Review and Potential Development of Solar Window Technology and Feasibility Study in Urban Area, Hong Kong as Case Study

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Abstract. Net Zero Energy Building (NZEB) has been a rising topic in recent years, the route to achieve NZEB through renewable energy generation with the adaptation of solar window is explored. Literature review with current market research on the technology are studied and consolidated. Transformation from the current semi-transparent to future visibly transparent solar window is observed. Potential development of modular design with Wireless Power transfer is suggested for wide application of solar window. In the light of the large potential of solar window, feasibility study is conducted to analysis the application of the technology in Hong Kong context in term of the climate and installation criteria due to the Feed-In-Tariff (FiT). Solar analysis of solar resource availability and electricity generation are evaluated and simulated by Radiance using the morphologies of Central, Hong Kong as case study. Equations are developed for setting up selection criteria and estimating the suitable area for installation. 40.1% of solar insolation on an unobstructed horizontal plane was identified as threshold for installation in Hong Kong and the minimum installation is estimated to be 50 m² in order to be cost effective.

1. Introduction
Net Zero Energy Building (NZEB) has been a rising topic in recent years, as there are growing concerns on climate change internationally due to the frequent and intense occurrence of its impacts, such as typhoon, flooding and drought. An increasing number of counties and regions have established different guidelines, roadmaps and targets to promote NZEB. Routes to achieve NZEB includes energy saving, efficient energy consumption, and renewable energy generation, while this paper would focus on renewable energy generation in building.

Renewable energy generation in building are mainly solar PV panel retrofitted onto roof or any horizontal platform directly exposes to sunlight. Based on a study on the development of rooftop PV system in Hong Kong, the potential annual energy generation is reported to be 5981GWh [1], which would be equivalent to 13.6% of total electricity consumption in Hong Kong in 2017 [2]. Hence, it is difficult for buildings in high-rise, high-density urban context to achieve NZEB by roof installation. In order to increase renewable energy generation, enlarging the catchment area for solar resources harvesting was proposed and Building Integrated Photovoltaic (BIPV) has been studied for a long time. However, the solar cells in BIPV installed on the building façade blocks the view of building occupants and for this reason, the popularity of BIPV installation is limited. Therefore, solar window, transparent / partially transparent energy generating window under sunlight, have been developed and commercialized lately. The technology generates renewable energy, while allowing quality views for building occupants.
2. Literature & Market Review

In general, there are two solar window configurations. The transparent PV (TPV) configuration generates power at the window. The concentrator technology, which uses window as the medium to transmit sunlight by total internal reflection and generates power at the edges of solar window. Both configurations are available in the market, which are illustrated in Figure 1 and summarized in Table 1 below.

![Illustration of configurations of a) Transparent PV (TPV) and b) concentrator technologies.](image)

2.1. Transparent PV (TPV) Technology

The configuration of TPV can be sub-divided into three types: Spatially segmented PV, Non-wavelength-selective (semi-transparent) thin film PV and Wavelength-selective (transparent/visibly transparent) thin film PV. The three types of TPV are listed according to the average visible transmission (AVT) in ascending order [3].

2.1.1. Spatially Segmented PV. The spatially segmented PV refers to the TPV with opaque solar cell across a transparent substrate, such as glass [3]. This type of solar window is commercially available for over a decade. However, similar to the conventional BIPV, the visible impact hinders the wide application of it, as shown in Figure 2a.

2.1.2. Non-wavelength Selective (Semi-transparent) Thin Film PV. As observed in Table 1, the most dominant technology in the market is semi-transparent thin film PV, which uses solar cell with band gap large enough or thin enough to allow only portions of visible light to pass through. The common materials used in commercialized semi-transparent thin film PV are amorphous silicon (a-Si) and cadmium telluride (CdTe). Semi-transparent perovskite solar cells are also reported in researches [4] [5]. The visual discomfort due to semi-transparent thin film PV is comparatively lower than that of spatially segmented PV due to its more evenly distributed light penetration. This technology is suitable for skylight and partially tinted window as it can block direct sunlight to reduce solar heat gain entering indoor space without obstructing occupants’ view. For example, the installation of Onyx Solar’s amorphous silicon glass in Bejar Market, Figure 2b, and residential building in Marin County.

2.1.3. Wavelength Selective (Transparent/Visibly Transparent) Thin Film PV. For the application of window, visibly transparent PV is preferred. Wavelength selective thin film PV uses materials that selectively absorb ultraviolet (UV) and/or near-infrared (NIR) to generate electricity. As only the non-visible light is absorbed, the solar window using this technology is called “visibly transparent” and it has a potential limit of 20.6% power conversion efficiency (PCE). Materials for this application include small organic molecules, polymers, nanotubes and salts. There are start-up companies in the market developing this technology and commercialized it. For example, Ubiquitous Energy, Figure 2c, has already established their production line.
2.1.4. Concentrator Technology

The configuration of concentrator can also be sub-divided into three types, Non-wavelength-selective and colorful Luminescent Solar Concentrators (LSCs), Non-wavelength-selective scattering concentrator and Wavelength-selective transparent LSCs in Figure 2d-f [3]. However, in the market, the products can be a mix of these three types concentrator technology by applying different materials and layers. It is a relatively new technology of solar window and currently, still under early research stage. Therefore, there are not many commercialized products available in the market, but only prototype.

![Figure 2 Installation and prototype of a) Spatially Segmented PV [6], b) Non-wavelength Selective (Semi-transparent) Thin Film PV [7], c) Wavelength Selective (Transparent/ Visibly Transparent) Thin Film PV [8], d) Non-wavelength-selective and colourful LSCs [9], e) Non-wavelength-selective scattering concentrator [10] and f) Wavelength-selective transparent LSCs [11].](image)

2.2. Development and Challenges

Based on the market and literature review, transparent solar window has already been invented technically. Start-up companies with related technologies were established and it is believed that transparent solar window shall be commercially available in the coming decade. For the building industry point of view, the biggest challenges of commercializing transparent solar window would be the payback period and maintenance.

Payback period does not only depend on technology developed, but also the local policy, such as Feed in Tariff (FiT) and subsidy. Therefore, it is not solely a technical challenge to be solved by the manufacturers and inventors, unlike maintenance issue. There are concerns about the replacement and lifetime of solar window about replacement frequency and easiness. Easy maintenance provides larger incentives for the building industry to adopt solar window, especially when maintaining solar window might need to use gondola and handle wiring inside metal frame. Modular design with wireless power transfer (WPT) solar window may help to solve the problem.

3. Technical Feasibility Study of Solar Window in Hong Kong

The technical feasibility in this paper will focus on solar resource and morphology by simulation under Hong Kong climate. Signature morphologies in Hong Kong was selected as study area, high-rise, high-density commercial area in Central.
Table 1. Summary table of solar window in the market. The readiness of technology decreases down the table as indicated in column “Current Status”.

| Technology | Transparency (%) | Efficiency (%) | Width (mm) | Height (mm) | Output Power (W) | Technology | Selective/ Non-Selective | Configuration | Country | Current Status   |
|------------|------------------|----------------|------------|-------------|----------------|------------|--------------------------|---------------|---------|-------------------|
| Solaria [12] | 40.0             | 6.5            | 1350       | 1725        | 150            | Crystalline Silicon (c-Si) | Non-Selective | Spatially Segmented PV | US        | Commercialized   |
| Sphdar [13] | 10 – 78          | 10 – 2.8       | -          | -           | -              | Spherical Silicon Solar Cell | Non-Selective | Spatially Segmented PV | JP        | Commercialized   |
| Taiyo Kogyo [14] | 5 – 10          | 5.9 – 4.9     | 980        | 950         | 46 – 55        | -          | Non-Selective             | -             | JP      | Commercialized   |
| Honergy [15] | -                | 5 – 6          | 635        | 1245        | 43 – 50        | Three-junction Amorphous Silicon (a-Si) | Non-Selective | Semi-transparent Thin Film PV | CN    | Commercialized   |
| Poly solar [16] | 10-50            | 10 – 6         | 600        | 1200        | 72 – 40        | Amorphous Silicon Tandem cell (aSiμc-Si) | Non-Selective | Semi-transparent Thin Film PV | UK    | Commercialized   |
| Poly solar [16] | 20.00            | 6.3            | 1100       | 1300        | 90             | Amorphous Silicon (a-Si), single junction | -          |               |               |               |
| Onyx Solar [7] | 10 – 30          | 5.8 – 2.8      | -          | -           | -              | Amorphous Silicon (a-Si) | Non-Selective | Semi-transparent Thin Film PV | SP    | Commercialized   |
| Solar First [17] | 10 – 80          | 10 – 2.2       | 600        | 1200        | 72 – 16        | Cadmium Telluride (CdTe) | Non-Selective | Semi-transparent Thin Film PV | CN    | Commercialized   |
| Physie [18] [19] | 90               | 0.8            | -          | -           | -              | Coating with inorganic materials doped with rare-earth metals in specific oxidation states | Selective | Luminescent Solar Concentrator | NL | Commercialized   |
| Glass to Power [20] [11] | 80               | 3.2            | -          | -           | -              | Colourless luminescent solar concentrator | Selective | Luminescent Solar Concentrator | IT | Commercialized   |
| ClearVue PV [21] | 70               | 3              | 500        | 500         | 8              | Advanced glazing technology with spectrally-selective thin film coating & inorganic nano-particle doped PVB Interlayer | Selective | Scattering Concentrator | AU | Commercialized Product & Prototype |
| Ubiquitous Energy [22] | 51.5             | 5.1            | -          | -           | -              | Solar cell that selectively transmit visible light while absorbing only the ultraviolet (UV) and infrared (IR) light and converting it into electricity | Selective | Transparent Thin Film PV | US | Start-up, Established Production Line |
| Next Energy Technologies [23] | 10 – 50          | 7 – 10         | -          | -           | -              | Low-cost, printable transparent energy-harvesting coatings | Selective | Transparent Thin Film PV | US | Start-up, Prototype |
| UbiQD [24] [25] | -                | -              | -          | -           | -              | Luminescent solar concentrating glass windows with quantum dot (QD) tints | Selective | Luminescent Solar Concentrator | US | Start-up, Prototype |
| Solar Window Technologies [26] | -                | -              | -          | -           | -              | Organic materials (polymers) coatings generate electricity using natural and artificial light conditions and even shaded areas | Non-Selective | Transparent Thin Film PV | US | Start-up, Prototype |
The objectives of this study are 1) to set up selection criteria for suitable location to install solar window, 2) to apply the criteria to identify the suitable location with sufficient solar resources in Central, and 3) to find out the relationship between the suitable location and morphology.

3.1. Simulation Assumption.
In order to study the impact of morphology on solar resources at façade, simulation tool, Radiance, was used with assumption listed in Table 2 below.

| Assumption                                      |                                  |
|------------------------------------------------|----------------------------------|
| Simulation Software:                            | Radiance                         |
| Weather Data:                                   | EnergyPlus CityU HK              |
|                                                 | (Typical Meteorological Year (TMY) file for Hong Kong, as visualized in Figure 3) |
| Study Period:                                   | Annual                           |

Figure 3. Visualization of weather data, a) total solar radiation, b) diffuse radiation and c) direct radiation.

The simulation result was standardized and presented in percentage of solar resource with reference to an unobstructed horizontal plane in simulation. The solar resource on the reference plane is 1421.1 kWh/m² according to Hong Kong Observative data [27].

3.2. Installation Criteria
Installation criteria shall be set up for judging the cost-effectiveness of installing solar window at that area. Suitable location for solar window installation shall have sufficient solar resources per unit area that can achieve payback period of around 10 years or less. Equation 1 below is used to determine the solar radiation threshold for installing solar window.

Equation 1

\[
\text{Threshold}_{solar} = \frac{\text{Cost}_{total}}{\text{PP}_{target} \times (\text{Rate}_{FIT} + \text{Rate}_{ele}) \times \text{PCE} \times \text{Insolation}_{ref} \times (1 - \text{Loss}_{overall})}
\]

Where,

- Threshold\(_{solar}\) = Threshold for Solar Window Installation (%)
- Cost\(_{total}\) = Total Cost of Solar Window System (HKD/m²)
- PP\(_{target}\) = Targeted Payback Period (year)
- Rate\(_{FIT}\) = Feed in Tariff Rate (HKD/kWh)
- Rate\(_{ele}\) = Saving from Solar Window System (HKD/kWh)
- PCE = Power Conversion Efficiency (%)  
- Insolation\(_{ref}\) = Solar Insolation on reference horizontal plane (kWh/m²·year)  
- Loss\(_{overall}\) = Overall Losses, e.g. system loss, temperature, shading etc. (%)  

According to the market research, solar window costs about 350 HKD/m² more than the ordinary glass [7]. Together with other necessary equipment, such as inverter, isolation transformer, for FiT,
transportation, manpower etc., the total cost is estimated to be around 1400HKD/m² as estimated from PV installation cost in Hong Kong.

Also, it is assumed that the solar window to be installed is around 5% PCE under Standard Testing Condition (STC), STC: The testing conditions to measure the nominal output power under irradiance of 1,000 W/m², with the reference air mass 1.5 solar spectral irradiance distributions and cell or module junction temperature of 25°C, as projected from Table 1. The overall losses are taken as 20% [28]. The FiT rate in Hong Kong is 3 HKD to 5 HKD depending on the installation capacity and the payback period is expected to be within 10 years.

With the above assumptions, the threshold of received solar radiation in Hong Kong is estimated to be 41.0% of solar insolation on an unobstructed horizontal plane. Therefore, only the location with solar resources above this value will be treated as suitable location for solar window installation.

3.3. Urban Scale Analysis in Central

As observed in Figures 4, southwestern and west façade received higher solar resource than southern and eastern façade in simulation. It is because high intensity solar radiation from the south and east is at a higher solar altitude than from the west and southwest according to Figure 3a. Solar energy from the higher altitude is less concentrated on a vertical surface as shown in Figure 3a. Meanwhile, high intensity solar radiation at low solar latitude from the southwest and west resulted the relatively high received solar radiation on façades directly facing to these directions, as presented in Figure 3b and c.

The area suitable for solar window installation on façade in southwest quadrant is 170,000 m², 27% of a total 720,000 m² studied area, while for eastern façade is only 1% of a total 280,000 m² studied area, which is 3,000 m². The overall feasible area for solar window installation in study region would be around 15% by taking northern façade into account. It can generate around 4.5 GWh if these areas are all installed with solar window and it is equivalent to annual electricity consumption of 800 people in Hong Kong [2]. It shows the potential of solar window installation in Central.

The identified feasible area for installation are mainly on the skyscrapers, for example, the second and fifth tallest buildings in Hong Kong, Two International Finance Canter (IFC) and The Centre. The building heights of these two buildings, 415m and 346m, is around a double of the average building height, 150m to 200m, in the study region. Meanwhile, skyscrapers are located far from each other that no significant shading effect is observed between them. This morphology makes Central to be feasible for solar window installation even it is a high-rise, high-density commercial area. However, for the high-density area with similar building height like Cheung Sha Wan in Hong Kong, solar window installation might not be suitable.

4. Discussion

Morphologically, it prefers super high-rise, low-density buildings over a cluster of mid-rise, high-density buildings for receiving higher solar resource. The result indicates that the urban design shall be low-density skyscrapers with a mix of different building height and the buildings with similar height shall be separated. These can be incorporated with the design criteria for urban wind environment in order to allow sufficient sunlight and wind penetrating into the area [29].
For better setting up the design criteria, an analytical method shall be proposed to roughly estimate the location for solar window installation on a building. As studied in the previous section, the feasible area on a façade for solar window installation is related to the solar altitude in that direction. Therefore, Equation 2 below is developed to serve the propose.

**Equation 2**

\[
A_{\text{feasible}} = \frac{W_{\text{building}}}{H_{\text{building}}} \times \left[ H_{\text{building}} - H_{\text{surrounding}} + d \tan(\alpha_{\text{low}}) \right]
\]

Where,

- \(A_{\text{feasible}}\) = Feasible area for solar window installation at upper part of studied façade (m²)
- \(W_{\text{building}}\) = Width of studied façade (m)
- \(H_{\text{building}}\) = Height of studied façade (m)
- \(H_{\text{surrounding}}\) = Height of the surrounding building in front of the studied façade (m)
- \(d\) = Separation between studied façade and the surrounding building (m)
- \(\alpha_{\text{low}}\) = Lowest solar altitude at studied direction (°)

After identifying the suitable area, assessment on the identified area shall be made to investigate the feasibility of solar window installation. The available and suitable area would affect the payback period of installation as the required equipment for FiT is independent from the area, but electricity generation does. Generally, the minimum solar window installation area shall be not less than 50 m² to be cost effective. However, the number varies depending on the system design. Therefore, the cost-effectiveness of installation shall be verified after system design and market research on the required equipment.

5. Conclusion

The objectives of this study are achieved. The available and emerging solar window technologies in the market and research are reviewed and summarized in Section 2. Currently, the major solar window in the market are semi-transparent thin film PV. But, the development of visibly transparent thin film PV and wavelength-selective LSCs would be an opportunity for wide application of solar window in the future. Potential development of modular design with WPT was proposed from industry point of view.

With a promising solar window technology developed, technical feasibility study of solar window installation in Central, Hong Kong is studied in Section 3. 40.1% of solar insolation on an unobstructed horizontal plane was identified as threshold for solar window installation. As a result, 15% of studied area in Central is feasible for the installation due to its morphology, low-density skyscrapers in the area.

Further application of this study was suggested in Section 4 with incorporating solar resource and wind environment analysis in urban design. Furthermore, the relationship between solar resource and morphology was also generalized by equation for preliminary study for other regions. Lastly, minimum installation area in Hong Kong was estimated to be 50 m² in order to be cost effective.

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