Review

Building Integrated Photovoltaic for Architectural Façades in Singapore

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ABSTRACT

Background: Singapore is a compact city-state predominantly of high-rise towers. Glass curtain walls are one the most popular building envelope systems in commercial development and there is much potential to incorporate emerging solar energy capture in façade technologies such as glass Building Integrated Photovoltaic (BIPV). Façades present a larger surface area, for instance, if compared to the roof area. Singapore buildings are the second largest energy consumer after vehicles. If well managed, the built environment plays a pivotal role in mitigating high-energy consumption, enhancing environmental protection and improving user-centered and aesthetic qualities of the built form. This includes architecture, landscape and urban infrastructure. Singapore's Sustainable Blueprint and Green Plan 2012 had set goals for the country to achieve economic growth and clean-living environment. With nearly 6 million people Singapore's population has been increasing since its independence in 1965, however, its electricity consumption has been decreasing since 2012. This is being achieved through sustainability programs such as the Green Mark Scheme set by the Building and Construction Authority (BCA) which is a government initiative.

Methods: This paper is based on a critical review of Glass Building Integrated Photovoltaic (BIPV) technology. It also reviews market models for the commercial uptake of technological innovation.

Conclusions: This paper presents recommendations to accelerate BIPV uptake in the property market. In particular in the Singaporean context and geographic equatorial location with high solar incidence. It provides short and long-term strategy for policy development and practice including clients, developers, architects and other project consultants who take early project-decisions. An adoption framework is put forward aligned with current (1) property market architectural trends, (2) technological innovation and (3) life-cycle costing assessment to support investment decisions at early project stages.

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ABBREVIATIONS

BIPV, building integrated photovoltaic; BISTPV, building-integrated semitransparent photovoltaics; PV, photovoltaic; BCA, building and construction authority, Singapore; CBD, City Business District; DSSC, Dye-sensitized solar cell; VfM, Value for Money

INTRODUCTION

The use of Building-Integrated photovoltaic (BIPV) systems and photovoltaic materials promises a simple yet, effective strategy to improve building energy consumption. They replace conventional building materials for the whole or part of the building envelope including façades, skylights, roof areas and other external building elements such as canopies in foyers and courtyards. Research and development (R&D) is fast advancing BIPV technology, but commercial uptake and implementation is lagging [1]. This paper is positioned in between BIPV R&D and its commercial uptake, in particular in equatorial climate zones with high solar incidence such a Singapore. A better understanding of (1) technological innovation and (2) stakeholder buy-in including client, architect and façade specialist were identified as key areas to look at in order to increase BIPV uptake. Strategies for uptake are often left to governments through incentive schemes such as tax-cuts, however this paper argues that BIPV technologies are reaching commercial maturity and therefore architects, developers and ultimately clients should start looking into opportunities to maximise uptake and thereby improve overall project value.

The premise of this paper is that BIPV technologies have reached product maturity and uptake rates should be faster. In order to achieve this, architectural, aesthetic and performance qualities of BIPV need to be taken into consideration from the outset when designing a building. Industry, including clients and developers should be looking into overall project value and not only limiting to the energy savings versus return on investments (ROI) rationale. BIPV already offers architectural possibilities by which creative architects, clients and developers can (and should) tap into, especially through BIPV integrated designs in commercial and residential projects. The vision is that, by addressing issues beyond energy performance criteria, BIPV can bring wider economic benefits for clients, industry, society and ultimately, the environment.

Empirical research has modelled consumer behavioural adoption of innovation, in particular diffusion of innovation [2] which refers to association of social and psychological factors when deciding on purchasing new products or adopting new policies. For example, Figure 1 shows a generic innovation adoption profile, the bell-curve, if looking from right to left, it firstly describes a the innovators or risk takers group representing all early adopters; this group is followed by a larger group of early technology adopters which represents those who “wait-a-bit” before jumping onto the bandwagon, then a large majority group which represent a broad market uptake, while the curve drops and fades away for late adopters and laggards groups. Note that the later might never get to use or adopt the innovation. Figure 1 also shows other two curves representing market phenomena or trends: Moore’s [3] “m-curve” (also known as the *chasm-plato*) and Market share “s-curve” [4]. Moor’s m-curve represents a rapid uptake however, a drop (or product abandonment) which can happen due consumer disappointment, i.e., if technology does not fulfill expectations, this is referred as the Chasm (which is the vertical line representing a drop or abandonment of the innovation). The chasm can happen for several reasons, one being the false, inflated (or hyped) value-benefit (or cost-benefit) perception however, if the product in question gets to pass the chasm line this is referred as the *pinch-point* where the innovation will need to make initial steps towards market penetration. The pinch-point happens as there is often a market drop after the hyped period. After the pinch point the curve reaches a “*plato*” and this represents product/market maturity. By simile there has been much hype around BIPV, the challenge thus is to get through the drop/pinch-point and reach a plato. The market share [4] split over the product lifecycle is represented by the thick s-curve in Figure 1 and this is the curve manufacturers and retailers are looking at. Overall, Figure 1 helps to speculate on various BIPV uptake scenarios ranging from a slow market uptake represented by Rogers’ bell diffusion curve to Moore’s rapid uptake with the risk of creating a false promise of BIPV benefits due marketing. This has to be carefully treated in order to manage consumer expectations of aspirations versus reality.

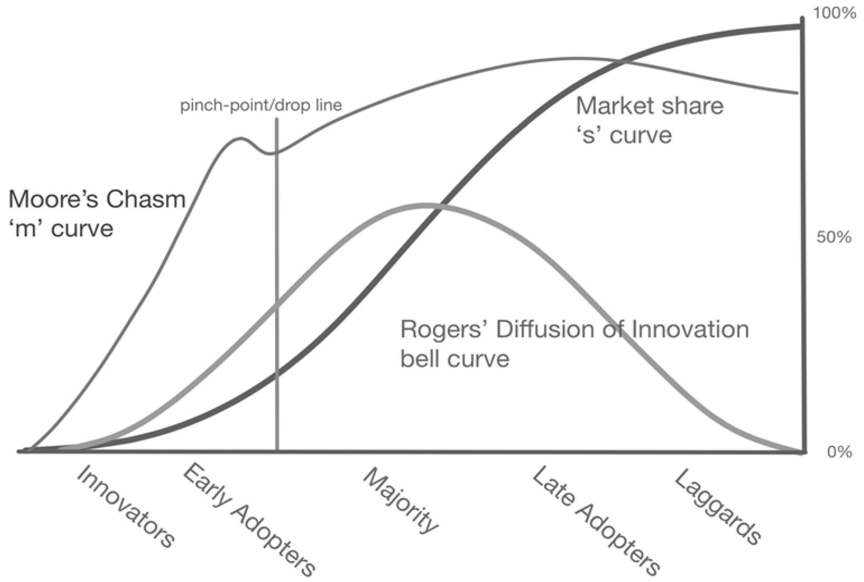

Figure 1. Overlapping market share, Rogers’ and More’s curves [2–4].

The current BIPV adoption situation in Singapore is expected to increase beyond a small number of boutique and pilot projects into a wider uptake, i.e., high-end residential and office development but permeating into a wider base such as high rise residential market for instance. The business case is to take this initiative forward by providing closer government support, training and advice on the use of BIPV technology and thus equipping key decision makers such as architects with the tools and methods to incorporate the technology in their designs, thus creating project value for clients beyond the cost-energy equation.

The expectation is that BIPV innovation will continue to provide new products, once the performance threshold is satisfied and production cost established. Market differentiation will be key through design, aesthetics, fashion and visual qualities of products entering the marketplace. For this to happen, BIPV technology will need to offer more and better architectural possibilities for designers with tangible value for money (VfM) over ROI proposition.

BIPV MULTICRITERIA VALUE ASSESSMENT

A review of secondary data indicates that the main barriers for BIPV uptake include inexperience and lack of knowledge of BIVP systems by property professionals including architects, façade specialists and contractors. Also, BIPV technology is to reach commercial maturity as return on investment and payback period will become clear [5]. A study by Jelle, Breivik and Rokenes [6] aligns with issues related to knowledge and capacity building at design, consultancy and onsite workmanship (i.e., building design and installation rather than product design and manufacturing). A better understanding of the following initiatives is paramount:

1. Early implementation: To implement BIPV façade systems especially in projects considering glass curtain wall as façade system. Key decisions come at conceptual project stages. Integrating the project at design and planning stages. This should help to optimise project schedule, enhance project quality, reduce project risk and ultimately provide a sound "value for money" proposition.
2. Value-add by design: To explore the design of PV glass product and BIPV technology. There are two main aspects to examine: technology performance and aesthetics. The incentives should move away from cost-performance towards life-cycle value.
3. Change management: Training and education programs should be established to overcome barriers of innovative Glass BIPV façade systems. This could be with official government support and industry seminars for building consultants and contractors.
4. Exposure to best practice: To promote best-practice scenarios utilising various channels from across trade journals to professionally curated web sites, blogs and social media. Figure 2 is a decision-making diagram

created by the authors to illustrate a case for BIPV incorporation from early project stages with the following objectives:

- To find out pilot projects that promote uptake of BIPV with glass curtain wall as an integrated façade system.
- To explore the design of glass curtain wall system and BIPV technology with bold aesthetic aspirations.
- To explore the design of glass curtain wall system and BIPV technology which can satisfy technological ambitions.
- To develop small scale pilot projects within universities and R&D, i.e., such as university pavilions.

Innovative BIPV glass façade projects will become increasingly popular as an alternative to conventional glass curtain wall system, making a distinctive feature and practical point-of-use as a source of power generation. In principle, the design of BIPV system should look at the larger picture including architectural, structural and aesthetic considerations [7]. The application of multicriteria evaluation methods are important at early project stages, especially when making the business case in order to justify the higher upfront capital cost of BIPV, e.g., if compared with other fenestration and cladding options. The multicriteria should look at wider benefits and not only at sustainability considerations. Some value-add propositions should include architectural design, comfort, building and construction efficiencies, for example if BIPV panels are pre-assemble with complete cladding panel off-site.

The following Figure 2 provides a schematic overview of participatory decision-making and actions leading to BIPV uptake including: early design strategies such as value versus costs of four dominant areas or segments such as (1) sustainability, (2) aesthetic, (3) functional and (4) construction segments. Attributes under each segment will emerge from stakeholder discussions creating a series of attributes. A matrix is generated with cost-benefit and overall project value. The process is reiterative, and the final appraisal helps to decide based on a multicriteria analysis evaluating by various stakeholders taking into account sustainability, design, technology innovation and building performance considerations.

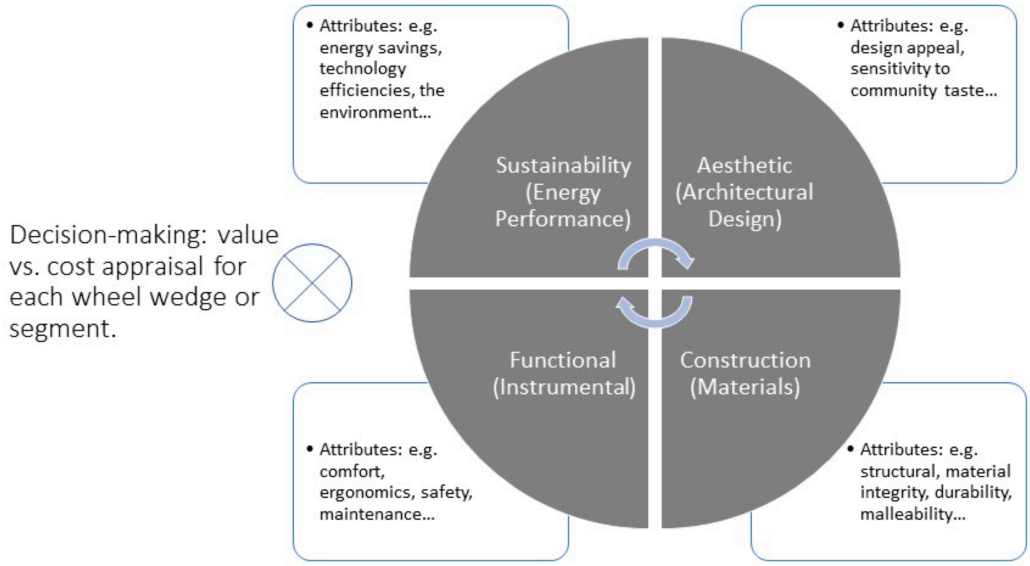

Figure 2. Decision-making: value vs cost multicriteria at early project stages [7].

A similar model is that of Singapore's Housing Development Board (HDB) which uses 8 Phases to assess the viability of Glass BIPV façade systems, the guideline is useful to architects, consultants, engineers and designers to evaluate BIPV façade designs at early project stages ([8], page 5):

1. Preliminary formulation of design concept and strategy.
2. Schematic design to determine the overall energy strategy for the project by estimating the energy consumption of the building and set target for the sum of energy to be generated from BIPV (and possibly other systems). Estimate the energy saving cost in the long run versus the capital cost, i.e., of the Glass BIPV façade system.
3. Determine the building shape, building size, building orientation and BIPV module that consider the daylight and PV collection. With regards to aesthetical features, architectural elements are to set differentiation and originality beyond beauty.
4. Design development of the conceptual design of Glass BIPV façade system which meet the building performance requirement. Iterate with previous point.
5. Estimate the Glass BIPV system energy-cost ratio and rank variants.
6. Consider the Glass BIPV overall value, i.e., as sustainability and lifecycle: run simulation and energy scenario; and life-cycle assessment (LCA), e.g., on the complete glass BIPV façade system.
7. Document complete building as a Building Information Model (BIM).
8. Competitive tender for construction commissioning including visual muck-up unit (VMU) and performance muck-up units (PMU).

Note that design, project development and construction is not lineal but the above is a start. There are also of procurement methods to consider [9].

BIPV IN SINGAPORE

Solar panel technology first appeared in the 1930's and since much of the R&D has been focused on improving energy performance. With the maturing of the technology and evolving market demand for BIPV technology. Current focus is to increase architectural and aesthetic design options. The lack of 'know how' on design and installation also presents a barrier for uptake. This paper argues that benefits are soon to out-weight impediments and thus BIPV technology take a wider market share [10]. This paper explores both dimensions of BIPV systems: (1) the technical improvements and (2) their aesthetic architectural qualities providing added value beyond the shortsighted cost-energy saving rational.

Energy consumption has negative impact on the environment and it heavily contributes to greenhouse gases emissions such as carbon dioxide [11]. To tackle this global challenge, Singapore targets to reduce electricity consumption by a least 15% by the end of the year (2020). This is a clear call for owners, developers and building professionals as the built environment is the largest electricity consumer [12]. The Building and Construction Authorities stablished the Green Mark Scheme (BCA 2017) which is a government initiative to support this target and was initiated as Singapore's response to the Paris Agreement 2016 which aims to reduce carbon emissions by 36% by the year 2030 [13].

Fossil fuel is the main source of energy used globally and accounts for about 70% of global greenhouse gas emissions, including non-renewable energy resources, bringing threats towards global warming [14]. Renewable energies such as solar, are cleaner and inexhaustible energy sources and become key sources on sustainable development providing a safe way to utilise resources for current and future generations [15]. The long-term aim is to fully uptake green technologies which stop energy consumption from non-renewable sources but also improve efficiencies and reduce on carbon emissions.

Solar is the most promising energy source for the future. It is a powerful renewable energy on earth that if well harvested can go far, for instance, one hour of sunshine is enough to cover the demand of the world's energy for the entire year [16]. The use of solar energy in new and old buildings has increased rapidly in recent years and expected to become an important global energy provider in the next 40 years [17]. In Singapore, the annual solar irradiation of about 1500 kWh/m^2 and due to Singapore's proximity to the equator is higher than in the south of Australia, Europe or North America for instance. Presenting a clear advantage as solar photovoltaic (PV) converts sunlight into electricity even if captured on a vertical plane rather than horizontal.

Currently in Singapore, solar energy harvesting only contributes about 2% of the electricity supply, clearly a missed opportunity. With abundant of sunlight all year long in Singapore, the Government is targeting to supply up to 15% of peak electricity supply with solar [18]. Due to the land limitation in Singapore, PV modules on roofs become insignificant on promoting solar energy to the country. BIPV modules can be integrated into the building envelope, such as building façades, roofs, balustrades, shading devices and skylights aligned with the trend of introducing biophilia and greenery [19]. The idea is to make partial or whole PV building exterior elements replace traditional elements such as glass panels or the more traditional cladding materials such as tiled or rendered panels, bricks or concrete blocks. The new BIPV modules and materials will generate electricity for building use and several early pilot projects can be seen in the BCA report [20].

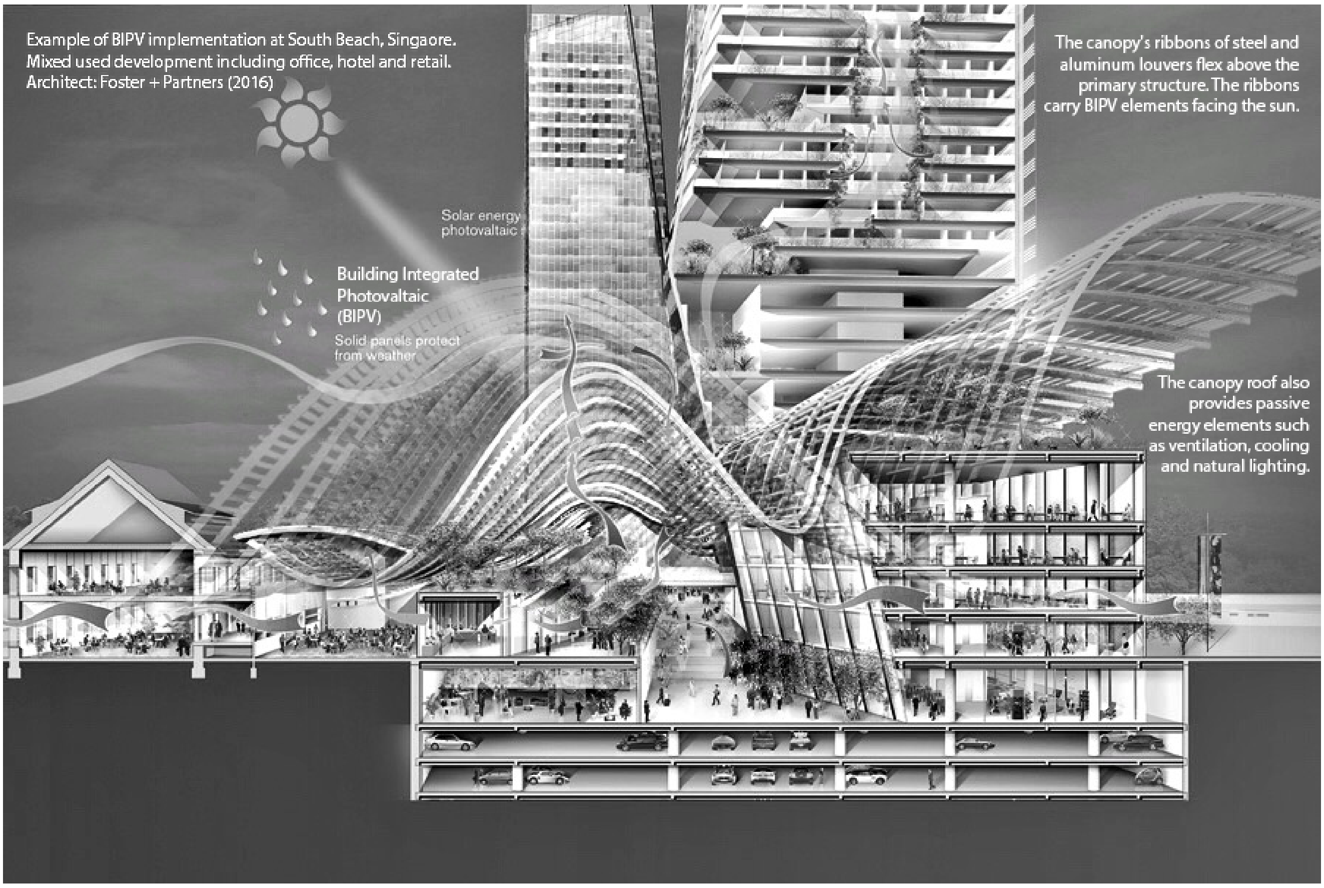

Figure 3. Mix-use development, South Beach Rd. Singapore. Image source: Foster & Partners (2016).

Curtain glass is one the most popular building techniques utilised for cladding of contemporary commercial and residential towers in Singapore. BIPV systems are a serious value proposition for replacing or complementing traditional cladding techniques and materials including curtain glass as BIPV hast the potential to capture solar energy over a larger surface area than the roof area [21], this is particularly relevant in tropical countries such as Singapore and equatorial regions or countries where facades are exposed to direct sun rays for longer time (year cumulative) than say, Europe or North America. The above Figure 3 illustrates the value of BIPV here discussed, it's a mix-use development in Singapore's CBD designed by Foster+Partners and completed in 2016. It was built as part of a new underground subway (MRT) station with oversite development, it incorporates BIVP technology in various building elements including cladding and roof area of two high-rise towers. The BIPV is also placed above the courtyard/atrium area, incorporated as *canopy-ribbons* of steel and aluminum louvers. Hwang et al. did research on the work done in commercial high-rise office buildings and BIPV [22].

BIPV GENESIS TREE

There are several BIPV systems commercially available and many more currently under R&D at universities or research laboratories. Figure 4 shows the genesis of BIPV technology-tree, it maps out both, commercially available and emerging photovoltaic technologies. BIPV glazing systems are stablished under two branches including *switchable* (or variable) transparency glazing which can be electrically and non-electrically actuated. The second branch considers *static* (or permanent glass transparency), from here two sub-branches emerge including fixed transparency devices and Photovoltaic (PV) glazing systems including 1st, 2nd (or Thin film) and 3rd generation technologies.

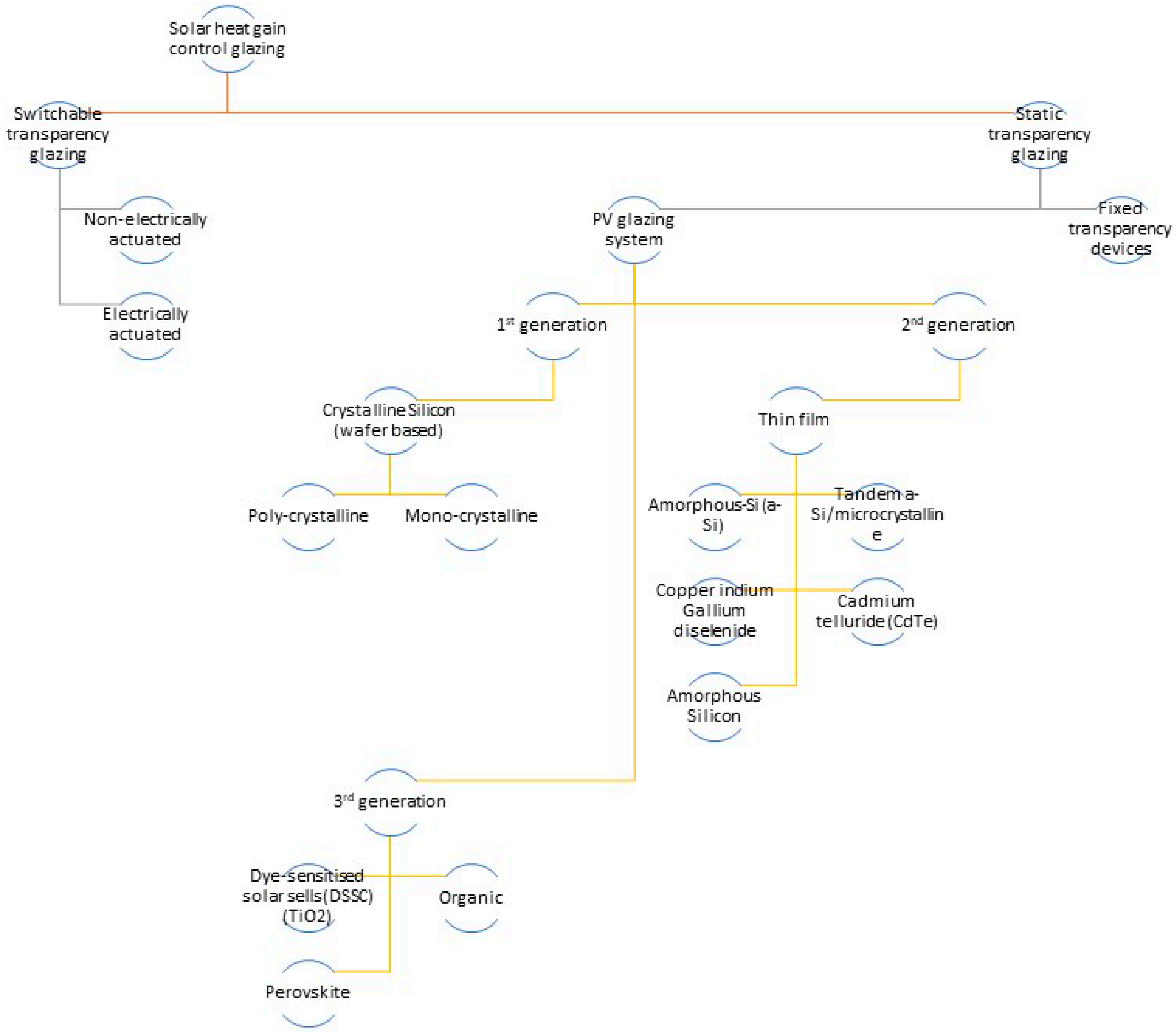

Figure 4. BIPV technology tree. Source: [23] and [43] combined.

Second and Third Generation PV Glassing

This system is the combination of glass and PV module technologies, such as thin-film solar cell. Thin-film solar cell is second generation PV cell which matches well with the glass substrate in terms of both aesthetic and energy efficiency of the building façade. So far, thin-film is the only technology to satisfy the advanced architectural trend of making the buildings look like a "blob" or a living organism [24]. This technology successfully transfers the semi-transparent Glass BIPV system blending into glass curtain walls, adding thus value to the overall project. Thus, the value proposition shifts from energy efficiency across to building aesthetics. Thin-film PV cells are thin layers of semiconductor materials and classified into four common types as follow:

Amorphous silicon (a-Si) and thin-film silicon (TF-Si)

- It consists of silicon atoms in a thin (1 mm thick) homogeneous layer deposited at −75 °C. It can lay on both rigid and flexible substrate that can then be applied onto curved surfaces and "fold-away" modules.
- Is also known as "thin-film" PV technology as cells are only 1 mm thick.
- It performs better at higher temperatures.
- It is a non-toxic material.
- One of the pioneers developed Uni-Solar, a triple layer system that is efficient when absorbing solar light.
- It is based on semi-transparent amorphous silicon solar cells that will be discussed in later part of this paper.
- The effect of a-Si thin-film BIPV system allows for natural light into the building, at the same time it serves as an energy generator [25].

Cadmium-Telluride (CdTe)

- CdTe solar cells are thin-film layers based on cadmium telluride as semiconductor to convert absorbed solar light into electrical energy [26].
- The upper layer of electrode of CdTe is made of tin oxide (SnO_2) or cadium-based stannous oxide (Cd_2SnO_4) and the lower layer is made from copper-doped carbon paste. Between the upper and lower layer, cadmium sulphide (CdS) is placed. CdTe is one of the most popular PV technologies being used for PV modules, and low in production cost.
- The R&D on schematic build-up of CdTe [27] combined with lightweight and flexibility of CdTe module [28].

Copper-Indium-Selenide (CIS) or Copper-Indium-Gallium-Selenide (CIGS)

- CIS or CIGS produced the highest energy production compared to the rest of thin-film solar cells. The power conversion efficiency is

reaching 20% on a glass substrate. The high absorption coefficient at the band gap of 1.5 eV made CIGS PV solar cells increased the use in space applications.
- The schematic build-up of CIGS and lightweight and flexibility of CIGS module.

Dye-sensitized solar cell (DSSC)

- DSSC is best considered as artificial photosynthesis. The performance is good even under indirect radiation, cloudy weather, and partially shaded surface.
- DSSC technology was governed by the Grätzel titanium dioxide (TiO_2) cell, achieved 13% energy conversion efficiency on small area device.
- DSSC is low in cost. The particles of titanium dioxide are coated with a photosensitive dye and suspended between two electrodes in a solution containing iodine ions. When this dye is exposed to light energy, some of its electrons jump on to the titanium dioxide particles, which are then attracted to one of the electrodes. At the same time, the iodine ions transport electrons back from the other electrode to refill the dye particles. This creates a flow of electrons around the circuit. Over time, the efficiencies will be established around 10% or more. It is very effective over a wide range of sunlight conditions.
- DSSC is semi-flexible and semi-transparent which makes it suitable to apply on solar fins, solar louvers, canopies, façade cladding, curtain wall, semi-transparent window and similar products and samples of DSSC PV cell modules [29].

Note that DSSC is a technology which in Figure 4 appears within the 3rd generation branch however, the BCA Singapore had placed it under the 2nd generation branch as thin-film technology, the rationale is that it can be applied on solar fins or louvers [23].

Coloured Glass BIPV

In the semi-transparent glass PV system, there are also coloured (or tinted) glass PV systems which are a desirable product for hi-end projects. There has been use of these panels in shades of grey or primary colours. This presents an exciting alternative to the traditional PV square and opaque panels which often diminish the aesthetics of buildings. Coloured glass BIPV technology could revolutionise the uptake rate of BIPV technology, especially if the glass panels are cleverly integrated onto the building skin, complete facade solutions and not simply as an addon as in most cases today [30].

Coloured glass solar systems are still new in the market and many products are under development to improve the performance. The main challenge for coloured PV panels is to achieve the same efficiency as ordinary black PV panels. Black is the best solar irradiance absorber; thus, PV panels are black or dark blue. Therefore, to move away from dark coloured PV is a challenge. PV also needs to align with specialist glass manufacturers in order to provide onsite maintenance and service in the geo-location they might be installed.

Methods that can be considered for colouring solar modules [31]:

- Use the coloured glass.
- Full area prints on glass with various patterns: resilient and durable.
- Use the coloured film.
- Use the anti-reflective coatings.

When it comes to the combination of colour, solar cells are available with various types of glass layer structures, there are two common ways of installation situations, i.e., glass-glass-PV modules (known as laminated glass) and PV thermal insulation glazing (also known as glass-vacuum glass).

1. Glass-glass module structure.
2. PV with three layers of glass.
3. PV thermal insulation glazing.

(1) and (2) are laminated PV glass and (3) shown different combination of PV thermal insulation glazing. Figure 5. Exemplifies configurations and materiality of PV cells.

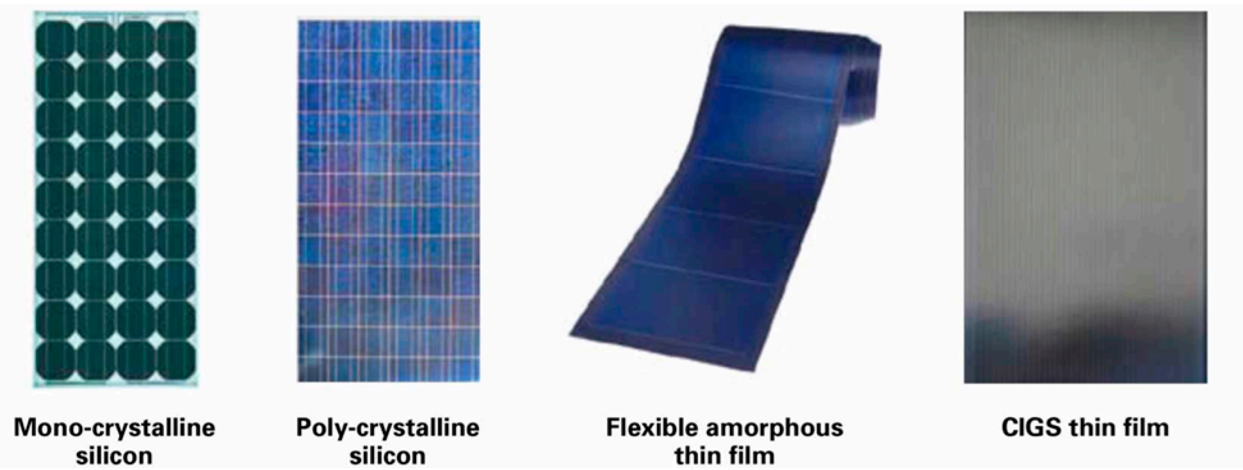

Figure 5. Materiality PV cells. Source: BCA 2008 ([23], page 8).

Solar cells in various colours. Lee et al. [29] investigated coloured BIPV system as listed and discussed including Cu_2O thin film adjusting transparency and color in semi-transparent a-Si:H cells. The following techniques apply when fabricating a-Si:H solar cells with different colours:

- Organic Photovoltaic is currently under R&D it contains plastic solar cells, it is expected to be affordable, lifespan is a shortcoming [30].
- The application of luminescent materials for coloured and design approaches in PV for architectural design [31]. This method supports

the PV modules, it can be designed in both, aesthetic and functional coloration in mind.

- A study discovered that the opaque black contact module is the best way to achieve target colour and high energy efficiency [32]. The results also developed a first ever sky blue and green large-area a-Si:H semi-transparent PV module that contributed further R&D. The trade-off remains light transparency versus opaque darkness for higher energy capture.
- Semi-transparent bi-facial BIPV modules aim to increase performance by using highly reflective material for exterior walls, i.e., when putting bifacial PV modules into the building envelope [33].
- Neutral and multi-coloured semi-transparent Perovskite solar cells. This method can overcome issues of market commercialisation as the Perovskite solar cells reduce material toxicity and increase stability and performance [34].
- Printed glass and colour matching procedure of (c-Si BIPV) modules with printed glasses [35]. This method works with bespoke production of coloured front glass and digital ceramic printing to cover the PV cells generating electricity with light radiation getting through the ceramic prints or fritz (i.e., small ceramic shading dots embedded in glass panels, often making design patterns, the pattern can be dense to block or reduce direct sun rays or glare).
- Coloured a-Si:H transparent solar cells that applied with ultrathin transparent multi-layered electrodes [36]. The glass panel is printed over triple high-bandgap layers to get over 20% efficiency, a high-performance BIPV glass façade and windows which is expensive.
- Colour and tone impact on the efficiency of solar radiation capture by crystalline silicon (c-Si) in PV modules. Results classify the colours corresponding to power losses [37]. White corresponds to the highest losses and black to lowest losses on PV power. The remaining colours were divided into two types: (1) yellow, red, orange and violet accounting for 55% power loss and (2) blue, green, grey and brown accounting for 25% power loss.
- Finally, Kromatix glass panels comprise the effect of diffused surfaces and interference filters [38], this system has successfully produced commercial colour-coated glass designed to reflect the prescribed colour spectrum while at the same time admitting maximum visible light which excites the black solar cell to perform to its maximum efficiency. These panels are leading the way to new consideration in solar architecture.

Glass BIPV façade is a promising technology and architectural element that can significantly contribute to renewable energy development. This paper critically reviews the technology benefit in an international context with the aim to increase its implementation in Singapore. The BCA Singapore has taken the initiative to promote BIPV systems including the production of PV and BIPV handbooks freely available for consultation to building owners, developers, architects and designers. Developing user-friendly, non-technical user guides for PV and BIPV uptake is important including pilot and demonstration projects, the next stage would be to increase the number of software tools and applications (including apps for tablets) to assist architects, clients and designers with the integration of BIPV in buildings. Software applications should be approved by government authorities and independent research institutions.

RECOMMENDATIONS AND FURTHER DISCUSSION

The following recommendations for the Singaporean market include:

For the next 5 years:

- To develop government certified software applications with user-friendly interface, specifically for BIPV façade design 3D visualisation and energy performance calculations. The applications could be in the form of plug-in to BIM authoring tools (such as Revit, ArchiCAD or Bentley). The applications should be intended for architects and façade designers, this is supported by Jakica and Zanelli [39,40].
- To develop training programs supported by government.
- To establish either tax rebate incentives when integrating BIPV in façades.

For the next 5 to 15 years:

- The Singapore government is to take initiative to build pilot projects including residential high-rise development (HDB) which demonstrate long-term value of utilising glass BIPV façade systems.
- Private sector is to showcase projects, this could include small scale architectural pavilions at building expos and events.
- Increase BIPV research and development (R&D) on chemical/material composite level such as those by Saifullah et al. [41] and Martellotta et al. [42] who work on building integrated semitransparent photovoltaics (BISTPV).

The important factor is to ensure that there is plenty of R&D in the pipeline. Government support is good but commercial demand will drive the agenda in years to come. Industry-research links with commercialisation are paramount. If revisiting the above Figure 4, undergoing R&D currently seats within the 3rd generation branch which needs to emerge into commercialisation.

The emerging BIPV technologies—e.g., Gosh et al. [43–45]—are indicative of current trends and efforts towards improving thermal performance of semitransparent CdTe based BIPV, this material shows an average U-value of 2.7 $W/m^2{\cdot}K$ which has the average U-value of 5.7 $W/m^2{\cdot}K$, and this is much better if compared to a single-glazed window. On the other hand, dye-sensitized solar cells (DSSC) can integrate onto the glass BIPV façade systems thus improving energy gains in visible transmittance BIPV. Also, DSSC improves in color quality and comfort level [42] and finally, for the first-time carbon counter electrode-based perovskite was fabricated to investigate is potential use in BIPV.

Lower solar gain and higher U-value makes this glazing a suitable candidate for warmer climate and summer season when indoor room temperature needs to be low to trim down air conditioning load and enhance occupant's thermal comfort. The advantage of the material is its translucency good for natural light capture and reducing glare which could be pervasive, especially in office and workplace settings [43].

In order to accelerate the uptake of BIPV several strategies and mechanisms have been presented including market and government driven. In recent years, Singapore government launched several incentives to support policy such as the Building Construction Authority and Energy Market Authority to provide financial support to incentivize the BIPV market in Singapore. Government policy support will have great impact on the entire chain of BIPV, from design support, product cost, installation and even engagement and feedback from building occupiers and end-users.

This paper presented the glass BIPV façade design process guidelines to assist on design decision making and suggested to simplify the complicated design process by using an easy-to-use BIPV design software which required further research shall integrated with digital PV glass product library and digital library of PV and BIPV standards, regulations, test, BCA handbooks and case studies.

Although a long-term government plan for BIPV uptake including policy is important, immediate BIPV uptake can happen within the property industry, architects, developers and clients are in the best position to integrate BIPV technologies at early project stages, maximising thus the overall value proposition. The innovation should respond to a holistic life-cycle economic driver rather than a cost-energy ration.

How is the future looking? A book recently published by this paper co-author [46] stablishes new directions for intelligent buildings in which the smart office building of the future will read occupants' emotional response to the environment around them and this will be the next level of smart (or intelligent) buildings [46]. The challenge at this point is to foresee the future of "*smart façade systems*" that capture energy and also respond to building internal environmental conditions such as glare, temperature, noise, space customisation for individual preferences. A step forward if for the BIPV R&D agenda to pursue comfort, design and aesthetic factors beyond energy gains. As a final note, there is emerging interest by industry on innovative procurement systems such as "*build-to-lease*" which is shifting the focus away from prioritising lowest initial cost into long term value such as in build-to-lease projects [47]. The push for BIPV uptake to should go beyond "only" technical challenges [48] and consider the wider sustainability, respond to global market demand [49] and provide life-cycle economic benefits. With value-add pilot project demonstrations should push BIPV *en vogue* and thus, the business case clearer. Buildings will hopefully increasingly become truly smart or intelligent.

AUTHOR CONTRIBUTIONS

GA-M brought the design and theoretical underpinnings into this paper including Circularity and Innovation Adoption models. JPF championed the literature review on BIPV technology discussed in this paper.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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