar Energy. **159** 710
[3] Scuderi G 2019 Designs. **3** 8
[4] Moor T, Egloff B, Tomovic T and Wittkopf S 2017 The Design Journal. **20** 1879-93
[5] Berkel B, Minderhoud T, Piber A and Gijzen G 2014 29th European Photovoltaic Solar Energy Conference & Exhibition vol. 1, ed Bokhoven T P, Helm P and Waldau A J (Amsterdam: Curran Associates, Inc.) p 3606