Toward a Smart Zero Carbon Future – Literature Review and Case Studies on Architectural Design Strategies for BIPV Systems in High-density Communities

C Y Xiang[1] **W T Wang**[1] **M K Leung**[2,3] **D Poon**[4]
[1] The Hong Kong University of Science and Technology, Hong Kong, 999077
[2] Behave Limited, Hong Kong, 999077
[3] Sustainable Design, Ronald Lu and Partners (Hong Kong) Limited, Hong Kong, 999077
[4] Behave Limited, Hong Kong
Email: dickenpoon@behave.asia

Abstract Aiming to develop a zero-carbon society, China has launched ambitious goals for 2030 and 2060. The building sector is one of the most carbon-intense industries, responsible for around one-third of greenhouse gas (GHG) emissions globally. This share is even higher in high-density urban areas. There is an urgent necessity to use renewable energy systems in the built environment, such as building integrated photovoltaics (BIPVs), so as to maximise the harvest of clean solar energy while reducing the GHG emissions. Based on recent national building regulations, all new buildings are required to install photovoltaic systems. However, there is a lack of systematic research and design methodologies to support BIPV systems in high-rise, high-density communities – here, both the roof and façade areas should be used to harvest solar energy. Key challenges to BIPV adoption in these communities are complex shadowing effects caused by the high-density context, self-shading effects caused by residential façade elements like balconies, potential glare caused by novel PV materials, and others. To overcome these barriers and realise future-oriented smart community designs, we conducted systematic research that included a literature review focusing on BIPV design in high-density communities, and case studies of a real project with BIPV systems designed by the authors.
The literature review investigates existing architectural design methods for BIPV application in this context. Typical BIPV systems are roof PVs, façade shading PV devices and semi-transparent glazing. Most current studies focus on energy

aspects, via simulations or experiments, leaving other design aspects, such as aesthetics and public acceptance, addressed less often. A case study analysis of the design for Treehouse, a net-zero tower, is presented, demonstrating the design methods and BIPV technologies used by the authors in a real high-density urban scenario. The findings and analysis will provide a foundation for future study. The authors recommend that holistic architectural design methods should be developed to support BIPV systems. These should have multiple objectives, including community planning, architectural geometry design, building orientation and arrangement, BIPV design and integration, visual and aesthetic performance, and others.

Keywords BIPV; Zero carbon; architectural design; community

1. Introduction

Climate change is one of the world’s grand challenges, one which all nations on Earth need to work together to tackle. Many countries have set out concrete plans and are taking action to reduce greenhouse gas emissions. China has also announced ambitious targets to peak its carbon emissions by 2030 and achieve full carbon neutrality by 2060. To fulfil these ambitious goals, it is necessary to implement clean energy systems on a large scale, such as solar energy and wind energy. Building integrated photovoltaics (BIPV) are an ideal approach to harvesting solar energy in the built environment; BIPV can also provide a foundation for the electrification of buildings. As a part of the building envelope, BIPV is an integrated system that brings together power generation, building component functions and aesthetics. The integrated BIPV component functions may include thermal insulation, noise prevention, weatherproofing, privacy protection, on-site electricity production, and offsetting the system’s initial costs [5]. In April 2022, The Chinese Ministry of Housing’s National Standard was updated to state that building energy efficiency and renewable energy utilisation of the general code now requires that all new buildings should have solar energy systems installed (sub-code 5.2.1.) [4].

Most of the prior studies and real-world projects related to BIPV are focused on low-rise buildings, like single-family houses or multi-storey apartments, for which the roof application of BIPV is the emphasis. However, studies have shown that in large, high-density cities, the façades of buildings have a higher solar potential than the roof areas. Thus, is reasonable to investigate façade integration of BIPV systems in high-density cities in addition to roof PV installations. However, in high-density urban environments such as compact communities, where the energy consumption is more intense, BIPV application is rarely explored. These could be due to several barriers: a lack of in-depth BIPV knowledge among architects, challenging shadowing and self-shading conditions in these high-density communities and the limited availability of BIPV products. Although there are extensive BIPV studies that focus on energy aspects via simulation or experiments, other design aspects like aesthetics and public acceptance are addressed less often. There is an urgent need for holistic architectural design strategies for BIPV application at the community level, especially in high-density urban contexts.

Aiming to overcome the existing barriers to BIPV application, realise future-oriented smart community complex design and provide a foundation for further BIPV design method development, this study first conducted a systematic literature review. Existing advanced BIPV design approaches and technologies that may be utilised in high-density communities were analysed. A case study of a BIPV project designed by the authors is then presented and discussed.

2. Research Questions and Methodologies

The research questions of this study are as following:

1) ***What are the existing design methods and technologies that support the BIPV application in high-density communities?***
2) ***What are the key challenges and barriers that need to be overcome to further promote BIPV application in high-density communities?***

To answer the two research questions, this study combines a literature review and project-based case study, providing an in-depth investigation from both academic and practical perspectives. The literature to be reviewed was selected by searching through relevant studies published within the last ten years on the databases of ScienceDirect and ResearchGate. The keyword combinations 'BIPV AND community'; 'BIPV AND neighbourhood'; 'BIPV AND high-density'; and 'BIPV AND district' were used. Around 70 publications were collected via this search. Based on an examination of the abstracts, 26 papers that were most relevant to the topic of this study were chosen for thorough review. The review process entailed examining the architectural design methods presented in the publications and categorising them into three aspects: energy, urban micro-climate and aesthetics. Promising BIPV technologies and trends were also grouped and listed in tables, while the challenges, barriers and suggested future research orientations were also summarised. The second part of this study consists of a case study of a carbon neutral high-rise office building design, called 'Treehouse', located in a subtropical, high-density urban area. The urban context, methods used to maximise PV solar potential and the efficiency of the design are all discussed, as are the various design challenges presented by the high-rise high-density subtropical climate.

3. Literature Review

3.1. BIPV Design Methods

Energy aspects are some of the most studied aspects of BIPV design [16]. A paper by Costanzo et al. focuses on energy aspects at an urban district level, presenting an integrated, bottom-up method that can support designers and engineers as they work to evaluate both the electricity generation potential of BIPV systems and the energy consumption demands of urban buildings [7] . The energy production of BIPV systems, and local climate-based direct and indirect solar irradiation were calculated through four types of modelling and simulation tools: 1) 3D model generation; 2) analysis of solar irradiance; 3) formatting weather data (TMY data set); and 4) the dynamic energy needs of urban buildings. A Python-based algorithm editor called Grasshopper was developed to connect the four aspects, after which the proposed method was tested in an energy simulation for an urban district in Turkey. The results showed that although the total renewable energy matching demands (set at 20% of the total energy consumption) could be met by the energy produced by BIPV systems, there were mismatches in the hourly scenarios.

The impacts of urban compactness on BIPV energy production were investigated by Mohajeri et al. [8]. The relationships between urban compactness and the corresponding solar potential of sixteen neighbourhoods totalling 11,418 buildings in Geneva, Switzerland were analysed. Through simulations run in CitySim software, the study showed that there was a reverse correlation between the compactness levels and the average annual solar potential of the building envelopes. An obvious decrease in solar potential was found on façade areas when the level of compactness increased, while the roof solar potential also decreased in high-density scenarios, but decreased by a smaller amount.

Sharing similar research interests, Poon et al. explored the relationship between urban morphology and the potential solar energy output of urban envelopes in Singapore [9]. Firstly, several urban morphological parameters were selected for analysis. These included average building height, building orientation, plot ratio, site coverage, height to width ratio, volume area ratio, compacity, difference between maximum and minimum building heights, sky exposure factor, and sky view factor. Then, an urban form archetype scenario builder was developed, which included five parameters: the number of buildings, site coverage, average building height, orientation, and the difference in building heights. In the third step, sky exposure performance and the façades' solar irradiation of the archetypal urban form were simulated via the Ladybug tool. Their findings showed that the height to width ratio, plot ratio, site coverage, and average building height were the urban design parameters that had the strongest linear correlations with the solar potential of the urban envelopes. This method provides a valuable reference for urban designers seeking to plan BIPV systems at the community or district scale.

Aside from the energy production and interior daylight aspects of BIPV, the ***urban microclimate*** impacts of BIPV systems on the surrounding urban context is a growing frontier that deserves academic research [10,11]. Boccalatte et al. investigated the optimal arrangement of BIPV envelopes for future net-zero energy building (NZEB) districts when considering the urban heat island effect and the need to mitigate reflected solar irradiation for the BIPV systems [12]. The approach used to predict the energy production of the BIPV systems at the district level was developed based on the integration of physical models and a design tool package using post-processing calculations. Based on the simulation, the study revealed a weak reduction in PV energy generation caused by the urban heat island effect (approximately 0.33%), while the increase in the BIPV coverage of the total façade area results in a significant decrease in PV efficiency, since this reduces the reflected solar irradiation of the broader urban area. The findings from this study are not only interesting, they may also be used as a reference for future BIPV design and application at the community level.

The ***aesthetics*** of BIPV is another important aspect that is receiving a growing level of interest [13-17]. A group of international researchers investigated the potential of combining BIPV façades with vertical farming systems through a web survey of experts in Singapore (Tablada et al., 2020). In their study, conceptual drawings of BIPV façades combined with vertical farming greenery were distributed with the survey, with a series of design variants including aesthetics, views from the interior, materialisation, operational ease, functionality, and overall architectural quality. The results showed a promising level of acceptability of the concept of façade-integrated vertical farming systems, however general concerns about the aesthetic quality of façades with integrated PV modules were also stated.

Researchers in Singapore have proved the feasibility of BIPV systems in high-density urban districts, as shown in a study by H. Sun, Heng, Tay, et al. [18] . Supported by a comprehensive mapping tool integrating a quantitative visual impact assessment and predictions about energy production, their study used several buildings in a commercial district as an analysis case. A series of BIPV design recommendations were proposed by the authors. These included high-efficiency BIPV products being recommended for façade areas with rich solar irradiance but low visibility. On the other hand, tailored BIPV products with satisfactory aesthetic performance, for example BIPV systems that match the colour of their surroundings; or with a novel appearance, for example a PV media wall, were suggested for façades that have high visibility. This research shares a similar concept with the LESO-QSV method developed by scholars from EPFL [19,20] . To evaluate the visual impacts of coloured BIPV renovation on building façades, the authors presented a novel approach supported by saliency mapping [21] – an advanced method that uses computer vision techniques to anticipate human visual attention. In this study, saliency mapping was applied to test the visual impact of coloured BIPV renovation design used in several buildings along Orchard Road in Singapore, while subjective surveys were carried out to collect people's preference for BIPV designs, so as to validate the predictions created by the saliency mapping. Satisfactory matches were found in the study results.

A summary of the representative design approaches found in the BIPV literature that were focused on the community or district levels is presented in Table 1 below:

Table 1. BIPV design approach.

Investigation focus	Authors and time	**Key findings**	Method type
Energy	Costanzo et al., 2018	Mismatch of PV energy production and energy needs in hourly scenarios.	Simulation
	Mohajeri et al., 2016	A reverse correlation between compactness levels and average annual solar potential on building envelopes, especially the façades.	Simulation
	Poon et al., 2020	Height/width ratio, plot ratio, site coverage, and average building height had the strongest linear correlations with the solar potential of the urban envelopes.	Simulation
Urban micro-climate	Boccalatte et al., 2020	A weak reduction in PV energy generation caused by the urban heat island effect; and a significant decrease in PV efficiency may be the result of an increase in the BIPV coverage of the total façade area.	Physical model test and simulation
Aesthetics	Tablada et al., 2020	High acceptance of integrated vertical farming on façades, while the aesthetic performance of BIPV modules could be improved.	Web survey
	H. Sun, Heng, Tay, et al., 2021	BIPV design recommendations were proposed regarding the visibility of façade areas.	Simulation
	H. Sun, Heng, Reindl, et al., 2021	Saliency mapping could be used as a reliable tool to estimate people's preferences in terms of BIPV design	Saliency mapping and subjective surveys

3.2. Promising BIPV Technologies

One of the most promising emerging BIPV technologies – and products – is the BIPV window, which utilises semi-transparent PV materials. One study shows that the PV potential of glazed areas of high-density urban blocks that contain high-rise and glazed buildings should be addressed and utilised [22]. Cheng et al. investigated the daylight and overall energy performance of double-glazed photovoltaic windows in cold regions of China through a comparison study [23]. A novel metric was used in the study, called the “ratio of N-Daylit area”. The ratio quantified the daylighting performance of photovoltaic windows, and a parametric study of various PV coverage ratios, window-to-wall ratios (WWRs) and orientations of double-glazed photovoltaic windows was conducted by using Daysim to simulate the annual daylight performance and energy consumption of a typical room in an office. Before the simulation, the reliability of daylight simulations was firstly validated using experimental measurements in a small office test cell. The results showed that the application of double-glazed photovoltaic windows can significantly reduce the energy consumption and improve the interior daylight performance of office rooms in cold regions of China. The optimal PV coverage ratio and WWR were also suggested by the researchers.

Another study on BIPV windows also pointed to the significance of utilising semi-transparent PV materials to save interior energy consumption. This study, conducted in a neighbourhood in Phoenix, Arizona in the United States [24], combined in-situ experimental measurements and a series of simulations via EnergyPlus software. The results showed that, compared with ordinary window glazing, BIPV windows could considerably lower the canyon air temperature and building cooling demand, thus achieving a reduction in cooling energy consumption of between 9.16% and 63.71%. A simulation study on the application of BIPV windows in different climate zones across China – conducted in the cities of Harbin, Beijing, Shanghai, Guangzhou, and Kunming – revealed similar energy-saving trends: up to 73% of energy consumption could be saved with the help of BIPV windows, while better interior daylight performance could also be achieved [25].

Another novel aspect of BIPV is the integration of food generation with PV systems. A study that took place in the contexts of Singapore and Southeast Asia investigated the sunlight availability and food production potential of tropical residential districts [26] . Based on computational simulations, 57 cases were evaluated regarding sunlight availability and the influence of three urban design parameters: plot ratio, site coverage and building height. The results revealed that the plot ratio and building height were the most influential urban design parameters in terms of PV energy and food production. Table 2 presents the current emerging and promising BIPV technologies and trends.

Table 2. Emerging BIPV technologies and trends.

Technology/trend	Authors and time	**Key findings**	Method type
Semi-transparent PV	Panagiotidou et al., 2021	BIPV should be applied to glazed areas of high-density urban blocks with high-rises and glazed buildings.	Simulation
	Cheng et al., 2019	Double-glazed photovoltaic windows can significantly reduce the energy consumption and improve the interior	Physical experiments and

		daylight performance for office rooms in cold regions of China.	simulation
	Chen et al., 2021	BIPV windows could considerably lower canyon air temperatures and building cooling demand.	Physical experiments and simulation
	Y. Sun et al., 2018	BIPV windows can save significant amounts of energy consumption and provide better interior daylight.	Simulation
Integration of food generation with PV systems	Tablada & Zhao, 2016	Plot ratio and building height are the most influential urban design parameters for PV energy and food production.	Simulation
	Tablada et al., 2020	High acceptance of façade integrated vertical farming, while the aesthetic performance of BIPV modules could be improved.	Web survey

4. Case Study

4.1. The HKGBC ANZ Ideas Competition and Treehouse

In 2021, Treehouse placed first in the "Future Building" category of the inaugural international Advancing Net Zero Ideas Competition organised by the Hong Kong Green Building Council. The competition aimed to generate ideas and solutions for carbon neutral high-rise office buildings in a subtropical, high-density urban context. The design adopted a transdisciplinary approach, with the design team comprised of architects, MEP engineers, structural engineers, climate engineers, sustainability engineers, smart building analytics engineers, service providers, and quantity surveyors.

Figure 1. Treehouse and the surrounding buildings.

Treehouse is a 220m-tall, Grade A office building, with a site area of 4,238 m^2 and a total gross floor area of 94,144m^2. The design responds to a hot and humid climate in a mixed-use, high-density district of Hong Kong. The energy use intensity (EUI) for the building's operational energy and upfront carbon were estimated at 51 kWh/m^2/year and 342kg CO_2-e per m^2 of construction floor area respectively, resulting in a substantially reduced carbon footprint of 9.3 million tonnes of CO_2-e, which is 74% smaller than the business-as-usual baseline.

4.2. Understanding the context

The building blocks that immediately neighbour Treehouse range from 90-310m tall. A solar radiation analysis (Figure 2) was carried out to understand their shading effects on the Treehouse façade. As most of the tall buildings are located on the south side of the building, the lower portion of the building has a relatively low solar irradiance which does not favour the installation of the solar panels.

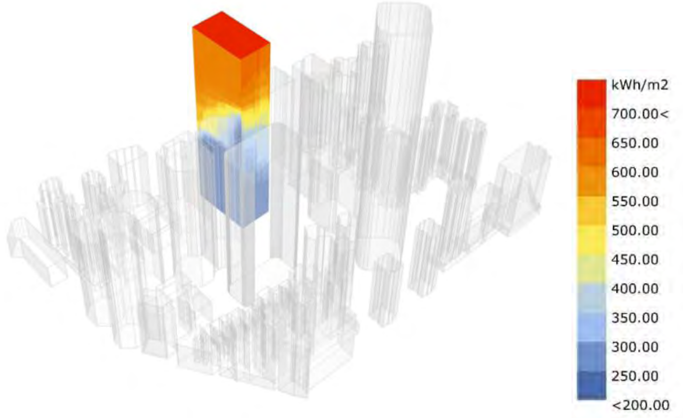

Figure 2. Annual solar radiation on the notional building mass.

4.3. Building mass optimisation to maximise solar availability

The design team devised a self-shading building form that enlarges the footprint of the building’s upper levels. In turn, this provides a larger area at the top of the building where photovoltaic (PV) panels can be placed – the location with the highest solar potential. The floor plates of the topmost three floors are also set back, creating an inclined angle towards the south for the PV panels. Therefore, the building’s tilt angle and size are maximised so as to create the highest efficiency for clean power generation. (Figure 3)

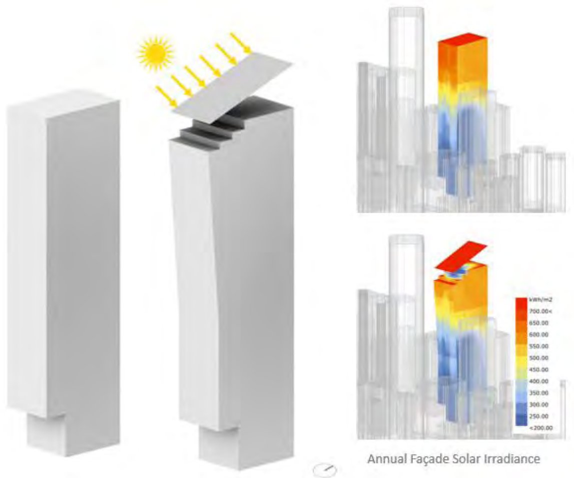

Figure 3. Optimised building form creates more solar availability for on-site renewable energy.

4.4. Maximised PV potential and efficiency

Various roof canopy shapes and tilt angles were simulated to optimise the solar energy generation potential, since typical crystallised silicon PV is sensitive to the angle of solar incidence (Figure 4). Different solar incidence angles dramatically affect power generation. PV panels installed vertically on the façade (yielding a solar intensity of about 0.5-0.8 Sun, compared with 1 Sun on a flat roof) may not operate effectively most the time. The team further optimised the area and shape of the roof canopy during the second stage of the competition, which led to an estimated potential energy generation of 512,187 kWh/year. The canopy's top skin is comprised of mono-crystallised PV and is anchored on glulam timber lattice. The bottom skin is made up of custom-designed two-sided greenery infill panels and is separated from the PV top skin by a ventilated space. The bottom green skin will shield occupants from the radiant heat of the PV and will provide cooling to the PV panels to increase their efficiency. The combined shading effect of the double-skin PV-clad tree canopy will also significantly reduce heat gain through the roof.

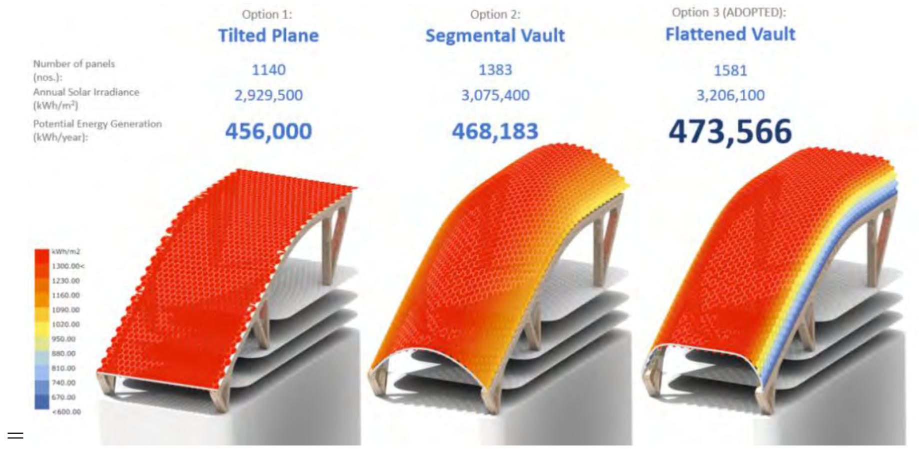

Figure 4. Optimisation of roof canopy for Mono-Si PV.

To further maximise PV potential, the team designed a high-performance integrated façade with a greater than two metre-deep overhang cladded with lightweight BIPV in the upper- and mid-zones of the tower. The façade also has an optimised tilt angle facing south to capture as much of the renewable energy on the building façade as possible. An emerging thin-film PV technology, Perovskite, was proposed for the façade. Perovskite has a higher generation efficiency under low light intensity (< 1 Sun). Research supports that 750nm-thick Perovskite PV reaches 20% efficiency at 0.5-0.6 Sun, or the same efficiency as mono-crystallised silicon PV under standard test conditions [1]. The team proposed adopting Perovskite technology to better utilise the solar resources available on a large low-solar-intensity vertical façade area. Future Perovskite PV panels are expected to be lightweight, flexible and easy to install on vertical façades. Neither structural loading nor embodied carbon increase with the installation of Perovskite PV on façades.

4.5. Challenges for high-rise high-density subtropical climates

Research shows that in future, the trend towards increased cooling loads brought by climate change will lead to an increase in total building energy use of 4.3% in subtropical Hong Kong [2]. Therefore, reducing the EUI and utilising on-site renewable energy are two solutions that may be employed to achieve net-zero. The Treehouse design, despite its total PV coverage of 13,471 m^2 and energy generation of 1,468,226 kWh/year (Figure 5), makes up only about 28.5% of the EUI.

Overhangs are one of the most effective passive architectural design elements for subtropical climates. Treehouse demonstrates that it is possible to achieve a lightweight solution that integrates solar panels on these overhangs. Besides a building's rooftop – usually the most effective place to install solar panels – overhangs, opaque façades and glazing are also potential places that can incorporate solar panels to maximise renewable energy generation. Overhangs should be considered first, as they have a larger sky view factor and receive more direct and indirect solar irradiance; while glazing is often shaded by overhangs or shading devices. Glazing integrated solar panels also need to balance aesthetics, views to the outside and visible light transmittance valued. Before implementing any solar panel solution, the specific urban context should be considered and self-shading studies should be carried out to understand solar potential panels in the high-rise high-density context.

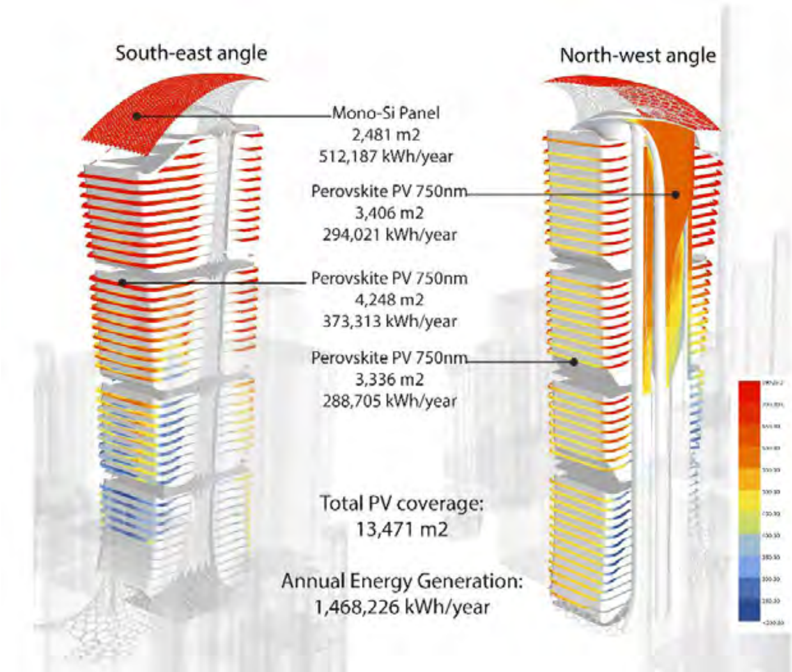

Figure 5. PV coverage and energy generation potential of Treehouse.

5. Discussion

Based on the literature review, several current research focuses were identified, including the aspects of energy production, BIPV and surrounding urban micro-climate, and the aesthetic performance of BIPV systems. Regarding to the emerging frontier of BIPV technologies or trends, there is a growing interesting in the fields of semi-transparent PV for glazing areas, and the combination of vertical greenery or farming and BIPV systems, for building projects in high-density urban communities. Although different approaches have been applied to explore these aspects, holistic architectural design methods covering the essential aspects and integrating the most promising BIPV technologies are still limited, the case study design presented by RLP teams has tackled the key technical aspects of BIPV design such as energy and urban micro-climate, the social sustainability aspects like aesthetic could be further investigated. In the BIPV technical applications, the Treehouse design has thoroughly considered the daylight optimization, reduction of cooling load by BIPV integrated shading device and the self-shading building geometry design. Semi-transparent PV could be the next step for BIPV design for similar projects in high-density context, while the vertical greenery systems can also be combined with façade integrated PV systems to create more advanced sustainable building envelopes, to promote the smart zero carbon future of our cities.

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