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Cost reduction and deployment of prefabricated building integrated photovoltaics

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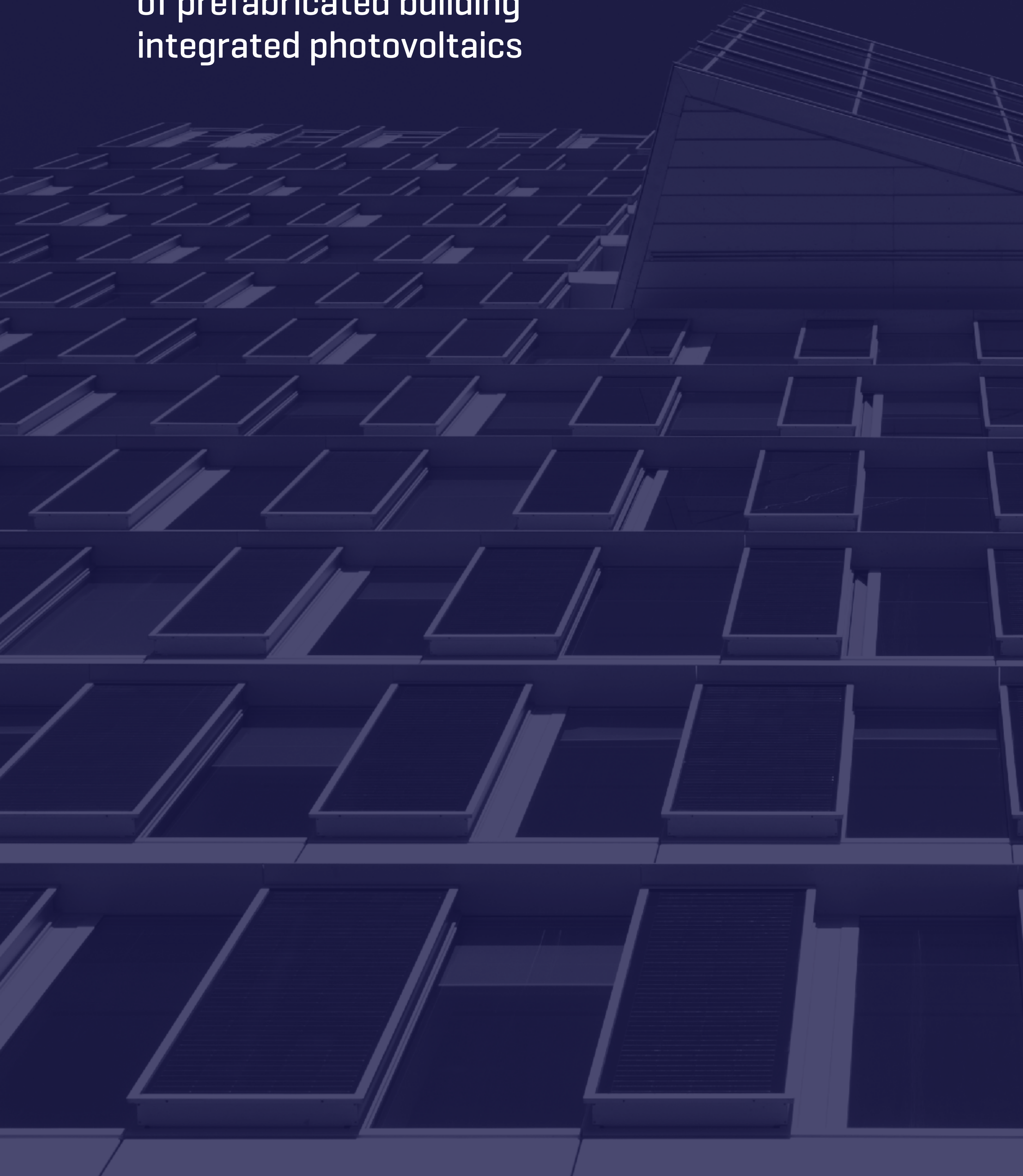

Cost reduction and deployment of prefabricated building integrated photovoltaics

Report written by:

Dr Rebecca Jing Yang
Prof. Ron Wakefield
Ms. Chathuri Gunarathna
Ms. Nilmini Weerasinghe
School of Property, Construction and Project Management,
RMIT University, Melbourne, Australia

RICS Research team

Katherine Pitman
Global Research Programme Manager
kpitman@rics.org

Steven Matz
Global Research Assistant
smatz@rics.org

Fabrizio Varriale
Global Research Assistant
fvarriale@rics.org

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List of abbreviations

AC	Alternative Current
ASI	Amorphous Silicon (glazing)
APVI	Australian Photovoltaic Institute
ARENA	Australian Renewable Energy Agency
a-Si	amorphous Silicon
BAPV	Building Attached Photovoltaics
BIM	Building Information Modelling
BIPV	Building Integrated Photovoltaics
BOM	Bill of Materials
BOS	Balance of System
CdTe	Cadmium-Telluride
CIGS	Copper Indium Gallium Selenide

CIS	Copper-Indium-Selenide
CO_2	Carbon Dioxide
c-Si	crystalline Silicon
DC	Direct Current
DER	Distributed Energy Resources
DSSC	Dye-Sensitized Solar Cells
EN	European
GST	Goods and Services Tax
GW	Giga Watt
H&S	Health & Safety
ICT	Information and Communication Technology
IEA	International Energy Agency
IEC	International Electro-technical Commission
IRENA	International Renewable Energy Agency
ISO	International Standards Organisation
kWh	kilo Watt hour
kWp	kilo Watt peak
Li-ion	Lithium ion
MOST	Ministry of Science and Technology
MWh	Mega Watt hour
NaS	Sodium Sulphur
NEA	National Energy Administration
NGO	Non-Governmental Organisations
Ni-Cd	Nickel Cadmium
NREL	National Renewable Energy Laboratory
NZE	Net Zero Energy
O&M	Operation and Maintenance
OPV	Organic Photovoltaic
PII	Permitting, Inspection and Interconnection
PSB	Polysulfide-bromide
PV	Photovoltaic
PVPS	Photovoltaic Power Systems
Q&A	Questions and Answers
R&D	Research and Development
RFID	Radio Frequency Identification
TF-Si	Thin-Film Silicon
UK	United Kingdom
US	United States
VRB	Vanadium Redox
ZnBr	Zinc Bromine

Executive summary

Purpose and scope of document

Technology development, commercialisation, and manufacturing scaling have contributed significantly to rapid reductions in solar Photovoltaic (PV) hardware costs. However, the soft costs, including design, financing, procurement, permitting, installation, labour, and inspection, have not declined rapidly. The lack of economic confidence and the lack of collaboration between the PV and building industries make the integration of prefabricated solar panels to the building envelope difficult. This research evaluates the mechanisms driving the cost reductions and deployment of prefabricated Building Integrated Photovoltaics (BIPV). The research aims to formalise a deployment framework by empirically decomposing prefabricated BIPV cost trajectories into a set of low- and high-level factors and identify their reduction potentials.

Methods

This study combines three main data collection methods: (1) literature review, (2) industrial workshop and (3) engagement in international communities. An extensive literature review was conducted to (1) identify all cost components of BIPV systems and present them in a single platform, (2) explore the cost reduction potentials and (3) investigate the deployment drivers of the technology. BIPV technology is compared with Building Attached Photovoltaics (BAPV) and traditional building envelope materials to distinguish its unique characteristics and benefits. The industrial workshop was organised by the research team to identify the industrial and practical perception of professionals related to the PV/BIPV industry. It also sought to compare literature review findings with real-world scenarios to identify the actual limitations of BIPV deployment. In addition, the research team participated in the activities organised by the International Energy Agency Photovoltaic Power Systems Programme (IEA PVPS) Task 15 through annual meetings and webinars to explore the deployment drivers of the BIPV technology with international experts. The data collected from these sources are critically analysed and discussed in this report.

Findings

- The main cost reduction potentials identified for hardware costs are: continuous R&D on alternative materials and waste reduction, automation and process optimisation, resource utilisation, minimising capital expenditure, government support to promote BIPV technology and enable mass production and bulk purchasing of materials.
- Soft cost reduction potentials identified in the study are: introducing BIPV-specific design tools, effective stakeholder collaboration via decentralised information platforms, introducing RFID-blockchain-based supply chain information-sharing platforms to avoid errors in the supply chain, introducing unified practice for PII (permitting, inspection and interconnection) procedures such as issuing building permits, connection related inspections, approvals and administrative work, introducing BIPV-specific building codes, standards, policies, incentives and low interest on loans. BIPV deployment drivers that can create a stable market and high demand for BIPV buildings are categorised under two main aspects: (1) technological advances via continuous R&D, specifically on coloured BIPV modules and mounting/fixing structures, and (2) social advances via knowledge awareness, BIPV-specific business models, BIPV product and process standardisation, BIM-enabled BIPV design assessment and optimisation, and quality assurance. Knowledge awareness is mainly achieved via maintaining a localised data repository on BIPV products and financial details, effective information sharing between building and PV industries and developing accredited training programmes that provide necessary knowledge and skill sets. BIPV-specific business models that consider BIPV implementation in the early design stage provide an effective collaboration between stakeholders and, centred on a client who owns the proposed building, can generate effective revenue streams for all stakeholders of a BIPV project. BIPV project and process standardisation can be achieved via introducing mandatory International Standards Organisation (ISO) and International Electro-technical Commission (IEC) standards, building codes and local regulations. BIM-enabled BIPV design assessment and optimisation can be used to digitalise the planning process and optimise the quality of the end product technically, economically and environmentally. Quality assurance is achieved via decentralised supply-chain information sharing, imposing importation standards and encouraging local manufacturing by providing incentives.
- Considering the similar characteristics shared by building prefabrication and BIPV, the study discusses the potential of integrating BIPV modules into the prefabricated building elements. This new building element is named as ‘prefabricated active solar building envelope’.
- The study introduces a framework for effective prefabricated active solar building envelope design and construction consisting of four key aspects: (1) early involvement of the prefabricated builder in the BIPV design process, (2) using parametric modelling and optimisation in prefabricated module design, (3) automated lean production to eliminate wastage, defective products, overproduction and uncertainties in prefabricated element manufacturing, and (4) proper planned and managed onsite installation.

Conclusions and recommendations

The study discusses a novel concept of a prefabricated active solar building envelope to accelerate the BIPV uptake. Accordingly, BIPV is considered as a sustainable building envelope material to develop sustainable prefabricated building modules. The end product is a prefabricated active solar building that can generate its own electricity through the envelope. This concept is in line with the BIPV cost reduction potentials and deployment drivers identified in the study and eliminates the lack of understanding between the building and PV industries via stakeholder collaboration and integration. Several stakeholder roles are integrated; for example, the role of the BIPV installer is integrated with the prefabricated builder, who specialises in both PV and prefabricated building construction. Accordingly, new business models are introduced. A proper collaboration between the stakeholders such as the client, architect and prefabricated builder can be evidenced within this concept to eliminate the knowledge gap and lack of understanding between the two industries. The study recommends (1) integration of PV modules with prefabricated building elements, (2) making the decision to use a prefabricated active solar building envelope prior to commencing planning, (3) the prefabricated builder's involvement in the project from the earliest stage of the design process, (4) builders partnering with PV manufacturers to deliver a design-specific BIPV system, (5) using the prefabricated active solar building envelope concept for client-owned buildings, and (6) using systematic design and management tools to identify the real value of the project and improve the economic confidence of the investors.

Research outcomes

This research will enrich current understanding of how to bring the hardware and soft costs of bespoke BIPV down. In addition, it will shed light on the effect of policy mechanisms and opportunities on the uptake and dispersion of prefabricated BIPV and low-carbon technologies in general. This work can help policymakers to implement their commitments under the Paris Agreement to address climate change. Findings of this study will support investors' decisions by setting out the financial risks of BIPV, provide suggestions to building professionals on value-for-money design and installation, and inform PV manufactures of technological innovations.

1.0 Introduction

By 2040, world energy consumption is expected to increase more than 55% (Energy Information Administration, 2013). Buildings remain a sector where efficiency improvement is critical to achieving the commitments of the Paris Agreement. Existing approaches for reducing the energy consumption in buildings are often centred on integrating 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 is common with solar PV to 'attach' 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 essentially indistinguishable.

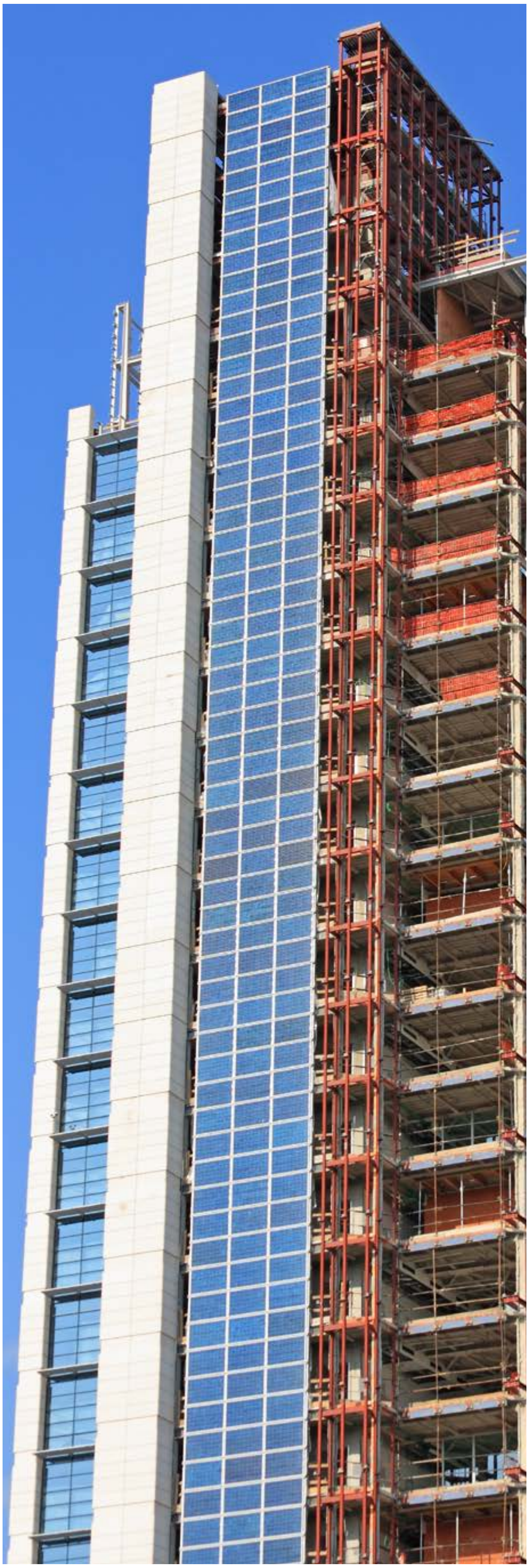
The International Energy Agency (IEA) Photovoltaic Power Systems Programme (PVPS) Task 15 report, defines BAPV (Building Attached Photovoltaics) as *'Photovoltaic materials that are not used to replace conventional building materials in parts of the building but simply attached to the building'* (IEA, 2018a) using mounting infrastructure (Osseweijer, 2016). The IEAPVPS Task 15 defined BIPV (Building Integrated Photovoltaics) as *'a PV module and a construction product together, designed to be a component of the building. A BIPV product is the smallest (electrically and mechanically) non-divisible photovoltaic unit in a BIPV system which retains building-related functionality. If the BIPV product is dismounted, it would have to be replaced by an appropriate construction product'* (IEA, 2018a). Accordingly, BIPV is a novel technology which integrates solar modules with building skin to generate energy while performing the general building material functions (Shukla et al., 2017).

PV usage has increased drastically since the year 2000 due to its proven effectiveness in reducing CO_2 emissions (Ren et al., 2009), and its total globally installed capacity has increased approximately from 5 GW to 401 GW from 2005 to 2017 (IEA, 2018b). Many countries such as China, Germany, the US, Japan, India and the UK are dominating the global PV market with the highest annual installation capacities and highest accumulated installed capacities (IEA, 2017). The majority of PV applications are presented through either Building Attached Photovoltaic (BAPV) systems or PV farms (IEA, 2017; James et al., 2013; Johnston and Egan, 2017). In terms of BIPV, the global estimated compound annual growth rate is 18.7% from 2013 to 2019 with a total installed capacity of 5.4 GW (PV Sites, 2018). Nevertheless, the real contribution of BIPV to the PV market up until 2018 is 2.3 GW (approximately 1% of the total global PV installed capacity until 2018) (Osseweijer et al., 2018). Therefore, BIPV is currently recognised as a niche product.

However, many successful BIPV projects have been completed all over the world. These projects range from simple inbuilt roof systems to complex façade systems with advanced technological applications (Mace et al., 2018). The most interesting fact of these designs is that they provide a significant aesthetic appearance in comparison to BAPV installations. This aesthetic green identity attracts investors and high paying tenants and provides a value addition to the building. Appendix 1 presents a summary of 18 global BIPV building profiles of recently completed projects.

Although photovoltaic technologies have experienced unprecedented cost reductions among electricity-conversion technologies since 2008, the integration of solar panels to the building envelope is deployed slowly in most countries. The lack of economic confidence by the building sector makes the integration of prefabricated solar panels to the building envelope difficult. In addition, the inability to effectively integrate the BIPV technology with the building industry prevents the rapid uptake of BIPV systems.

This research aims to evaluate the mechanisms driving the cost reductions and deployment of prefabricated BIPV. It is conducted under two main stages. In the first stage, the study formalises a framework to empirically decompose BIPV cost trajectories and determine their opportunities for cost reduction. In the second stage, the study critically evaluates the BIPV deployment drivers, with a special concern on effective integration of BIPV technology with prefabricated building construction. BAPV and conventional building envelope materials are used as the reference cases to distinguish the similarities and differences of the technologies and identify the reasons of the comparatively slow uptake of BIPV.



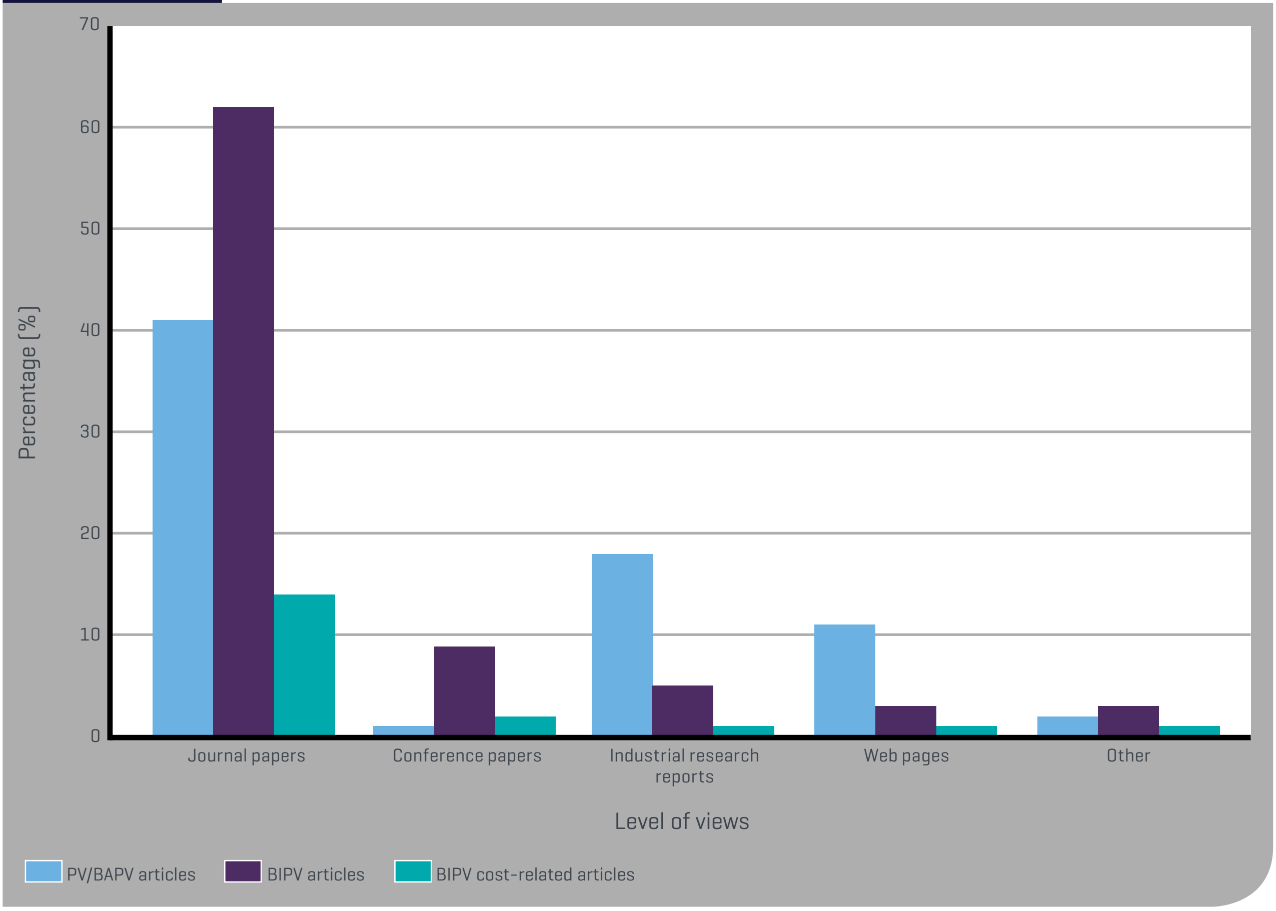
2.0 Research methodology

The purpose of this research is to investigate the cost reduction potential and deployment drivers of BIPV systems. Several data collection methods were used in this study to achieve this. The study commenced by conducting a comprehensive literature review using journal papers, conference articles, technical reports, books, magazines and web articles/reports by renewable energy authorities.

Many studies were available in relation to the technical aspects of BIPV systems. Moreover, there were numerous studies that sufficiently discussed the cost reduction and deployment of PV systems in general or BAPV applications. The initial search collected 176 articles and reports. However, most of them did not exclusively discuss BIPV cost reduction and deployment, as this is not yet a popular topic among the academics and industrial researchers. Nevertheless, they provided a valuable input in understanding the background of the BIPV technology, hardware and soft costs, cost reduction potentials, BIPV deployment drivers and the current limitations that prevent deployment. Furthermore, PV/BAPV related articles were reviewed to identify similarities and differences between BAPV and BIPV technologies. Figure 1 presents a summary of the literature review. Articles from more than 30 journals, including yet not limited to (1) Renewable Energy, (2) Renewable and Sustainable Energy Reviews, (3) Energy and Buildings, (4) Applied Energy, and (5) Solar Energy were reviewed. In addition, the reports collected from the (1) International Energy Agency (IEA), (2) International Renewable Energy Agency (IRENA), (3) Australian Photovoltaic Institute (APVI), (4) Australian Renewable Energy Agency (ARENA), and (5) National Renewable Energy Laboratory (NREL) also provided valuable information.

Parallel to the comprehensive literature review, two other sources were used in data collection: (1) a BIPV industrial workshop and (2) participation in international communities in BIPV. The industrial workshop was organised as a one-day event in November 2017 in Melbourne, Australia, with the participation of approximately 100 key PV delegates from the Australian PV/BIPV and construction industries who came to share their knowledge, opinions and experience. The workshop mainly focussed on identifying BIPV cost reduction potentials and deployment drivers. Delegates were from: (1) PV/BIPV-related academia, research and development, (2) PV/BIPV-related building, construction, operation and maintenance (O&M), (3) PV/BIPV-related consultancy, (4) regulators/local council/government, (4) PV/BIPV and related infrastructure suppliers/retailers, (5) PV/BIPV system installation, (6) PV/BIPV-related IT personnel, (7) law firms, (8) PV/BIPV-related manufacturing, (9) utility suppliers, (10) non-governmental organisations (NGO), and (11) financial institutes/investment/insurance companies.

Figure 1 **Summary of literature review**



There were six keynote speakers who discussed the BIPV industry and its uptake, including Q&A sessions and two separate discussion sessions.

The research team participated in an international webinar organised by IEA PVPS Task 15 on the topic 'Investigating Business Models for BIPV'. The webinar's focus was to introduce BIPV-specific business models to drive its uptake. More than thirty international professionals joined the webinar to discuss the uptake of BIPV. The recording was shared by IEA PVPS Task 15 group. Findings of the literature review, industrial workshop and the IEA PVPS Task 15 webinar are critically compared and analysed in the following sections.

One of the investigators of this project is an expert representing Australia in the IEA PVPS Task 15 group. The group consists of 30 BIPV experts from approximately 14 countries. IEA PVPS Task 15 is conducting a number of studies on different aspects of BIPV technology with the main purpose of accelerating its uptake (IEA, 2018d). Introducing BIPV-specific business models, digitalisation of BIPV system implementation using Building Information Modelling (BIM), standardisation of BIPV process and products, imposing BIPV-specific standards and regulations, introducing an international framework for BIPV specifications and investigating the environmental benefits of BIPV are some of the latest areas focussed on. In addition, it is focused on identifying the BIPV system costs through the investigation of the business arrangements used by the prevailing BIPV projects (IEA, 2018c). Through participating in the Task 15 annual meetings and discussions with experts, an international viewpoint on BIPV deployment was also reached.

3.0 BIPV cost breakdown

The cost of a PV system can be generally allocated into two main categories: hardware costs and soft (non-hardware) costs (Fu et al., 2016). Hardware costs include modules, inverters, mounting systems, electrical cabling, meters, batteries and other related structural and electrical items that integrate the entire system (Ikkurti and Saha, 2015). Soft costs include all secondary expenses required to complete the system. Hardware cost is mainly the production cost of a hardware element and includes labour, raw materials and other materials, running costs and company overheads. Soft costs are extremely diverse as they include all necessary costs from design stage to the end of the BIPV lifecycle, such as labour costs, legal costs, permit fees, insurance costs, administrative costs and other operation costs (Strupeit, 2017: Bakos et al., 2003). This section explores the details of both hardware and soft costs of BIPV in comparison to BAPV.

3.1 BIPV system cost

It is crucial to have a generic idea about the total system cost prior to decomposing the hardware and soft cost trajectories. Hence this section discusses the BIPV system cost and how it varies with module types (i.e.: crystalline silicon: (c-Si), thin-film) and building envelope elements (i.e. roof, façade). Two significant comparisons are found in the current literature and critically analysed in the following paragraphs.

The first comparison is put forward by James et al. (2011) in the National Renewable Energy Laboratory (NREL) report of 2011. The authors compared three hypothetical BIPV system costs with a rack-mounted crystalline silicon (c-Si) PV system cost. The three hypothetical BIPV systems are (1) c-Si BIPV roof tile system (capacity – 5.7 KW, efficiency – 13.8%, area – 0.58 m^2), (2) Copper Indium Gallium Selenide (CIGS) thin-film BIPV roof tile system (capacity – 4.7 KW, efficiency – 11.2%, area – 0.58 m^2) and (3) amorphous silicon (a-Si) flexible thin-film BIPV roof tile system (capacity – 2.5 KW, efficiency – 5.8%, area – 0.58m^2). BAPV system (capacity – 5 KW, efficiency – 14.5%, area – 1.28m^2) is used as the reference case to compare with the other three systems. All systems are residential roof systems and the BIPV systems are offsetting the conventional roof tile (i.e. asphalt shingles) costs. The costs are presented considering the end user/customer's view point.

According to the above study, the c-Si BIPV roof tile system and CIGS thin-film BIPV roof tile system costs are lower than the reference BAPV case. This is mainly due to the lower cost per W of installation materials (for supportive structure), installation labour of supportive structure, overheads and profit. The a-Si flexible thin-film BIPV roof tile system cost is slightly higher than the reference case with higher cost amounts of installation labour, indirect capital costs, overheads and installer's profit. Furthermore, since it is a flexible system, there is an additional cost for special packaging suitable for flexible packaging. Nevertheless, this system has less expensive PV modules and a high amount of material offset compared to the other three systems.
In general, thin-film BIPV modules are comparatively less expensive than the c-Si modules. The report does not provide a solid reason for this cost diversity, yet it can be assumed that the manufacturing cost of c-Si modules is higher than thin-film modules due to the lengthy production process. This is further explained in section 3.2.

According to James et al. (2011), a significant difference can be seen in installation labour costs. Labour costs related to the module installation and electrical cabling of BIPV systems are comparatively higher than BAPV systems. In addition, labour costs are significantly higher in a flexible BIPV system (BIPV a-Si flexible thin-film system). The report put forward several reasons for this cost difference such as: the complicated wiring process of BIPV, the need for careful material handling and installation accuracy (since BIPV modules should be installed as a building material). The larger the modules are, the harder the installation. When constructing a building, the envelope installation cost is inevitable anyway, and should be offset from the BIPV cost. However, the installation cost of related hardware (i.e. fixing methods of BIPV roof tiles and mounting accessories of BAPV) is considerably low in all BIPV systems in comparison to BAPV systems. This is mainly due to the higher amount of additional hardware used in BAPV systems and the additional time required to fix them. The material offsets provided by the BIPV systems are considerable in reducing total BIPV system costs. The comparison of the above systems revealed that depending on system variables such as module types, size, installation methods and material offsets, BIPV systems are economical and even less expensive in comparison to BAPV systems. The report concluded that BIPV systems should no longer be considered as expensive and beyond affordable in the energy market.

The second comparison is by Yang and Carre (2017) of a large-scale BIPV application in Australia. This study conducted a feasibility analysis of three BIPV designs for a student accommodation building in Melbourne. The considered designs are (1) BIPV façade system (capacity – 70.72 KW, area – 884.54 m^2), (2) BAPV flat roof system (capacity – 131.56 KW, area – 828.22 m^2) and (3) BAPV angled (300) and flat tiles combined roof system (capacity – 114.40 KW, area – 720.19 m^2). All PV modules are poly-crystalline products.

According to this study, the BIPV façade system cost is slightly lower than the BAPV flat roof system and slightly higher than the BAPV angled and flat combined roof system. The main feature that can be seen in the cost comparison is that the installation cost of the BIPV façade system is significantly higher than the other two designs. Although the study did not provide a solid explanation for this cost difference, it is anticipated that (1) the careful material handling, accurate installation, maintaining the architectural appearance, complicated wiring and cabling of the BIPV façade and (2) different installation methods of façade system and roof system are the reasons for the higher installation cost of the BIPV system. This is further explained in section 3.2.

Yang and Carre (2017) also compared the BIPV façade cost with that of conventional façade material. Consultation with a professional quantity surveying company in Melbourne indicated that the general total cost of building façade is more than US$200/m^2. This would make the integrated polycrystalline PV design feasible within the product lifecycle. In the case of building façade costing more than US$230/m^2, by using centralised inverters, the payback period of building integrated façade design can match that of roof mounted designs, which is around 6-9 years. This outcome gives the industry more confidence and options to apply façade integrated PV for energy generation. Considering most roof spaces are much smaller than façade areas in buildings, BIPV façades would potentially be the future direction for onsite energy generation. Also, through international engagement, the team obtained the cost information provided by a professional BIPV company in Denmark; a typical roof integrated thin-film BIPV system (efficiency: 12%) cost (excluding installation) is approximately US$146/m^2, which is economically feasible.

3.2 BIPV hardware costs

BIPV hardware mainly consists of PV modules, inverters, storage devices, fixing accessories and cabling. This section critically analyses this hardware under two main categories: (1) BIPV modules and (2) Balance of System (BOS) (inverters, storage devices, fixing accessories, cabling and other). The study will also compare BIPV module prices with conventional building material prices to understand the affordability of BIPV products.

3.2.1 BIPV module costs

Module cost is the major component of a BIPV system, which varies from 43% to 77% of the construction cost of an integrated PV design (Yang and Carre, 2017). Modules are made of semiconducting materials and categorised under three distinguishable technological generations as follows:

1. **First generation:** Crystalline silicon (c-Si) (monocrystalline silicon, polycrystalline silicon) semiconductor materials are used (Peng et al., 2011).
2. **Second generation:** Thin-film is developed using different types of materials, including (i) amorphous silicon (a-Si) and thin-film silicon (TF-Si) (ii) Cadmium-Telluride (CdTe), and (iii) Copper-Indium-Selenide (CIS) or Copper-Indium-Gallium-Selenide (CIGS) (IRENA, 2012; Peng et al., 2011).
3. **Third generation:** Innovative materials are used, e.g: ultra-high efficiency solar cells, organic PV cells (OPV), dye-sensitized solar cells (DSSC).

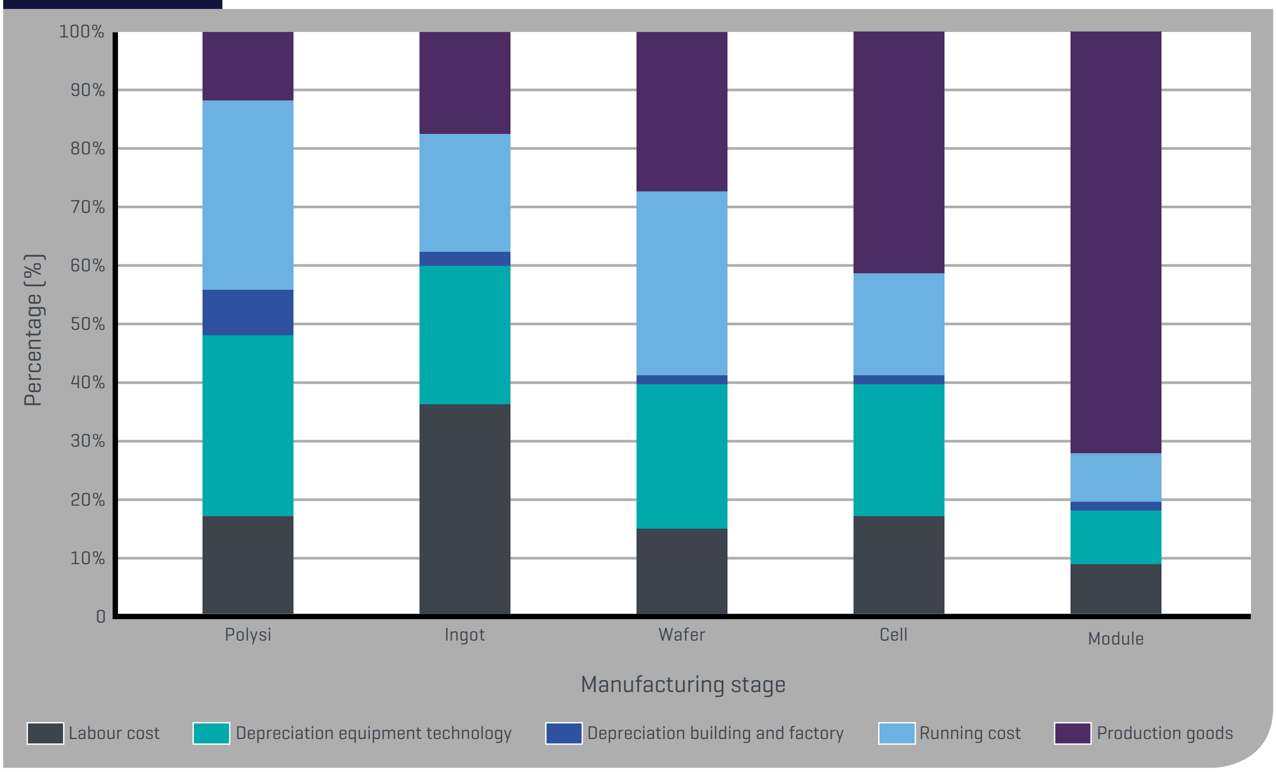
80-85% of global PV modules are made of c-Si materials whereas the remaining 10-15% are made of second generation thin-film materials (Cengiz and Mamiş, 2015; Hwang et al., 2012; Płaczek-Popko, 2017). Similarly, the global BIPV market is dominated by c-Si materials, covering 60% of the production, while the remaining 40% is manufactured with thin-film and other innovative cell materials (Snow, 2015). As per the latest statistics of the International Renewable Energy Agency (IRENA) (2018), the trading prices of different PV modules declined rapidly from early 2011 to early 2015. However, the cost difference between crystalline modules and thin-film modules was significantly high until 2015, after which the difference became insignificant. According to IRENA (2018), the rapid cost reduction of PV modules from 2011 to 2015 made it difficult for manufacturers to achieve the desired cost margins. Moreover, the comparatively low prices of crystalline modules from China became a threat to several other countries such as in Europe and Japan, who were the key players in PV module exportation. From 2015 onwards, global PV module prices are kept within an accepted range. As per the latest cost information from IRENA (2018) and PV Magazine (2018), a good quality PV module price is currently around US$0.40/W, with price varying slightly depending on the material and cell efficiency.

The manufacturing cost of PV modules is highly dependent on the type of PV technology due to diverse manufacturing processes. The manufacturing process of crystalline PV is wrapped around four main steps: ingot casting, wafering, cell processing and module assembly (Canizo et al., 2009; Cengiz and Mamiş, 2015). Each of these steps accounts for a specific percentage of the total production cost; 17% for converting raw silicon into an ingot, 20% for wafering, 22% for cell processing and 41% for module assembly (Cengiz and Mamiş, 2015). Even though the crystalline PV manufacturing cost is discussed under the main stages of the production process, thin-film and other innovative PV modules manufacturing costs are not discussed under production stages, as there is only a single manufacturing process (IRENA, 2012).

The manufacturing cost of PV modules generally consists of direct and indirect labour, raw materials, depreciation of manufacturing equipment and company overheads (Canizo et al., 2009; Horowitz et al., 2015; IRENA, 2012). However, different studies have decomposed the manufacturing cost in different ways. Cengiz and Mamiş (2015) have decomposed the crystalline PV module manufacturing cost under labour, depreciation of building and factory, depreciation of technical equipment, running costs and production goods. This study has given the percentage of each of these costs under the above stated main four stages of the crystalline PV manufacturing process. Figure 2 shows a graphical comparison between manufacturing costs.

According to Figure 2, the highest and lowest shares of labour costs occur in the ingot casting stage and module assembly stage respectively. The depreciation cost of technical equipment is approximately similar in the ingot casing, wafering and cell processing stages yet low in the module assembly stage. The depreciation cost of the building and factory is very low in wafering, cell processing and module assembly stages yet slightly higher in the ingot casting stage. Nevertheless, in comparison to other costs such as labour, depreciation, running costs and production goods the depreciation cost of the building and factory in all four stages is considerably low. The study of Cengiz and Mamiş (2015) did not define what the running costs are even though it is included in the manufacturing cost breakdown. However, in comparison with other similar studies such as IRENA (2012), Kalowekamo and Baker (2009) and Canizo et al. (2009), it can be explained as the costs related to O&M and company overheads other than depreciation. The highest share of running costs can be seen in the wafering process and the lowest in the module assembly stage. Similar to the running costs, the study did not explain what the production goods are. Nevertheless, by comparing with a similar study conducted by Canizo et al. (2009) and considering the percentage amounts in the graph, production goods can be explained as the material input for the specific output of each production stage. In particular, for ingot casting, the material input would be the silicon feedstock (Canizo et al., 2009). Similarly, for wafering, the material input would be the developed ingots.

Figure 2 **Manufacturing cost share of first generation**



Source: Cengiz and Mamis (2015)

According to Figure 2, the highest production cost can be seen in the module assembly stage and the lowest can be seen in the ingot casting stage.

The report published by the IRENA (2012) under the cost analysis series of renewable energy technologies provides a similar cost breakdown for crystalline, thin-film and organic PV modules. The report explained the manufacturing costs of crystalline silicon modules similarly to Cengiz and Mamiş (2015), yet the manufacturing costs of the other two PV module types are discussed considering the material. According to the report, the manufacturing cost of each module type can be divided into five subcategories called material cost, labour cost, O&M cost, depreciation cost and glass cost. The reasons for indicating the cost of glass separately are (1) the high amount of glass usage to deposit the solar cells and (2) glass is not a main material used in cell manufacturing (IRENA, 2012). As per the report, the material costs of thin-film and organic PV and the cost of glass required for cell integration are approximately similar. Furthermore, the material costs and cost of glass together are more than 50% of the total manufacturing cost. O&M costs of each thin-film and organic PV are different from one type to another. CdTe modules have the highest O&M cost. The depreciation cost of TF-Si and CIGS modules are comparatively higher than the other module types. Interestingly, the labour costs of all thin-film and organic PV modules are significantly low when compared to the crystalline modules. This is mainly because thin-film and other innovative PV modules production can be highly automated and require fewer machines than the silicon production process (Cengiz and Mamiş, 2015). Thin-film and organic PV manufacturing also require low material and energy input.

In addition, to the aforementioned major cost components, PV module production requires several other materials. In particular, the wafering, cell processing and module assembly stages of crystalline silicon PV modules require materials such as slurry, wire, crucible, aluminium and silver, chemicals, glass, frame, back sheet, junction box and cable (Kavlak et al., 2017). These other materials also impact the module cost calculation. PV module manufacturing plants are highly capital intensive and production cost depends on the technology, plant size, geographical location, labour rates, availability and cost of raw materials, scale of production, profit margin and capital costs (Kavlak et al., 2017; Sandor et al., 2018). Labour cost is significant in manufacturing cost. For example, PV module prices in Asian markets are lower due to the low labour cost (IRENA, 2016).

Crystalline silicon modules are generally expensive in comparison to thin-film PV modules (Candelise et al., 2011; IRENA, 2012). Nevertheless, the uptake is comparatively high due to the higher efficiency (IRENA, 2012). The manufacturing cost of crystalline PV is high in comparison to thin-film modules due to the complex production process, especially in the wafering stage (Candelise et al., 2011; IRENA, 2012).

Standard PV modules are generally used in BAPV applications or rooftop PV systems (Pagliaro et al., 2010). BIPV modules are mostly custom-made as per the project requirements, therefore, thin-film materials such as amorphous silicon are highly recommended for custom-made module manufacturing (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 and thus 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 can provide the desired qualities in BIPV module manufacturing, and therefore, are widely used in the BIPV sector. Moreover, experiments have revealed that the efficiency ratio of BIPV systems is better when the modules are made of thin-film materials (Heinstein et al., 2013).

As explained in the introduction, BIPV modules perform as a building envelope material while generating onsite electricity (Aste et al., 2016). Therefore, BIPV could save money due to the replacement of conventional building material, which would be a potential saving to the total construction cost. According to the cost data provided in the project report titled *BIPV market and stakeholder analysis and needs* in PV Sites (2016), BIPV roof module costs are comparatively higher than conventional roofing materials. However, this comparison does not include the financial benefits of BIPV modules from onsite electricity production. The PV Sites (2016) cost data also suggests that BIPV façades are cost effective and competitive with conventional façade materials. For example, the BIPV wooden façade price is low compared to glazed curtain walls and window façades under certain conditions. Furthermore, the BIPV façade price range is similar to the metal façade price range. Moreover, the BIPV façade price range covers some parts of the other cold façade price ranges such as fibrocement, brick, ceramic and stone. BIPV balconies and solar shading prices are affordable in comparison to expensive warm façade such as glazed curtain walls and windows. The key feature to be considered is that the price range comparison given in the PV Sites (2016) project report does not include the material offset and dual functionality (as a building material and an electricity generator). Therefore, true financial benefits cannot be encountered via this sort of comparison (PV Sites, 2016). Nevertheless, it provides a perfect idea about the price range of BIPV products in comparison to conventional building materials.

3.2.2 BIPV balance of system costs

The balance of system (BOS) costs generally account for 10-16% of the BIPV construction cost (Yang and Carre, 2017). However, depending on the size and complexity of the system, it can amount to up to 50% of the total construction cost (i.e. the economic viability study conducted by Haque et al., 2012 on an academic building). The literature review found that most of the BOS components such as inverters and storage devices are common to both BAPV and BIPV systems. Therefore, it was difficult to find studies that specifically discuss BIPV BOS costs. Accordingly, the following paragraphs describe the BOS costs in general point of view.

The inverter is the main component of the BOS and contributes 10-19% of the total system cost (Ziuku and Meyer, 2013). It is a solid-state electronic device that converts variable direct current (DC) power output into alternative current (AC) to transfer PV power generation for commercial need. The efficiency of an inverter is nearly 98% (Jan et al., 2017). Depending on the quality, size and efficiency, the cost of a solar inverter generally lies around the US$900-2,500 range (O'Neil, 2017). Central inverters, string inverters and micro inverters are the common types generally used in the PV/BIPV industry (IRENA, 2016; Noone, 2013). The type of inverters varies with the system requirements such as off-grid, on-grid, battery storage, residential and commercial use and capacity. Power output (three phase or single phase), cost, system size, efficiency are key criteria for inverter selection (Jana et al., 2017; Hassaine et al., 2014). Many innovative technologies are emerging by adding modern features on efficiency, size, easy installation and other advanced features with control strategies. Table 1 presents the global inverter technology prices.

According to Table 1, inverters mainly consist of power electronic materials, control cards, magnetic filters and distribution boards (IRENA, 2016). The inverter manufacturing process includes circuit-board printing, inverter assembly, inverter testing, finishing and shipping. In addition, it consists of several indirect costs such as depreciation of the plant and equipment, labour and running costs (Solar World, 2016). According to Table 1, micro inverters are the most expensive in comparison to string and central inverters. This is due to the relatively high cost components such as power electronics, control cards, and cost margin (IRENA, 2016). Nevertheless, the efficiency of micro inverters is comparatively lower than the other two inverters. Micro inverters tend to shine in limited shading; nevertheless, they are capable of delivering higher overall energy yields in comparison to string inverter systems when physical and environmental conditions such as orientation, tilt angle and access to sun are ideal. Central inverters are the cheapest and most efficient inverter type and can be bought considerably cheaper from China than from other manufacturing countries. String and central inverter types are cheaper in China than European countries and the US due to the inexpensive supply chain of materials, low labour wages, limited testing and other requirements (Lacey, 2013). Nevertheless, this does not necessarily indicate that the quality of Chinese inverters is low.

Table 1 Market price of inverters in 2015

Characteristics	Central inverters	String inverters	Micro inverters
Capacity	>100kWp	<100kWp	Module power range
Efficiency	Up to 98.5%	Up to 98.0%	90.0-95.0%
Price (US$/W)	0.14	0.18	0.38
Power electronics	0.015	0.017	0.069
Control cards	0.001	0.002	0.010
Filters	0.006	0.006	0.010
Distribution board and others	0.020	0.026	0.010
Indirect cost	0.075	0.100	0.117
Margin	0.023	0.030	0.063
Chinese products	0.03-0.05	0.06-0.08	-

Source: IRENA, 2016

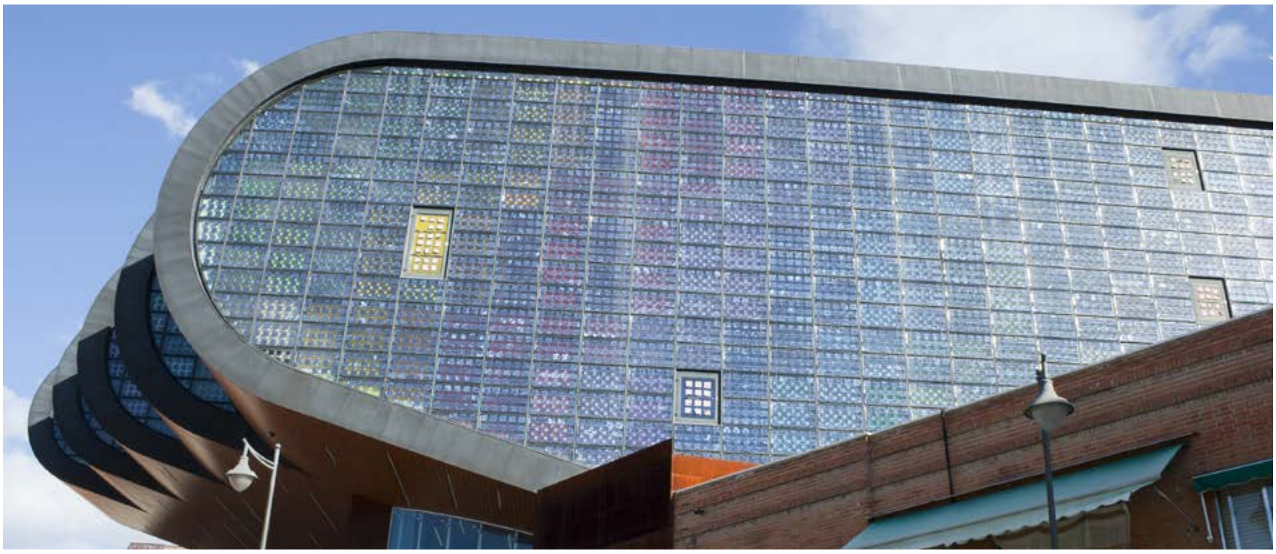
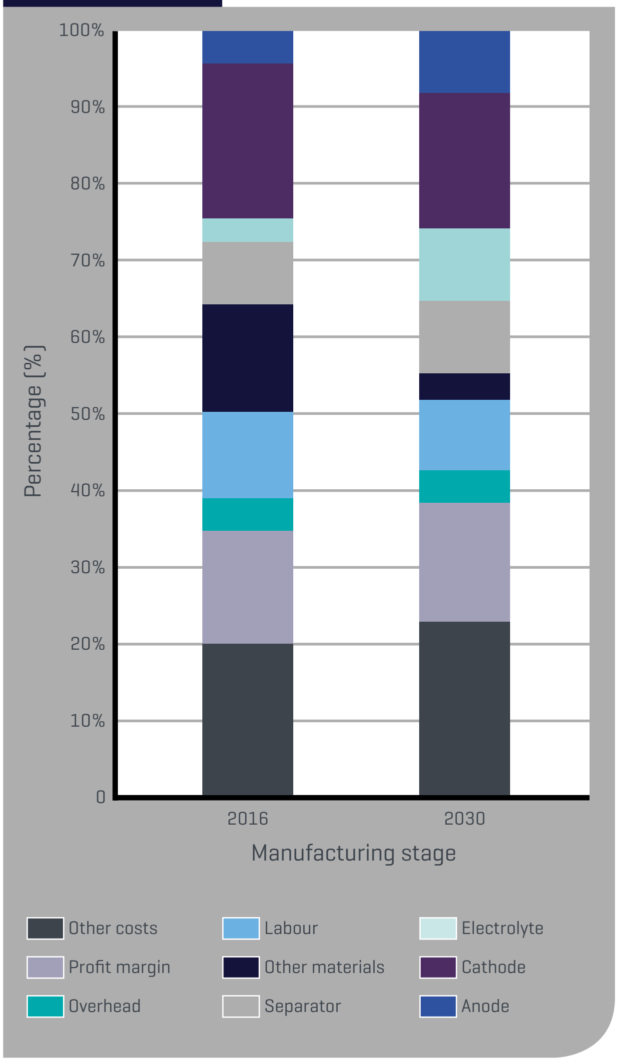


Image source: Clavivs / shutterstock.com

Figure 3 **Lithium-ion battery: Cost breakdown for 2016 and projected cost breakdown for 2030**



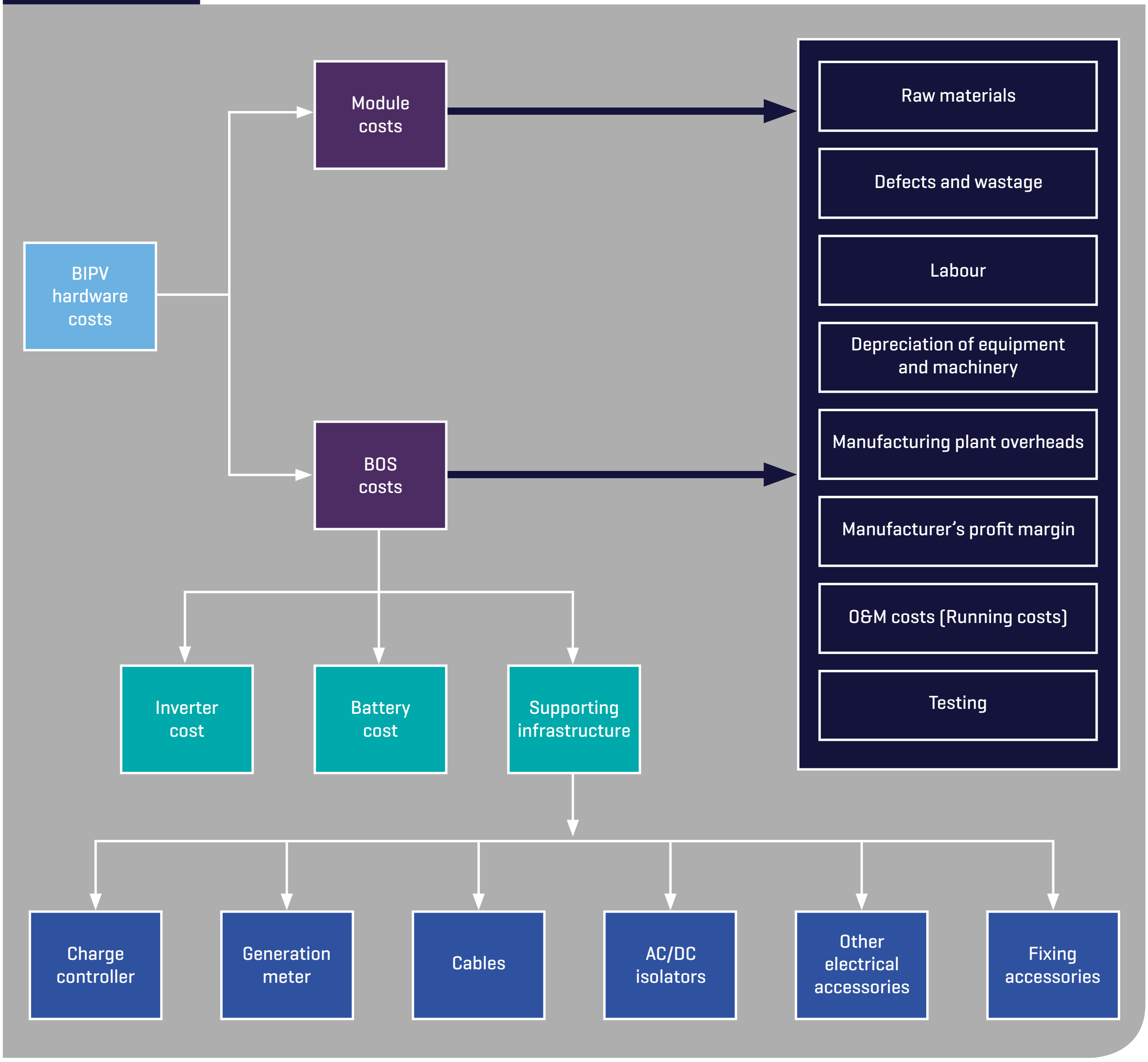
Source: IRENA [2017]

Energy storage systems/batteries are another major BOS component in a PV system. A wide range of battery technologies including lead-acid batteries, sodium sulphur batteries (NaS), lithium ion batteries (Li-ion), nickel cadmium batteries (Ni-Cd), metal-air batteries, super capacitors (electrochemical capacitors) and flow batteries (ZnBr, VRB and PSB) are generally used for renewable energy storage (Toledo et al., 2010).

According to current and projected battery cell prices (for 2014, 2017 and 2020) for utility-scale application, provided by the project report titled *Battery storage for renewables: market status and technology outlook* of IRENA (2015), a significant price fall can be evidenced in lithium-ion batteries. This is due to the high demand in the PV market for this battery, owing to favourable qualities such as high discharge lifecycle, high power density and high performance in comparison to other batteries (IRENA, 2015). The manufacturing cost of a lithium-ion battery in 2016 was approximately US$580/KWh and it is forecast that in 2030, the cost will be around US$220/KWh (IRENA, 2017). Figure 3 shows the cost breakdown of lithium-ion batteries in 2016 and the projected cost breakdown in 2030.

According to Figure 3, most of the cost components given are the materials used in battery production. The total material cost amounts to approximately 50% of the total production cost (IRENA, 2017). The remaining 50% includes labour, overhead, profit and any other required expense. Figure 3 also indicates a possible reduction in labour requirement and higher profit margins in the near future. Batteries have different chemical compositions (Fellet, 2016). The composition of cathode and anode can differ depending on the parameters such as power and capacity. Accordingly, their prices will be different from each other. Furthermore, the total storage system cost can vary with the location, application, additional equipment needed, vendors, commercial availability and size (IRENA, 2015).

Figure 4 **BIPV hardware cost breakdown**



In addition to inverters and batteries, BIPV systems have additional supporting equipment such as charge controllers (to maintain the safety of the battery and other equipment), generation metres (devices to pass electricity to grid and domestic use), cables, AC and DC isolators and other electrical devices (Tadesse, 2017). Furthermore, BIPV requires fixing accessories for system installation. The NREL Report of 2011 highlighted that the main cost difference between the BAPV and BIPV supporting equipment is that BAPV requires a significant amount of mounting infrastructure whereas BIPV only requires inexpensive fixing accessories for installation (James et al., 2011). According to the findings of this report, when considering the reference case (BAPV roof tile system) and the derivative case (c-Si BIPV roof tile system) explained in Section 3.1 (paragraph 2), the elimination of mounting hardware can generally reduce US$0.27/W from the BIPV system, which is approximately 40% of the total cost reduction (James et al., 2011). Nevertheless, the cost of supporting equipment is not well-addressed or analysed in the BIPV academia.

Based on the aforementioned analysis, the study developed a detailed cost breakdown considering all hardware cost components. Figure 4 shows the cost breakdown of BIPV hardware costs. According to Figure 4, the manufacturing costs of all BIPV hardware consist of eight cost categories; raw materials, defects and wastage, labour, depreciation, overheads, profit, O&M and testing.

3.3 BIPV soft costs

BIPV soft costs include all other costs except the system hardware (Keller, 2013). In fact, soft costs include the costs spent during the entire BIPV lifecycle for getting the systems up and running (Ajwang et al., 2017). BIPV soft costs emerge from the design stage to operational stage until the end of its lifecycle (Bakos et al., 2003). Many previous studies have identified several soft costs such as design consultancy, design tools, installation labour, administrative costs in the permitting, inspection and interconnection (PII) processes, supply-chain costs and maintenance costs (Ajwang et al., 2017; Strupeit and Neij, 2017; Yang and Zuo, 2016).

However, there is a scarcity of literature that provides all soft costs associated with the BIPV lifecycle in a single platform, as the categorisation of soft costs are always diverse from one study to another. In particular, some researchers consider the installation cost in general by including installation labour (structural), installation labour (electrical), overhead and profit margins and taxes (James et al., 2011), while some researchers consider each of these costs as separate soft costs (Ajwang et al., 2017; Energy Market Authority and Building and Construction Authority, 2009; Holton et al., 2014; Norton et al., 2011; Santos and Takata, 2014; Tominga, 2009; Yang and Zou, 2016).

During the literature review, it was identified that most soft cost categories are common to both BAPV and BIPV systems. The current literature mainly discusses the main soft cost categories such as installation labour, design consultancy and customer acquisition. Nevertheless, there are a number of soft costs that should be considered in each stage of the BIPV lifecycle. Based on a comprehensive literature review, this study identified these soft costs and plotted them in a single platform, shown by Figure 5. The soft costs of the BIPV lifecycle are categorised under six stages: (1) design-related costs, (2) procurement-related costs, (3) construction and installation costs, (4) PII-related costs, (5) O&M costs and (6) disposal-related costs. They are discussed in detail in the following sections.

Figure 5 **BIPV soft costs**

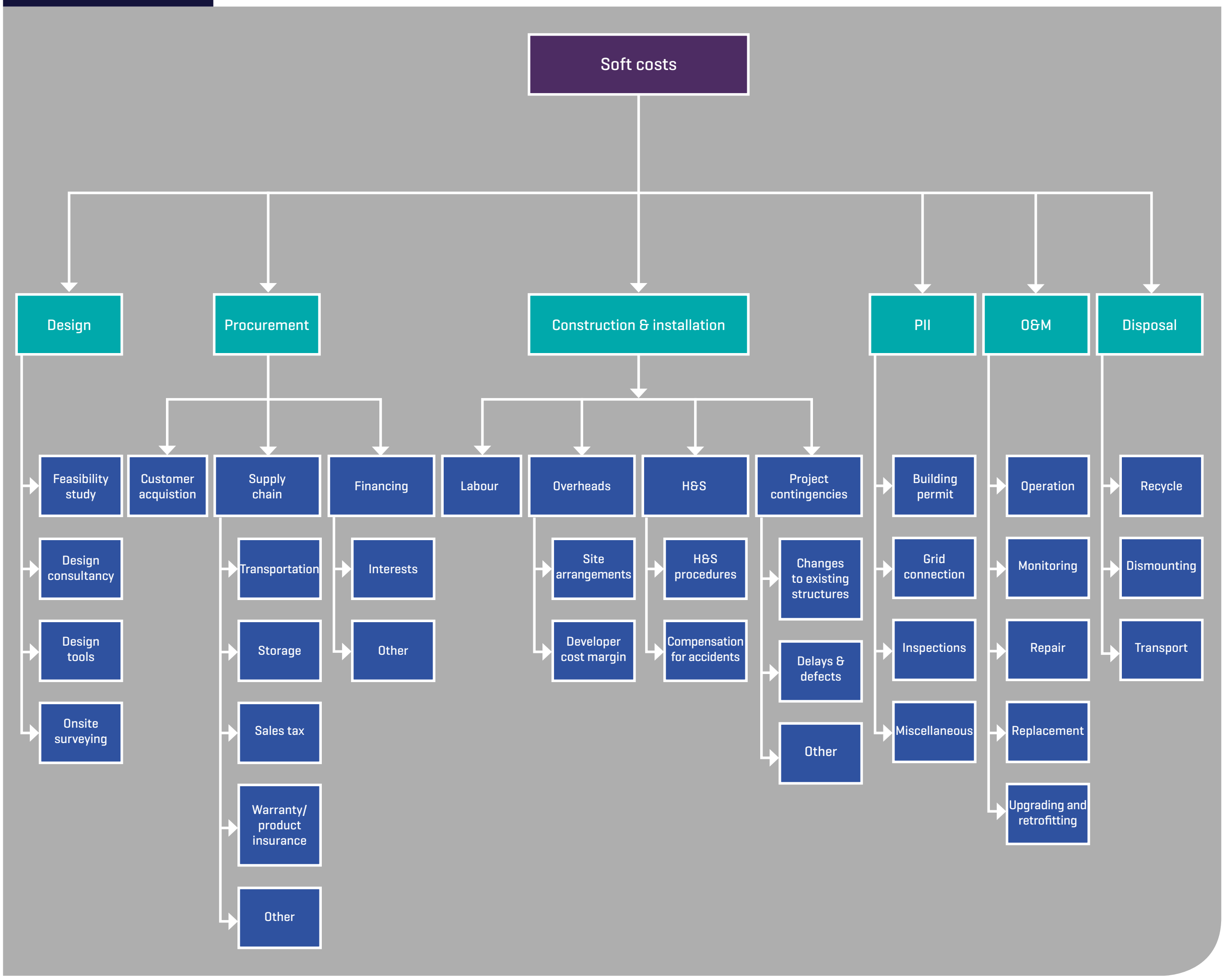


Image source: Hans Engbers / shutterstock.com

3.3.1 Design-related soft costs

Unlike BAPV systems, BIPV modules are integrated into the building envelope as building materials, therefore, BIPV soft costs need to be considered from the early design stage of the building (Bonomo et al., 2017). Accordingly, BIPV soft costs first appear in the feasibility stage of the building (Bakos et al., 2003). The cost of the feasibility study includes the costs of site investigation, preliminary designs, report preparation, travelling and accommodation (Bakos et al., 2003; Sagani et al., 2017). BIPV designing includes structural designing of the building, electrical layout, BIPV system design and providing an aesthetic appearance to the building (Bakos et al., 2003). Accordingly, a number of experts such as structural engineers, electrical engineers, architects, and BIPV specialists will be involved in the design stage (Dricus, 2011; Ikkurti and Saha, 2015; Solar Server, 2010). The design-related costs include consultancy wages, onsite surveying, design tools and equipment (Keller, 2013; Yang, 2015). It is very difficult to identify the exact cost for each of the cost categories due to their subjective nature. In general, the design cost will be around US$0.32/W (Aste et al., 2016) (Refer to Appendix 2). However, this amount will vary with the complexity, size and multidisciplinary involvement of the project.

3.3.2 Procurement-related soft costs

Both BAPV and BIPV systems acquire procurement-related costs such as costs associated with customer acquisition, financing and installer/integrator margin (Morris et al., 2014; Norton et al., 2011; Strupeit and Neij, 2017). Customer acquisition includes all sales and marketing expenses, including advertising, sales calls, site visits, initial bid preparation, and contract negotiation (Fu et al., 2016; Sagani et al., 2017). There are several supply chain costs such as costs and fees associated with inventory, shipping, transportation and handling of equipment (Fu et al., 2016). 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 (Energy Market Authority & Building and Construction Authority, 2009; Holton et al., 2014; Norton et al., 2011; Santos and Takata, 2014). The general customer acquisition cost of a BAPV system varies within the US$0.01-0.31/W range depending on the demand, public awareness and the related administrative procedures (see Appendix 2) (Fu et al., 2016; Strupeit and Neij, 2017). The customer acquisition cost of a BIPV system will be slightly higher than this range since BIPV is still a niche market (Ossweijer et al., 2018). There are several studies that discuss some of the supply chain costs of BIPV systems. In particular, the transportation cost of a mono-crystalline BIPV roofing system is approximately US$2.19/W in Italy (Cucchiella et al., 2012). The packing cost of a 53 kg weight ASI Glass modules is US$9.25/kg in Germany (Tominga, 2009). If it is flexible packaging (flexible thin-film products), the cost will be comparatively high and around US$0.50/W in the US (James et al., 2011). For example, the freight cost will be 15% of the total cost of BIPV modules imported from Germany to Australia (Tominga, 2009). These costs are shown with their system details in Appendix 2.

3.3.3 Construction and installation-related soft costs

Construction and installation-related costs of BIPV include skilled labour, construction supervision, specialised consultation, health and safety, and project contingencies such as delays and training (Bakos et al., 2003; The Centre for a Sustainable Built Environment, 2005). It is difficult to ascertain whether BAPV or BIPV have lower installation costs due to labour costs varying depending on the country, region, skill, availability and complexity of the job. BIPV consumes more time for installation due to the high number of modules (James et al., 2011). However, since these modules are relatively small, they are easier to move and handle than BAPV modules. Moreover, BAPV modules require the installation of mounting systems prior to the installation of modules, which again takes more time in comparison to BIPV systems (James et al., 2011). Nevertheless, BIPV requires a complex and time-consuming electrical wiring process. According to the cost comparison of the NREL report of 2011 (Section 3.1), the total installation cost of a c-Si BIPV roof system (derivative case) is lower than the total installation cost of a similar BAPV roof system (reference case). However, this can be reversed in special circumstances such as dealing with flexible BIPV modules (James et al., 2011). The labour costs of several countries for both BAPV and BIPV systems are given in Appendix 2.

There are several costs other than installation labour that should be taken into consideration, such as health and safety costs, and project contingencies. The health and safety costs of BIPV systems include the safety precautions, clothing and equipment, supervision during construction and compensation for accidents (The Centre for a Sustainable Built Environment, 2005). Project contingencies include changes to existing structures, delays due to extreme weather, underestimated items and product defects, breakage and reordering replacements. PV installers have similar overhead costs despite of the technology, though special cases such as flexible thin-film applications and BIPV systems with significant aesthetic appearance will have comparatively higher overhead costs (James et al., 2011; Heinstein et al., 2013).

3.3.4 PII-related soft costs

One of the most significant soft costs of both BIPV and BAPV is Permit, Inspection and Interconnection (PII) costs (Keller, 2013; Strupeit and Neij, 2017). In general, all PV installations (i.e. BAPV and BIPV) have to undergo certain approval processes such as obtaining necessary permits for installation, inspections by the relevant parties and interconnection procedures (Burkhardt et al., 2015). Accordingly, there will be PII associated costs such as permitting fees, staff hours for preparing and submitting permits and interconnection applications (Fu et al., 2016). Furthermore, there will be several site inspections and interconnection-based reviews by the local utility for which a considerable cost has to be spent (Burkhardt et al., 2015). A number of prevailing literatures emphasise that the regulatory process-related costs have a considerable impact on PV prices (Seel et al., 2014). The main difference of BIPV and BAPV systems with regard to PII costs is that for BIPV, a building permit should be taken prior to construction whereas for BAPV, the permit and approval should be taken for its installation (for BAPV, it is not mandatory to get the permits and approvals before construction) (Heinstein et al., 2013; Sozer and Elnimeiri, 2007). PII costs vary depending on the local policies and administrative processes (Burkhardt et al., 2015). For example, the US PII costs are considerably higher than other countries such as Germany and Australia due to different policies and procedures of different states. Nevertheless, it generally lies between US$0.01-0.06/W (Refer Appendix 2) (Seel et al., 2014; Strupeit and Neij, 2017).

3.3.5 Operation and maintenance-related soft costs

O&M-related costs are common to both BAPV and BIPV systems yet several differences can be seen when comparing these costs (Bonomo et al., 2017). Both systems are considered to require low maintenance, yet BIPV maintenance is complex and time consuming due to the high number of integrated modules (Ikkurti and Saha, 2015; Keller, 2013). Operation of the system, monitoring, maintenance, repairs, periodic upgrading and retrofitting will create a considerable amount of cost in the BIPV and BAPV lifecycles yet in different magnitudes (The Centre for a Sustainable Built Environment, 2005; Strupeit, 2017; Yang and Zou, 2016). There can be unforeseen situations such as damage to modules and buildings, extreme weather events (snow loads/wind/lightning), fire, overvoltage, theft and vandalism, random yield loss during breakdown times and systemic yield underperformance (Strupeit, 2017). All these events will require repair/replacement and compensation, which require finance. For both systems, there will be system updates time to time that require upgrading and retrofitting, which will be an additional expense (Energy Market Authority & Building and Construction Authority, 2009).

Periodic system checks and cleaning have to be performed, requiring a considerable amount of money to be spent as a part of maintenance costs. In fact, cleaning the systems in high-rise or unusual geometric-shaped buildings will cost more (Sozer and Elnimeiri, 2007). In a case of retrofitting, a detailed survey has to be carried out to identify the probable cost of structural repairs during the process (Gindi et al., 2017). It is vital to conduct a cost-benefit analysis prior to carrying out the retrofitting to ensure its benefits withstand the cost. All these procedures require expertise involvement, which creates consultancy and administrative fees. O&M costs of several countries are given in Appendix 2.

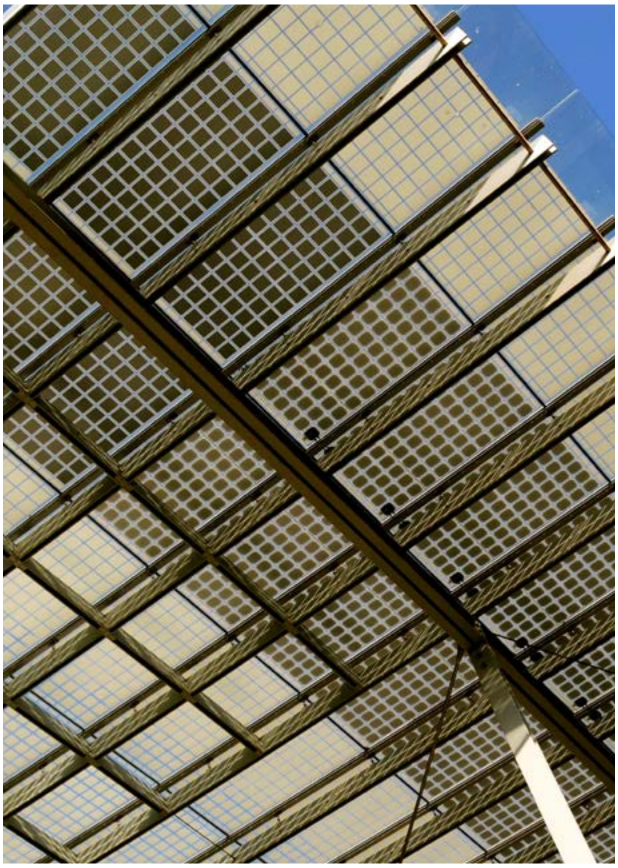
3.3.6 Disposal-related soft costs

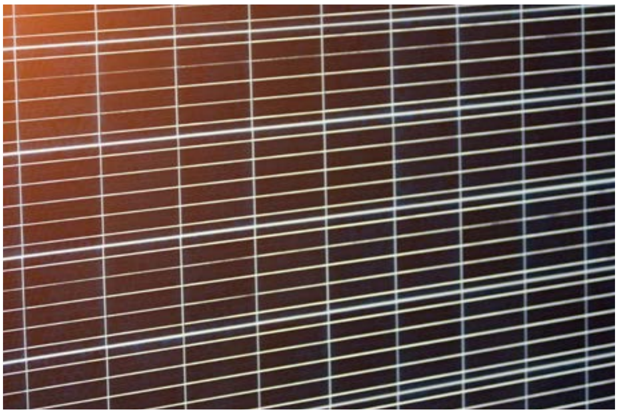
Even though rarely discussed, disposal costs are common to both BAPV and BIPV systems (Strupeit and Neij, 2017; Yang and Zou, 2016). This includes recycling, dismounting and transportation costs (Energy Market Authority & Building and Construction Authority, 2009; Sozer and Elnimeiri, 2007). Recycling BIPV materials involves extra costs because of the need for careful handling, careful dismounting, transportation and environment-friendly storage (The Centre for a Sustainable Built Environment, 2005). If the BIPV materials are hazardous (such as thin-film PV), additional safety procedures and hazardous disposal requirements will be required which will create several costs (Eiffert, 2003).

The lifecycle of BAPV and BIPV systems has certain similarities and differences. In particular, the BIPV lifecycle begins with the building's lifecycle, yet the BAPV lifecycle has no connection to the building's lifecycle. Several literatures that discussed soft costs have provided some specific cost details in their journal papers/technical reports. Appendix 2 presents the cost details of BIPV and BAPV systems in different countries over the past 15 years. Even though the study's main concern is BIPV, BAPV soft costs are also included in Appendix 2 due to their approximate similarity to the BIPV soft costs.

The current literature has only considered significant cost items such as designing, installation, customer acquisition, PII costs, maintenance costs and several supply chain costs, mostly due to their significance in comparison to other soft costs. As shown in Appendix 2, a significant difference in costs can be seen between the countries (several costs can be compared due to the similar time period and similar nature). For example, the installation costs (structural BOS) of Malaysia and Colombia in an approximately similar time period (2012 and 2011) for a similar system (yet different capacities) can be compared to realise that the Colombian installation cost at that time period was extremely high (Malaysian structural and electrical installation cost: US$1.03 + US$0.24 = US$1.27/W; Colombian structural and electrical installation cost: US$1.91 + US$2.62 = US$4.53/W). Similarly, the PII costs of Germany and the US for similar systems in a similar time period (2014) can be compared to identify that the US PII costs are four times higher than the Germany (US = US$0.24/W; Germany = US$0.06/W).

During the literature review and industrial workshop, it was realised that there is very limited information about BIPV cost categories. Often, BIPV project costs are publicly available as a lump sum rather than a comprehensive breakdown. Hence, it is difficult to figure out the exact current amounts for the aforementioned soft costs. One of the main reasons for this limitation is the lack of globally recognised BIPV-specific standards. There are no regulations and restrictions that determine the level of standards required for a BIPV project other than the general PV standards and several inconsistent international BIPV standards. For example, there are several European standards such as EN 50583 series for PV integrated buildings and PV as a construction product, International Electrotechnical Commission (IEC) standards such as 82/1055/NP for PV roof applications resulting in project IEC 63092, 82/888/NP for PV curtain wall applications resulting in project IEC 62980 and International Standards Organisation (ISO) standards such as project ISO 18178 for laminated solar PV glass by ISO TC160: Glass in building (IEA, 2018f). However, the majority of these standards are not successful in determining BIPV standards due to the ambiguities and discrepancies they have with each other. In addition, BIPV requires local standards that fulfil regional or state requirements, however, it is difficult to identify such local standards. For example, in Australia, there are not enough BIPV projects to emphasise the need for local standards or to identify the standard requirements by observing past projects. Hence, BIPV projects are completed diversely all around the world. This makes it impossible to compare the soft costs and come up with a general figure. Therefore, currently, BIPV soft costs are determined case by case even in one country. This study identified that this is a significant knowledge gap with regard to identifying the cost reduction potentials of BIPV systems. As the initial step, the study focused on the available cost information (i.e. Appendix 2) of different countries in the past 15 years to investigate the similarities and differences as described in the above paragraphs. With this cost information, it is possible to identify which countries have low cost BIPV/BAPV options and the ways of reducing/maintaining such low costs. These ways of reducing/maintaining low costs are explained in the prevailing literature along with the aforementioned cost details. They are discussed in the following section.





4.0 Cost reduction potentials

The global PV market has been unstable in the past due to the high module cost and limited public interest (Osseweijer et al., 2018). However, due to the sudden module price decline in 2012 (refer Figure 4: IRENA, 2018) and effective government support, public interest increased, putting the market into a more stable condition (Strupeit, 2017). The current PV market is in a more mature stage and has obtained healthy growth over the years (Osseweijer et al., 2018). A significant market growth was evidenced in 2016 and 2017 with a global installed capacity of 100GW (IEA, 2018b). In particular, BIPV technology received increased interest as an emerging market segment in the PV industry (Osseweijer et al., 2018).

PV academia has identified the rapid module price reduction as one of the key reasons (sometimes the main reason) for accelerated PV uptake in the past six years (Strupeit and Neij, 2017). Similarly, reducing hardware and soft costs of BIPV systems could drive the uptake of BIPV. As explained in Section 3, there are a number of hardware and soft costs associated with BIPV systems. Therefore, it is crucial to identify the ways to reduce those costs to accelerate the uptake of the technology. The following sections explain how these costs could be reduced.

4.1 Hardware cost reduction potentials

This section discusses the cost reduction potential of BIPV hardware under two main categories: (1) BIPV module cost reduction and (2) BIPV BOS cost reduction. The cost reduction potential of BIPV hardware is mostly associated with the manufacturing process. Furthermore, these cost reduction potentials are available in both macro and micro scales.

4.1.1 Cost reduction potentials of BIPV modules

As mentioned earlier, PV module prices have fallen significantly (IRENA, 2018). In particular, c-Si modules that were earlier considered to be very expensive are now competing price-wise with thin-film modules (IRENA, 2018; PV Magazine, 2018). Reasons include the Chinese production of low-cost c-Si modules and increased competition from low-cost thin-film modules. However, currently, both c-Si and thin-film modules have approximately similar costs (IRENA, 2018). According to the latest statistics, these costs are not rapidly falling over time anymore (PV Magazine, 2018).

As per the findings of the industrial workshop, there are three main areas to be considered in reducing the cost of PV modules: (1) continuous research and development (R&D) on PV materials, (2) the manufacturing process, and (3) promoting the technology. R&D is an area for the scientists and researchers to focus on. The main focus should be on introducing alternative cheap cell materials and waste reduction. Automated manufacturing and process optimisation, resource utilisation and minimising capital expenditure are the three main aspects that should be considered in reducing the manufacturing process related costs. Promoting BIPV technology will enable mass production, thus economies of scale and reduce the unit price of BIPV modules. Government support can be used to promote the technology. These cost reduction potentials are discussed in detail in the following paragraphs.

R&D on PV materials

- **Alternative cell materials:** The cost of materials is a significant factor in PV module prices. Scarcity of main raw materials generates high prices (IRENA, 2018). This has been highlighted as a potential barrier to cost reduction (Candelise et al., 2011). There are two types of materials; (1) direct materials and (2) the materials used to complete the module (e.g. metal contacts, lamination, scribing, annealing) (Zweibel, 1999). In particular, the price decline of poly-silicon has enabled the reduction of crystalline module costs (Pillai, 2015). Many efforts have been made to reduce the cost of PV modules through innovative materials and new product development (Bakos et al., 2003). For example, thin-film products were invented as an alternative to expensive c-Si modules (IRENA, 2018). Similarly, organic photovoltaic cells have been introduced as a low-cost alternative to both c-Si and thin-film products (Kalowekamo and Baker, 2009). Shortage of c-Si raw materials also accelerates the need for innovative material technologies, thinner wafers and alternative ways to use PV-grade silicon (Cengiz and Mamiş, 2015). Therefore, continuous R&D is required to identify low-cost alternative materials for PV-module production and to control the unsustainable raw material usage.
- **Wastage reduction:** R&D is also required to find methods of minimising wastage. In particular, reducing silicon consumption per W or per kg, improving ingot growth, increasing the number of wafers per ingot, avoiding sawing losses of wafers and minimising wastage of materials through increasing cell efficiency are some significant areas of research with regard to crystalline modules (Canizo et al., 2009). Minimising wastage will reduce the module cost by limiting the material usage.

Manufacturing process

- **Automated manufacturing and process optimisation:** Labour cost is one of the main cost components in module manufacturing. In most European countries, the US and Australia, the hourly rate for labour is high (IRENA, 2018). As a result, the module prices of these countries are high in comparison to Asian countries such as China and Japan. An effective way to reduce the high cost of labour is using automated systems to carry out the production (Zweibel, 1999). Other than minimising the labour requirement, automated systems provide additional benefits such as reducing materials usage, simplification of the module manufacturing process, limited manufacturing errors, limited manufacturing time consumption, limited wastage and improved quality (Fellet, 2016; Cengiz and Mamiş, 2015). All these benefits directly involve reducing the manufacturing process cost and the PV module price. Furthermore, this automated production can be optimised with regard to material input, scale of production, quality of output and machinery performance to achieve more cost reductions (IRENA, 2012; IRENA, 2018).
- **Resource utilisation:** The findings of the industrial workshop revealed that the manufacturing process of PV modules includes resources such as raw materials, labour, machinery, tools and equipment. It is crucial to utilise these resources with minimum material input, minimum labour involvement, minimum machinery, tools and equipment depreciation, and minimum time consumption to gain maximum output. To achieve these conditions, manufacturers should focus on careful planning, resource allocation and quality control (Ventre et al., 2001). Wastage should be minimised effectively. Considerable wastage could be evidenced in the conversion of ingots to wafers in c-Si modules (Canizo et al., 2009). This can be avoided by increasing the number of wafers per ingot through careful planning and usage of advanced equipment. In the manufacturing process, substantial consideration should be given to effective cell structure development and avoidance of material losses due to sawing wafers (Canizo et al., 2009; Zweibel, 1999). Resource utilisation could be effectively carried out by automated manufacturing and process optimisation (IRENA, 2015).
- **Minimising capital expenditure:** As per the discussion under this topic in the industrial workshop, the capital expenditure of a manufacturing plant is normally recovered from the production. Therefore, the module price will include a certain amount for capital expenditure. However, by minimising capital expenditure, it is possible to minimise the amount allocated in the module price. Opportunities are available to reduce high capital cost such as system integration, outsourcing O&M, equipment leasing and adhering to innovative technologies (Powell et al., 2015).

Promoting BIPV technology

- **Government support:** Government involvement is crucial in promoting the technology. Government policies and incentives for local manufacturers can enhance the PV module manufacturing of countries (Sandor et al., 2018). In particular, government support such as low-interest bank loans and low import-related taxes (i.e.: Goods and Services Tax (GST) and duty) would reduce the cost of capital and accordingly the module price. Government support could also assist in reducing the material import expenses (Pillai, 2015). Furthermore, the government can assist in R&D procedures to minimise the production cost of PV modules by providing funding and other facilities (Branker and Pearce, 2010; Yang and Zou, 2016).
- **Mass production and bulk purchasing of raw materials:** Promoting the technology will create a demand. Accordingly, more products will be required. Therefore, scale of production will be increased. An increase in the scale of production and manufacturing plant size enable the reduction of the cost of the PV modules by dividing manufacturing cost among a larger number of PV modules (Pillai, 2015). In general, the plant overheads and rent of the building and machinery will be allocated among the manufactured items, so by having a greater number of products the cost allocation per product will be reduced (IRENA, 2012; Zweibel, 1999). In addition, the benefits of bulk purchasing of raw materials include discounts, offers and incentives from the material suppliers (Pillai, 2015; IRENA, 2016). This will reduce the total cost of materials and consequently the module prices.

Every cost reduction potential discussed in the above paragraphs relates to one or more other cost reduction potentials. These connections are presented in Figure 7. By executing automated production and process optimisation, a significant amount of waste can be reduced. In addition, automated production and process optimisation can utilise the resources and enable mass production. On the other hand, R&D on identifying the ways to reduce waste include technological innovations such as manufacturing machinery, introducing optimisation techniques and using minimum material combinations. Government support and involvement in promoting BIPV technology will increase the demand for BIPV modules and accordingly, the scale of production will be increased. When the scale of production is increased, the manufacturers will require bulk purchasing, which may create a potential scarcity of raw materials, and demand for alternative materials. Hence, R&D on finding alternative cell materials is required. Similarly, the automated manufacturing and process optimisation can minimise the capital expenditure. In addition, to have connections with each other, these hardware cost reduction potentials are also connected with the BIPV deployment drivers, which are discussed in detail in the sections 5 and 6.

4.1.2 Cost reduction potential of BIPV BOS

Similar to PV modules, the BOS components such as inverters and batteries have their own manufacturing process. The types of cost incurred in the manufacturing process of these components are the same as PV module costs. The inverters, batteries and supporting infrastructure costs include raw material costs, labour, depreciation, running costs, overheads and profit. Therefore, cost reduction potential is common to BOS components.

The cost reduction potential for inverters mainly appears with inverter technologies (IRENA, 2017). Innovating technical features, including adding new functions and improving efficiency or optimising inverters could reduce the cost of the inverters. Cost reduction can be achieved by continuous investment in R&D to develop more advanced inverters and to improve the manufacturing processes (IRENA, 2012). Automating the manufacturing process and reducing the manpower requirements are some other approaches to reduce the cost of inverters (IRENA, 2016).

Statistics indicate that the price of batteries is declining along with the price decline of PV modules and inverters (IRENA, 2017). In the recent past, the price of li-ion batteries has fallen due to high demand created by their desirable performance as a PV storage unit (IRENA, 2015). Li-ion batteries possess favourable qualities that provide satisfactory results as a storage unit. Cost of raw materials is significant in battery manufacturing. For example, if the price of materials such as lead increases, it will create a significant impact on battery prices (Hanley et al., 2009). Therefore, the continuous R&D to identify new/alternative, chemically stable materials, improve the production process and increase efficiency can control the material intake and subsequently the battery costs (Diouf and Pode, 2015; IRENA, 2017). Furthermore, the increase in the scale of production, a more effective supply chain of materials and automated manufacturing are common cost reduction approaches for batteries (IRENA, 2017; Fellet, 2016). The cost reduction potentials of batteries can also be investigated in terms of production stages (IRENA, 2017). Based on the battery technology type, anode, cathode, electrolyte, separator and other materials, production processes are different, thus improvements in manufacturing equipment, proper component design and effective resource allocation can reduce the production costs of batteries.

According to the findings of the industrial workshop, in general, the supporting infrastructure material costs are low in comparison to PV modules, inverters and storage systems. Furthermore, they are not exclusive to the PV market, thus identifying their cost reduction potentials could be relatively difficult. Moreover, the cost reduction potentials of supporting infrastructure are not well-addressed in the PV academia. Nevertheless, the cost reduction potentials discussed for the PV modules can be applied for these supporting infrastructure materials as they have their own production process.

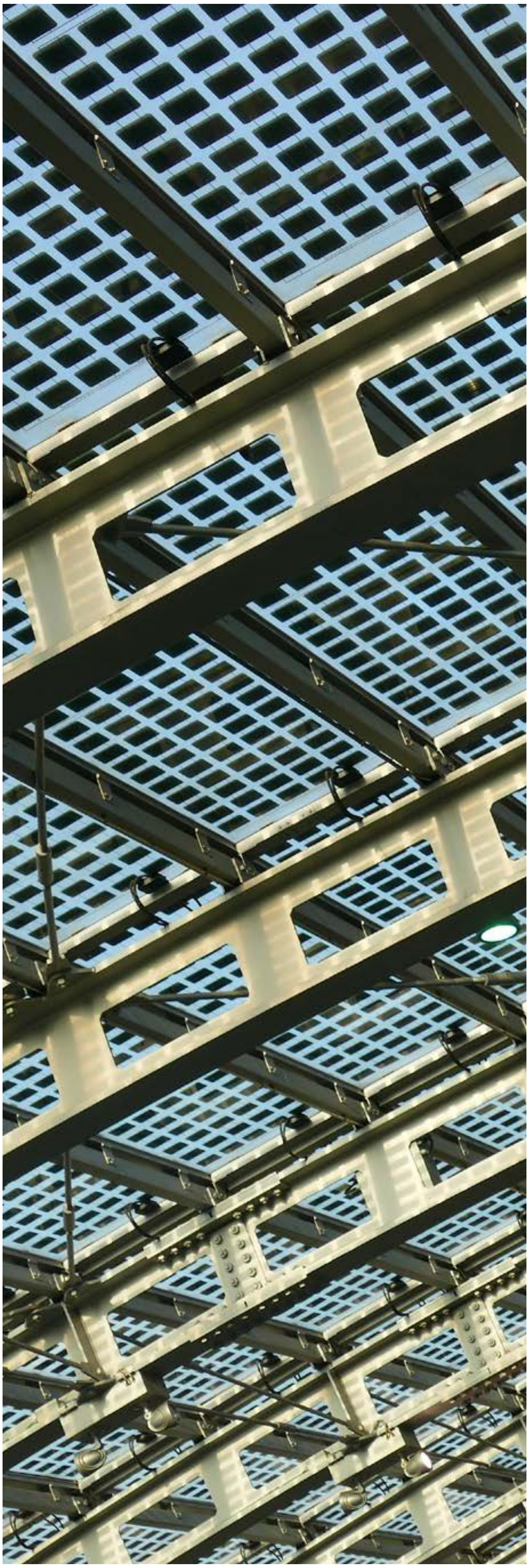


Image source: Hans Engbers / shutterstock.com

4.2 Soft cost reduction potentials

In general, BIPV is considered to be an expensive source of energy due to its complexity, design issues and relatively limited production capacity (Bonomo et al., 2017). In particular, the soft costs in each stage of the BIPV lifecycle are significant contributors of high system cost. Nevertheless, there is potential to reduce BIPV system soft costs. It is more effective to discuss this potential with regard to the BIPV lifecycle, so as to provide more specific details. The following sections explain the soft cost reduction potentials of BIPV systems under the main stages of its lifecycle.

4.2.1 Cost reduction potentials in the design stage

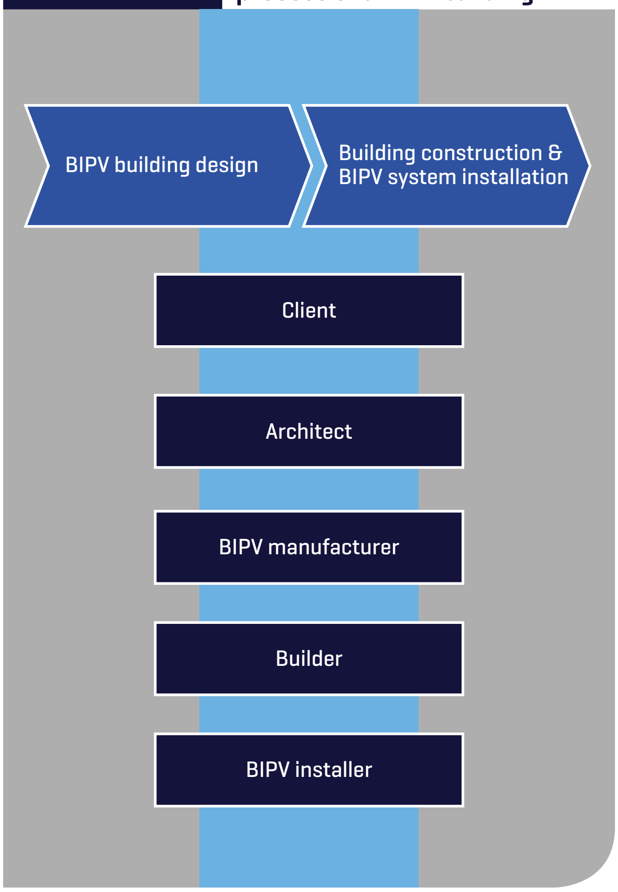
One of the main barriers of BIPV designing is the scarcity of BIPV-specific design tools. Since BIPV system design includes customisation, multidisciplinary involvement and specific architectural requirements, it is ineffective and time consuming to use general design tools available for PV design (Bakos et al., 2003; Bonomo et al., 2017). In fact, having flexibility in designing the building envelope to meet various visual and functional aspects will potentially enhance the building performance. In addition, geometrical shapes of the solar building envelope itself have significant impacts on the overall energy performance, daylighting and economic benefits. It is obvious that general PV design tools are incapable of providing the design flexibility and geometrical configuration of the building envelope.

A recent paper published on prevailing solar PV design tools emphasised that a number of parameters that come under the technical, economic, environmental and geophysical categories should be considered when optimising the design and management of a PV system (Wijeratne et al., 2018). Furthermore, the authors identified 14 key issues of current PV design tools including the absence of detailed localised climate and geographical data, limited availability of localised databases for PV product cost and energy prices, limited local building codes and standards, limited attention on the design and valuation of roof/façade integrated PV systems, significant information gaps in finance modes and contractual choices, no means to compare alternatives or optimised PV designs, limited information on O&M costs and limited consideration on construction/installation and the commissioning process. The study concluded that none of the prevailing design tools and software can consider all design optimisation parameters and address the key issues related to PV project design and management. Using these tools in BIPV building design will generate incomplete and incomprehensive designs that do not consider many of the parameters. As a result, there will be significant design errors and late additions which require expensive changes and rework. Therefore, BIPV-specific design tools and software that can provide an all-inclusive and all-considered design process are essential to reduce the cost. In addition, design optimisation can enhance the economic confidence of the clients to invest on BIPV projects.

The design stage of BIPV requires the involvement of many stakeholders, such as client, designer (architect), PV module manufacturer and builder. This multidisciplinary involvement in the design stage is time consuming, exhausting and expensive, especially when the stakeholders are not well-aware of each other's disciplines (Curtius, 2018). Integrating PV and building industries via stakeholder integration in the design stage would be a better solution to avoid the miscommunication and lack of understanding between the two sectors (Osseweijer et al., 2018). Figure 6 presents the integrated stakeholder involvement in the design and construction of a BIPV building.

Other than the above approaches, it is possible to avoid expensive and time-consuming structural and architectural changes during construction if a comprehensive design is made and kept to by the design team (Sozer and Elnimeiri, 2007). Moreover, it is crucial to consider the effective ways of integrating BIPV modules into the building envelope from the very first stage of the design to avoid the delays and issues related to the approval process and acquiring building permits. Furthermore, conducting a comprehensive design process and maintaining thorough communication can reduce BIPV design costs in a considerable manner (The Centre for a Sustainable Built Environment, 2005).

Figure 6 **Stakeholder involvement in the design and installation process of a BIPV building**



4.2.2 Cost reduction potential in the procurement stage

Importing BIPV modules and BOS components is common in many countries. It is one of the basic ways of reducing BIPV installation costs in countries where the local production is very expensive or infeasible (Greenmatch, 2018; Ng and Mithraratne, 2014). However, as per the findings of the industrial workshop, unnecessary expenses are often occurred due to not having a proper information-sharing system for the BIPV supply chain. 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. If there is a decentralised information-sharing platform such as the 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. Accordingly, R&D in this area should be encouraged and well-funded.

In addition, supply chain costs can be reduced by increasing the market transparency (i.e. publishing the performance records of PV installers and ranking the BIPV/ BAPV installers/ builders) (Strupeit, 2017). Online orders and delivering on time can reduce administrative-related costs and storage costs. In addition, having permanent storage facilities can reduce storage costs as well as the damage to the manufactured products (The Centre for a Sustainable Built Environment, 2005).

Customer acquisition costs can be significantly reduced by garnering positive media attention to provide free promotion and generate investor interest in green technologies such as BIPV (Mace et al., 2018). In several countries such as Germany and the UK, the government and private banks provide attractive low mortgage rates for BIPV installed buildings in order to encourage the use of BIPV technology (The Centre for a Sustainable Built Environment, 2005; Yang and Zou, 2016). In addition, Germany has followed several techniques to reduce financing costs such as knowledge enhancement of private banks and institutional investors regarding PV systems, modernising the administrative processes, providing exclusive bank staff for PV financing procedures, reducing institutional barriers on applying for loans and maintaining a healthy competition between the financial institutions (Strupeit and Neij, 2017).

4.2.3 Cost reduction potential in construction/installation stage

Using well-trained labour and professionals and thorough supervision will reduce the BIPV installation cost effectively (Sozer and Elnimeiri, 2007). As described in Section 4.2.1, integrating PV technology with the prefabricated building construction industry will eliminate the complex and time-consuming BIPV module installation onsite. Instead, a simple installation procedure will be required to fix the PV integrated prefabricated building elements (Osseweijer et al., 2018). This will reduce the installation labour, time and excess fixing procedure. Recent studies have shown that reducing installation time will lessen both non-value-added labour activities such as unexpected breakdowns, transportation and installation delays and value-added labour activities such as module and racking installation (Holton et al., 2014). Moreover, if value-added and non-value-added activities of a typical installation process can be reduced, a huge amount of installation labour costs can be effectively saved (Morris et al., 2014). This can be effectively done by using PV integrated prefabricated building elements.

Installation time can also be reduced by using light-weight PV modules and smaller module sizes (James et al., 2011), standardised cabling systems and designated tools (Strupeit and Neij, 2017). Comprehensive planning, effective communication and coordination among the stakeholders can avoid unnecessary delays in installation and rework (Mace et al., 2018). The experience and competency gained through practice can also reduce the construction-related soft costs in a considerable manner.

4.2.4 Cost reduction potentials in PII procedure

Having different administrative and legislative procedures with regard to PII processes can harm controlling and reducing the related costs (Burkhardt et al., 2015). Therefore, several countries such as Germany and Japan put forward several methods to manage the PII procedures in a unified manner (Freidman et al., 2016). In particular, Germany has introduced two governing Acts (The national Renewable Energy Sources Act and the German Energy Act) to control the impact on different practices (Burkhardt et al., 2015). This would provide the country with a national policy and incentive structure and direct the stakeholders to follow a unified practice with regard to PII requirements. Japan maintains a uniform basis in relation to PII procedure by a firm market control upheld by the domestic PV manufacturers (Freidman et al., 2016). In Japan, there are few types of PV systems in comparison to other countries and that helps in ensuring quality control and consistency. These arrangements by Germany and Japan have made their PII costs significantly low in comparison to the US, which has different PII-based administrative and legislative procedures in different states (Burkhardt et al., 2015; Freidman et al., 2016). It is also recommended to reduce the working hours on issuing permits and approvals by avoiding unnecessary steps and streamlining the permit-related administrative work (Tong, 2012). Furthermore, it is ideal to have a detailed process map that indicates all necessary information such as current administrative cycle and costs, unneeded actions causing rework and other factors affecting time, complexity, and cost during the PII stage of the system to avoid unnecessary costs. In addition, maintaining permitting process and inspection procedures avoid solar installers working against regulations, reduce competition and provide better profit margins (Supreit and Neij, 2017).

4.2.5 Cost reduction potentials in operation and maintenance

One of the main ways of compensating for the O&M cost is selling the excess electricity to a utility company (Sozer and Elnimeiri, 2007). Since the need to transmit electricity from power generation stations to end users over long distances is reduced, there will be limited infrastructure to maintain other than the BIPV modules and it will be a considerable cost reduction when compared to the conventional grid system (Yang and Zou, 2016). Since O&M could result in unforeseen damage to properties, having proper insurance is crucial, as is insurers publishing guidelines to increase installation quality to minimise potential damage during operation (Strupeit, 2017). Furthermore it is highly recommended to follow the operation guidelines to minimise unnecessary operational costs. A proper survey and accurate cost-benefit analysis can reduce the additional and unnecessary costs of retrofitting (Gindi et al., 2017). In particular, it is recommended to use inverters with displays for easy monitoring and taking assistance from utility companies with regard to metering and grid connection to reduce the unnecessary costs of rework, changes and damage repairs (The Centre for a Sustainable Built Environment, 2005).

4.2.6 Cost reduction potentials in disposal stage

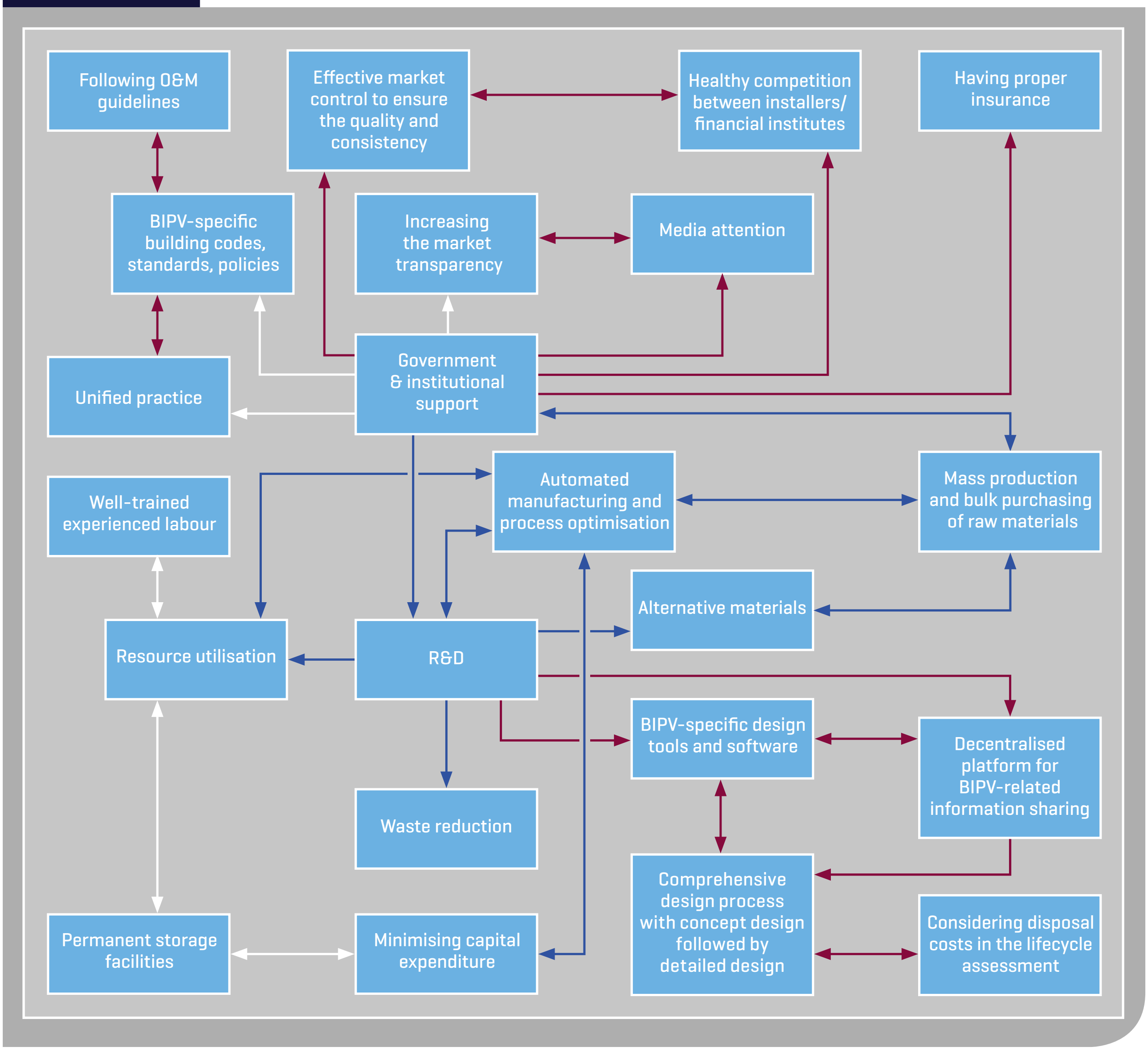
As per the current literature, following an environment-friendly disposal method will reduce the additional costs that may occur in relation to health hazards (The Centre for a Sustainable Built Environment, 2005). Considering disposal costs in the lifecycle cost assessment will avoid unexpected expenses of disposing of BIPV systems (Sozer and Elnimeiri, 2007; Strupeit and Neij, 2017; Yang and Zou, 2016). Currently, PV panels are treated as electronic and glass products in recycling. Since BIPV is part of the building envelope, BIPV waste should be considered as part of the building wastes and processed according to the construction waste management. BIPV recycling as a compatible process can be executed parallel to building waste recycling. However, current construction waste management practices do not include BIPV.

4.3 Relationships of hardware and soft cost reduction potentials

Most cost reduction potentials of renewable technologies are often connected with each other. Figure 7 demonstrates these relationships. The connections between hardware cost reduction potentials are shown in blue arrows and soft cost reduction potentials in red arrows. The connections between hardware and soft cost reduction potentials are shown in white arrows. Some of these relationships are discussed under the hardware cost reduction potentials in Section 4.1.1. According to Figure 7, a number of hardware and soft cost reduction potentials have a relationship with R&D in BIPV technology. 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 are required to reduce the design stage costs, therefore, R&D on developing such tools and software is required.

Cost reduction potentials such as increasing market transparency, introducing BIPV-specific building codes, standards and policies, maintaining a unified practice for the PII process and effective market control are related to government and institutional support. It is mainly due to government and related authorities being the governing members of the BIPV market. For example, Sweden has 14 agencies to advocate the solar energy promotion (Palm, 2015). In Germany, renewable energy-related matters are governed by the National Renewable Energy Sources Act and the German Energy Act to provide a uniform base in the PII process (Burkhardt

Figure 7 Relationship map of BIPV cost reduction potentials



et al., 2015). The Ministry of Science and Technology (MOST) and the National Energy Administration (NEA) have initiated a number of programmes and related rules to increase the PV/BIPV consumption in China (Grau et al., 2012). Nevertheless, it is difficult to pin point BIPV-specific governing bodies and policies. Furthermore, the government is one of the main sources of funding for BIPV-related R&D, thus they have a relationship with each other. In fact, the Australian government has allocated A$100m to establish the Australian Solar Institute with the aim of providing adequate support to retain and develop the future generation of solar expertise and researchers (Bahadori and Nwaoha, 2013). The institute acts as a collaborator of universities, research institutes and the industry and assists in building relationships with overseas research organisations. The Dutch government is actively involved in BIPV-related R&D by providing necessary funds and encouragement (Osseweijer et al., 2016). A leading university in the Netherlands is taking the initiative to conduct a multidisciplinary course for BIPV specialisation by partnering with institutions from Austria, Germany and Cyprus. The Chinese government also provides funds for renewable energy research including pilot studies and rural utilisation of renewable energy (Song et al., 2016).

Integration of PV and the building industries would assure resource utilisation and minimum usage of capital expenditure due to the merger of two capital intensive sectors. Alternative materials and automated manufacturing and process optimisation will increase the production capacity. Likewise, there are numerous relationships between the hardware and soft cost reduction potentials which are indicated in Figure 7.

4.4 Conceptual framework for BIPV cost reduction potentials

Based on the literature review and the industrial workshop outcomes, a conceptual framework is built by empirically decomposing BIPV cost trajectories into a set of low- and high-level factors. According to the framework, each stage of the BIPV lifecycle is considered including the manufacturing stage, design stage, procurement, PII, construction and installation, O&M and disposal stage. The manufacturing stage includes the raw materials and manufacturing process costs, whereas in all other stages, installation-related softs costs are identified. Each stage contains critical costs that determine the system cost and non-critical costs that should be considered in the system cost but are insignificant as percentages. Critical costs are identified in red, whereas non-critical costs are identified in blue in the conceptual framework. Figure 8 demonstrates the conceptual framework of BIPV costs and their reduction potentials. According to Figure 8, significant cost reduction potentials in the hardware costs lies in the manufacturing process. Manufacturers are putting more pressure on R&D to develop alternative materials and cut wastage to reduce the cost of the PV modules. Manufacturers also need to rethink on their investment on capital expenditure and O&M costs of manufacturing plants by (1) conducting a cost-benefit analysis of investing in advanced technological machines and equipment, (2) better utilising labour, and (3) estimating financial benefits of producing PV integrated prefabricated building elements in a single manufacturing plant (this will be further discussed in section 6.0).

According to the conceptual framework, design consultancy and design tools are the critical costs in the design stage. The cost reduction potentials of these costs mainly lie with integrating PV technology with the module building industry. All costs identified in the procurement procedure are critical for BIPV technology, mainly due to the novelty of the technology to the industry. The main cost reduction potentials identified are having a decentralised supply chain, introducing low interest mortgage policies and full transparency of installer performance. Labour costs are the most critical cost in the construction and installation stage. It is one of the main soft costs that determine the BIPV system cost of any country. Much potential has been identified to reduce this cost all over the world such as reducing labour hours by using PV integrated building modules, using skilled and well-trained labour and thorough supervision. The PII stage includes two critical costs; costs associated with taking necessary approvals and grid connection. Government control, policies and standard procedures are the main cost reduction potentials of these two costs. O&M costs are not identified as critical costs and not often taken into consideration. The main reason for such low consideration is the low maintenance required by the technology with limited operational procedures. Following the standard manuals and guidelines represent the main cost reduction potentials of monitoring, operation, repair, replacement and upgrading costs. The final stage considered in the framework is disposal of a BIPV system once its lifecycle is over. Similar to the operation and maintenance stage, the costs of this stage are neither critical nor discussed in the BIPV academia. However, considering these costs in the lifecycle cost of BIPV systems can reduce unexpected expenses in the long run.

Figure 8 **Conceptual framework for cost reduction potentials of BAPV/BIPV systems**

BIPV life cycle	Manufacturing stage	Design stage	Procurement Stage	Construction/ installation stage	Permit, inspection & interconnection stage	Operation & maintenance stage	Disposal stage
Cost categories	Material cost Manufacturing plant overheads Labour cost Manufacturer's profit margin Defects and wastage O&M costs (running costs) Depreciation of equipment & machinery testing	Feasibility study Design consultancy Design tools Onsite surveying	Customer acquisition Supply Chain costs Financing costs	Labour Overheads Health and safety Project contingencies	Building permit Grid connection Inspections Miscellaneous	Operation Monitoring Repair Replacement Upgrading & retrofitting	Recycling Dismounting Transport
Cost reduction potentials	• R&D on PV materials – Alternative materials – Wastage reduction • Manufacturing process – Automated manufacturing and process optimisation – Resource utilisation • Mass production of bulk purchasing of raw materials • Promoting BIPV technology – Government support – Minimising capital expenditure	• Introducing BIPV-specific design tools and software • Design optimisation • Maintain a reliable and comprehensive design process that involves a concept design followed by a detailed design • Maintain thorough communication	• Introducing decentralised information sharing platform such as RFID and blockchain-based supply chain management system for reliable supply chain communication • Increasing the market transparency by publishing the performance records of PV installers and ranking the BIPV installers/builders • Online ordering and delivering on time to reduce administrative related costs and storage costs • Having permanent storage facilities to reduce the storage costs and avoid damage to the products • Positive media attention to gain free promotion • Provide low mortgage rates for BIPV installed buildings • Knowledge enhancement of private banks and institutional investors regarding PV systems • Modernising the loan administrative processes • Providing exclusive bank staff for PV financing procedures • Reducing institutional barriers on applying for loans • Maintaining a healthy competition between the financial institutions	• Using well-trained labour and professionals • Thorough supervision • Integrating PV technology with the prefabricated building construction industry to eliminate the complex and time consuming BIPV module installation on site • Reduce value-added and non-value-added activities to reduce labour • Using light-weight PV modules, smaller module sizes, standardised cabling systems and designated tools • Comprehensive planning, effective communication and coordination among the stakeholders to avoid delays and rework • Experience and competency gained through practice	• Introducing national policy and incentive structure for PII process • Follow a unified practice with regard to PII requirements • Effective market control to ensure the quality and consistency • Reduce the working hours on issuing permits and approvals by avoiding unnecessary steps and streamlining the permit related administrative work • Have a detailed process map that indicates all necessary information and steps to avoid unnecessary costs • Maintaining fragmented permitting process and inspection procedures to avoid working against regulations, reduce competition and provide better profit margins	• Selling excess electricity to a utility company • Having proper insurance • Insurers' active participation in damage prevention by publishing guidelines to increase the installation quality and reduce damage occurring during operation • Follow the operation guidelines to minimise unnecessary operational costs • Conducting surveys and accurate cost-benefit analysis to reduce the additional and unnecessary costs of retrofitting • Use inverters with displays for easy monitoring • Taking the assistance from utility companies for metering and grid connection to reduce the unnecessary cost of rework, changes and damage repairs	• Following environment-friendly disposal methods • Considering disposal costs in the lifecycle cost assessment to avoid unexpected expenses of disposing BIPV systems • Considering BIPV waste as a part of building waste and process under the construction waste management • Recycling BIPV waste as part of the building waste recycling process

5.0 BIPV deployment drivers

BIPV technology is still considered an expensive technology with limited market stability (PV Sites, 2018). Despite its unique advantages of multi-functionality and potential financial benefits, the deployment of the technology has been limited due to some technical and socio-economic aspects. The deployment drivers are discussed accordingly through technological and social advances.

5.1 Technological advances

The technical deployment focuses on increasing the system performance by continuous R&D. Figure 9 summarises the R&D focus on BIPV. Two areas should be especially highlighted for BIPV technological advances in comparison to BAPV:

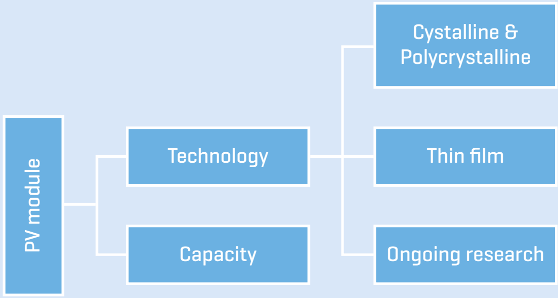
1) Coloured BIPV

The current technological advances make BIPV a reliable option for building envelope materials. The additional capability of generating onsite energy has made BIPV much more advantageous. However, the challenge is that the architectural objectives cannot be always achieved when using BIPV as a building envelope material, especially, the provision of view and daylight against the energy performance (IEA, 2018g). In order to accelerate the BIPV uptake, the difference between BIPV and conventional building envelope materials should be reduced as much as possible in terms of architectural and construction aspects. Recent R&D has developed several BIPV modules with different colours and sizes, showing its ability to provide the preferred aesthetic appearance. Anti-reflection colour coating is one successful method used to add colour to monocrystalline and polycrystalline BIPV cells (IEA, 2018g). It originally provides blue colour and based on the thickness of the anti-reflection coating, converts into other colours. Some thin-film and organic PV modules have coloured/semi-transparent layers to increase the daylight intake. Especially, organic PV can be found in a wide range of coloured and transparent modules. There are BIPV products with coloured/patterned interlayers (IEA, 2018g). In these modules, a laminated coloured/patterned interlayer is included either as an additional encapsulant sheet or the main encapsulant sheet. Amorphous silicon modules are combined with coloured polymer films as the back encapsulant to provide coloured PV glass with different transparencies (IEA, 2018g). Some BIPV products contain coated, printed, specially finished and/or coloured front glass instead of the back encapsulant. Even though these products optimise the visual comfort of the buildings, they do not always provide better results in terms of design flexibility, production flexibility, cost effectiveness, building performance and energy efficiency. Therefore, more R&D is required to overcome these challenges.

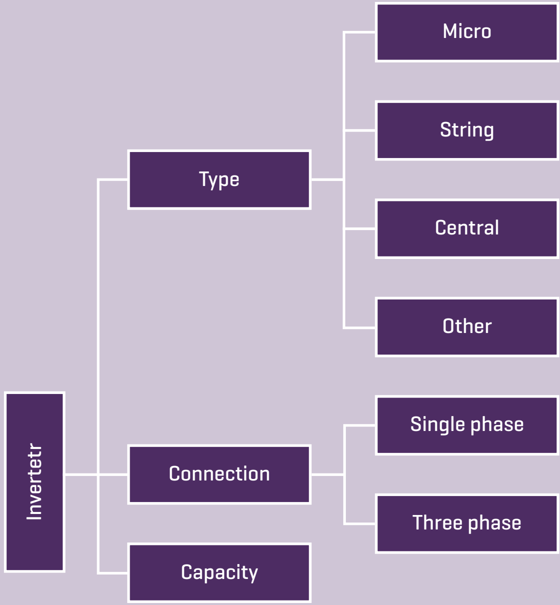
2) Mounting/fixing structures

Since BIPV products are integrated into the building envelope, ways to reduce wind exposure and structural loads, and ease of manufacturing and installation should be emphasised. BIPV modules are quite heavy (Ikedi et al., 2010), thus their weight should be considered when designing a BIPV building. If BIPV is installed as retrofitting or refurbishment, the prevailing building structure may be incapable of supporting the additional weight. One solution for this issue is using thin-film BIPV cells instead of crystalline silicone cells as they possess thin layers of semiconductor material that can reduce the system weight (Chen et al., 2012). Nevertheless, thin-film photovoltaic elements are usually less cost-effective in comparison to crystalline silicone modules in terms of payback period. The PV industry has often come across the technical issue of mechanical stress to a BIPV system and the negative effect it generates on the building (Yang, 2015). The building should be able to bear the live loads such as snow and wind on the BIPV system (Firges et al., 2013). A number of issues can be associated with mechanical stress, for example, the inadequate allowance for additional loads can bend and/or fragment PV modules, demanding critical repairs or replacement. Moreover, the inability of building structure to move or absorb the additional loads can detach the BIPV modules from building envelopes causing a hazardous environment to the public and the building occupants. These areas need professional collaborations across the PV and building sectors.

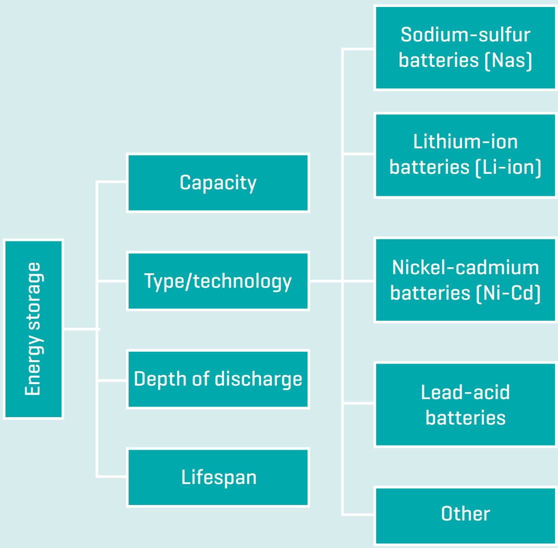
Figure 9 **Technological advances in BIPV**



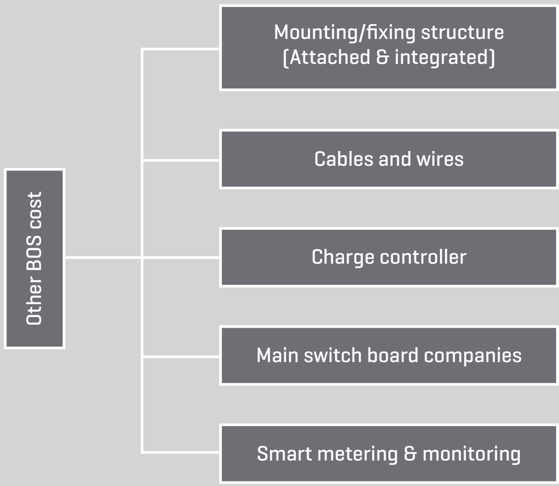
- Efficiency
- Manufacturing waste
- Metal production such as Tellurium for cadmium telluride (CdTe), and indium, gallium and selenium for copper indium gallium dieseline (CIGS)
- Substituting a more abundant material for the silver



- Lifespan
- Reliability
- Integrating AC intelligence into each module-Plug-and-play installation



- Lifespan
- Charging hours
- Toxic
- System design – optimise storage size to better match fluctuating demand and electricity price curve



- Reduce wind exposure – enables the downsizing of structural components to minimise the impact of wind loads to allow lighter, cheaper structures (e.g. module spacing, site layout, spoiling and deflection technologies, and flexible structure)
- Use module for structure – using rigid glass modules as part of the structural system enables the downsizing of racking systems
- Leverage high-volume, lean manufacturing

5.2 Social advances

Although continuous R&D is important for BIPV uptake as discussed in Section 5.1, currently, BIPV is recognised as a technically feasible option of renewable energy generation. Nevertheless, its economic feasibility and social acceptance are not yet highly recognised. Five key deployment drivers are proposed here: (1) knowledge awareness, (2) BIPV-specific business models, (3) BIPV product and process standardisation, (4) quality assurance in procurement, and (5) BIM-enabled BIPV design assessment and optimisation. The following sub sections will discuss these socio-economic deployment drivers of BIPV technology.

5.2.1 Knowledge awareness

Lack of BIPV information to clients and architects is one of the main barriers to driving its uptake. There are no comprehensive databases that provide information such as product specifications and detailed cost breakdowns. The recent study of Wijeratne et al. (2018) identified 14 key issues that could be encountered in prevailing PV design and management tools and many of them are about limited information. In particular, the absence of detailed localised climate and geographical data, limited availability of localised databases for PV product cost and energy prices, limited local building codes and standards, significant information gaps in finance modes and contractual choices, lack of information on localised government incentives, limited availability of BOS product information and limited information on O&M costs are several information-related issues identified in the study. The study recommends maintaining a localised data repository to provide a comprehensive information-sharing system for all interested parties that includes adequate and systematic information on meteorological conditions, building codes and regulations, energy prices, energy consumptions against different building sectors, O&M costs, contractual options, financial options, carbon emission factors and government incentives (Wijeratne et al., 2018). In addition, it recommends maintaining continuous system performance records to demonstrate the energy and financial benefits and increase the confidence of investors to invest in BIPV projects. The findings of the industrial workshop also recommend maintaining a comprehensive database of BIPV products along with their specifications and prices to support the decision-making of BIPV designers, investors, installers and other interested parties.

Lack of understanding between the PV and building industries is another practical problem for uptake. Traditional PV installers, architects and engineers do not possess an adequate knowledge on BIPV characteristics and features. It is mainly due to the limited education and training on structural and architectural integration of PV systems into the building envelope.

Local contractors and builders are unable to carry out BIPV projects due to the lack of knowledge and awareness of the technology and its applications (Alnaser and Flanagan, 2007). Nevertheless, PV manufacturers are keen to receive positive feedback from the construction sector regarding the system performance as it can endorse their products in the building industry. In fact, manufacturers are prepared to redesign their products to compete in the international market by changing design specifications to suit local building codes and standards, climatic conditions and market requirements (Yang and Li, 2007). Nevertheless, the building industry is still struggling with numerous technical and economic issues in relation to BIPV building construction; therefore, until a proper understanding can be established on the accurate implementation of BIPV systems, building professionals will hesitate to adopt this technological initiative (Koinegg et al., 2013). Hence, it is crucial to provide opportunities for information- and knowledge-sharing amongst the building and PV manufacturing sectors (Yang, 2015). Limited public awareness and negative perception of the technology costs also add barriers for BIPV deployment (Shukla et al., 2016). Currently, BIPV projects are mostly applied in innovative client-owned buildings since clients can make decisions on the add-on costs and own the long-term benefits without complicated agreement among stakeholders. Partly this is because the unique benefits of BIPV technologies (or even the technology itself) have not been promoted to the general public sufficiently.

Scarcity of properly designed and well-accredited training programmes within the building and PV industries cause significant knowledge gaps when adopting BIPV technology (Close et al., 2006). Including BIPV as a topic in tertiary education or even having separate courses for BIPV building construction is another strategic method of increasing the public awareness (Curtius, 2018). These training programmes should be introduced by both industries to allow construction professionals such as architects and builders, and PV professionals, including installers and PV manufacturers, to acquire the required knowledge and skills in system design, development and maintenance (Frontini et al., 2012). Government bodies, tertiary educational institutes and professional associations can collaboratively take the responsibility to develop such training programmes. Providing complete transparency about BIPV installers by publishing performance records of BIPV installers, ranking BIPV installers/builders (Strupeit, 2017), issuing quality certificates and awards for BIPV green constructions is another effective way to convert the negative public perception into a positive one and increase public awareness.

5.2.2 BIPV-specific business models

Conventional electricity generation and distribution is centred around an authority that receives revenue by simply selling the generated electricity to the customers (Hamwi and Lizarralde, 2017). It is a simple arrangement where a tangible commodity (electricity) is exchanged between a buyer and seller. However, with the rapid deployment of distributed energy resources (DER), this buyer-seller arrangement becomes complex with the involvement of number of parties such as multiple sellers, third-party service providers and multiple buyers (Burger and Luke, 2017). In this arrangement, buyers who have DER play a dual role as buyers and sellers. In addition, the electricity distribution is not just limited to selling a tangible commodity (electricity) it also provides several intangible services (e.g.: demand side management, energy storage, energy efficiency management) along with the tangible commodity to generate multiple revenues (Hamwi and Lizarralde, 2017). Unlike the conventional energy market that is governed and operated by the government and utility companies, the DER energy market consists of number of participants such as DER hardware sellers, DER installers, DER O&M services providers and DER-related information and communication technologies (ICT) providers. All these participants provide different services and accordingly require different business arrangements. The conventional business model is neither suitable nor applicable to the DER market. Therefore, the DER market requires distributed generation-specific business models. In fact, different DERs require different business models based on their characteristics and performances. For example, PV system owners mainly focus on the revenue earned from the generated electricity (IEA, 2018e). However, BIPV installation has a different focus as it has additional revenue achieved via replacing building envelope materials, as sometimes building materials are higher than BIPV cost. In addition, the BIPV cost structure is different to that of BAPV or ground mounted PV and it consists of comparatively more key partners and activities. Therefore, it is ineffective to use general PV business models for BIPV arrangement.

The IEA PVPS Task 15 (2018c) has introduced two novel BIPV-specific business models; (1) on-bill financing and (2) BIPV as a service, which can attract the interest of investors. According to the on-bill financing model, the building owner occupies the building and has a contract with a utility company to install and own the BIPV system. This arrangement is highly beneficial for the building owner who cannot afford the BIPV upfront cost. Furthermore it limits the building owner's risk of operating a BIPV system as the ownership belongs to an experienced utility company. According to the second business model, the building owner can either own or lease the BIPV system from a utility company. This model also limits the risk of the building owner. Moreover, both of these models provide the additional advantage of BIPV modules replacing the building envelope materials, thus, the building owner's investment on the building will be reduced by a significant amount. Having these kinds of business arrangements enable more investment on the technology, thus increasing the deployment.

The key factors for a successful BIPV installation include: (1) implementation in the early design stage, (2) having a committed building owner, (3) having standard PV modules, and (4) including all values in the economic analysis (IEA, 2018d). Therefore, a BIPV business model should consider all of the above factors. For example, both aforementioned business models have a committed building owner who receives different business arrangements to install and operate a BIPV system. However, these business models do not emphasise the need to consider the BIPV installation in the early stage of the building design. This is mainly due to the lack of understanding of the PV industry about the construction sector.

The main barriers to creating a successful BIPV business model are: (1) the lack of collaboration between stakeholders, (2) still being an expensive option compared to other similar technologies such as BAPV and solar farms, which as a result generates indistinct value propositions, and (3) lack of specific regulations. The lack of collaboration between the PV and building industries can be eliminated by the involvement of building stakeholders and PV stakeholders in the early design stage, which is explained in Section 6.0. BIPV should be considered as a part of the building industry, and as another method of more sustainable construction like offsite construction methods (i.e.: prefabricated building construction, modular construction). Under the current industry situation, the best arrangement for a BIPV project is in client-owned buildings. Within such a business arrangement, the decision of having a PV integrated building envelope can be made at the earliest stage of the design to avoid subsequent issues in detail planning and taking approval. Furthermore, it can reduce the additional and unnecessary expenses of retrofitting the technology to an already constructed building. In addition, it can effectively receive the exclusive revenue of material cost offsets.

5.2.3 BIPV product and process standardisation

BIPV always has to deal with two different standardisation and regulation schemes: one derived from the requirements from the building side, often regulated in local building codes, and international ISO standards; the other from the electrical side, with international IEC standards, and also mandatory, not fully harmonised local regulations (IEA, 2018f). BIPV uptake can be accelerated by 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 issues such as delays due to confusion during design, getting approvals (i.e. building permits), and even safety problems. For example, higher fire risks of BIPV façades and roofs due to the possible electrical arcs in string connectors and the junction box can cause serious consequences (Mazziotti et al., 2016). In addition, BIPV modules themselves can start a fire as they acquire sufficiently high voltages and quickly propagate the fire externally via their surface, hindering fire-fighters in their rescue operations (Yang et al., 2015). Hence, fire resistance and safety should be highly considered during BIPV product manufacturing and system occupancy. 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.

A brief review on current regional and international standards and drafts that are either dedicated to BIPV or are frequently referenced in BIPV standards/drafts, was conducted by IEA PVPS Task 15 recently (IEA, 2018f). It took the European BIPV standard EN 50583 as the basis to identify 'basic requirements' on BIPV modules and standards as construction products and as electrical components, to which durability/reliability, water and air tightness, seismic resistance and other requirements were added. International standards that were equivalent to originally referenced EN standards were identified and tabulated. The authors recommend that three categories, 'internationally mandatory', 'useful to design BIPV' and 'useful to characterise BIPV', be addressed at the international standardisation level, but there is no need for a pass/fall criteria. However, the fire safety, seismic resistance air permeability, water tightness and wind resistance can be addressed best at the national or local level.

5.2.4 BIM-enabled BIPV design assessment and optimisation

Flexibility in the building envelope design to meet various visual and functional aspects has the potential to enhance building performance. Geometrical configurations of the building envelope itself have significant impacts on the overall energy performance, daylighting and economic benefits. The complexity in design modelling, and overall system optimisation create significant hurdles for the adoption of the active solar building envelope and net zero energy (NZE) building. As explained in the recent studies of Hachem-Vermotte (2018), Hachem et al. (2014a), Hachem et al. (2014b) and Aelenei et al. (2014), using different multiple folded planar surfaces (folded plates) with varying tilt angles can significantly increase the energy generation. Therefore, proper tools are essential in BIPV design assessment and optimisation. In addition, a systematic design tool is required to identify the real value of BIPV assets in the building and PV market. Wijeratne et al. (2018) proposed a reliable platform for PV design and management. According to the platform, prevailing design tools should be improved in terms of information, simulation and analysis options and PV system operation (Wijeratne et al., 2018). This study also emphasises the need for such improvements and the need to introduce a system to support BIPV decision-making.

According to Wijeratne et al. (2018), the proposed platform considers BIPV design and management in a holistic manner. In particular, it consists of a number of local product databases to select the best products for the design and a virtual model builder to develop the design. Not only does it deliver a 3D view, it also provides an automatic PV layout design optimisation. The installation process simulation and impact analysis will minimise the errors of BIPV installation in the real world. The platform also considers weather and terrain data, environmental benefits, O&M, energy consumption and generation information, building regulations and lifecycle cost-benefit analysis. This platform will assist the decision-making of BIPV design and management in a systematic manner while addressing the practical difficulties of stakeholders (Wijeratne et al., 2018).

BIM-enabled design assessment and optimisation is another systematic way of BIPV designing. BIM can be used to link the design stakeholders, facilitate decision-making via providing access to product databases, enable digital data modelling (such as parametric modelling) and optimisation. Other than enabling 3D model designing, it can facilitate other works such as bill preparation and specifications and method statements development. In addition, it digitalises the planning process to simplify the BIPV design and management and allow the involvement of non-experts. The BIM platform can be an open or closed system according to the stakeholder requirements and control the level of flexibility of the design process. It can circulate digital product data models that facilitate a comprehensive planning process by considering both building and BIPV system components in details. By including BIPV standards and specification information to the system, BIM can ensure producing a high-quality BIPV design as per the local building and energy regulations.

5.2.5 Quality assurance

According to the findings of the industrial workshop, most of the countries that actively use BIPV technology are unable to manufacture locally 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 US, Malaysia, Australia are importing BIPV components from China, Singapore, Japan and Germany (Ng and Mithraratne, 2014; PV Magazine, 2018; Tominga, 2009). There is some concern about the quality of these imported products; especially when they are imported from Asian countries (IRENA, 2018), and that importation discourages local production (PV Magazine, 2018). The findings of the industrial workshop revealed that governments can address these issues by (1) motivating local production with incentives specific to BIPV manufacturing and installation, (2) minimising the taxes related to local production and (3) establishing international and local BIPV-specific standards for manufacturing and importing products as described in Sections 3.3.6 and 5.2.3. Furthermore, governments should enact BIPV-related regulations and incentive schemes that ensure the security of entire BIPV lifecycle, not just the installation (Osseweijer et al., 2018). This legislation should be clearly distinct from PV.

As discussed in the soft cost reduction potentials of procurement stage (Section 4.2.2), a proper information and tracking system can assure the quality of imported items. This can be achieved via a RFID and blockchain-based supply chain management system. The system consists of all necessary product information, specifications, prices and the origin of the products. Use of blockchain will ensure the accuracy of information, secure transactions and zero information gaps. Therefore, the buyers can identify the high-quality products, easily buy them via the system and track the products (enabled by RFID) until delivered to the site. By establishing an effective cross-country supply chain management system, the threat of importing low-quality products can be significantly reduced and subsequently avoid incidents such as fires discussed in the previous section.

A significant collaboration between the PV and building industries is essential in executing the aforementioned BIPV deployment drivers. Integrating these two industries is the best way to achieve collaboration. Since BIPV is manufactured offsite, it can be identified as a prefabricated building element. In addition, this study emphasises that BIPV is better identified as a sustainable building product rather than a renewable energy technology. This is further explained in the following section.

6.0 The concept of a prefabricated active solar building envelope

BIPV is generally recognised as a renewable energy technology. However, it performs as a building envelope material providing visual comfort, weather protection, insulation, privacy and protection while generating onsite electricity. This multifunctional ability suggests that BIPV modules should be considered as sustainable building products that possess the additional capability of generating electricity. Therefore, the general viewpoint of BIPV being a renewable energy technology should be changed into a prefabricated sustainable building product. Lutzkendorf (2013) identified that the future of the sustainable building industry lies in integrating BIPV modules with the prefabricated building elements for simultaneous energy saving and generation. In addition, the future BIPV products will come to the market as multifunctional PV building components that fulfil all required functions of a building element with additional capability to generate electricity in both new building construction and renovations by providing prefabricated curtain façades, roofs, balconies, shutters and awnings.

Building prefabrication and BIPV share similar characteristics. Both products are produced off construction sites. There is no onsite construction except module assembly and installation, which reduces the onsite labour significantly. Both products use automated manufacturing processes, which require high capital and upfront costs. The automation allows scale of production, reduces wastage and utilises resources. The only difference between these two products is that BIPV can generate onsite electricity while performing as a building envelope material. Considering the similar qualities between BIPV and prefabricated building products, this study recommends taking BIPV modules into the prefabricated building elements. This new building element can be named ‘prefabricated active solar building envelope’. Before discussing this concept, a general idea about the prefabricated building construction is provided in following paragraphs.

Prefabricated building construction is a more sustainable construction method that manufactures building elements/parts/modules in an offsite manufacturing plant (Chang et al., 2018). 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, standardised design and avoiding weather extremes during construction (Kamali and Hewage, 2016). In the past, prefabricated building construction was identified as an expensive method of construction with high capital and upfront costs (Badir et al., 2002). Furthermore, it limited the uniqueness and flexibility enclosed in customised architectural design due to the standard module production (Chang et al., 2018). Accordingly, the construction sector and general public had a negative perception about this construction method; thus, its uptake was considerably slow. One of the main reasons for the aforementioned barriers was not having a 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 the client, architect, builder and prefabricated module manufacturer could be involved in the design process. The current prefabricated building industry understood this concept and successfully collaborated with the stakeholders in the design process and reduced a number of barriers that existed earlier. In particular, the leading prefabricated construction companies in Australia adapted a self-performing business model that lets them 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.

There are two main business models in the prefabricated building industry: (1) outsourced module manufacturing and (2) in-house module manufacturing. In an outsourced module manufacturing arrangement, the prefabricated builder does not own a manufacturing plant. Therefore, he/she purchases the prefabricated building elements manufactured as per the building design from a separate manufacturing plant. In the second business arrangement, the prefabricated builder owns a module manufacturing plant and does in-house manufacturing. These business arrangements are shown in Figures 10 and 11.

According to Figure 10, the prefabricated builder will collaborate with the client, architect and the design team in the design stage to develop a final design and subsequently hires a prefabricated building element manufacturer to manufacture the building elements. The manufacturer has his/her own design team who will do the building element modelling and other module-based designing prior to manufacturing. The prefabricated building element manufacturer has connections with a number of material suppliers to purchase building materials for the production. According to Figure 11, instead of having a separate manufacturer, the prefabricated builder has his own manufacturing plant. Based on the design developed in the design stage, he conducts module manufacturing with the assistance of his design team and material suppliers.

Figure 10 **Outsourced module manufacturing business arrangement**

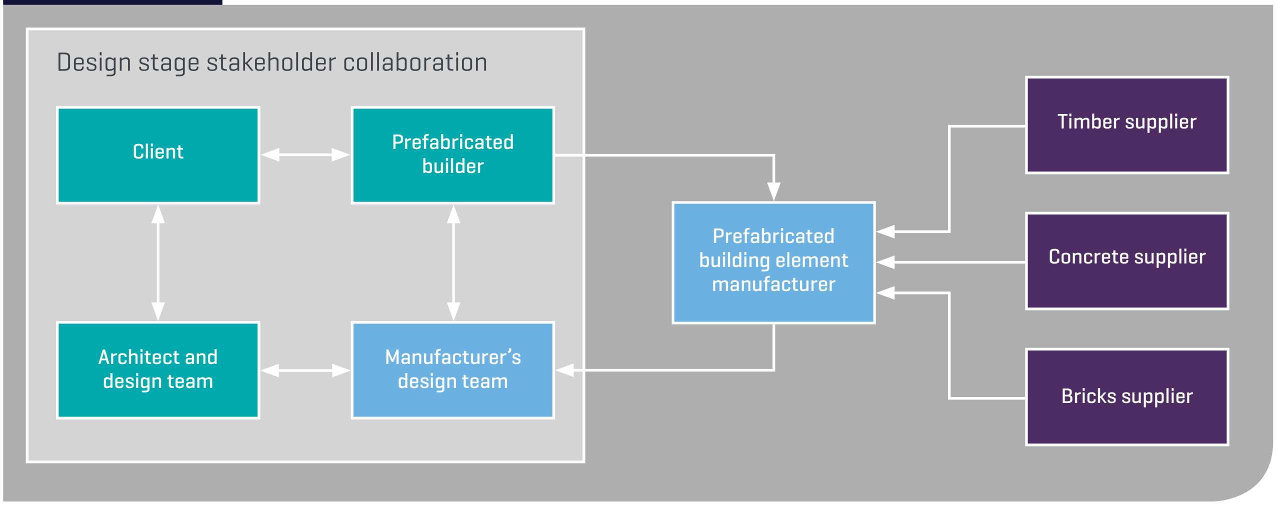
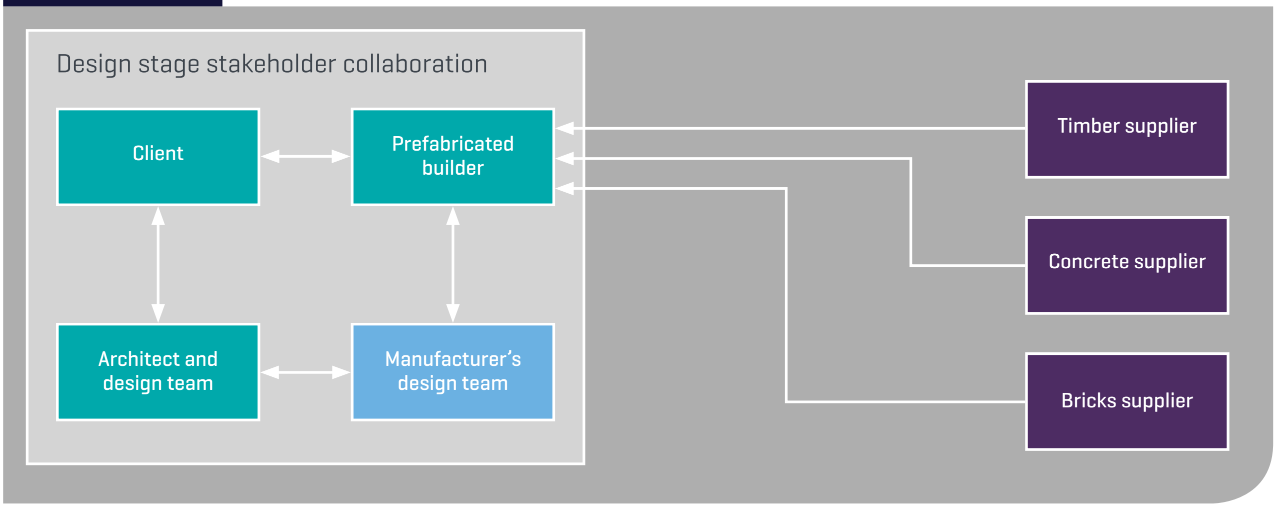


Figure 11 **In-house module manufacturing business arrangement**



The prefabricated builder is involved in the project prior to commencement of the design process. Once the architect has developed the concept design, the prefabricated builder evaluates the way of breaking down the design into prefabricated building elements. In the evaluation, he considers different parameters such as size, shape and weight against the logistic plan for effective transportation, onsite mobilisation and storage (Hickory, 2018; Kamali and Hewage, 2016). Currently, many prefabricated builders use BIM/parametric modelling to achieve the optimal design for prefabricated modules. After that, the detail design will be developed and technical drawings will be prepared along with the construction documentation. Then, the project design stage will be completed, allowing the prefabricated building element manufacturer to commence the manufacturing process. If the prefabricated builder does not own a manufacturing plant, he/she will outsource module manufacturing to a professional prefabricated building element manufacturer. This manufacturer will receive the detailed drawings and module breakdown schedules to proceed manufacturing. If the prefabricated builder owns a manufacturing plant, he/she will, along with his manufacturing design team, conduct the manufacturing process. Based on the detail design, the prefabricated elements will be designed using BIM/parametric modelling and accordingly develop parametric shop drawings. Based on these shop drawings, a 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.

Figure 12 **Outsourced module manufacturing business arrangement for construction of prefabricated active solar building**

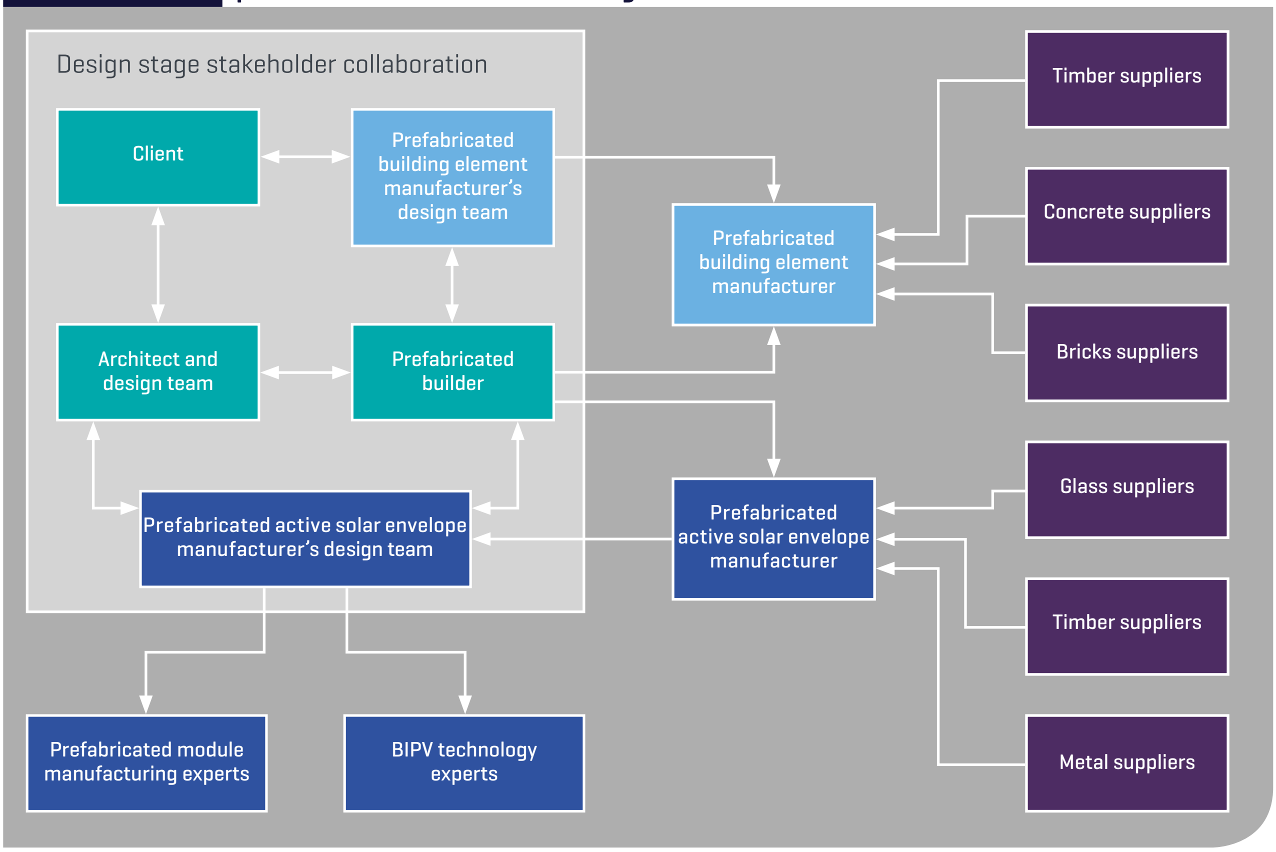
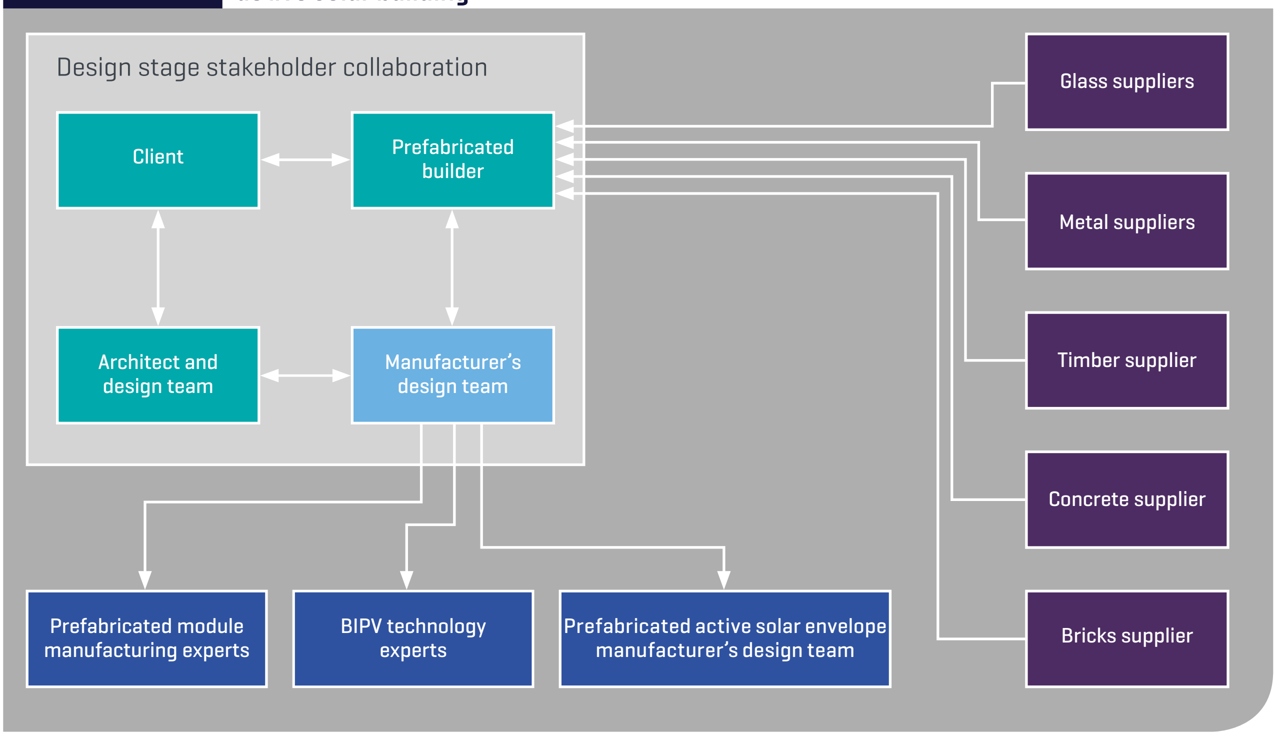


Figure 13 **In-house module manufacturing business arrangement for construction of prefabricated active solar building**



There are many advantages of integrating the BIPV industry with prefabricated building construction. The materials required for completing the BIPV module such as glass, metal and wood will be reduced/eliminated and the manufacturing process of BIPV modules will be shortened accordingly, and the labour and machinery requirement will also be reduced for both industries. Moreover, by integrating BIPV modules into prefabricated building elements, a single manufacturing process can be introduced for both sectors that will avoid significant manufacturing costs for both industries. In particular, hardware cost reduction potentials such as waste reduction, resource utilisation and minimising capital expenditure can be achieved via this new concept of a prefabricated active solar building envelope. Since there is no requirement for BIPV onsite installation (other than BIPV integrated prefabricated module assembly), a significant amount of labour costs and installation time can be reduced. In addition, this process can reduce the high capital and upfront costs of both industries and increase the customisability of BIPV systems.

Considering the current business arrangement and project process of the prefabricated building industry, this study investigated a reliable way to integrate BIPV technology with the prefabricated building elements to achieve the concept 'prefabricated active solar building envelope'. The first step of this integration is to provide a reliable business arrangement. This can be effectively achieved via the stakeholder collaboration explained in Figures 12 and 13. According to Figure 12, the prefabricated builder outsources manufacturing to two prefabricated manufacturers: (1) the manufacturing of the prefabricated active solar envelope to an experienced manufacturer who has prefabricated building experts as well as BIPV experts in his design team and (2) the manufacturing of prefabricated building elements that do not include any PV component to a general prefabricated building manufacturer. Sometimes, both of these roles can be played by a single prefabricated manufacturer who specialises in active solar building envelope manufacturing as well as the general prefabricated element manufacturing. The manufacturers purchase required materials from building material suppliers and PV material suppliers. According to Figure 13, the prefabricated builder owns a manufacturing plant and a manufacturing team consists of prefabricated building experts, BIPV experts and prefabricated active solar building envelope experts. Despite the business arrangement, the prefabricated active solar building construction will follow the project process indicated in Figure 14.

According to Figure 14, the prefabricated builder is involved in the project at a very early stage and prior to commencing any planning. When the project architect develops a conceptual design, the prefabricated active solar builder reviews the module breakup parameters against the logistic plan and the BIPV module integration parameters against the module breakup. After that, the detail designs are developed using BIM and parametric modelling and finalised with the optimal design. The optimal design will be finalised considering factors such as maximum generation capacity, effective building morphology, best economic value and high indoor environmental quality. Once the designing stage is completed, either the in-house or outsourced manufacturing will commence. According to this arrangement, the prefabricated builder/prefabricated active solar manufacturer should have the knowledge, resources and technology for BIPV and prefabricated module integration. In addition, the manufacturer's design team should consist of architects, PV consultants and engineers who specialise in such an integrated system. To improve the quality of production by reducing the material wastage, defective products and high time consumption, automated lean manufacturing will be used with the assistance of information technology (Li et al., 2017) such as Grasshopper-Tekla live link. This live link enables Grasshopper to develop algorithmic modelling for Tekla Structures (Tekla Structures, 2018). Automated lean production provides a data-driven prefabrication process by avoiding uncertainties, limitations and overproduction and systematically links the designing, manufacturing and onsite assembly without any insignificant waiting time (Li et al., 2017). Based on the aforementioned discussion, Figure 15 demonstrates a framework for effective prefabricated active solar building construction.

Stakeholder integration and collaboration can be evidenced in the concept of prefabricated active solar building construction. For example, in the design stage, the client, architect, design team and the prefabricated active solar builder are brought together to develop the design. Having such collaboration can eliminate the lack of understanding between the building and PV industries because all parties can share their knowledge and insight with each other. In addition, this collaboration provides comprehensive information as well as brainstorming sessions for each industry to be educated about the other industry. Moreover, this collaboration will generate an accurate and feasible design and limit the probable changes and errors in the future. Stakeholder integration is also achieved by the concept of prefabricated active solar building construction via introducing a new role for the builder as the prefabricated active solar builder. This new role is formed by integrating the BIPV installer and prefabricated builder. Similarly, the role of manufacturer under this novel concept is formed by integrating the PV manufacturer and prefabricated building element manufacturer.

Figure 14 Stakeholder-integrated project process for prefabricated active solar building construction

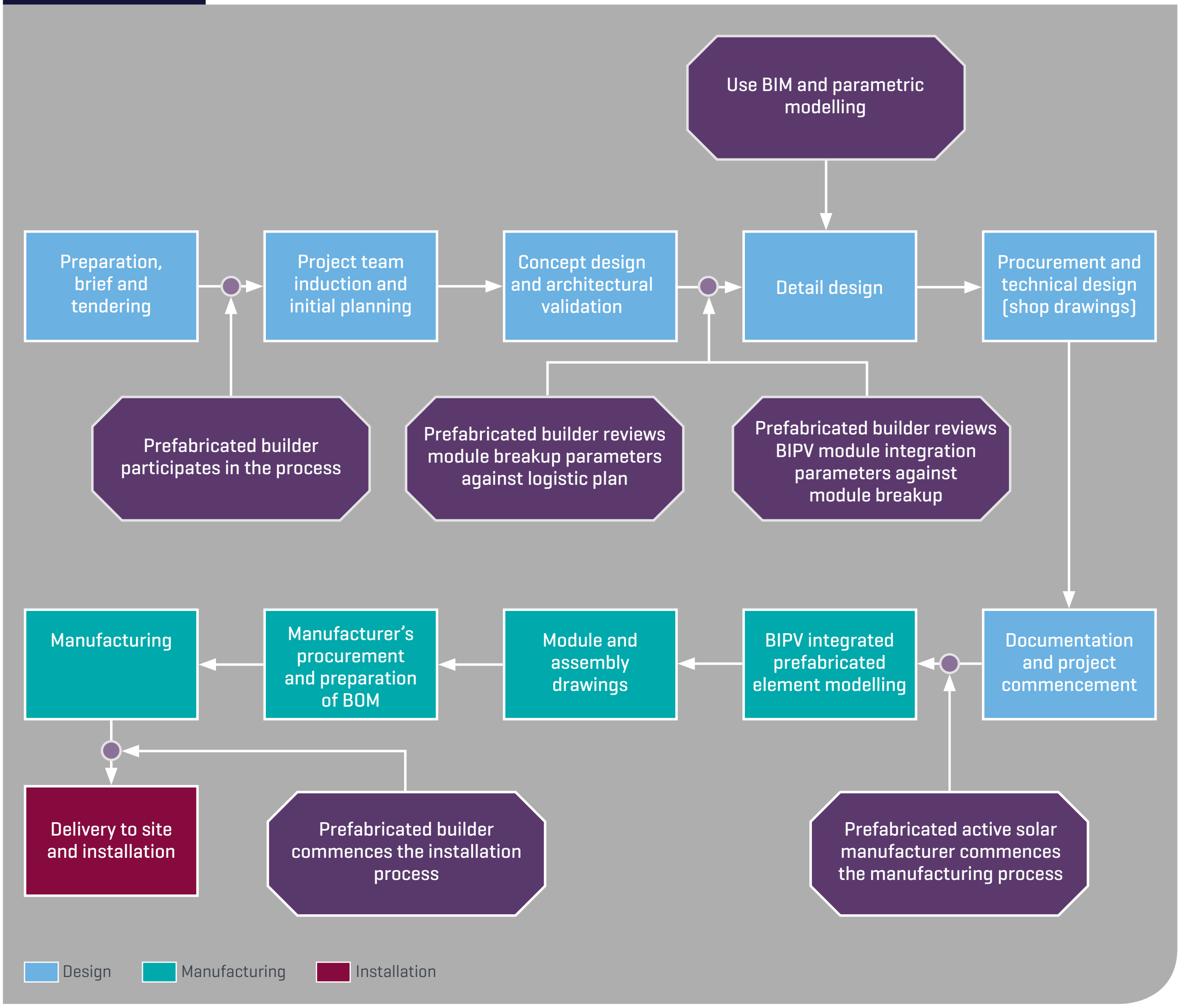
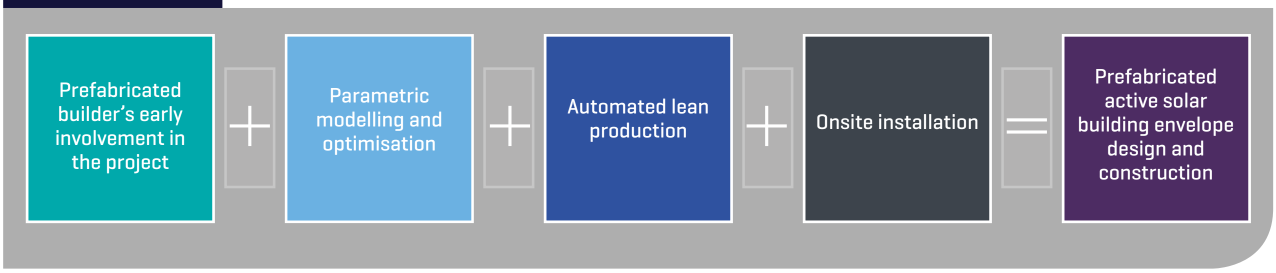


Figure 15 Framework for prefabricated active solar building envelope design and construction



7.0 Conclusion and recommendations

This report conducted a comprehensive analysis of the prevailing literature, the data collected from an industrial workshop and a webinar on BIPV technology to collect all available information regarding BIPV costs and their reduction potentials into a single platform. Based on the findings, a conceptual framework has been developed summarising all costs and their reduction potentials along the lifecycle. Moreover, the report identified a number of BIPV deployment drivers that can create a stable market and high demand for BIPV buildings. During the study, it was identified that there are limited studies that specifically discuss the hardware and soft costs of BIPV systems. Moreover, most of the technical reports issued by solar PV institutes, agencies and bodies all over the world provide little comprehensive financial details about BIPV systems. Nevertheless, there is adequate information regarding the technical aspects of the technology. The lack of information indicated a clear knowledge gap, which this study is intended to fill.

Based on the analysis, it was identified that at each stage of the BIPV lifecycle, there are critical costs that considerably affect the total system cost, and non-critical costs that do not significantly change the system cost. Material costs, running costs, labour costs, overheads and depreciation are the critical costs identified under the hardware costs during the manufacturing stage. Design consultancy, design tools, customer acquisition, supply chain costs, financing costs, labour, overheads, building permit and grid connection-related costs are the critical costs identified under the soft costs. Continuous R&D on alternative materials and waste reduction, automation and process optimisation, resource utilisation, minimising capital expenditure, government support to promote BIPV technology that enables mass production and bulk purchasing of materials are the main cost reduction potentials identified for hardware cost. Introducing BIPV-specific design tools, RFID-blockchain-based supply chain information-sharing platforms to avoid errors in the supply chain, unified practice for PII procedures, BIPV-specific building codes, standards, policies and incentives and low interest loans are some soft cost reduction potentials identified in the study. The study focused on the technological and socio-economic perspective of BIPV deployment drivers. Accordingly, seven main deployment drivers were introduced: technological advances in (1) coloured BIPV and (2) mounting and fixing structure; and social advances in (1) knowledge awareness, (2) BIPV-specific business models, (3) BIPV product and process standardisation, (4) BIM-enabled BIPV design assessment and optimisation and (5) quality assurance.

The study recognised BIPV as a sustainable building envelope material due to the multifunctional ability of the technology. It also pointed out the similarities and common practices of BIPV and building prefabrication. The study explained a novel concept of a ‘prefabricated active solar building envelope’ in which BIPV modules are integrated with prefabricated building elements and manufactured in a single manufacturing plant. Based on the new arrangement, some stakeholder roles such as BIPV installer and prefabricated builder in the PV and prefabricated building industries are effectively integrated. In addition, the lack of understanding of the PV and building industries is eliminated via stakeholder collaboration in the design and manufacturing stages.

Prefabricated active solar building construction also has certain limitations. In particular, it is unclear the level of involvement of the client in this process. It is very difficult, if not impossible for the client to change the design at a later stage. Energy penetration and how the revenue is achieved are not considered under this integrated arrangement. In addition, the relationship between the client and the energy sector is not well-explained and defined. It is one of the main reasons for only considering the client-owned buildings for implementing this concept. Therefore, further discussion is required addressing these limitations.

The study recommends (1) integration of PV modules with prefabricated building elements, (2) making the decision to use a prefabricated active solar building envelope prior to commencing planning, (3) a prefabricated builder’s involvement in the project from the earliest stage of the design process, (4) builders partnering with PV manufacturers to deliver a design-specific BIPV system, (5) using a prefabricated active solar building envelope concept for client-owned buildings, and (6) using systematic design and management tools to identify the real value of the project and improve the economic confidence of the investors. In addition, the study identified that the comparatively limited attention and encouragement given to BIPV technology has hindered the potential to reduce system costs and the rapid uptake of the technology. Therefore, the study suggests that it is better to provide a similar motivation and attention as BAPV to BIPV systems to enjoy the unique and long-term financial benefits of the technology.

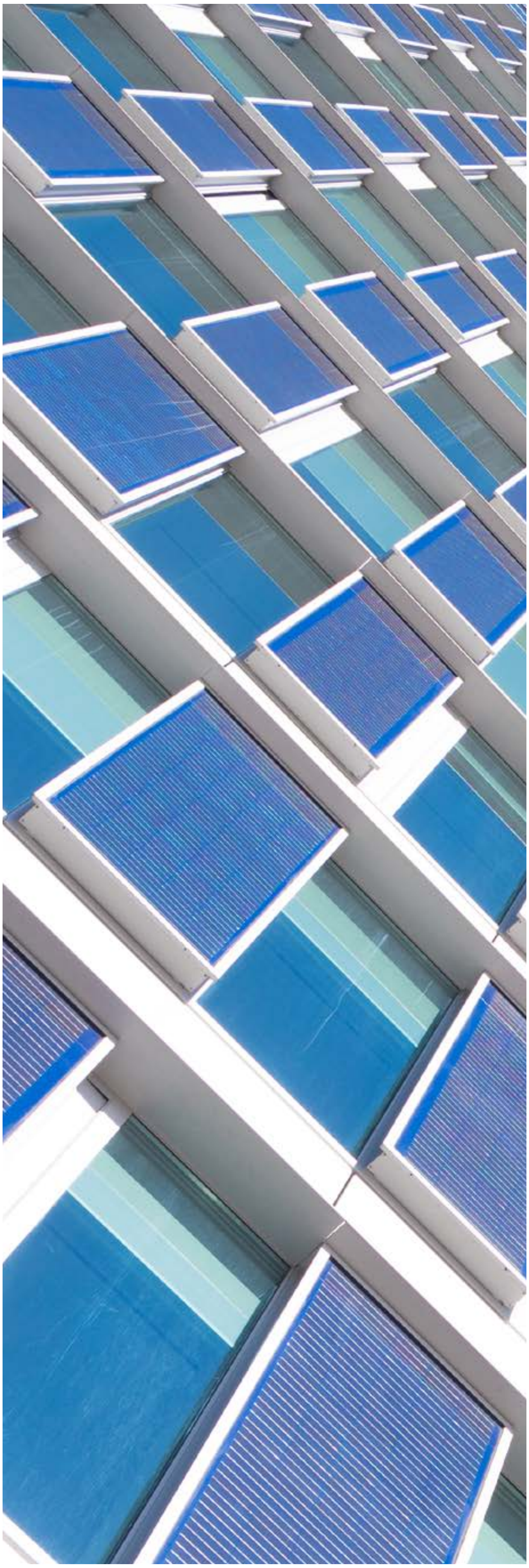


Image source: Hans Engbers / shutterstock.com

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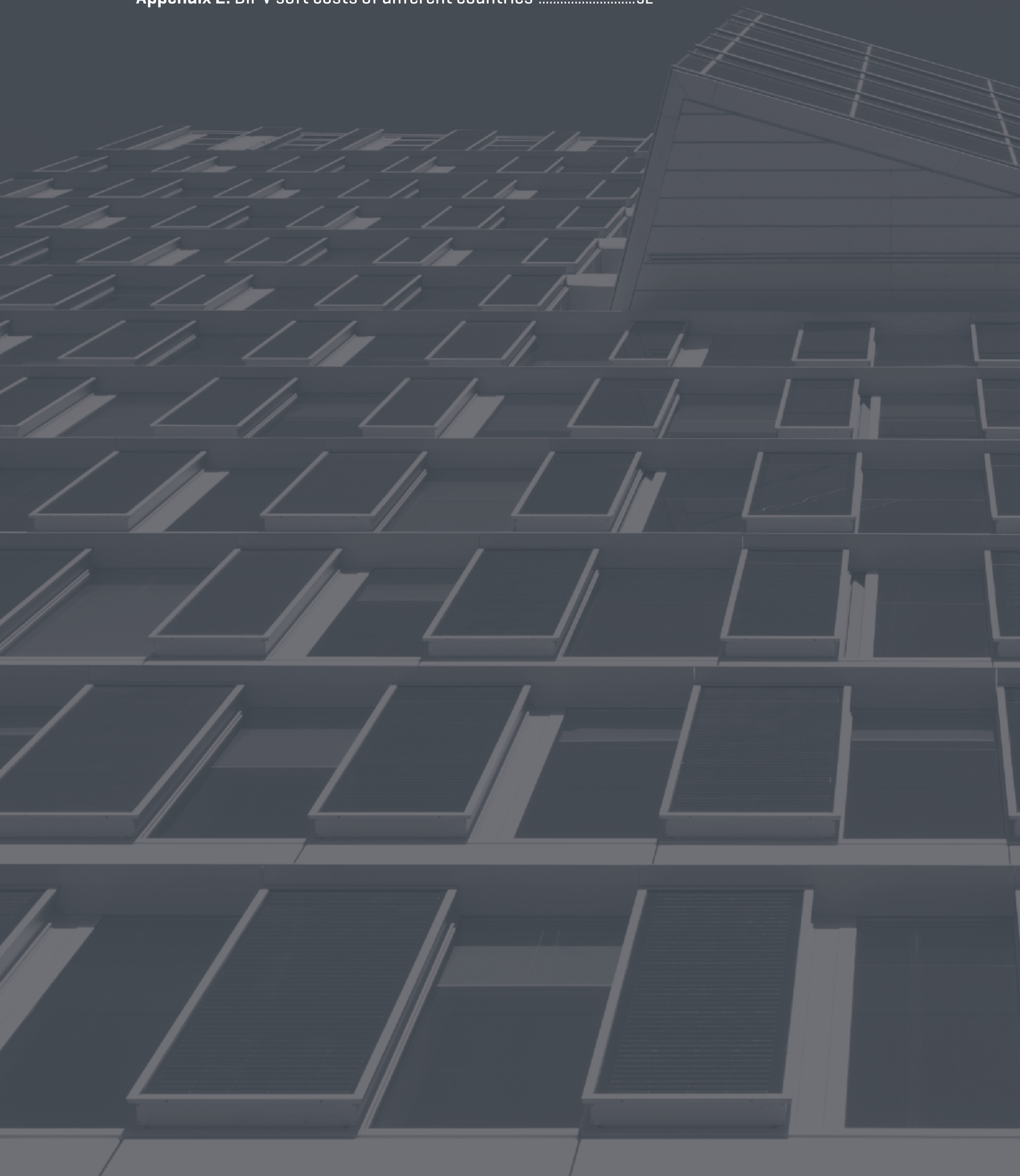

Appendix 1: BIPV project profiles

BIPV Type	Project	Description
Roof	**Ministry of Defence Building** France	This building was constructed in 2014 in Balard and consists of an 8,000 m^2 photovoltaic roof made of nearly 1,500 different mono crystalline module shapes to match the roof geometry. The system generates 860 MWh of electricity per year from the 820 kW capacity modules (ISSOL, 2018).
	Kings Cross Station UK	Kings Cross station consists of a modern BIPV building roof. The 1,392 custom-made glass laminated units cover an area of 2,300 m^2 with two-barrel vaulted glass roofing structures spanning the main platforms. The system produces 175,000 kWh of electricity each year, saving over 100 tonnes of CO_2 emissions per annum. The total project cost is US$1.72m and the system capacity is 240kWp. This building was constructed on 2012 (Romag, 2018).
	Gold Coast Stadium Australia	Gold Coast Stadium in Australia used 600 custom made PV panels integrated into the roof to finish the stadium roof, bringing an aesthetic appearance. The BIPV system was installed in 2011 with the capacity of 215 kWp (Energy Matters, 2011).
	Tsuneishi Group (Zhoushan) Shipbuilding China	The production base building of Tsuneishi Group Shipbuilding Co. Ltd located in China consists of a 19 MW capacity BIPV rooftop. This building was constructed in 2017, including 76,923 PV panels in the roof. Its expected electricity generation is 418 million kWh for 25 years. The system used glass-coated PV modules fastened by aluminium alloy brackets and stainless-steel fasteners, helping to ensure a lightweight and durable rooftop structure. It can reduce approximately 600,000 tons of CO_2 emissions within the considered 25 years. The solar installer of this project invested 100% of the system cost and handles the operation for the following 25 years.
	Perpignan Rail Station France	A semi-transparent solar wave roof was installed above the Perpignan railway station building in France in 2012, accommodating polycrystalline silicon cells on a 2,700 m^2 area. The system capacity is 250 kWp and it generates 260 MWh energy per year (ISSOL, 2018).
Façade	**Yunnan University** China	Yunnan University of China installed a BIPV system on the south face of a 5-storey building in 2014. The total area of the system is 1,560 m^2, including 720 monocrystalline silicon double-glazing PV modules. The modules are installed with 85° tilt angle and 6 m away from the building for the ventilation. The cell efficiency of the system is 8.25% and the system capacity is 4080 Wp (Wang, et al., 2018).
	Energy Building, Union Drammen Norway	This building was constructed in 2015 in Norway and consists of a screen-printed PV glass façade that is made of high-efficiency mono crystalline technology. This iconic design façade is the world's first project that has an applied printed layer on the first glass of the PV glazing. The system contains a 1,275 kW capacity provided by 26 different shapes of PV safety glasses over a 1,215 m^2 surface to generate 55.5 MW of annual electricity (ISSOL, 2018).
	Freiburg Town Hall Germany	This municipal administration building in Germany used integrated crystalline PV and glass modules in a curtain wall façade. These modules are swivelled 36 degrees away from the plane of the façade and carried by slender aluminium brackets that are projected at the level of the floor slabs. The total system in spread over 26,115 m^2 with 216 kW capacity.
	Coca-Cola Headquarters Mexico	Femsa's headquarters: Coca-Cola's main bottling plant in Mexico installed a BIPV façade with 588 m^2 surface area in 2015. The system consists of large-sized grey amorphous silicon PV glass modules, with 20% of semi-transparency. The system can generate 17.23 kWh per year while avoiding 11.539 CO_2 emissions per year (Onyx Solar, 2015).

BIPV Type	Project	Description
Façade (continued)	**Copenhagen International School** Denmark	The Copenhagen International School building in Denmark used colour PV modules on 600 m^2 surface area of its façade. The building was constructed in 2017. This 700 kW BIPV system can generate 500,000 kWh/year, covering 50% of the total annual electricity consumption of the school (Mace et al., 2018).
	Treurenberg building Belgium	The Treurenberg building in Belgium has accommodated its façades (east, south and west) and 667 m^2 of roof area with mono crystalline solar modules. The total system capacity is 122 kWp. This building was constructed in 2015 with the intension of fulfilling the total building energy consumption. The total system cost is US$0.448m (Mace et al., 2018).
Skylight	**Novartis Pharmaceuticals Corporation´s headquarters** US	The headquarters of the Novartis Pharmaceutical Company in New Jersey, US has installed a PV skylight in a 2,500 m^2 area that consists of 820 crystalline modules with the power capacity of 340 Wp. The system is capable of generating 273,000 kWh per year and reduces nearly 185 tons of CO_2. (Onyx Solar, 2018).
	Bejar Market Spain	Refurbishment of the Bejar Market of Spain in 2015 included a 176 m^2 photovoltaic skylight. The system comprises amorphous silicon modules of different transparency percentages and colours. The system capacity is 6.7 kWp and it can generate almost 9,000 kWh of energy per year, and prevent the release of 6 tons of CO_2 (Onyx Solar, 2018).
Pergola	**Scotch College** Australia	The Scotch College in Australia installed a solar pergola with a capacity of 4.32 kW in 2015. Amorphous Silicon thin-film PV modules featuring 95% resistance to heat gain and 20% natural light penetration were used in the pergola. The total system cost is US$70,000 (Onyx Solar, 2018).
	Tanjong Pagar Singapore	Tanjong Pagar is the tallest building in Singapore and consists of a large photovoltaic pergola covering 2,600 m^2 of area. It is located at the entrance to the building and contains 125 kWp power capacity. The pergola is made of 858 amorphous silicon photovoltaic glass modules, with a 10% semitransparency. The system can produce 125,810 kWh per year (Onyx Solar, 2018).
Balcony	**The General Apartment Building** Australia	The General Apartment Building in Australia was constructed in 2015 and consists of a BIPV balcony made of amorphous silicon cells integrated triple laminated glass modules. The glass obtains 10% transparency and the system spreads over 120m^2 area of the balcony. It is a 5kWp capacity system which generates 2,075 kWh per year (Onyx Solar, 2018).
Multiple BIPV Applications	**Hikari Building** France	Hikari is a building project developed in 2015, with multiple BIPV applications. It consists of a transparent BIPV façade, balcony and a roof and generates 15,000 kWh/year. The total system capacity is 190 kWp. This building project used multi-crystalline cells mounted with bolted glazing façade and custom-made metal support. The BIPV modules are spread over 520 m^2 and the building is occupied for commercial application in Lyon, France. (Gaiddon, et al., 2016).
	Hanergy Headquarters China	Hanergy headquarters in China has incorporated thin-film solar technology into curtain-walls, skywalks and a flexible roof system using 600 m^2 area. The system capacity is 600kW and it fulfils 20% of the total electricity demand of the building. The system can produce 500,000 kWh/year, reducing 2,500 tons of CO_2 emissions. The BIPV components are equipped with superior low-light performance, high temperature resistance, customisable shapes and colours, stable light transmittance, and improved malleability over traditional panels (Hanergy, 2015).

Appendix 2: BIPV soft costs of different countries

Country	Soft Cost	System specifications	Cost (US$)	Year
Germany	Administrative costs (law-related)	5 KW BAPV system	0.01/W	2017
	Administrative costs (PII)	5 KW BAPV system	0.01/W	2017
	Customer acquisition cost	5 KW BAPV system	0.04/W	2017
	Marketing and advertising cost	5 KW BAPV system	0.02/W	2017
	Packing	ASI Glass modules (1205 X 1028 X 27 mm) 50 Wp,53 kg	9.25/kg	2009
	Freight (15% of product cost)	ASI Glass modules (1205 X 1028 X 27 mm) 50 Wp,53 kg	71.26/kg	2009
	Overhead & profit (installer firm)	5 KW BAPV system	0.23/W	2017
	Grid connection and commissioning	5 KW BAPV system	0.02/W	2017
	PII costs	5 KW BAPV system	0.06/W	2014
Italy	Designing and project management	11KW Polycrystalline BIPV roofing system	0.32/W	2016
	Transport	11.52 KW system with Mono-crystalline BIPV roofing	2.20/W	2012
	Installation cost (Total)	11KW Polycrystalline BIPV roofing system	0.64/W	2016
	Installation cost (Electrical BOS)	11.52 KW system with Mono-crystalline BIPV roofing	1.26/W	2012
	Installation cost (Structural BOS)	11.52 KW system with Mono-crystalline BIPV roofing	1.17/W	2012
	Inverter replacement	11.52 KW system with Mono-crystalline BIPV roofing	0.95/W	2012
Greece	Design, engineering and installation costs	2.25 KW Mono-crystalline BIPV roofing system	2.44/W	2003
	Feasibility study, development and miscellaneous	9.87 KW BAPV system	0.12/W	2017
	Transport	2.25 KW Mono-crystalline BIPV roofing system	0.48/W	2003
	Installation cost (Electrical BOS)	2.25 KW Mono-crystalline BIPV roofing system	2.76/W	2003
	Installation cost (Structural BOS)	2.25 KW Mono-crystalline BIPV roofing system	2.82/W	2003
	Monitoring	2.25 KW Mono-crystalline BIPV roofing system	0.48/W	2003
	Inverter replacement	2.25 KW Mono-crystalline BIPV roofing system	1.98/W	2003
US	Customer acquisition	5.6 KW residential BAPV system	0.31/W	2016
	PII costs	5 KW residential BAPV system	0.24/W	2014

Country	Soft Cost	System specifications	Cost (US$)	Year
Australia	Customer acquisition	5 KW BAPV residential system	0.04/W	2016
	Profit	5 KW BAPV residential system	0.27/W	2016
	PII, contracting, financing and other	5 KW BAPV residential system	0.03/W	2016
India	Installation cost (Total)	7KW system with Micro-inverter	1.79/W	2015
	Installation cost (Total)	7VKW system with string inverter	2.36/W	2015
	Installation cost (Electrical BOS)	3.32 KW BIPV Roofing system	0.64/W	2009
	Installation cost (Structural BOS)	3.32 KW BIPV Roofing system	0.98/W	2009
	Inverter replacement	7KW system with Micro-inverter	0.11/W	2015
	Inverter replacement	7KW system with string inverter	0.74/W	2015
Malaysia	Installation cost (Electrical BOS)	5.76 KW Mono-crystalline BIPV roofing system	1.03/W	2012
	Installation cost (Structural BOS)	5.76 KW Mono-crystalline BIPV roofing system	0.24/W	2012
	Inverter replacement	76 KW Mono-crystalline BIPV roofing system	0.85/W	2012
Colombia	Installation cost (Electrical BOS)	0.84 KW Mono-crystalline BIPV roofing system	1.91/W	2011
	Installation cost (Structural BOS)	0.84 KW Mono-crystalline BIPV roofing system	2.62/W	2011
	Inverter replacement	0.84 KW Mono-crystalline BIPV roofing system	1.90/W	2011

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