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The path to the building integrated photovoltaics of tomorrow

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Abstract

Building integrated photovoltaic (BIPV) systems may represent a powerful and versatile tool for achieving the ever increasing demand for zero energy and zero emission buildings of the near future, offering an aesthetical, economical and technical solution to integrate solar cells producing electricity within the climate envelopes of buildings. This work addresses possible research opportunities and pathways for the BIPVs of tomorrow.

Keywords: Building integrated photovoltaic; BIPV; Solar cell; State-of-the-art; Tomorrow; Future

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1. Introduction

As the world's demand and focus on renewable and non-polluting energy, together with energy efficiency, are ever increasing, zero energy and zero emission buildings are rapidly drawing attention. In order to become a zero energy or zero emission building, such a building need to harvest energy from its surroundings, where energy from the sun is one of the obvious choices. Building integrated photovoltaic (BIPV) systems, where solar cells are integrated within the climate envelopes of buildings and utilizing solar radiation to produce electricity, may represent a powerful and versatile tool for reaching these goals with respect to both aesthetical, economical and technical solutions.

Building integrated photovoltaic (BIPV) systems replace parts of the conventional building materials and systems in the climate envelope of buildings, such as the roofs and facades. BIPV systems are considered as a functional part of the building structure, or they are architecturally integrated into the

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building's design (Peng et al. [1]). Hence, the BIPV system serves as a building envelope material and power generator simultaneously (Strong [2]). This work investigates several possible research opportunities and pathways for the BIPVs in the future. For further overview and elaborations within various aspects of BIPVs it is referred to the study by Jelle et al. [3].

2. Categorization of state-of-the-art BIPVs

The range of state-of-the-art BIPV products is very wide, and they may be categorized in several different ways, where one possible categorization is into BIPV foil products, BIPV tile products, BIPV module products and BIPV solar cell glazing products [3]. In addition, the group building attached photovoltaic (BAPV) products should also be mentioned. BAPV products are regarded as add-ons to the buildings, hence not directly related to the building structures' functional aspects (Peng et al. [1]). That is, BAPVs are not BIPVs, i.e. the BAPVs are not integrated into the outer building envelope skin, thus not replacing the traditional building parts as the BIPVs are doing.

Examples of solar cells integrated as BIPV tiles and BIPVs as solar cell glazing products for roofs are shown in Fig. 1. Solar cell glazing products offer a solution for utilizing the fenestration with regard to daylight, solar heat gain, solar shading, miscellaneous architectural expressions, and finally solar energy gain by converting solar radiation into electricity.

Figure 1. Examples of BIPV tiles (left) and BIPVs as solar cell glazing products for roofs (right) (Applied Solar 2010 [4], ASI® Glass photovoltaic modules Schott Solar AG [5]).

Some BIPV products exhibit a variety of properties, thereby making it more difficult to categorize them. Yet in other cases it might even be rather difficult to determine whether a PV product should be considered as a BIPV product or not, e.g. due lack of of information and uncertainty about how the product is mounted. For a comprehensive state-of-the-art review of these BIPV systems, including references and contact information, it is referred to the work by Jelle et al. [3].

Evaluation of BIPVs involve several properties, e.g. solar cell efficiency $\eta = P_{max}/(\Phi A)$ where Φ is the input solar radiation in W/m^2 and A is the solar cell surface area in m^2, maximum power point P_{max} in W or Watt-peak (Wp), open circuit potential or voltage U_{oc}, short circuit electrical current I_{sc}, fill factor $FF = P_{max}/(U_{oc}I_{sc}) = (UI)_{max}/(U_{oc}I_{sc})$, band gap E_g and quantum yield φ = number of photo-electrons divided by number of photons. The values reported by solar cell manufacturers are mainly obtained according to standard test conditions (STC) or nominal operating cell temperature (NOCT).

3. The path to the BIPVs of tomorrow

3.1. PV development and impact on BIPVs

Development within the PV materials and solutions and their technologies may have an even stronger impact on the development of BIPVs in the years to come if one is able from the PV based research to tailor-make solar cell materials and solutions for building integration.

As for the advances in PV technology, in Fig. 2 there is given a timeline for reported best research-cell efficiencies, depicting all verified records for various PV conversion technologies, including crystalline

Si, thin-film, single-junction GaAs, multijunction and emerging technologies, collected from solar companies, universities and national laboratories [6]. The advances in these PV technologies and their increasing efficiencies will naturally be exploited in the coming BIPV products to be made.

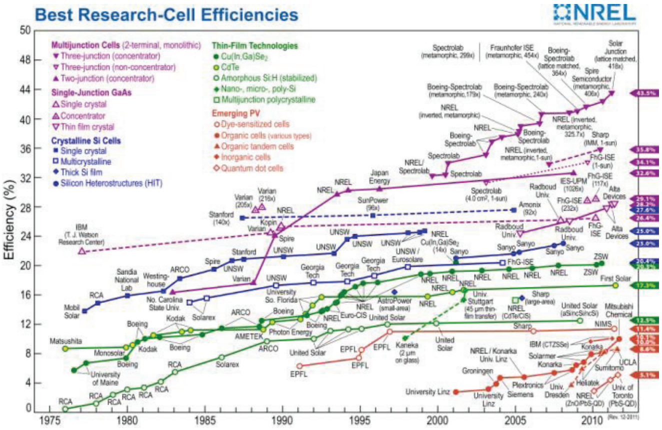

Figure 2. A timeline for reported best research-cell efficiencies, depicting all verified records for various PV conversion technologies like crystalline Si, thin-film, single-junction GaAs, multijunction and emerging technologies [6].

3.2. New materials and solutions for BIPVs

The research paths for possible new PV technologies that may initiate and advance into new innovations, and which may be developed into BIPVs, may be found in miscellaneous fields, e.g. ultra-low cost and low-medium efficiency organic based modules, ultra-high efficiency modules, solar concentrator and/or solar trapping systems embedded in the solar cell surface and material beneath, and flexible lightweight inorganic thin film solar cells, and several others some of them yet to be discovered. Carrying out the research and development of the PV and BIPV materials and solutions for the future one may bear in mind the following words: ”*think thoughts not yet thought of*” and ”*the more we know the more we know we don't know*” [7].

One strategy utilized to achieve high solar cell efficiencies is to make so-called sandwich or stack solar cells, which use several different material layers and cells with different spectral absorbances to harvest as much as possible of the solar radiation in a wide wavelength range. An example of a triple solar cell with its configuration and spectral responses is shown in Fig. 3 [8]. The top cell layer absorbs the blue light and allows the other wavelength parts of the solar radiation to pass through. The green and yellow light is then absorbed by the middle cell layer, and the red light is absorbed by the bottom cell layer. Hence, a much larger portion of the solar radiation is utilized.

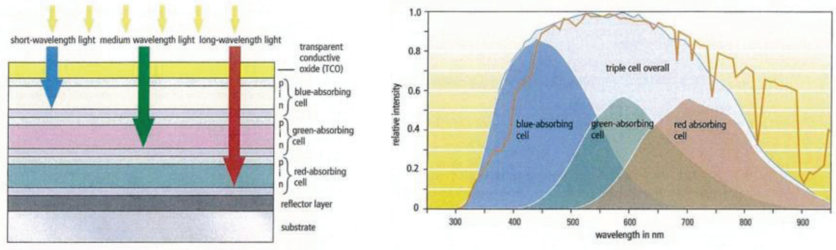

Figure 3. An amorphous triple solar cell with its configuration (left) and spectral responses (right) [8].

Ultra-low cost and low-medium efficiency organic based modules are based on dye sensitized solar cells (DSSC), extremely thin absorbers, organic polymer cells and others. Organic semiconductors are less expensive than inorganic semiconductors like Si. The superior material properties of polymers combined with cheap processing techniques has made polymer-based materials present in almost every part of the modern society [9]. The highest reported efficiency for an organic solar cell (with the exception of DSSC) is 6.5%, and this makes them competitive with CO_2-producing technologies [10]. However, the polymer solar cells are more sensitive to degradation, where ultraviolet solar radiaion and oxygen from the atmosphere may oxidize the organic layer. More stable devices have already been made and progress in this field is important for polymer solar cells to have a future as commercial devices and to be used in various BIPVs [11].

Ultra-high efficiency modules are based on quantum cells and nano-structured devices, where e.g. the record efficiencies for polymer-based solar cells have been observed in disordered nano-structured heterojunctions, and further gains are expected upon optimizing ordered nano-structure architectures [10]. Solar concentrator systems are described with arrays of PV modules that are mounted onto large movable structures which are continuously aimed at the sun.

Dye sensitized solar cells (DSSC) usually have a titanium dioxide (TiO_2) substrate material like in the Grätzel solar cell. The technology is often compared with and stated to imitate the photosynthesis, and is by Grätzel called ”the artificial leaf” [12]. The cells absorb across the visible spectrum and therefore lead to an increased efficiency ranging from 7% under direct solar irradiation (AM1.5) and up to 11% in diffuse daylight [13,14,15,16]. The TiO_2 material is a renewable and non-toxic white mineral, thus giving smaller environmental impacts, where an easy manufacturing process contributes to lower costs. Coloured dyes for use in DSSC based on the TiO_2 cell are developed by Massey University’s Nanomaterials Research Centre and they predict costs of one 10th of the Si based cells [17]. The reduced production costs and the decreased environmental impacts result in shorter energy and economical payback time, and therefore makes the technology very promising. The market share for this technology is still very small, but it is expected to rise and may achieve a great influence in the future.

Yet another innovative option for more effective harvesting of solar energy is so-called ”antennas” depicted in Fig. 4, which can harvest several wavelengths, i.e. a much broader spectrum of the solar radiation. This may be compared to the more ”traditional” sandwich solar cells. ”The use of antenna-sensitizer molecular devices may constitute a viable strategy to overcome problems of light harvesting efficiency in the spectral sensitization of wide-bandgap semiconductors.” [18].

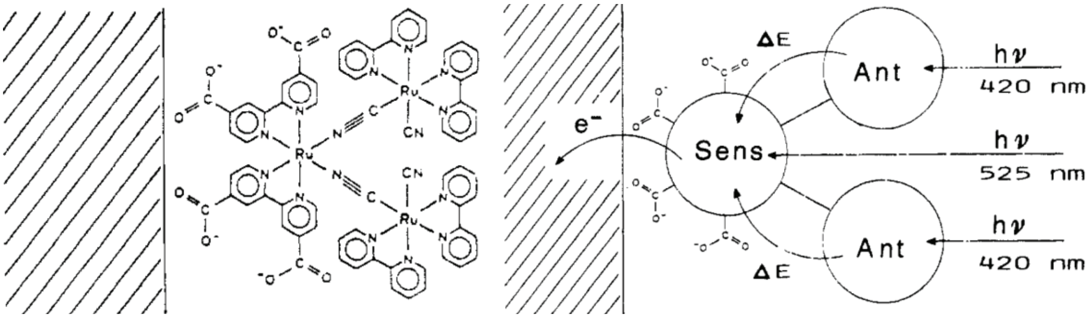

Figure 4. Illustrative representation of the adsorption mode of the trinuclear complex on the TiO_2 surface (left) and block diagram showing the function of the trinuclear complex as an antenna-sensitizer molecular device (right) [18].

As noted in the above (Fig. 2), research laboratories have for many years produced high-performance solar cells with efficiencies up to 25% - 40% [8,19]. One approach is to use materials with higher purity and to eliminate the impurities along in the process. Also the back surface can be passivated with silicon oxide and amorphous silicon to minimize recombination losses at the surfaces and contacts. Textured surfaces and buried contacts with minimal shading reduce optical losses. The total production is very expensive and is to date for use in laboratories only. Another way of increasing the efficiency may be concentrated photovoltaic (CPV) cells. Efficiencies reaching 43.5% has been achieved for commercial-ready CPV cells [19]. These cells are typically applied in the concentrator modules based on a concept of the small-aperture refractive concentrators [20].

Flexible CIGS (copper indium gallium selenide) and CdTe solar modules are shown in Fig. 5 (configurations) and Fig. 6 (photos). In an experiment performed by Buecheler et al. [21], the flexible and lightweight CIGS and CdTe solar devices have yielded an active area efficiency of 14.7% (CIGS) and 9.4% (CdTe). These lightweight devices allow building integration in structures which can not take the additional load of heavy and rigid glass laminated solar modules. ”The flexible solar modules can be laminated to building elements such as flat roof membranes, tiles or metallic covers without adding weight and thus, the installation costs can be reduced significantly.” [21].

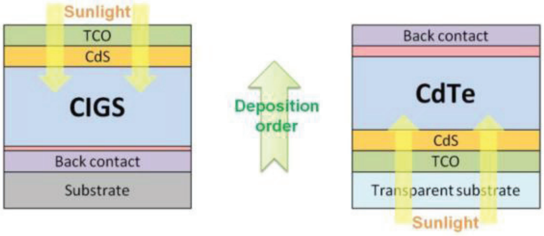

Figure 5. Schematic built-up of CIGS (left) and CdTe (right) thin film solar cells [21].

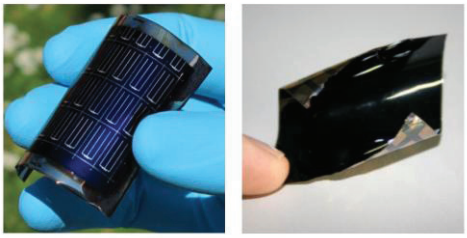

Figure 6. Flexible CIGS (left) and CdTe (right) solar cells on polyimide substrates [21].

The German company PVflex Solar GmbH has said that ”thanks to flexible lamination, CIGS solar cells now have the ability to both realize their potential as the most efficient thin film technology and to dominate the building-integrated photovoltaics (BIPV) market in the future” [22].

New solar cell material technology includes crystalline Si on glass (CSG), copper indium gallium diselenide (CIGS), microamorphous Si cells, concentrating systems and hybrid solar cells (HIT). Dow Chemical has introduced a line of CIGS-based solar shingles that will be commercially available in late 2011. The BIPV solar shingle installs and performs like a standard asphalt shingle, has an expected lifespan of 15-20 years (on par with conventional asphalt shingles), and has received a GLOBE Foundation award for ”Environmental Excellence in Emerging Technology” [23,24]. This is expected to be a huge contribution in bringing affordable renewable energy to consumers. Hence, the development of new PV materials and technologies will in the future contribute to new and improved BIPV products, e.g. with higher solar efficiencies.

In the recent experimental investigations carried out by Semonin et al. [25], they have reported photocurrent quantum efficiencies exceeding 100% in a quantum dot solar cell, being enabled by multiple exciton generation (MEG). The MEG process may occur in semiconductor nanocrystals or quantum dots where absorption of a photon with at least twice the bandgap energy creates two or more electron-hole pairs. Thus, miscellaneous new and exciting discoveries within solar cell research will with time find its way into the PV and BIPV systems for the buildings of tomorrow.

Furthermore, the solar cell glazing products available today have potential for optimization, e.g. the solar radiation utilized in a solar cell cannot be exploited as daylight in the buildings. Hence, ”one might also envision incorporating solar cells or photovoltaics with electrochromic materials in completely new fenestration products, where the photovoltaic and electrochromic material or materials cover the whole glazing area.” [26].

The PV industry offers many and various solutions. Normally, there is room for improvement in each specific system, e.g. regarding ventilation rate, positioning, removing of snow, etc. To ensure a good integration, the BIPV systems should be included early in the planning process. Therefore, a well-established communication between the planners and manufacturers of BIPV products is important for the development of new BIPV solutions. For mono- or polycrystalline PV cells it is very important to achieve a sufficient ventilation rate, as the solar cell efficiency normally decreases with increasing temperature, and should thus be planned ahead of the construction phase. The BIPV systems are expected to improve in the near future both regarding efficiency of the product and the production phase, hence leading to decreased energy payback time. However, this will be dependent on the market situation and/or subsidies.

Miscellaneous PV surface solutions for increasing solar cell efficiency and/or profitability may be envisioned. Various solar radiation trapping mechanisms might be embedded in the surface. Furthermore, one may be able to make an exterior surface capable of harvesting as much solar energy as if the whole exterior surface was covered with a PV material, while in fact the actual PV material surface is considerably smaller and located somewhat beneath the exterior surface, hence reducing the PV material costs. In principle, the latter solution might be viewed as a special built-in concentrator system integrated within the PV surface, thus requiring less (expensive) solar cell material. Thus, the idea may then be to fabricate a ”solar concentrator” at a microscopic material level embedded in the solar cell surface and beneath [3].

Inverted pyramid texturing of a solar cell as illustrated in Fig. 7 is another option for more effective solar energy harvesting [27]. The great light trapping properties of the inverted pyramid geometry is due to the following three effects: (a) reduced front surface reflectance by providing the opportunity for a portion of the incoming solar rays to undergo a triple bounce, (b) increase in path length of the solar ray through the cell, thus absorbing a larger fraction of the solar rays which has entered the cell before exiting the cell, and (c) increase in amount of solar rays reflected from the back surface, by total internal reflection at the front surface/air interface by making the incident angle greater than the critical angle. The inverted pyramid texture on solar cells is estimated to give cell efficiencies of approximately 24% with realistic cell design and material parameters [27].

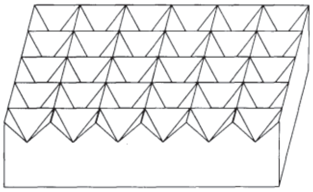

Figure 7. The inverted pyramids geometry utilized for light trapping on Si solar cells [27].

An option for the future that e.g. Enecolo and SolarPower Restoration Systems Inc. have looked into is to integrate the PV cells in materials at an early stadium, e.g. in prefabricated concrete plates [16,28]. As concrete is one of the most widely used construction materials in the world, and the integration of PV with concrete surfaces has remained largely undeveloped, this research field has a huge potential.

Thin laminate or paint layer solar cell materials represent another future option. Javier and Foos [29] fabricated a complete photovoltaic cell using a handheld airbrush, dilute solutions of CdSe and CdTe nanorods, commercially available silver paint, and transparent-conducting-electrode-coated glass, as depicted in Fig. 8. They explored the suitability of a handheld airbrush to create high-quality films and were able to form ultra smooth surfaces from 20 to 500 nm thickness. The current estimated efficiency is very low, but the research demonstrates the variety in the potential of PV cells [29].

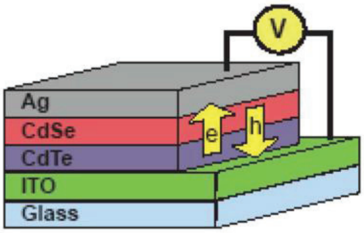

Figure 8. Schematic view of a PV cell composed of ITO-coated glass, CdTe and CdSe nanorods, and silver paint. Electrons (holes) are preferentially pushed towards the Ag (ITO) electrode as depicted by the arrows [29].

Integrating PV with smart windows in a way so that the PV elements will provide shading when there is need for it is yet another research path [30]. Hence, electricity will be produced while the window blocks the solar radiation. In the building industry electrochromic windows with no external wiring are at the moment most desirable. The National Renewable Energy Laboratory of Golden (USA) has built self-powered photovoltaic electrochromic devices up to 25 cm^2 [31]. For these self-powered PV electrochromic devices, "…the main concerns for future large-area applications are the possible loss of the energy generated by the PV device for larger dimensions, a small range of optical modulation and rather low transmittances in the clear state." [31].

3.3. Long-term durability of new materials and solutions

Incorporation of new building materials, integrated technology and solutions need to be planned simultaneously with the building envelope. Various requirements for rain, wind and air tightness, building physical considerations and long-term durability towards climate exposure have to be evaluated. Building physical considerations include investigation of the heat and moisture transport and with this any condensation risks. New materials might change the heat and moisture transport and distribution within the building elements and envelopes, and knowledge about these aspects are hence crucial in order to avoid any building damages and performance degradations.

Long-term durability versus the various climate exposure factors need to be considered. Examples of this are: Solar radiation (UV-VIS-NIR), ambient infrared (IR) heat radiation, high and low temperatures, temperature changes/cycles giving freezing/thawing processes, water (e.g. moisture and wind-driven rain), physical strains (e.g. snow loads), wind, erosion (also from above factors), pollutions (e.g. gases and particles in air), microorganisms, oxygen and time for all the factors above to work [32].

All new products should achieve approval in accordance with the current standards. For thin-film PV cells the test procedures are given in standard EN 61646 [33], and for crystalline Si PV cells EN 61215

[34] applies. Several of the given tests are to determine the durability of the product at different conditions, and all climate exposure factors above except for pollution and microorganisms are included. Test procedures for these factors may be found in the standard UL 1703 [35]. Naturally, some new materials and technologies will not be covered by these standards. Thus, the further development of new materials and solutions will arise a need for new standards specifying procedures for these materials and solutions.

Note that the standards describe test procedures for the robustness of terminations test. However, since the standards are based on the PV module only, further testing procedures of the module integrated in the building should be developed with the increasing interest and production of BIPVs.

3.4. Future visions for BIPVs

The main target of BIPVs replacing conventional roof and facade materials is already in progress as the global market for BIPVs was $\$1.8 \cdot 10^9$ in 2009, and is expected to grow to $\$8.7 \cdot 10^9$ in 2016 [23]. Nevertheless, in the world of today, there is still a great need of increasing the volume of PV and BIPV produced electricity for the world of tomorrow.

Several new possible pathways and opportunities exist beyond the current BIPVs. Some of them have already been mentioned in the previous chapters. New developed technologies may give a huge variety of solutions. Low production costs, low environmental impacts and high efficiencies are key factors for the future BIPVs.

The research and development of solutions regarding BIPVs for the retrofitting market are of great importance as the volume of existing buildings is many times greater than the volume of buildings to be constructed in a foreseeable future. The market for retrofitting of roofs is already under development and is growing, e.g. in Hong Kong, where similar BIPV concepts can be applied to facade systems [36]. Easy application of PV cells in existing materials is essential, and it may in the future be performed by e.g. various paint techniques.

Internal energy storage may also be envisioned in future solar cell materials, e.g. analogous to a photoelectrochemical solar cell (PEC) with internal storage. Various battery-technologies, e.g. metal hydrides, and nano technologies, could represent some of many possible ways of increasing the energy storage density.

There is a great need for governmental subsidies in various countries to get the industry started, e.g. as it has been carried out with success in southern Europe. Furthermore, a system for feeding the grid with PV electricity is necessary.

An almost unlimited range of opportunities is offered by BIPVs as solar cell glazing products, providing both solar shading, daylight transmission and producing electricity.

Forthcoming theoretical and experimental explorations may provide the PV and BIPV industry with several new and innovative materials and solutions. ”Future solar cell materials may also be envisioned as thin laminate or paint layers, hence also enabling application by paint brush or spray.” [26]. A development towards higher efficiency and better thermal insulation properties increases the energy efficiency and shortens the payback time, e.g. highly relevant in the northern part of Europe and elsewhere with colder climate seasons.

4. Conclusions

The several state-of-the-art building integrated photovoltaic (BIPV) products existing on the market today offer a wide range of integration of photovoltaic (PV) systems into buildings. Continued research and development within both PV and BIPV materials and technologies will yield better and better BIPV solutions in the years to come, e.g. with respect to increased solar cell efficiency, reduced production costs and improved building integration.

New and innovative solutions may reduce costs and increase the market share, amongst other in the retrofitting market. The chosen solutions should be easily applicable, where one example of a future vision is paint applications of PV cells. It is crucial that all new technologies and solutions are thoroughly tested and approved in accordance with existing standards, and furthermore, there is also a need for development of new standards and methods, e.g. regarding long-term durability versus climate exposure.

Acknowledgements

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