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A Comprehensive Review on the Cost Reduction and Uptake of BIPV through the Integration of PV and Prefabricated Building Industries

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Abstract

Current approaches for the reduction of energy consumption in buildings are often predicated on the integration of bespoke renewable technologies into building projects. Among various renewable energy sources, solar energy is an attractive option in many countries with access to abundant solar resources. Although photovoltaic technologies have experienced exceptional cost reductions among electricity-conversion technologies since 2008, the integration of solar panels into building envelopes has been deployed slowly in most countries. Building Integrated Photovoltaics (BIPV) still exists in a niche market in comparison to Building Attached Photovoltaics (BAPV) and most of the building professionals are reluctant to implement BIPV mainly due to the high capital cost. BIPV cost includes a number of cost elements from the design stage to disposal stage of its life cycle. This paper intends to identify the cost reduction potentials and deployment drivers of BIPV modules and propose a timely relevant solution of integrating PV and offsite building industries to produce PV integrated prefabricated building modules. Automation and process optimization, resource utilization, integrating PV technology with prefabricated building construction, mass production and bulk purchasing of materials, continuous R&D on alternative materials and waste reduction, government support and minimising capital expenditure are the main cost reduction potentials identified for hardware cost. Introducing BIPV specific design tools, effective stakeholder collaboration via decentralized information platforms, integration of PV and building industries for stakeholder collaboration, Radio Frequency Identification (RFID) blockchain-based supply chain information sharing platforms to avoid errors in supply chain, unified practice for permit, inspection and interconnection (PII) procedures, BIPV specific building codes, standards, policies and incentives and low interest loans are some soft cost reduction potentials identified in the study. In order to obtain a rapid uptake, the study recommends the integration of PV and building industry elements through (1) participation of BIPV manufacturer/installer in the building design process, and (2) BIPV integrated prefabricated building construction.

Introduction

Buildings remain a sector where efficiency improvement is critical to achieve as per the commitments of the Paris Agreement. Current approaches for the reduction of energy consumption in buildings are often predicated on the integration of bespoke renewable technologies into building projects. Among various renewable energy sources, solar energy is an attractive option in many countries with access to abundant solar resources. Although it has been common to ‘attach’ solar PV modules to an existing building fabric, often after the building has been constructed, an integrated approach is more productive whereby the PV module and building element (such as a roof or façade) are produced concurrently and are basically indistinguishable. BIPV is a novel technology which integrates solar modules as part of the building skin to generate energy while performing the general functions of building materials (Shukla et al., 2017). Although photovoltaic technologies have experienced exceptional cost reductions among electricity-conversion technologies since 2008, the integration of solar panels to building envelopes has, to date, been deployed slowly in most countries. BIPV usage has gradually increased during the past decade with the global estimated BIPV annual growth rate of

18.7% from 2013 to 2019 and a total installed capacity of 5.4 GW (PV Sites, 2018). BIPV still exists in a niche market in comparison to BAPV and most of the building professionals are reluctant to implement BIPV mainly due to the high capital cost. BIPV costs include a number of cost elements from the design stage to disposal stage of its life cycle. This paper intends to identify the cost reduction potentials and deployment drivers of BIPV modules and propose a time relevant solution of integrating PV and offsite building industries to produce PV integrated prefabricated building modules. This paper is structured under two main stages. In the first stage, the study discusses the BIPV cost trajectories and opportunities for cost reduction. In the second stage, the study critically evaluates the BIPV deployment drivers with special concern on the effective integration of BIPV technology with prefabricated building construction. BAPV and conventional building materials are used as the reference cases to distinguish the similarities and differences, and identify the reason behind the slow uptake of BIPV technology.

BIPV Applications in Buildings

According to the International Energy Agency (IEA) PVPS Task 15 report, BAPV is defined as "Photovoltaic materials that are not used to replace conventional building materials in parts of the building yet simply attached to the building" using mounting infrastructure (IEA, 2018). The IEA PVPS Task 15 defined BIPV as "a PV module and a construction product together, designed to be a component of the building. A BIPV module is the smallest (electrically and mechanically) non-divisible photovoltaic unit in a BIPV system which provides building-related functions. If the BIPV module is dismounted, it would have to be replaced by an appropriate construction product" (IEA, 2018). BIPV mainly substitutes facades, skylights, windows, shades and roofs (Pagliaro et al. 2010). It is a solution for building owners who concerned with the aesthetic appearance of the roof mounted PV. BIPV provides unique benefits compared to BAPV such as (1) providing an iconic architectural design and (2) executing the main functions of a building envelope material (Shukla et al., 2017). Unlike BAPV modules, BIPV are designed to meet major building material requirements such as controlling intrusions, weather protection (protect from rain, wind, heat and cold), insulation, noise control and privacy while supplying comfort, fresh air and daylight. In particular, BIPV systems' ability to provide adequate daylight is useful in reducing/ eliminating the electricity consumption for lighting during day time (Chow et al., 2013). In addition, the air gaps inserted in the BIPV panels can be used to absorb the heat from the panels which can be directed into the building to provide space heating (Agathokleous et al., 2017).

BIPV Cost Aspects

BIPV modules perform as a building envelope material while generating onsite electricity (Aste et al., 2016). Therefore, in comparison to the conventional building construction, BIPV buildings provide material offsets with possible reduction in the total building construction cost. According to the cost comparison of PV Sites (2016), BIPV roof module costs are comparatively higher than the conventional roofing materials. However, this comparison does not include the financial benefits of BIPV modules resulting from both onsite electricity production and material offset. On the other hand, BIPV façades are cost effective and competitive with conventional façade materials (PV Sites, 2016). For example, BIPV integrated wooden façade price is low compared to glazed curtain walls and window façades under certain conditions. It is recently identified that the unit area cost of an architectural glass can be 1.65 times more expensive than the PV modules (Sorgato et al., 2018). Further, BIPV façade price range is approximately similar to the metal façade price range. Moreover, BIPV façade price ranges and other cold façades price ranges such as fibrocement, brick ceramic and stone allign with each other up to a certain extent (PV Sites, 2016). BIPV balconies and solar shading prices are affordable in comparison to expensive warm façades such as glazed curtain walls and windows.

The cost of BIPV can be divided into two main parts; hardware and soft costs. Hardware costs include all the hardware components of the system such as PV modules, inverters, storage units and supporting infrastructure. Soft costs include all necessary service costs from the design stage to the end of the BIPV life cycle such as labour costs, legal costs, permit fees, insurance costs, administrative costs and other operation costs. The cost diversifications of BIPV systems can be further unravelled by identifying both hardware and soft costs in detail. Therefore, following sections discuss the hardware and soft cost components of a BIPV system.

Hardware costs

BIPV hardware mainly consists of BIPV modules, inverters, storage devices, fixing accessories and cabling. Manufacturing process of these hardware elements are diffrent to each other and accumilates different costs. The module cost is the major component of a BIPV system which varies from 43% to 77% of the total cost (Yang and Carre, 2017). They are made of semi conducting materials and categorized under three distinguish technologies: (1) crystalline silicon (c-Si) such as monocrystalline silicon, polycrystalline silicon, (2) thin film such as amorphous silicon (a-Si), Cadmium–Telluride (CdTe), and Copper-Indium-Selenide (CIS), and (3) innovative materials such as ultra-high efficiency solar cells, organic PV cells (OPV) and Dye-sensitized solar cells (DSSC) (Peng et al., 2011). The global BIPV market is dominated by c-Si materials covering 60% of the production while the remaining 40% is manufactured by thin film and other innovative cell materials. Manufacturing process and the cost elements are diverse in the above technologies. The trading prices of different PV modules experienced a rapid decline from early 2011 to early 2015 (IRENA, 2018). On the other hand, the cost difference between crystalline modules and thin film modules was noticable until 2015 when the difference became insignificant. According to IRENA (2018), the rapid cost reduction prior to 2015 has made it difficult for manufacturers to achieve the desired cost margins and created different trade disputes due to high competition. Moreover, the comparatively low crystalline module costs of China became a threat to several other countries such as Europe and Japan who were the key players in PV module importation. As per the latest cost information of IRENA (2018), a good quality PV module price is currently around USD 0.40/W and varies slightly depending on the material and cell efficiency.

The standard PV modules are generally used in BAPV applications or roof top PV systems (Bonomo et al., 2017). BIPV are mostly custom-made modules, thereby thin film modules are highly recommended in BIPV projects (Powalla et al., 2017). In particular, c-Si modules are available mostly in rigid, opaque and flat forms due to the specific material properties of silicon. Consequently, they require specific encapsulation or perforation to acquire the desired qualities such as customisability, transparency, appearance and flexibility of a BIPV system (Heinstein et al., 2013). This limits the c-Si module usage in BIPV system development. Conversely, thin film PV modules have the ability to provide the aforementioned desired qualities in BIPV module manufacturing, and lend themsevles to being widely used in the BIPV sector. Moreover, the recent experiments have revealed that the performance ratio of BIPV systems is better when the modules are made of thin film materials (Tsai & Tsai, 2018). The Balance of System (BOS) costs generally obtain 10-16% of the BIPV construction cost (Yang and Carre, 2017). Most of the BOS components such as inverters and storage devices are common to both BAPV and BIPV systems. The inverter is the main component of the BOS and contributes 10-19% of the total system cost (Ziuku and Meyer, 2013). Depending on the quality, size and efficiency, the cost of a solar inverter generally lies around the USD 900-2,500 range (O'Neil, 2017). Energy storage systems/ batteries are another major BOS component in a PV system. Lithium-ion batteries are the most popular option for PV/BIPV systems. The reason for this high demand is the favourable qualities it contains such as a high discharge life cycle, high power density and high performance attributes in comparison to other batteries (IRENA, 2017). The manufacturing cost of a lithium-ion battery in 2016 is approximately USD 580/kWh and is forecasted to fall to around USD 220/ kWh by 2030.

Soft costs

BIPV soft costs emerge from the design stage to operational stage until the end of its life cycle (Wu et al., 2018). They first appear in the feasibility stage of the building (Sagani et al., 2017). The cost of feasibility study includes the costs of site investigation, preliminary designs, report preparation, travelling and accommodation. BIPV designing includes structural designing of the building, electrical layout, BIPV system design and providing an aesthetic appearance to the building (Bonomo et al., 2017; Sagani et al., 2017). A number of expertise such as structural engineers, electrical engineers, architects, and BIPV specialists will be involved in the design stage. The design related costs include consultancy wages, onsite surveying, design tools and equipment (Yang, 2015). It is very difficult to identify the exact cost amounts for each of aforementioned cost categories due to their subjective nature however, in general, the designing cost will be around USD 0.32/W (Aste et al., 2016). The procurement cost is mainly the customer acquisition cost, supply chain cost and financing. Customer acquisition includes all sales and marketing expenses including advertising, sales calls, site visits, initial bid preparation, and contract negotiation (Fu et al., 2016). There are several supply chain costs such as costs and fees associated with inventory, shipping, transportation and handling of equipment. The costs associated with warranty, storage, miscellaneous charges, interest charged on borrowed capital, insurance and incentives are some other costs to be considered in the procurement process.

Construction and installation related costs of BIPV include skilled labour, construction supervision, specialized consultation, health and safety and project contingencies such as delays and training (James et al., 2011; Strupeit and Neij, 2017). In general, BIPV consumes more time for installation due to the high number of modules and complex and time consuming electrical wiring process (James et al., 2011). A building permit should be taken prior to construction according to the country's approval process of permit, inspection and interconnection (PII) (Burkhardt et al., 2015). PII costs vary depending on the local policies and administrative processes. It generally lies between USD 0.01-0.06/W (Strupeit and Neij, 2017). Operation of the system, monitoring, maintenance, repairs, periodic upgrading and retrofitting will create a considerable amount of cost in the BIPV (Tadesse, 2017). In fact, cleaning the systems in high-rise or unusual geometric-shaped buildings will generate more costs such as health and safety, careful handling and means of mobilization (Kumar et al., 2018). Nevertheless, BIPV systems are considered as low maintenance applications. Disposal of BIPV systems includes recycling, dismounting and transportation costs (Wang et al., 2018). Recycling BIPV materials will raise extra costs of careful handling, careful dismounting, transportation and environment-friendly storage (Ritzen, 2017, Toosi et al., 2018). If the BIPV materials are hazardous (such as thin-film PV), additional safety procedures and hazardous disposal requirements (Tammaro et al., 2016) will be required which will create additional costs.

Cost Reduction Potentials

PV researchers have identified the rapid module price reduction as one of the key reasons (sometimes the main reason) for accelerated PV uptake in the past 6 years (Strupeit and Neij, 2017). In fact, the recent studies revealed that replacing the conventional building materials with BIPV materials have more economic benefits (Sorgato et al., 2018). The majority of the PV module types are considerably cheaper and highly affordable. In particular, there are novel thin film PV module types such as Dye-sensitized solar cells (DSCs) which manufacture using non-toxic inexpensive raw materials and less energy consumption (Biyik et al., 2017). Due to the reduced manufacturing costs, these PV modules are comparatively cheap and affordable. The costs of BOS components are also reduced over the time, parallel to the PV module cost reduction (Sorgato et al., 2018). The continuous research and experiments in the past decade on improving cell efficiency, developing sophisticated energy management systems and introducing alternative cell materials facilitated the hardware cost reduction (Bonomo et al., 2017). In addition, the automated manufacturing process enabled mass production and increased the economies of scale thus, the cost per product was reduced significantly. However, it should be noted that BIPV hardware costs are not always economical. For example, BIPV roof module costs are often higher than the conventional roofing materials (PV Sites, 2016). Similarly, BIPV façades can be expensive in comparison to concrete wall or general cladding. On the other hand, there will be situations in which the conventional building materials can provide better aesthetic appearance with a limited cost whereas it will be very expensive if the same aesthetic appearance is to be achieved from BIPV modules. Therefore, it can be said that even though BIPV modules and

BOS costs have been reduced significantly, BIPV still can be an expensive option depending on the building design and the aesthetic requirements.

Unlike the hardware costs, a considerable reduction cannot be evidenced in the BIPV soft costs over the last 6 years (Strupeit and Neij, 2017). Due to the integrated nature and novelty of the technology, the design stage of BIPV buildings are comparatively complex and time consuming (Yang and Zou, 2016). On the other hand, much attention has to be given to the aesthetic appearance of the design, therefore, skilled labour and expertise involvement are necessary. This makes the PV integrated building construction highly labour intensive thus, expensive in comparison to BAPV systems. In fact, the recent studies demonstrate the relevancy of accuracy in installation procedures, effective operation and adequate maintenance which again confirm the labour intensiveness in BIPV life cycle (Bonomo et al., 2017). The main reasons for limited soft cost reduction are the scarcity of suitable technology, BIPV specific regulations and collaboration between the PV and building industries.

BIPV soft costs can be reduced by introducing new BIPV specific design tools and software as one of the main barriers of BIPV designing is the scarcity of BIPV specific design tools (Bonomo et al., 2017). Having a paramatric modelling and assessment platform specific to BIPV (similar to Building Information Modelling - BIM), communication and information sharing which can integrate the input of each stakeholder is ideal for design cost reduction. Moreover, integrating modular construction and PV technologies to produce a prefabricated PV integrated building modules have a strong possibility to reduce the design time and costs (Osseweijer et al., 2018). In particular, this can eliminate the involvement of several stakeholders which saves a significant amount of money. It is possible to avoid expensive and time consuming structural and architectural changes to the design if a reliable design stage is maintained which initially links with the concept design and followed by accurate design development (Bonomo et al., 2017). Unnecessary expenses are often inccurred due to not having a proper information sharing system for the BIPV supply chain. In particular, miscommunication with regard to the specifications of BIPV systems, payment information and tracking the shipment can generate additional costs such as extra storage fees, time consuming refund procedures and labour idling due to late delivery (Koppelaar, 2017). If there is decentralized information sharing platform such as RFID and blockchain-based supply chain management proposed by Tian (2016), reliability, authenticity and traceability of the information can be assured and the costs incurred due to miscommunication can be eliminated. In addition, supply chain costs can be reduced by increasing the market transparency (i.e.: publishing the performance records of PV installers, ranking the BIPV/BAPV installers/ builders) (Strupeit and Neij, 2017). Using well-trained labour and professionals and thorough supervision will reduce the BIPV installation cost effectively (James et al., 2011). One of the main ways of compensating the O&M cost is selling the excess electricity to a utility company (IEA, 2018).

There are several ways that government could assist in reducing BIPV soft costs. One such approach is introducing BIPV specific building codes, manufacturing and installing standards and related regulations (James et al., 2011). Not having standards and building codes specifically established for BIPV systems create numerous expensive designing issues such as delays due to complications during designing, obtaining approvals (i.e.: building permits) and incorrect decision making (James et al., 2011; Mace et al., 2018). For example, in Australia, the general standards for solar PV such as AS/NZS 5033:2014 are currently used for BIPV system design and installation (Global Sustainable Energy Solutions, 2014). This may lead to confusion as the method of BAPV installation is different from that of BIPV and creates additional costs. Since BIPV technology is integrated with building construction, a specific set of building codes for BIPV buildings should be introduced (Ossewijer et al., 2018). This can be done by harmonising the current building codes with energy performance requirements and aesthetic requirements expected by BIPV technology. Most of the countries who actively use BIPV technology do not have local manufacturing due to material shortage, high capital costs and lack of government support. Therefore, these countries tend to import the BIPV modules and BOS items from other countries. In particular, the countries such as USA, Malaysia and Australia are importing BIPV components from China, Singapore, Japan and Germany (PV Magazine, 2018).

However, a specific concern would be raised about the quality of these imported products; especially when they are imported from less developed countries (IRENA, 2018; PV Magazine, 2018). On the other hand, importation would discourage the prevailing local production (PV Magazine, 2018). The government can eliminate these issues by (1) motivating local production with incentives specific to BIPV manufacturing and installation, (2) minimising the taxes related to local production, (3) establishing BIPV specific standards for manufacturing and importing products and (4) maintaining an effective certification process to assure the quality of the BIPV projects as well and the quality of the imported products. Further, the government should enact BIPV related regulations and incentive schemes which ensure the security of entire BIPV life cycle, not just the installation (Osseweijer et al., 2018). This legislation should be clearly distinct from general PV.

Most of the cost reduction potentials are connected to each other. In particular, automated manufacturing and process optimization is one of the main hardware cost reduction potentials. In order to make the manufacturing fully automated, the relevant machines and equipment should be developed and for this purpose, R&D is required. Similarly, BIPV specific design tools and software should be necessary to reduce the design stage costs, therefore, developing such tools and software is necessary and it can be done via R&D. In addition, many cost reduction potentials such as increasing market transparency, introducing BIPV specific building codes, standards and policies, maintained unified practices for the PII process and effective market control are related to the government and institutional support. It is mainly due to the fact that the government and related authorities are the key governing members of the BIPV market. Furthermore, the government is the main source of funding for BIPV related R&D, and thereby has a significant role to play in supporting market acceptance. Integration of PV and building industries will help enable resource utilization and minimum usage of capital expenditure due to the merger of two capital intensive sectors. Alternative materials and automated manufacturing and process optimization will increase the production capacity. Likewise, there are numerous relationships between the hardware and soft cost reduction potentials.

Discussion

BIPV technology is still considered as an expensive technology with limited market stability (PV Sites, 2018). Despite its unique advantages of multi-functionality and long-term financial benefits, the deployment of the technology has been limited due to numerous reasons such as low efficiency, lack of BIPV specific building codes, standards and policies, lack of understanding of the BIPV manufacturers about the construction sector, lack of local knowledge, scarcity of BIPV specific design tools, lack of government support and lack of public awareness (Ossewijer et al., 2018). Addressing these issues would drive the uptake of BIPV technology and stabilize the BIPV market. During the literature review, the study has identified several major BIPV deployment drivers which accelerate the BIPV usage all over the world. They are; (1) government support and involvement, (2) increase cell efficiency, (3) introducing BIPV specific business models, (4) increasing customizability and aesthetic appearance and (5) increasing public awareness. Most of these BIPV deployment drivers are currently discussed to some extent; nevertheless, the real contribution of BIPV to the PV market up until 2018 is 2.3 GW (approximately 1%) (Osseweijer et al., 2018). As per the findings of this review, the main reason for such low contribution is the lack of understanding and collaboration between the PV and building industries. Several studies such as Curtius (2018) and Osseweijer et al. (2018) have identified this same issue in their recent studies. It is relatively difficult to integrate these two sectors as they are not well-aware of each others disciplines (Curtius, 2018).

There are several stakeholders that should be involved in the design process in order to develop a successful and realistic design. As per the prevailing business arrangements, sometimes, the PV manufacturer and PV installer or builder and PV installer can be a single company which specializes in both services. Nevertheless, the client, architect, BIPV manufacturer, builder and BIPV installer should actively participate in BIPV building design process to share their knowlege and insight in developing the design. According to the client's requirements, the architect will design the building considering the technical and structural consultancy of the BIPV manufacturer, installer and builder. This collaboration will generate an accurate and feasible design and limit the probable changes and errors in the future. These stakeholders will also engage in the building construction and BIPV installation process to advise and monitor the builder and BIPV installer. Osseweijer et al. (2018) also suggested that it is better to introduce a BIPV specific business model which vertically integrates the main stakeholders to increase the efficiency and competitiveness. Such stakeholder integrated business model will generate a possibility for BIPV technology to survive as an individual industry without just being another technology. Nevertheless, the study of Osseweijer et al. (2018) does not discuss how to form a stakeholder integrated business model. This study identifies integrating PV panels with prefabricated building elements as one effective way of stakeholder integration.

Prefabricated building construction is a sustainable construction method which manufactures building elements/parts/modules in an offsite manfuacturing plant (Kamali & Hewage, 2016). It provides a number of benefits such as reduced material wastage, high quality production, fast onsite assembly, easy dismantling and compatible reuse (Chang et al., 2018). In particular, significant cost reductions can be achieved through energy efficient manufacturing, limited labour usage in assembling, limited time consumption for project completion, standardized design and avoiding weather extremes during construction (Kamali & Hewage, 2016). In the past, prefabricated building construction was identified as an expensive method of construction with high capital and upfront costs. Further, it limited the uniqueness and flexibility enclosed in customized architectural design due to the standard module production (Chang et al., 2018). Accordingly, the construction sector and general public had negative perceptions about this construction method, thus, its uptake was considerably slow. One of the main reasons underlying the aforementioned barriers was not having proper stakeholder collaboration. In particular, a considerable upfront cost could be reduced and the design flexibility could be successfully achieved if the stakeholders such as client, architect, builder and prefabricated module manufacturer were involved in the design process. The current prefabricted building industry understood this concept and successfully integrated the stakeholders in the design process and reduced a number of barriers that existed earlier.

Even though modular construction is not well-adopted by the Australian building industry, the prefabricated timber/metal frame construction is highly popular in the country (Lopez and Froese, 2016). These frames are cost effective since they are manufactured in a factory environment using modern technology, software and equipment and delivered to the site with clear installation instructions. It reduces the cost of labour, wastage and erection time. Since timber is a well-known material in the Australian building frame construction, the workers are familiar with the construction process thus no further assistance is required. However, there are challenges such as being a threat to the existing construction related businesses, providing adequate supply to demand, competition with other materials, negative perceptions and technical limitations in fixing. In the past, there were a limited number of experts available in modular building industry in Australia (Lopez and Froese, 2016). However, in time, the industry realized the unique benefits of prefabricated building construction and invested on this construction method to have better results (Blismas & Wakefield, 2009). Today, there are several major builders who effectively use modular construction as their main method of building construction (Hickory, 2018). They have their own manufacturing plants in which novel technology is used for the manufacturing process. On the other hand, they have innovative business approaches in developing reliable building modules. In particular, the leading prefabricated construction companies in Australia adapt a self-performing business model which allows them to change the design process as per different requirements (Hickory, 2018). It assists in acquiring the intended design by controlling the design aspects, procurement and delivery. Accordingly, all necessary stakeholders are involved in the construction design process.

Prefabricated builders need to be involved in the project at the earlier stages of the design process. Once the architect has developed the concept design, the builder evaluates the best way of breaking down the design into prefabricated building elements. In the evaluation phase, he considers different parameters such as size, shape and weight against the logistic plan for effective transportation, onsite mobilisation and storage (Hickory, 2018; Kamali & Hewage, 2016). After that, the detail design will be developed and technical drawings will be prepared along with the construction documentation. Then, the project's design stage will be completed, allowing the prefabricated builder to commence the manufacturing process. Currently, many prefabricated builders use BIM/parametric modelling to acquire the optimal design for prefabricated modules. Based on the detailed design, the prefabricated elements will be designed using BIM/parametric modelling and accordingly develop parametic shop drawings. From these shop drawings, Bill of Materials (BOM) will be developed and the manufacturing process will be executed. Once the manufacturing is done, the modules will be transported to the site and assembled as per the building design.

Prefabricated building industry and BIPV industry have a number of similar characteristics. In particular, both industries manufacture their products in offsite manfacturing plants. There is no onsite construction except module assembly and installation. Both industries obtain automated and standardized manufacturing process which allows scale of production. In addition, both industries are sustainable yet require high capital and upfront costs. The main difference of these two industries is that BIPV technology is not popular and widely used as the prefabricated construction. Considering the similar qualities of BIPV and prefabricated building industries, this study proposes to integrate BIPV modules into the prefabricated building elements. There are many advantages of merging BIPV and prefabricated building construction industries. In particular, the materials required for completing the BIPV module such as glass, metal and wood will be limited/ eliminated and the manufacturing process of BIPV modules will be shortened accordingly. On the other hand, the labour and machinery requirement will also be limited for both industries. Moreover, by integrating BIPV modules into prefabricated building elements, a single manufacturing process can be introduced for both sectors which will avoid significant amount of manufacturing costs for both industries. Since there is no requirement of BIPV onsite installation (other than BIPV integrated prefabricated module assembly), a significant amount of labour costs and installation time can be reduced. This process can reduce the high capital and upfront costs of both industries and increase the customizability of BIPV systems.

If BIPV modules are integrated with prefabricated building elements and manufactured under a single process, the prefabricated builder will become the BIPV integrated prefabricated builder who specializes in prefabrication and BIPV technology. Similar to the prefabricated building construction process, this BIPV integrated prefabricated builder needs to be involved in the project at the earlier stage of the design process. The BIPV integrated prefabricated building construction process is presented by Figure 1. According to Figure 1, when the project architect develops a conceptual design, BIPV integrated prefabricated builder reviews the module breakup parameters against the logistic plan and the BIPV module integration parameters against the module break up. Once the design stage is completed, the BIPV integrated prefabricated builder commences the manufacturing process of BIPV integrated building elements. According to this arrangement, the BIPV integrated prefabricated builder should have the knowledge, resources and technology for BIPV and prefabricated module integration. Therefore, their company will adapt a new business model which facilitates this integration. In addition, they will have their own design team consisting of architects, PV consultants and engineers who specialize in such integrated system. Technical assistance is vital in adapting the aforementioned process; software for designing and machinery, tools and equipment for manufacturing. In particular, BIM and parametric modelling can be used in the module design process. These applications use computers to design 3D models of building elements considering their real world behavior (DesignTech, 2018). There are several design tools such as cad, revit, rhino, grasshopper and sketchup which effectively perform parametric modelling, therefore, such technologies can be adapted in BIPV integrated module design. However, there is a scarcity of BIPV specific design tools which can be used along with the aforementioned building design tools. It is ideal to have a BIPV specific design tool which can provide design specifications to these building design tools in order to develop BIPV integrated prefabricated building element design. Therefore, further research should be aimed at developing BIPV specific design tools which are compatible with current building design tools.

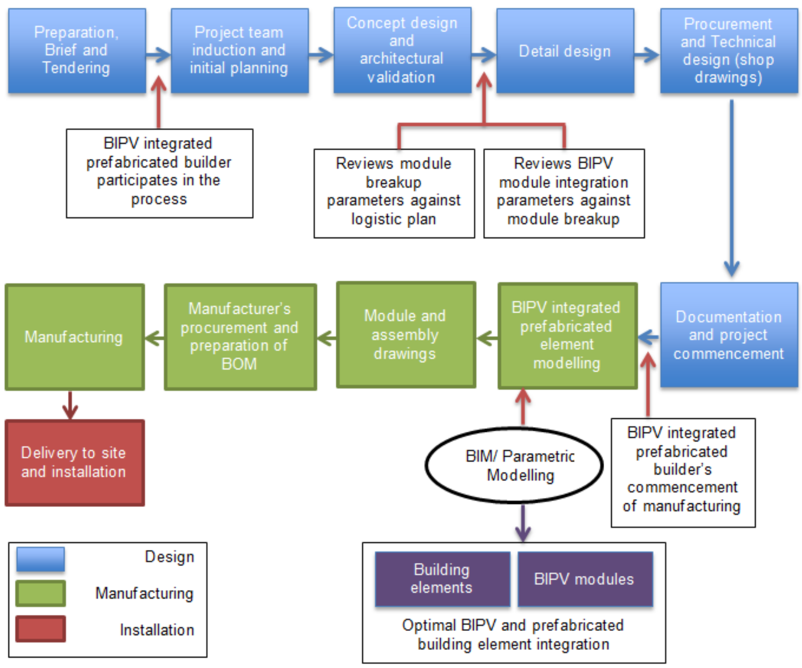

Figure 1: Stakeholder-integrated project process for BIPV integrated prefabricated building construction
Source: Adapted form Hickory (2018); RIBA (2013)

Conclusion and Recommendations

BIPV is among the most promising sustainable technologies emerging in the building industry however, its contribution to the PV market is still insignificant. The main reasons for such low contribution are the lack of understanding between the PV and building industries, slow soft cost reduction, lack of collaboration between the stakeholders, limited knowledge and technology and lack of BIPV specific regulations. This paper conducted a comprehensive review to identify the effective ways to eliminate the aforementioned issues and accelerate the BIPV uptake. While the government's involvement in establishing necessary regulations is important, the building industry should take necessary actions in creating a solid customer base for the BIPV technology. Introducing BIPV specific business models is one such approach of attracting the customers. Eliminating the lack of understanding between the two industries can reduce the system costs and attract the investors. Considering the advantages and the positive characteristics of the prefabricated building industry, this study introduces to integrate the PV and prefabricated building industries by assimilating the PV modules into the prefabricated building elements. Further, the study recommends having a comprehensive design process with the participation of the consultants of both PV and building industries. In the proposed model, BIPV integrated prefabricated builder who specializes in prefabrication and BIPV technology will involve in the initial planning stage to deliver a reliable BIPV system. Innovative design technologies including BIM and parametric modelling can be used in the module design process to effectively design the BIPV system.

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