Chapter

Reimagining Building Facades: The Prefabricated Unitized BIPV Walls (PUBW) for High-Rises

Tianyi Chen, Chye Kiang Heng and Shin Woei Leow

Abstract

In urban settings, building-integrated photovoltaics (BIPV) on facades prove more effective than rooftop installations, especially for tall structures with limited roof area. Yet, the absence of ready-to-use BIPV solutions restricts their broader use. This research presents a prefabricated unitized BIPV wall system, using light gauge steel structure prefabrication. The innovative BIPV system boasts a multifunctional, modular design, ensuring quick installation and meeting airtightness standards. The design process encompasses cross-sectional design, PV mounting, 3D modeling, and full-scale mock-up demonstrations in Singapore. Remarkably, the prefabricated units are preassembled and pre-wired, allowing three non-specialized workers to install from inside buildings, eliminating the need for scaffolding. The study offers insights into the new BIPV system's advantages, identifies its constraints, and suggests avenues for future enhancement.

Keywords: building-integrated photovoltaics, BIPV, solar energy, prefabricated construction, opaque PV, photovoltaics implementation

1. Introduction

Over the past decade, worldwide greenhouse gas emissions have surged, hitting unprecedented levels in recorded history [1]. Nations aligned with the Paris Agreement are committed to slashing their carbon outputs. As a result, they are formulating energy blueprints to shift their energy sources and diminish dependency on fossil fuels.

Unlike building-attached photovoltaics (BAPV) that need extra structures for installation, BIPV systems integrate photovoltaic modules directly into the building's facade, serving both as an envelope and a power generator. With silicon costs dropping, PV module prices are now on par with common construction materials like marble and aluminum cladding [2]. While rooftops offer solar exposure, their space is limited by infrastructure equipment. In contrast, building facades offer ample space for PV integration, making them ideal for BIPV.

In urbanized cities, tall buildings dominate the skyline. Their design influences material choices, demanding innovative construction and safety solutions. Currently, the main issue with tall structures and BIPV facades is accessibility. The installation and construction require workers to use scaffolding or elevating platforms for PV module installations, often preceded by fixing aluminum cassettes. This process is not only tedious but resembles the construction approach of BAPV, emphasizing the challenges with time and costs previously noted [3]. Elevated BIPV work presents safety concerns, with PV components vulnerable to adverse weather, impacting performance and safety [4]. Some prefabricated curtain wall systems with PV technology offer installation from inside but compromise on power generation or integration areas.

Prefabricated construction is a method wherein building components are produced and assembled in an offsite factory before being transported to the construction site for erection [5]. This technology brings several advantages [6]. Primarily, it can expedite the process of on-site installation. Additionally, it allows for stringent quality control of construction in the controlled environment of the offsite factory, thus promoting material efficiency. Lastly, it mitigates the risk associated with laborers working in hazardous environments.

Presently, several studies are concentrating on the intersection of the photovoltaic industry with the prefabrication construction sector. RICS [7] proposed the concept of a prefabricated BIPV business model to reduce costs in industry development. Large prefabrication construction firms can establish dedicated PV departments, thereby eliminating the need for end-users to deal with contracts and maintenance of the PV system in their residences [8]. This arrangement also simplifies the process of accessing renewable energy subsidies. Further, Longas et al. [9] proposed the concept and prototype of a PV system featuring a laminated timber wood structure using prefabricated construction. Valckenborg [10] incorporated PV thin film within an aluminum folded structure to expedite construction. However, these current studies fall short of satisfying the requirements of high-density urban development when integrating with PV systems, as is the case in Asian countries like Singapore.

This study introduces a new design for a fully prefabricated BIPV wall suitable for tall structures, streamlining PV installation, and wall structuring without exterior scaffolding. The outcome is the prefabricated unitized BIPV wall (PUBW). This multi-layered, opaque BIPV wall minimizes on-site height-related risks, ensures efficient electricity generation, faster construction, cost savings, and protects PV components from prolonged adverse weather during building.

2. Various BIPV building integrations

The various types of BIPV building integrations introduced in the previous section can be mainly divided into two categories: roof system integration and facade system integration. The following illustrates the concept details of each type of building integration and the advantages and disadvantages when integrated with the PV panel.

2.1 Roof PV systems

Skylights use glazes to cover a part or entirety of a roof or atrium [11]. Skylights allow people to enjoy sunlight in an indoor environment. PV modules can replace glass to form semi-transparent or opaque parts in the skylight. By changing the density of the silicon crystal material on the glass, the indoor lighting and shading effects can be adjusted.

Cold roofs comprise an external cladding material, an air cavity, and a load-bearing substructure [12]. The ventilated air cavity dissipates the temperature of the outer cladding material. It is also known as a discontinuous roof because the cladding material usually forms a watertight layer of tiles, slate, sheet metal, etc. PV can replace the cladding material and mimic its color and texture through external coatings, making it "invisible". This type of PV integration is widely used especially where the roof receives sufficient solar radiation and has a certain angle of inclination.

A shed roof is the external extension space of a building with climate protection functions, such as shelter from sun and rain. PV replaces the cladding or glazing material of the canopy and does not require the same thermal performance considerations as skylights.

2.2 Facade PV systems

A rainscreen wall comprises cladding, an air cavity and a substructure bearing the load. This type of wall uses a ventilated air cavity to dissipate solar heat; hence, it is also called a cold wall [13]. PV modules replace the external cladding material and increase the efficiency of electricity production, particularly silicon PV, owing to rear ventilation. Slits could be present between the PV cladding and other cladding materials; hence, no significant pressure difference occurs between the cavity and the exterior. The water that penetrates inside the cavity eventually drains out of the cavity through evaporation and natural outflow. The substructure bearing load is protected against water.

A curtain wall is a strong representation of the industrialization of the building facade, mainly comprising an extruded aluminum frame and filled glass or metal panels, which can be modularly manufactured and pre-assembled, such as unitized curtain wall, or assembled on site, such as stick curtain wall [14]. Curtain walls need to meet the function of resistance of horizontal load and transfer to the main structure of the building, such as wind force and earthquake, as well as airtightness, heat insulation, sound proofing, etc. They are self-standing structures and bear no dead load weights from the building, hanging from the edge of the floor slab by bracket components. PV usually takes the place of filled clear glass (vision window) or metal plate/opaque glass (spandrel).

A BIPV double skin comprises two layers of glass. The outer skin is mainly intended for lighting purposes, while the inner glass has an insulating effect. The distance between the two layers of glass varies from about 20 cm to 2 m, acting as heat insulation, thermal insulation, sound insulation, etc. The ventilation method (e.g., mechanical, natural or hybrid) and opening and closing time control of the air cavity can be adjusted depending on the climate conditions of the building for energy saving. PV replaces part or the entirety of the outer skin of the glass.

BIPV shading devices are generally placed on the external surface of a building facade to control the intensity of light and heat entering indoors [15]. Various configurations and functional options are available, such as providing shade from top sunlight, the east morning sun or the west sun in the evening. Thus, the power generation function of PV and shading can well complement each other.

3. Prefabricated construction technologies

There are various construction materials that can be utilized for prefabricated construction, such as concrete, laminated timber wood, steel, and light gauge steel. This research incorporates a light gauge steel structure as the principal structural system due to its recyclable nature, which makes it apt for application in high-density

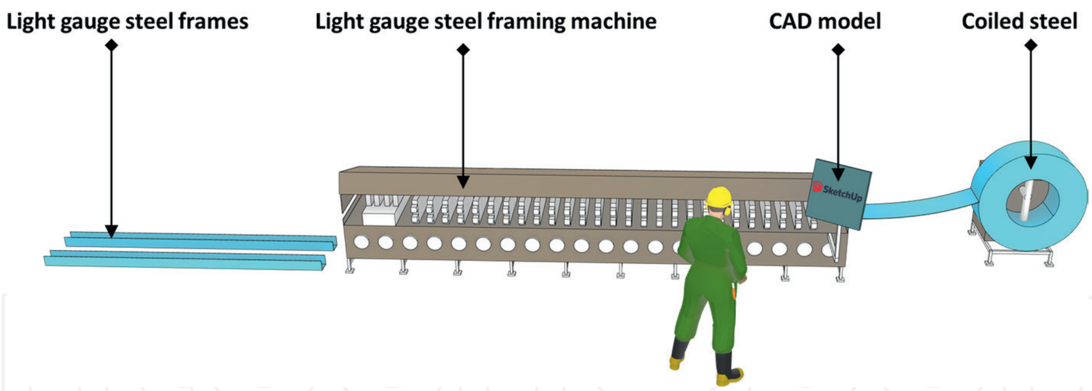

Figure 1.
From coiled steel to the creation of light gauge steel frames, the manufacturing process is automated in the factory, translating CAD models directly into finished products.

urban areas like Singapore. **Figure 1** illustrates the automated fabrication process of light gauge steel frame components in the factory setting, utilizing data imported from the digital model.

In Singapore, prefabricated prefinished volumetric construction (PPVC) leverages a light gauge steel structure as its primary architectural element to enable the creation of high-level prefabricated buildings. The low embodied carbon of light gauge steel structures confers environmental advantages, with the added benefit of recyclability. For the design at hand, a C-shaped channel with a 2 mm thickness is adopted as studs. The study positions the load-bearing studs at intervals of 1000 mm. To counteract seismic and lateral wind load forces, as well as to sustain the weight of photovoltaic (PV) panels, three potential systems—X-bracing, sheathing panel, or a combination of both—are proposed as a means to withstand forces in the horizontal plane [16]. In this research, a blend of X-bracing and sheathing panel is utilized. Beyond their use in building façades, light gauge steel structures demonstrate high versatility as they can also be incorporated into roofs and partition walls.

Utilizing computer-aided design and automation, the C-channel structure can be tailored for specific lengths and hole placements, optimizing infrastructure embedding and PV panel holding, which reduces costs and time. For projects with substantial PV areas, one can either customize PV sizes or use automated tools to modify the light gauge steel structure to fit the PV dimensions and design. Being lightweight, these structures can be preassembled off-site and conveniently transported for on-site installation.

4. The design of prefabricated unitized BIPV wall (PUBW)

4.1 2D cross-sectional design

This research examines the environmental factors to identify the materials and sites associated with each layer of the BIPV façade, aiming to establish a standard 2D cross-sectional design. Such factors should be taken into account for PUBW. **Figure 2** presents the load-determining factors under consideration, which influence the selection of materials to be implemented in the construction system.

The strategy for weather control (including barriers against water, air, and vapor) aims to ensure the wall's water and air seal. PV, serving as the rain screen system's

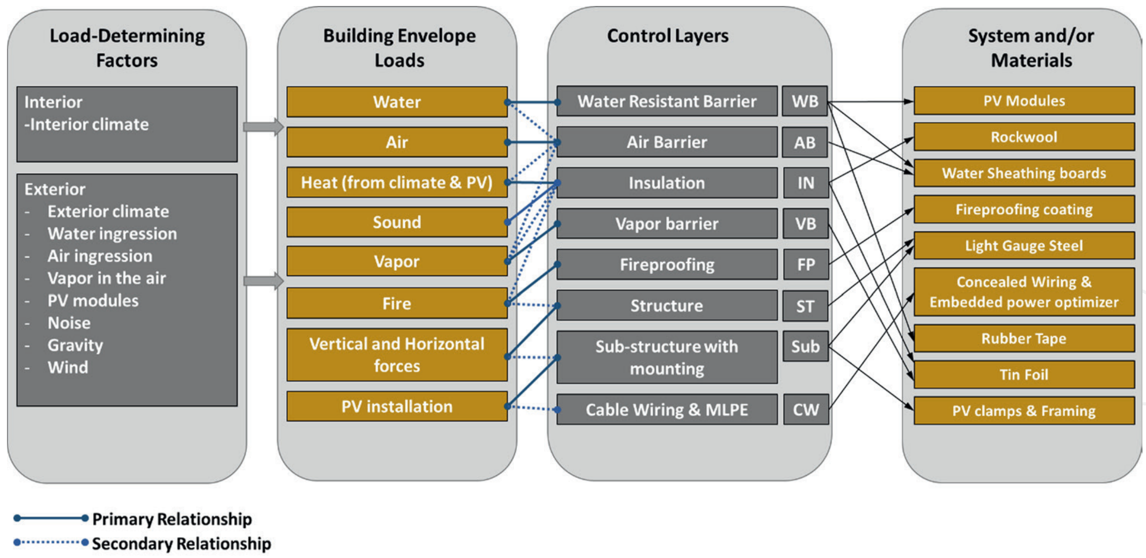

Figure 2.
Analysis of the functional layers in PUBW components.

cladding, is naturally waterproof, preventing most rainwater from coming into direct contact with the external wall and wires. Additionally, the seals between units must uphold weatherproofing standards.

Each PV module is equipped with a module-level power electronics (MLPE) to enhance power generation, especially when PV modules experience partial shading. Having pre-wired and pre-installed MLPE devices simplifies the installation for workers without electrical expertise.

Figure 3 depicts the standard horizontal and vertical cross-sections of PUBW. BIPV façade designs must meet core structural and weatherproofing standards to ensure a secure and cozy interior for inhabitants.

4.2 Mounting design

PV mounting systems greatly influence solar systems' esthetics and efficiency due to shading potential and load bearing. They fall into two categories: linear- and point-fixing systems [9]. Linear systems include mullion-transom and structural sealant systems. Mullion-transom systems have protruding elements causing potential for shadowing and debris accumulation. Structural sealant systems, without protrusions, use sealants for holding PVs and require extra precautions if above 8 m. Point-fixing systems are of three types: drilled spot, clamp fixing, and undercut anchor. Drilled spot systems demand specific PV types due to hole placements. Clamp fixing systems employ U-shaped clamps, while undercut anchor systems, reducing shading, need specialized glass types. This study's prototype employs the mullion–transom system for PV mounting.

4.3 Joint design

Joint design is crucial for functional continuity in independent prefabricated units [17]. It needs to ensure waterproofing, provide a "plug-and-play" assembly, and permit indoor manual installation without outdoor equipment like cranes. The PUBW's steel frame is consistently thin as it is non-structural. An "interlocking" design, like a

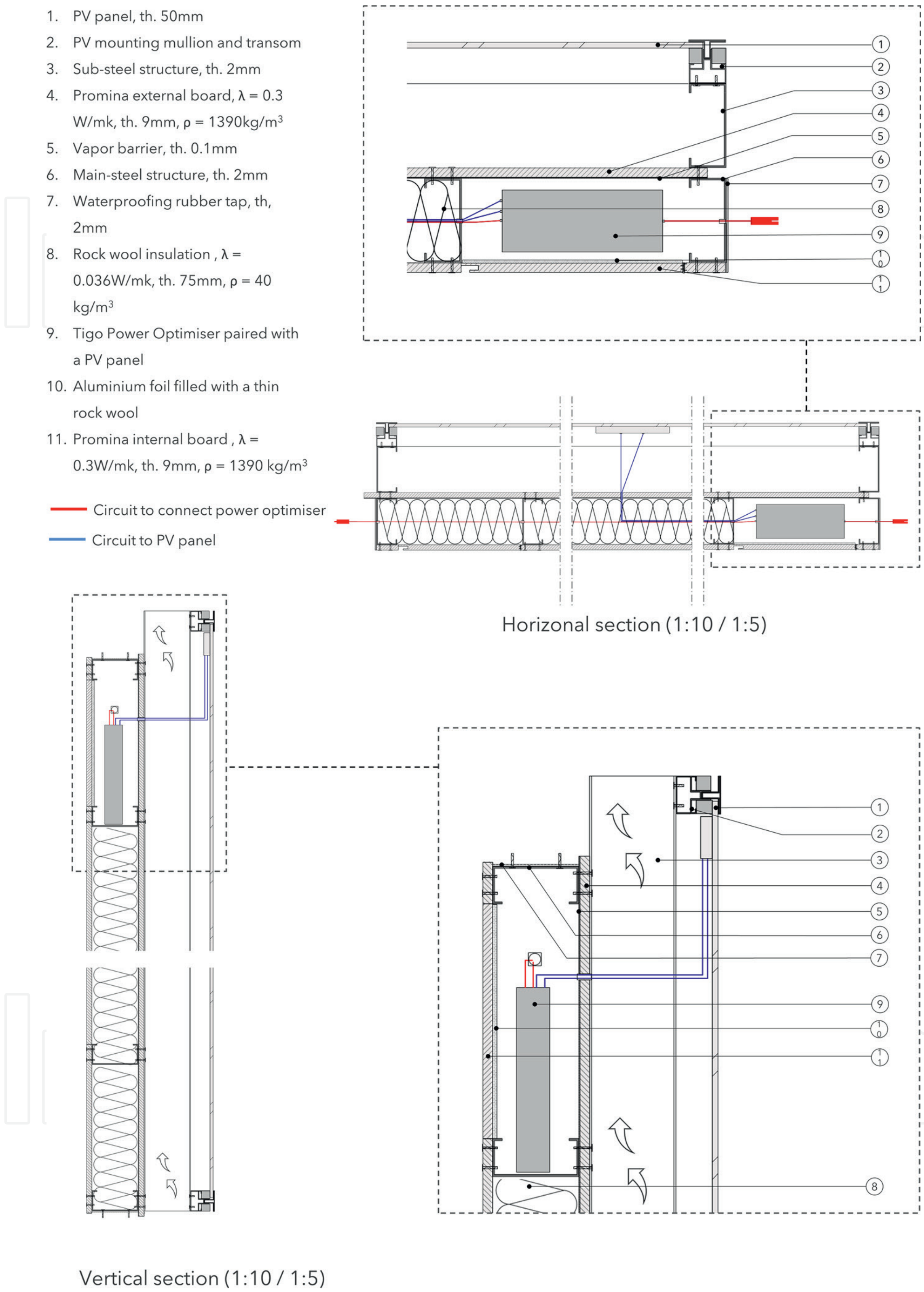

Figure 3.
2D horizontal cross-section of the preassembled unitized BIPV facade.

unitized curtain wall system, ensures seamless fitting and weatherproofing between adjacent units (**Figure 4**). This design uses male/female junctions for waterproofing and easy installation. Corners of the units allow for connections, making installations

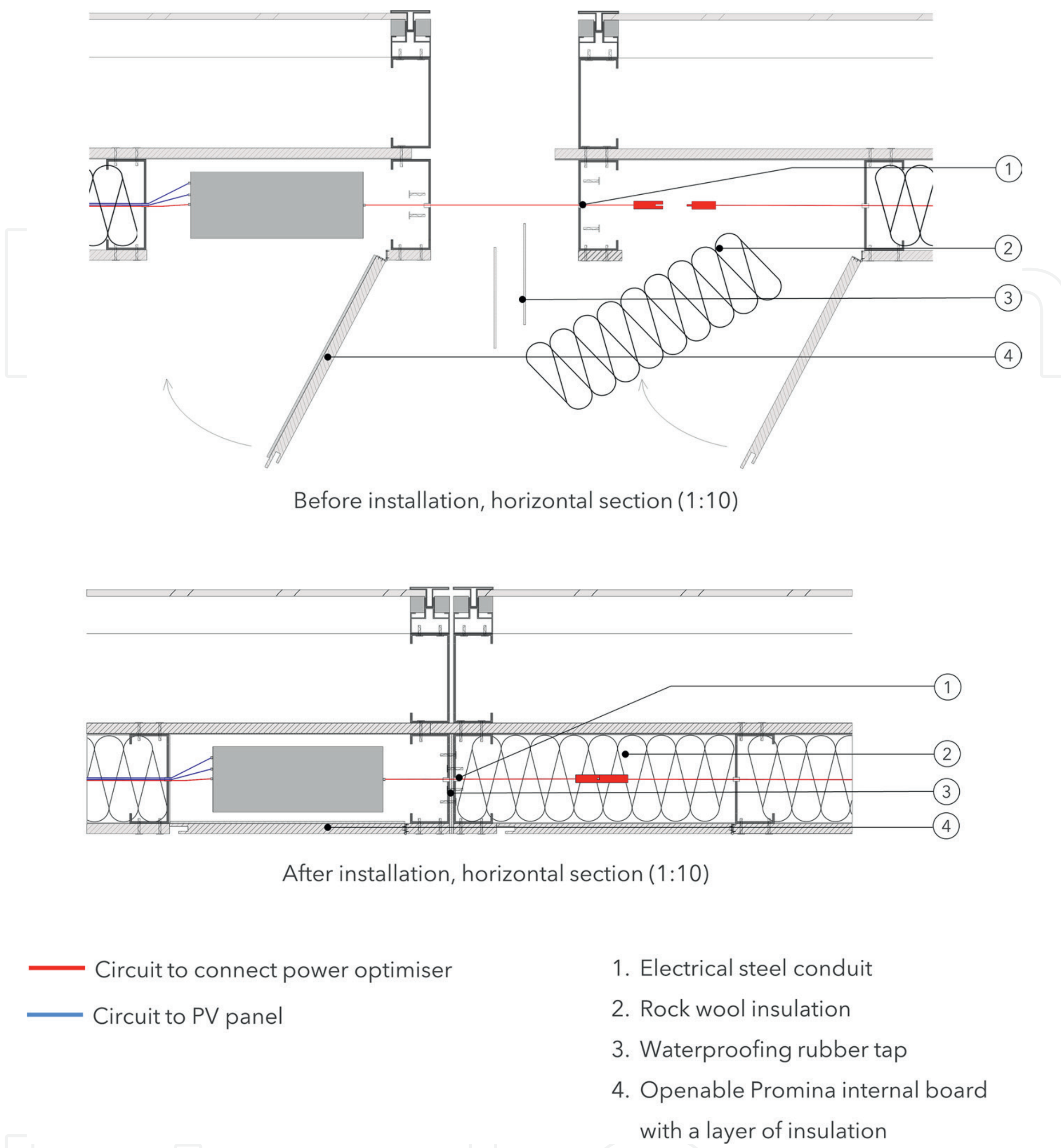

Figure 4.
Interlocking joints ensure a weatherproof and swift dry installation.

possible with just manual labor. Post-installation, equipment like MLPE devices fit into reserved corners, protected by rock wool insulation, ensuring no overheating. Accessible plasterboards ease future maintenance. After assembly, the interior wall gets painted for visual consistency. This system's design offers architects flexibility, as shown in combined sections with different unit types.

4.4 3D Modeling design

3D models of the PUBW units are created for initial system validation, which displays each layer's representation, clarifying design details (**Figure 5**). Moreover, **Figure 6** provides a glimpse into the off-site pre-assembly, aiding in worker training for fabrication and installation.

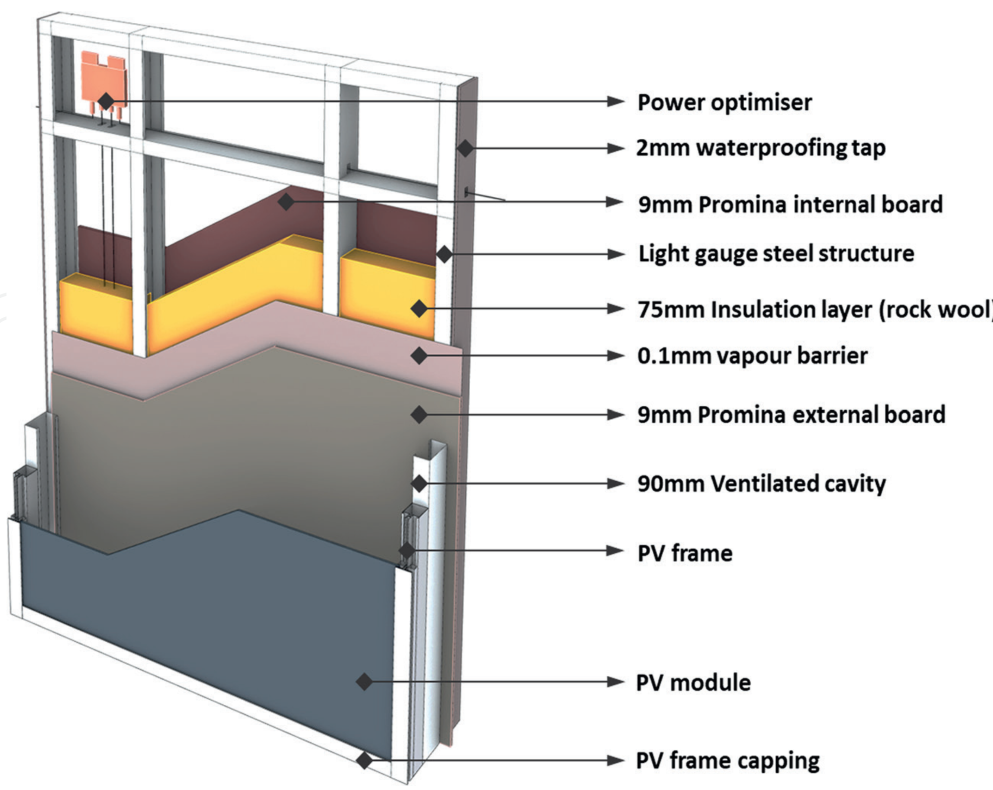

Figure 5.
3D model of the PUBW.

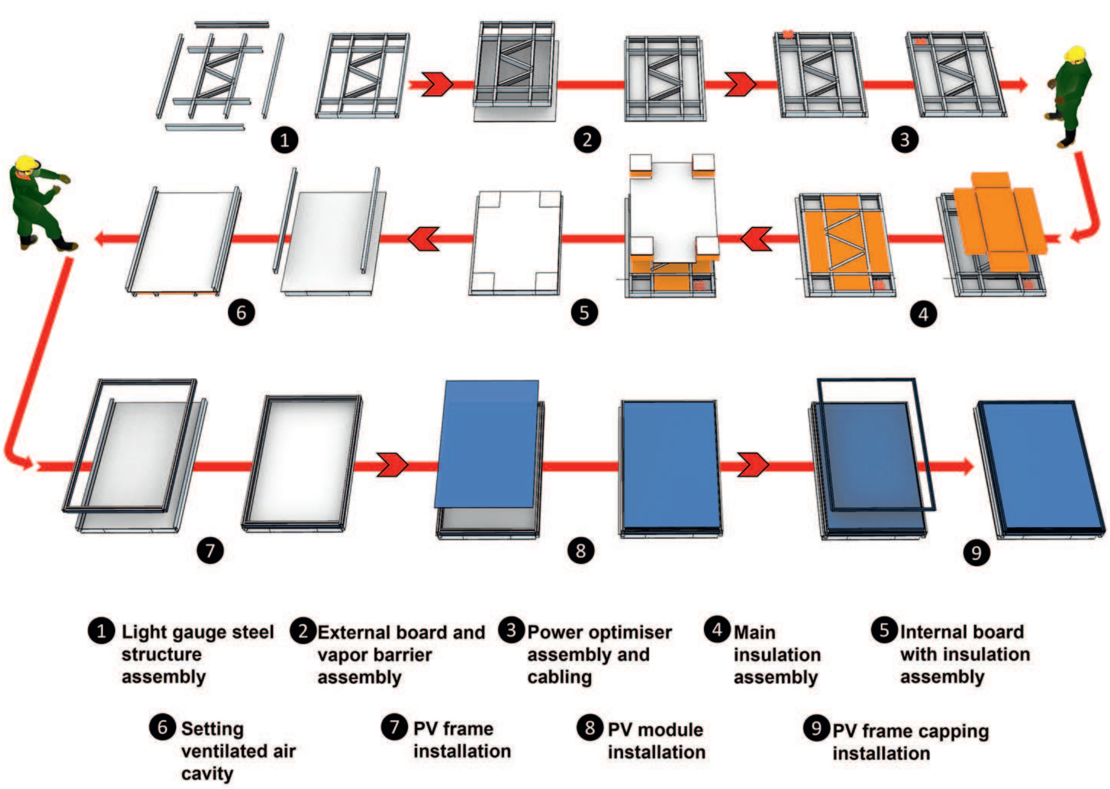

Figure 6.
Workers can be trained to understand the preassembly process through 3D models.

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Figure 7.
The mock-up of the PUBW.

4.5 System mock-up

The "Modular Pod" prototype, made of light steel, showcased the PUBW on its eastern side (**Figure 7**). It was divided into two floors to replicate high-rise construction. Using standard building components and commercial PV modules, the prototype reflected actual dimensions. The installation was efficient, needing only three workers for assembly and PV wiring. After completion, the interior was painted for esthetics.

5. Conclusions

This research introduces a PUBW that combines architectural assembly and PV-powered energy, facilitating easy, scaffold-free installation on-site. Ideal for tall residential buildings with predominantly opaque facades on the west and east sides, this prefab façade shortens construction duration and simplifies BIPV system installation. Furthermore, it offers architects considerable design versatility and supports tailored mass production.

Technology can be adjusted to accommodate varying construction scenarios. If lifting or hoisting equipment is available on-site, the size of the PUBW can be scaled up to form a mega panel composed of several individual panels. Architects are free to design the material combination within the mega panel. For instance, they can integrate metal sheet panels with PV panels or modify the color of the panels. The larger size of the mega panel, compared to the standard size of PUBW, allows for faster and easier construction with the aid of hoisting machinery. This significantly increases the efficiency of on-site installation.

Furthermore, to enhance the efficacy of BIPV construction, it is of paramount importance to develop a comprehensive Building Information Modeling (BIM) digital library for PUBW or analogous BIPV prefabricated products. Digitized components within BIM can be viewed as a composite of multifaceted information, encompassing data on product logistics, associated costs, and photovoltaic performance metrics. By incorporating these digitized components into their BIM designs, architects can significantly economize on time, facilitate a more streamlined design procedure, and consequently accelerate the iterative process of design.

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