New & Renewable Energy 2019. 12 Vol. 15, No. 4
ISSN 1738-3935
https://doi.org/10.7849/ksnre.2019.12.15.4.047

[2019-12-PV-006]

Review on the Progress in Building Integrated Photovoltaic Materials and Module Technology

Muhammad Aleem Zahid[1)]· Sanchari Chowdhury[1)] · Kumar Mallem[1)] · Eun-Chel Cho[2)*] · Junsin Yi[2)*]

Received 10 September 2019 **Revised** 7 November 2019 **Accepted** 11 November 2019

ABSTRACT A building integrated photovoltaic (BIPV) is an innovative, promising and practical technology for buildings with net zero CO_2 emissions. This Review paper addresses the development of a curtain wall module, color module, lightweight module and anti-soiling techniques in BIPV Technology. Selecting the best material permits a high conversion efficiency and bright color of the module at the same time. Curtain wall and light weight solar PV cells fabricated using an established procedure could increase the applications of solar PV cells.

Key words Building Integrated Photovoltaic, Light Weight Module, Colored Module, Anti-Soiling

Subscript

PV : Photovoltaic
BIPV : Building Integrated Photovoltaic
CW : Curtain Wall
TCO : Transparent Conductive Oxide
ARC : Anti-Reflective Coating

1. Introduction

Energy from sun is inexhaustible, clean and abundant among renewable energy sources presently available[1]. In single day, the irradiation on the earth from the sun approximately gives ten thousand times than the everyday use[2]. The challenge is gathering huge amount of energy at reasonable cost. Most capable technology is photovoltaic (PV). Building Integrated Photovoltaic can substitute conservative building material in portions of building covers such as walls, rooftops or facades.

Researchers showing their interest in BIPV technologies due to fact that it provide a very good potential for incorporation into buildings for the supply of electrical loads. BIPV's have a great capability to replace nearly all outside building materials and hence are able to minimize overall long term costs. These systems are also reflected as building integrated energy storage systems. New and advanced PV technologies would lead to low cost and highly efficient BIPVs which would end in quicker pay back periods. BIPV have a great potential to support design net-zero

1) PhD Student, Department of Electrical and Computer Engineering, Sungkyunkwan University
2) Professor, Department of Electrical and Computer Engineering, Sungkyunkwan University
***Corresponding authors:** junsin@skku.edu (JSY), echo0211@skku.edu (ECC)
Tel: +82-31-290-7139 Fax: +82-31-299-4974

energy buildings due to improved solar energy utilization. BIPV is now measured as a useful building structure portion and design due to their features like flexibility, size, appearance and shape[3]. It is used with metal or glass, in opaque and semitransparent surfaces that are common in architecture. The BIPV structure contributes as building construction material and generator on same time[4]. BIPV has huge benefit as related to non-integrated PV system since here is no necessity of land sharing for the facilitation of PV system. The electricity generating BIPV can lessen the building material cost and attain lot of saving in terms of mounting budget because there is no need of assembly components like rails and brackets in BIPV[5] also this system generates clean electricity. All of the mentioned advantages have initiated the global growing attention in BIPV. This paper is showing the progress in BIPV technologies.

2. Curtain Wall Module

Organizations of Curtain wall (CW) PV systems are prefabricated that are integrated with outside of building act as a protective skin. PV is considered as a cladding element or material of CW and important part of skin. Such PV systems have vital role in energy approach of a building and environmental aspects.

Li et al. constructed and tested Solar Thermal Curtain Wall (STCW) as covering of building in individual house[6]. He analyzed the effect of integrated solar PV collector to wall. The yearly performance of STCW has examined. They analyzed through the use of numerical model supported by investigational data.

Goncalves, Juliana et al. presented the enactment of a CW in real time conditions[7]. The average Performance Ratio was achieved 94.2%. A finite element method has designed and confirmed with investigational data. This model is helpful to optimize the thermal performance and to support the choice for the suitable location for the converter in the BIPV frame for electronics components operating temperatures.

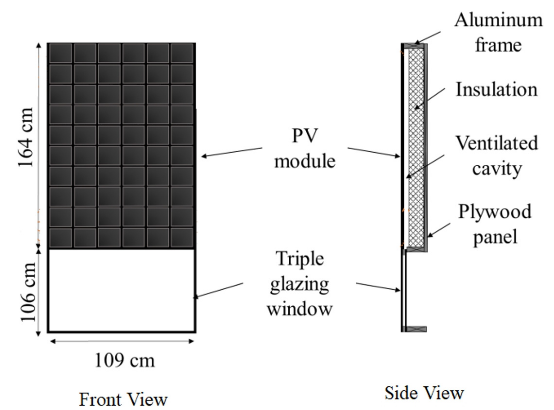

Fig. 1. Schematic diagram of BIPV CW design[7]

An, Weiguang, et al. employed theoretical analysis and experimental methods to investigate the influence of analogous curtain wall on decreasing flame spread features of insulation resources upon the building façade[8]. A formulation is developed to expect the radiant hotness response from CW, it is more prevailing as compared to heat response.

$$V_{f,thick} \sim V_g \frac{\lambda_g \rho_g c_g (T_f - T_v)^2}{\lambda_s \rho_s c_s (T_v - T_\infty)^2} \tag{1}$$

Eq. (1) shows that flame speed rate is directly proportion to the flame temperature T_f.

Chen, Ke, and Weisheng Lu responds a detailed study of an effective application of design for manufacture and assembly (DFMA) for industry based design method to curtain walls in commercial building located at Wuhan China[9]. This study gives valued information

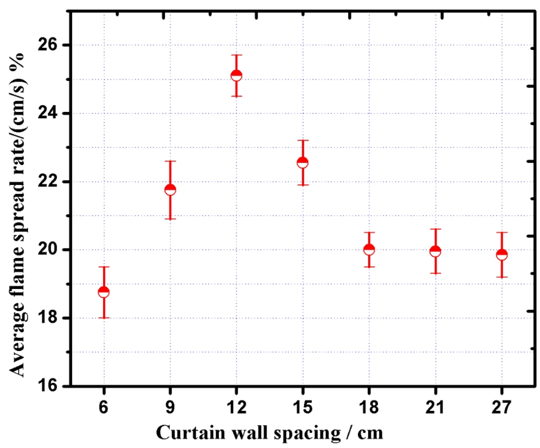

Fig. 2. Flame spread as a function of spacing

Table 1. DFMA in Architectural Projects

Type of facilities	Construct of DFMA principles
Solar Tower[10].	Lessening fabricating price by using already assembled modules. Reducing transport and assembly cost
Super structure and sub structure of channel[11].	Lessening figure of parts. Shortening manufacturing and assembly stages. The Weight and size of constituents should be easily handled.
Assembly of fibre–strengthened polymer bridge surfaces[12].	Lessening on–site attached influences and fasteners. Minimizing figure of fragments in assembly. Reducing rotation and movements. Minimizing standardization and repetition.

about the ways DFMA, which will be useful to the architectural industry. Table 1 shows some of the DFMA implementation in Architectural Projects.

3. Light Weight Module.

Light weight module may result in reduces module and system cost. These modules are easily adaptable to various regional conditions and climates. These modules allowing reuse, recycling and refurbishment without any waste generation. Crystalline Si and thin film PVs are looking for light weight and installed on any arrangements especially integrated in to building facades and roofs and solar powered drones or planes with the reduced weight.

Martins, Ana C., et al. proposed a PV module of 6 kg/m^2[13]. The module was composed of glass free front sheet and composite back sheet. They showed that the thermal conductivity and manufacture process need to be tuned to allow excellent class sandwich adhesive once processing due to presence of honey comb structured core and sandwich architecture. The module showed 2.4% loss of power after 200 thermal cycles and no symbol of bending and delamination.

Martins, Ana C., et al. proved that they are capable to fabricate glass free light weight module with stiff composite sandwich back sheet weight of 5 kg/m^2[14]. They showed that rigidity of composite back sheet has a strong influence on hail resistance. This outcome is recognized to energy dissipation globally of the hails impact over the entire assembly. While front sheet is concerned, they showed that volume of poly–meric front sheet has a great influence on resistance to hail, also they proved that material distribution in volume can support mitigating hail induced damage. Finally, they showed that it is possibility to fabricate light weight module which is glass free using accurate trade–off between reinforcing back sheet and front sheet stiffness.

Martins, Ana C, et al develop light weight glass free PV module (6 kg/m^2) comprises of polymer front layer and composite sandwich back structure (vacuum bag process and thermosetting epoxy resin)[15]. To simplify the fabrication various encapsulant foils e.g. ionomer polyolefin (PO), EVA is used instead of thermoset epoxy. Outcome shows that stable back sheet structure is best to produce by PO adhesive. The use of this particular polymer allows minimization of processing time from 24 hours to 30 minutes. Two light weight PV cell modules are fabricated with this back sheet which depicts excellent electrical performance under damp heat (DH) and thermal cycling (TC) tests, and it shows the output power loss of 2% and 3%. This configuration then extends up to sixteen cell module.

$$E' = 2(1+v)\cdot G' \quad (2)$$

$$D = E\cdot I \quad (3)$$

Where G' shear storage modulus, v poison's ratio, D bending stiffness, and I sandwich inertia.

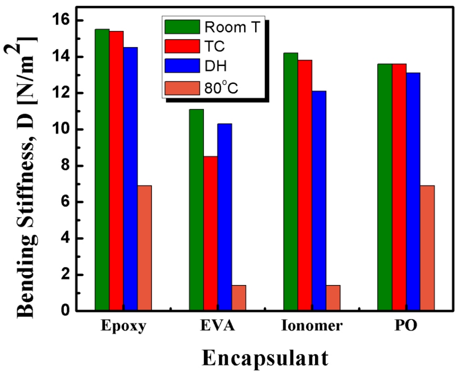

Fig. 3. Bending stiffness measured for various adhesives[15]

4. Colored Module

Power Generation and efficiency of PV is highly dependent on the color of solar cell. Researches are conducting to maximize the power efficiency of colored modules because PV colored window are the integral part of building

Myong, et al. inspected color design of 1.43 m^2 a-Si:H semitransparent glass to glass PV module[16]. Excluding red color (a-Si:H), multiple ideas were designed by joining the clearness of back contacts and also by laser pattering procedures. Systematic analyses of color were used in CIELAB color space. Furthermore, the fusion kind module by light blue color was attained by using blue polyvinylbutyra films. Thus it is decided that opaque back contact (OBC) kind module approach through esthetic blue color is finest scenario to accomplish highest efficiency of 7.2%. As Pmax is not decreased back glasses color, the proposed concepts are considered as esthetic and stable PV modules.

S.Yeop Myong, Jeon S. Won used glass to glass semitransparent PV module[17]. Variety of colors can be selected with 3D color layer based skill. Solar cube blocks were produced. Every cube area is 1.41 m^2 specifically transparent back glass Yellow module, transparent back glass orange module, transparent back glass green module, dense back contact sky blue module and hybrid light blue module. Result shows that Pmax has decayed with color. Opaque back contact type color modules achieve the highest efficiency of 7.2%.

Blasi, Benedikt, et al. explained that by using MORPHO effect, glowingly colored photovoltaic modules consisting of high tolerance could be fabricated[18]. They demonstrated green, red and blue colors BIPV modules. By the use of this technology, a huge number of colors can obtain. Through this approach, a huge choice of designs can be readily accessible for designers and architects. So far glass module is adopted, standard PV cells could be used for module design allowing this technique to be very promising. This technique

Fig. 4. Modules with green, blue, red colors[18]

can also be applicable for solar thermal collectors.

Peharz, et al. conducted the basic physical calculations to quantify an influence of variable colors on PV power loss[19]. Specifically, monochromatic multiple colors are examined by creating pill strong box reflection bands and incident spectrum of solar reference. Lasting solar strength is thought to convert in crystalline silicon solar cells. Furthermore, power loss associated to uniform colors explained in RAL color set is examined. The crux of the results is that less power loss lower than 7% are realized by extremely saturated monochromatic colors. High power loss shown by standardized colors. Colors like green, blue, dark grey, black and brown corresponds to almost partial loss of power as determined for orange, yellow, violet, red, white colors.

Amara, Mohamed, et al. focused on the brightness and color space by changing the dynamics of anti-reflective flat silicon PV solar cells[20]. They validate thermal effect by selecting color and the brightness with minor effect on renovation efficiency excluding dark blue PV solar cells. The optical simulations display the adopted color for particular layer anti-reflective coating (ARC) will not change with the spot of viewer whatever the color will be. The usage of double layered ARC enhances the flexibility to adjust the wanted color highly enhanced in the yellow and green ways. Lastly, selecting the exact material permits highly conversion efficiency and bright color at the same time.

Yoo, Gang Yeol, et al. applied single dimension Photo Crystal Dichroic filter on $Cu(ln, Ga)(S,Se)_2$ for generation of great performance colors on thin film PV cells for BIPV applications[21].

Soman, et al. integrated nano-photonic coating technology known as Selectively Modulated Aesthetic Reflector Technology (SMART) to matured crystalline silicon solar cells to design colored cells[22]. They used single dimensional dielectric photonic crystal to reflect sun light and examine different colored appearance for solar cells. Silicon oxynitride (SiON) and silicon nitride (SiN) dielectric varying thickness layer and composition were used to manufacture SMART coatings. The performance and efficiency of colored cells have been revealed on 156 cm^2 cell areas. RGB shows the power conversion efficiency of 70-80% based on diverse colors. While white shows 59% of efficiency as related to standardized reference crystalline silicon solar cells.

$$n_{eff} = 2\left[\frac{1}{n_{hi}} + \frac{1}{n_{lo}}\right]^{-1} \qquad (4)$$

Where n_{eff} is effective refractive index, n_{hi} and n_{lo} refractive index contrast of material.

Ji, Chengang, et al. presented a novel methodology for fabricating dark-colored cell with brilliant angular insensitivity and great efficiency by coating a cry-

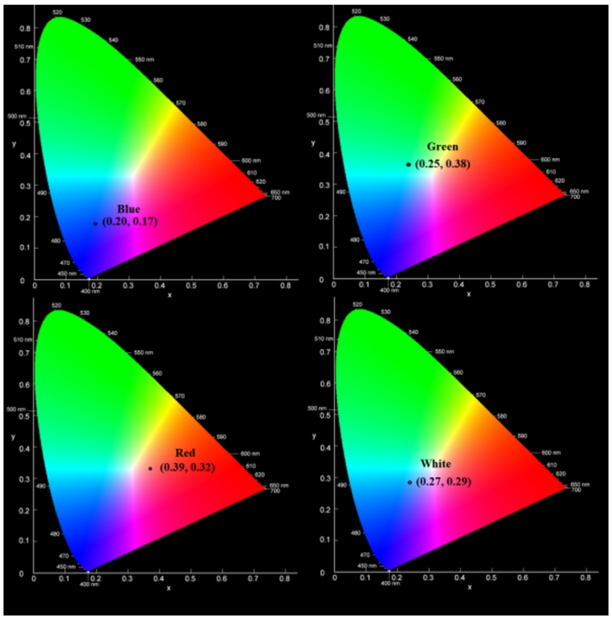

Fig. 5. CIE1931 chromaticity diagram of (RGB) and white smart coating[23]

stalline silicon solar panel through a transreflective color filtering scheme[23]. The five layered filter create vivid colors and transfer the remaining broadband light across the whole solar spectrum on to the silicon solar panel below, going to a whole high power conversion efficiency of ornamental solar cells. This superficial method with a few layers can embellish solar panels for improved building integration. It can simply substitute whenever the colored structures are damaged or a diverse color is wanted, thus holding a definite potential for future BIPV.

5. Anti-soiling techniques

Anti-soiling coating have many benefits in terms of minimize PV power efficiency losses. Many anti-soiling techniques have been proposed.

Hanaei Hengameh, Assadi M Khalaji, Saidur R discussed: 1) the fundamental / desired properties of anti-soiling and antireflection coatings. 2) Methodologies for film processing on silicone and silica substrate. 3) Benefits and potential of combining carbon nanotubes (CNT) in antifouling coatings and ARCs. 4) About treatment, utility and current data development of a coating based on CNT[24].

Miller David C, et al. focused on Evaluation of PV Module Surfaces Test Standards and Abrasion Testing[25]. Following points are summarized from their research: 1) Detailed analysis of abrasion classification and PV test methods of PV module technology. 2) The robustness of the surface of the front PV module is linked with impact of active particles and contamination through soiling. 3) Antireflective films are taken into account. 4) Literature for the tests and standards of fall and forced sand are examined and studied. 5) Several abrasion testers and structures are evaluated.

Bahattab MA, et.al discussed anti-soiling and anti-reflective films by sol-gel treatment using nano-technology[26]. Porous films of SiO_2 are ARC and mitigating. Research laboratory experiments consume artificial powder, then it is compared to an outdoor exposure experiences. The surface coverage of the sample correlates with its optical performance. Coating on films are witnessed to considerably enhanced transmission for dust uncovered related to non-coated models

Pulipaka S, Kumar R, simulated Irradiance loss aspect which computes the connection between irradiance, the angle of inclination and PV output power[27]. Sieves analysis and artificial soiling experiment are performed to attain contour development data and contour analysis is usually used to conclude the power difference between clean panel and a dirty panel. A correction aspect is used to compute the power of the clogged module

6. Conclusions

According to review, it is concluded that BIPV is an emerging technology and can perform dual functions such as providing building envelopes and producing electricity for buildings. This paper reviews the progress of curtain wall, light weight, and color PV modules. As the land area of Korea is limited, it is necessary to apply PV system to the building in urban area. The curtain walls and color modules provide a solution to install a PV system in the building, which matches the exterior color and shape of the building. Lightweight modules are a solution that can be installed on top of a building with a load limit. BIPV has a direct impact on the lighting conditions and internal climate of building. This will lead to a minimization in demand of cooling energy.

So, BIPV performs the functions of emission reduction and energy conservation.

Acknowledgement

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government (MOTIE) (20193010014780) and Development Program of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) through a grant funded by the Ministry of Knowledge Economy, Korea 201930 10014850).

References

[1] Union of Concerned Scientists, 2015, "The solar Resource", https://www.ucsusa.org/resources/solar-resource

[2] Swiss BiPV Competence Centre, Energy from the Sun, http://www.bipv.ch/index.php/en/technology-top-en/potential

[3] Peng, C., Huang, Y., and Wu, Z., 2011, "Building-integrated photovoltaic (BIPV) in architectural design in China", Energy and Build., **43**(12), 3592-3598.

[4] Strong, S. 2010, "Building Integrated Photovoltaics (BIPV), Whole Building Design Guide", http://www.wbdg.org/resources/bipv.phpS.

[5] Neuwald, J., "All you need to know about building integrated photovoltaics - Part 2", http://www.roofconsult.co.uk/articles/kalzip2.htm

[6] Li, R., Dai, Y.J., and Wang, R.Z., 2015, "Experimental and theoretical analysis on thermal performance of solar thermal curtain wall in building envelope", Energy Build., **87**, 324-334.

[7] Gonçalves, J.E., Lehmann, J., Yordanov, G.H., Parys, W., Baert, K., and Saelens, D., 2018, "Experimental performance of a curtain wall BIPV element under realistic boundary conditions" Conference: European Photovoltaic Solar Energy Conference and Exhibition EUPVSEC2018, https://www.eupvsec-proceedings. com

[8] An, Weiguang, et al., 2018, "Experimental study on downward flame spread characteristics under the influence of parallel curtain wall", Appl. Thermal Eng., **128**(5), 297-305.

[9] Chen, K., and Weisheng, L., 2018, "Design for manufacture and assembly oriented design approach to a curtain wall system: a case study of a commercial building in Wuhan, China" Sustainability, **10**(7), 2211.

[10] Peterseim, J.H., White, S., and Hellwig, U., 2016, "Novel solar tower structure to lower plant cost and construction risk", Proceedings of AIP Conference, **1734**, 070025.

[11] Kim, M.K., McGovern, S., Belsky, M., Middleton, C., and Brilakis, I., 2016, "A suitability analysis of precast components for standardized bridge construction in the United Kingdom", Procedia Eng, **164**, 188-195.

[12] Mara, V. and Kliger, R, 2016, "An approach to the development of connections between fibre reinforced polymer bridge decks", Case Stud. Struct. Eng, **5**, 18-26.

[13] Martins, A.C., Chapuis, V., Virtuani, A., and Ballif, C., 2017, "Ultra-Lightweight PV module design for Building Integrated Photovoltaics", Proceedings of 44th IEEE Photovoltaic Specialists Conference.

[14] Martins, A.C., Chapuis, V., Virtuani, A., Perret-Aebi, L.E., and Ballif, C., 2017, "Hail resistance of composite-based glass-free lightweight modules for building integrated photovoltaics applications", Proceedings of the 33rd European Photovoltaic Solar Energy Conference and Exhibition.

[15] Martin, A.C., Chapuis, V., Virtuani, A., Li, H.Y., Perret-Aebi, L.E., and Ballif, C., 2018, "Thermo-mechanical stability of lightweight glass-free photovoltaic modules based on a composite substrate", Sol. Energy Mater. Sol. Cells, **187**, 82-90.

[16] Myong, S.Y. and Jeon, S.W., 2015, "Design of esthetic color for thin-film silicon semi-transparent photovoltaic modules", Sol. Energy Mater. Sol. Cells, **143**, 442-449.

[17] Biyik, Emrah, *et al*., 2017, "A key review of building integrated photovoltaic (BIPV) systems", Eng. Sci. Technol.

Int. J., **20**(3), 833-858.

[18] Bläsi, B., Kroyer, T., Höhn, O., Wiese, M., Ferrara, C., Eitner, U., and Kuhn, T.E., 2017, "Morpho Butterfly Inspired Coloured BIPV Modules", Conference: 33rd European PV Solar Energy Conference and Exhibition, At Amsterdam, The Netherlands.

[19] Peharz, G., and Ulm, A., 2018, "Quantifying the influence of colors on the performance of c-Si photovoltaic devices", Renewable Energy **129**(Part A), 299-308.

[20] Amara, M., Mandorlo, F., Couderc, R., Gerenton, F., and Lemiti, M., 2018, "Temperature and color management of silicon solar cells for building integrated photovoltaic", EPJ Photovol., **9**, 1-11.

[21] Yoo, G.Y., Kim, W., Min, B.K., and Do, Y.R., 2018, "Color-generating 1D PC dichroic filter on Cu (In,Ga) $(S,Se)_2$ thin-film photovoltaic cells for building integrated photovoltaics", Integrated Photonics Research, Silicon and Nanophotonics. Optical Society of America.

[22] Soman, A. and Aldrin, A., 2019, "Colored solar cells with spectrally selective photonic crystal reflectors for application in building integrated photovoltaics", Solar Energy, **181**, 1-8.

[23] Ji, C., Zhang, Z., Masuda, T., Kudo, Y., and Guo, L.J., 2019, "Vivid-colored silicon solar panels with high efficiency and non-iridescent appearance", Nanoscale Horiz., **4**(4), 874-880.

[24] Hanaei, H., Assadi, M.K., and Saidur, R., 2016, "Highly efficient antireflective and self-cleaning coatings that incorporate carbon nanotubes (CNTs) into solar cells", Renew. Sustain. Energy Rev., **59**, 620-635.

[25] Miller, D.C., Muller, M.T., and Simpson, L.J., 2016, "Review of artificial abrasion test methods for PV module technology technical report NREL/TP-5J00-66334", National Renewable Energy Laboratory (NREL), Golden, CO, United States.

[26] Bahattab, M.A., Alhomoudi, I.A., Alhussaini, M.I., Mirza, M., Hegmann, J., Glaubitt, W., and Lobmann, P., 2016, "Anti-soiling surfaces for PV applications prepared by solgel processing: comparison of laboratory testing and outdoor exposure", Sol. Energy Mater. Sol. Cells, **157**, 422-428.

[27] Pulipaka, S. and Kumar, R., 2016, "Analysis of irradiance losses on a soiled photovoltaic panel using contours", Energy Convers. Manag., **115**, 327-336.