A new approach for the project process: prefabricated building technology integrated with photovoltaics based on the BIM system

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Abstract. Due to global warming and energy crisis, it is necessary to reduce CO2 emission and explore on-site renewable energy for the building industry. Prefabricated Prefinished Volumetric Construction (PPVC), a game-changing prefabrication technology, has advantages of labour-saving, leaner work processes with less dust, waste on the construction site, and better quality. To integrate renewable energy on-site, it is necessary to combine photovoltaics industry with building industry. Building-integrated photovoltaics (BIPV) serves the dual function of building skin, replacing conventional building envelop materials and transforming solar energy into electric power. Recently, we are investigating building-integrated photovoltaics (BIPV) as an integral part of the prefabricated prefabricated volumetric construction (PPVC) process. By identifying the similarities and benefits of the integration of BIPV and PPVC, we propose to use building information model (BIM) system as the platform to manage the data and share the information from design to building completion. The research also advises a project process workflow indicating the tasks in each stage for different stakeholders.

1. Introduction

The Singapore government agreed to reduce greenhouse gas emissions by 36% from the 2005 levels by 2030 based on the Paris Agreement. Due to land limitations and the scarcity of resources, Singapore can reduce its reliance on fossil-fuel energy using solar energy, an abundant renewable energy. The building industry has attracted attention from all over the world, as there is a demand to enhance efficiency. For example, the Singapore government requires all new buildings in Singapore to achieve a green level of certification with the recognized rating system, including Green Mark by the Building and Construction Authority (BCA). The Singapore government’s current target is to generate 350MWp of solar power to satisfy 5% of the energy demand by 2020. Additionally, solar energy is estimated to contribute 8% of Singapore’s projected peak electricity demand by 2030 and up to 30% in 2050.

Although it is common to attach photovoltaics (PV) modules to existing buildings as additional façade components, building-integrated photovoltaics (BIPV) is more productive for generating energy and performs the general functions of building materials. The cost of PV technology has been remarkably reduced since 2008; however, BIPV usage is still part of a niche market compared with building-applied photovoltaics (BAPV). The development of applying PV panels to building envelopes
is slow in many countries because of the lack of a holistic design-construction model and high costs. The Housing and Development Board, the largest residential real estate developer in Singapore, encourages the promotion of solar renewable technology and prefabricated building technology. Furthermore, the Singapore government demands a mandatory building information modeling (BIM) system for building projects. This provides an opportunity to the PV industry collaborating with the building industry to develop a new model based on the BIM system.

By identifying the similarities and benefits of the integration of BIPV and PPVC, the research proposes to use building information model (BIM) system as the platform to manage the data and share the information from design to building completion. We also advice a project process workflow indicating the tasks in each stage for different stakeholders.

2. BIPV Challenges and Perspectives

2.1. BIPV Definition

According to the BCA of Singapore, BIPV is defined as a PV module that can replace the traditional building component as part of a building envelope (e.g. window glass or roof/wall cladding), thereby serving a dual purpose and offsetting some costs [1]. However, BAPV is defined as a PV module that simply attaches to the building using mounting infrastructure without functioning as a building envelope [1]. BIPV can offer special benefits other than those of BAPV for aesthetic visual expression and a dual function as a building envelope to provide indoor comfort (e.g. water proofing, airtightness, and weather protection). Therefore, many aspects are involved to be considered to integrate PV on the building envelope shown in Figure 1 [2].

2.2. BIPV Application to Buildings

Although the price of BIPV products is relatively high, it can bring more economic advantages when replacing conventional materials as well as offset installation fees compared with BAPV products. Nowadays, PV cell types can be divided into silicon-based and non-silicon-based materials. Silicon-based materials are relatively inexpensive and durable to be implemented on roof and facade; therefore, they are suitable building envelope materials. Moreover, a silicon-based thin-film PV module can provide flexibility to the building form design together with a membrane or kinetic system. According to [3], the BIPV market products can also be divided into four kinds, foil, tiles, modules and solar cell glazing. Figure 2 shows a complete above category [3].

2.3. BIPV Cost and Barriers

Even though the cost of PV technology has experienced a distinctive decrease, professionals in the building industry are still reluctant to apply PV to building envelopes. The reason for this is the hardware of the PV system (i.e. PV modules, inverters, storage units, and supporting infrastructure) is manufactured independently by different contractors. Because of the highly competitive pressure from the market, the PV industry has had no time for design and research but has been urged to acquire a return on their investment in the short term. Additionally, good-quality PV modules still require the soft costs of the feasibility study, electrical layout, aesthetic design, and software development.

On the one hand, by introducing an automated manufacturing process can reduce hardware costs. Thus, it can be beneficial to mass production and customization. Meanwhile, due to the large numbers of PV modules that need to be assembled on the façade, more intensive labor and longer working hours are required in comparison to other traditional materials, such as concrete walls or metal cladding. If the PV manufacturing and assemblage can be proceeded in an off-site factory, it could reduce the labor costs and improve the precision of the project.
On the other hand, BIPV soft costs can develop digital design tools for architects and stakeholders to share information on the same platform. However, there are no specific BIPV design tools in the early design stage. With parametric modeling and solar potential analysis, architects can be more confident in integrating solar panels with the initial façade design. Moreover, the consultants from each stakeholder can provide reliable information to the architects to reduce the costs at different design stages.

Considering the potential of cost reductions for hardware and software, we can find that each factor is related to each other and converges to establish the digital platform to manage the information from design to construction, such as computer-aided design (CAD) and computer-aided manufacturing (CAM) tools. Furthermore, the BIPV product and design need to be standardized, modularized, and customized, which relies on an advanced digital design tool to provide flexibility to the architects as well as demands an intense and precise manufacturing method to achieve mass production. The rise of prefabricated building technology in Singapore satisfies the BIPV needs for centralized manufacturing and sharing the digital platform to manage the life cycle of BIPV.

Figure 1. Aspects need to be considered to integrate PV on the building envelope. Source: [2]

Figure 2. BIPV system categorization. Source: [3]

3. PPVC in Singapore Building Industry

3.1. DfMA and PPVC Definition
Because of strong pressure to improve productivity performance in the construction industry, the Singapore Economic Strategies Committee set the goal from 2010 to 2020 with 2 to 3% growth in productivity per year. To achieve the goal for the economy, the BCA announced the first Construction Productivity Roadmap to reduce foreign construction workers by 20 to 30% by 2020 and rely on new manufacturing technology to increase productivity performance while decreasing the high cost of hiring foreign worker. Prefabrication technology is the key to reaching this goal because it has proved that off-site production is more productive than on-site activities [4].

To invest in and stimulate precast technologies, the BCA has adopted Design for Manufacturing and Assembly (DfMA) technologies that consider manufacturing in the conceptual design stage to ensure a logical and organized construction process. The typical DfMA is composed of two parts: Design for Manufacture (DfM) and Design for Assembly (DfA) [5]. DfMA contains two main features:
• It is seen as a systematic procedure that adds value to the construction and production process by using and producing standardized components to decrease the design of various components [6] and is applied in the early design stage.

• Its value lies in the development of an evaluating method, allowing objective criteria to appraise the construction system by quantifying the effect of buildability on construction productivity, such as Singapore’s Buildable Design Appraisal System (BDAS).

Prefabricated Prefinished Volumetric Construction (PPVC) is one of the DfMA technology, the highest level of off-site production. PPVC enables to assemble the whole apartment units by prefabricated units, completing with internal finishes and fixtures. The prefabrication process is totally off-site and is installed on-site. It is suitable to form modular apartments, especially for prison-cell units or hotels and motel rooms (Figure 3).

3.2. PPVC Benefits

The first PPVC project in Singapore was a student dormitory at Nanyang Technological University. The dormitory consists of 1900 PPVC steel modules that were delivered to the site (six to eight modules each day) during construction. Although it cost 18% more than the traditional construction method, it was finished within a shorter period. The first private-sector project using PPVC, the Changi Crowne Plaza Hotel extension, decreased the construction time by 17% and labor cost by 40%, although it increased the manufacturing cost by 10–15%. Interestingly, there were over 4,000 different modules for the 638-unit project, one the largest applications of PPVC modules in the world (Figure 4).

As Singapore’s younger generation tends to choose careers in “FinTech” (financial technology), Singapore’s construction industry relies on foreign construction labor, resulting in high costs. As the main manufacturing locations are indoor automated factories, PPVC building technology brings many benefits. It can reduce time and labor investment by having fewer trade sub-contractors and crowded construction sites during project peak and reducing idling and down time due to weather. It also improves the safety on site and quality of the construction because the chance of work injuries (e.g.
work-at-height accidents) is reduced by working in an indoor factory that ensures appropriate supervision and consistent quality. In addition, the whole manufacturing process creates less construction material wastage and has the flexibility to incorporate “green” features, such as BIPV technologies. The combination of the PPVC and BIPV industries could benefit both by offsetting the fees of PV panel installation, adding the value of renewable energy on-site, and reducing the costs of labor and training. However, a strong platform is required to share the knowledge and information from all stakeholders by comprehensively linking the downstream activities, such as procurement, fabrication, transport, and installation, with upstream activities from briefing, options appraisal, and concept design.

Figure 4. Crown Plaza Changi Airport Hotel with PPVC. Source: https://www.bdcnetwork.com/it-only-took-26-days-complete-construction-crowne-plaza-changi-airport-hotel-extension.

4. BIM System

4.1. Definition
BIM is the process of producing a model of an asset that contains information about the asset. Unlike other non-BIM modeling software, BIM software is developed with the aim of streamlining the processes of design, manufacturing, and assembling [8]. Generally, the prefabricated building technology DfMA, including PPVC, prefabricated bathroom units (PBU), and other precast technology, is a component-based fabrication method that has high similarities with BIM modeling, which manages the geometry as building components or a catalogue embedded with parametric control. The BIM platform of building systematical thinking is an effective management solution for converging all building information into geometries, including material layering, budgets and costs, product names, and even the time-frame simulation of the whole construction process on-site, which is different from other non-BIM parametric software (e.g. Rhino/Grasshopper) that only contains geometrical properties, such as sizes, colors, and textures.

4.2. Benefits of BIM
There are normally six main stages from design to construction: project brief development, concept design development, detailed design development, pre-construction, construction, and post-completion. In the first two stages, project brief development and concept design development, the architect mainly proposes the initial idea for the building design, giving the approximate quantities, size, shape, and location for the building and defining the repetitive modules. Once they have entered the detailed design development and pre-construction stage, all consultants are involved in adding detailed information on the structure and MEP to the model, as well as developing the supply chain input so that the rich data model is ready to send for fabrication. For the stage of construction and post-completion, the model can reflect the construction process and simulate the design changes made on site, turning into a “smart” building monitoring the changes in the building over time after completing the construction.
Considering the involvement of BIM in the different stages of building design to construction, renewable energy experts, construction consultants and other stakeholders can elaborate well in the beginning of the project. A higher degree of prefabrication and sustainability can be achieved due to the prefabrication schedule and repetitive module developed in the early design stage having less impact on the final construction once the design has changed. If the renewable energy module, such as the PV panel, is added to the prefabricated PPVC module as the digital library on the BIM platform, it can offset the fees and save the time required for the extra installation, meanwhile providing higher customizability opportunities for clients and architects regarding visual expression. However, there are no specific PV module design tools based on the BIM platform that enable architects to customize their project-based PV module or the product library based on the current market. In addition, the chances to evaluate the performances of the building and PV panels after the construction are lacking. Thus, it is necessary to develop a new project model process to integrate PPVC building fabricated technology, BIPV technology, and the BIM platform to add more sustainable value to the design.

5. A New Model for the Sustainable Building Industry

A new project model BIM-PPVC BIPV system (BPB) should be investigated based on the BIM digital design and management platform that incorporates PPVC building technology and integrated BIPV technology. As seen in Figure 5, the intersection of the BIM system, PPVC technology, and BIPV technology is at the core of the BPB (BIM-PPVC BIPV) system.

If we only consider the integration between the BIM system and PPVC technology, the benefits of renewable energy from BIPV technology are not utilized. Although many successful buildings have been designed with the BIM system and PPVC technology, most of them find it hard to achieve a net-zero-energy building or lose the opportunity to be energy saving after completion.

Component-driven design and a prefabricated volumetric module in an indoor factory with the BIM system as an effective management tool enable the reduction of waste of materials and reduction of labor costs, improving the quality and precision of construction, such as buildings in the Singapore Changi Crown Hotel, See Figure 4. With the combination of BIPV technology, buildings can harvest solar energy on-site and decrease greenhouse gas emissions in the long term.

![BIM-Prefabricated PV system](source)

On the other hand, the intersection between the BIM system and BIPV technology alone would largely fall in the domain of solar potential exploration in building envelopes and solar panel automated arrangement, excluding the possibility of prefabricated building modular applications. The BIM-PV Web Tool, created by Construct PV, successfully enables architectural designers to customize the PV module in the early design stage, linking with the BIM platform as the parametric model with material layer properties. However, the PV module design result does not cooperate with the building prefabricated process.
Finally, BIPV and PPVC technology cannot successfully integrate with each other without sharing the BIM system. Even though the two industries, PV technology and prefabricated building technology, have their own various design and construction tools, the separate management platforms cannot converge all the information from different consultants, resulting in PV products as an additional layer attached to the building surfaces. The architects can easily give feedback from 3D visualization based on the BIM system; thus, the changes in the PV module can be immediately reflected in the construction model in the factory.

The key benefits of the BIM-PPVC BIPV (BPB) model are as follows: The BPB model refers to a conceptual collaborative method to combine PPVC and BIPV technology based on the BIM system. Detailed models from BIPV and PPVC design can be developed as an information library model in the BIM system due to the similar feature of component-driven design in the two industries. Additionally, the two industries require intensive labor to fabricate products equipped with precise information and automated manufacturing facilities, which offers opportunities to integrate the fabrication and installation process in the same working indoor factory place, improving the efficiency of labor management and construction quality. Moreover, the BIM system enables architects and other consultants to design the BIPV envelope in the early stage together, thus having less impact on the construction stage due to the changes in BIPV or PPVC design. This provides the opportunity to reduce the cost and material waste by setting up a mass production strategy and defining repetitive modules for both PV and building units in the early stage. Lastly, the building performance evaluation and monitoring can be reflected in the updated BIM system, such as electricity generation, water supply, and electrical network performance. The data-rich model can help to improve and study the whole life cycle of the materials.

5.1. The Workflow
Figure 6 shows the six typical stages of the project process. The BCA of Singapore suggests the BIM-PPVC steps during the process. The present study further proposes the BIPV design steps to embed PV design and fabrication with the prefabricated building technology in the BIM system, adding the value of sustainability to the PPVC technology. The workflow chart demonstrates the possibility of combining the two apparent parallels, the PV and PPVC industries, on the same working system BIM platform, presenting the tasks at each stage and relations.

6. Conclusion
Even though BIPV is the most reliable and promising renewable energy technology in the Singapore scenario, the promotion of PV in the building industry is still lacking. By understanding the PV hardware and soft costs, sustainability of the PPVC fabrication process, and BIM systematical design and control, the paper presents a new conceptual project process model, BPB (BIM-PPVC BIPV model), which serves as a theoretical framework to identify the possibility of combining the PV and PPVC industries through the BIM system. Introducing the BPB model will be an effective approach to attract users to BIPV technology. The similarities between the two industries, such as intensive labor and component-driven design, provide solid ground to use the BIM system to manage the component data from design to post-completion. The present study suggests a comprehensive workflow and tasks to be completed for each stage in the project process as well as encourages the consultants to cooperate with architects to develop a customized PV module in the early design stage to establish reliable and effective BIPV-integrated prefabricated strategies.
Figure 6. Key BIM actions for the DfMA approach at various stages. Source: by authors based on [8]

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