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BUILDING INTEGRATED PHOTOVOLTAICS SYSTEMS STATE-OF-THE-ART REVIEW

BY

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Abstract. Building integrated photovoltaics (BIPVs) are modern photovoltaic (PV) modules which are integrated into the building’s envelope. Usually, these devices replace the conventional roofing system, but they may be also integrated into the facade. The modules integration has a significant advantage in limiting the overall cost of the construction. Furthermore, building integrated photovoltaics, in comparison to non-integrated ones, don’t require stand-alone systems or allocation of land. This paper presents the state-of-the-art review regarding the existing BIPVs technologies. Also, in the second part of the paper, future research directions are discussed.

Keywords: envelope, photovoltaic tiles, thin-film technologies, wafer-based technologies, solar cell glazing.

1. Introduction

Nowadays, fossil fuels are used to generate most of the world's energy. When fossil fuels are burned, the stored carbon and other greenhouse gases are

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released into the atmosphere. The power industry emissions of harmful gases were estimated, in 2005, at 10.9 gigatons per year of carbon dioxide equivalents (GtCO2e). This represents approximatively 24% of the total global greenhouse gas emissions (GHC). Furthermore, it is predicted that until 2030, the emissions will increase up to 18.7 GtCO2e per year (McKinsey et al. 2009).

Solar energy is the most plentiful, clean and inexhaustible renewable energy resource currently available (Peng et al. 2011). The Swiss BiPV Competence Centre (2010) stated that the sun's irradiation on the earth surface generates about 10000 times more energy compared to mankind's daily use need (Alsema, 2000). However, harvesting this convenient energy at a feasible cost is a real challenge.

Nowadays, photovoltaic (PV) panels have become reliable solar energy harvesting devices, which are used, most often, as a back-up solution to fill the energy gap of the conventional suppling and distribution systems. This is because the PV panels absorb approximately 80% of incident radiation, but they have a very low conversion efficiency. Thus, a lesser quantity of the absorbed radiation is stored as electrical power, while the majority is transformed into heat.

On the other hand, the building integrated photovoltaics (BIPVs) are newly developed, highly efficiency photovoltaic materials, which can replace the conventional construction materials used for the building envelopes (Peng et al. 2011; Strong, 2010). Thus, BIPVs have a significant advantage in comparison to non-integrated systems, since there is no need for stand-alone facilities or land allocation for the modules (Raugei and Frankl, 2009). Also, from the economical point of view, the on-site mounted PV modules can lower the solar system costs, since they do not utilize additional assembly components like rails and brackets (Neuwald, 2011; Strong, 2010).

BIPVs systems can be esthetically appealing and offers many opportunities for cutting-edge architectural design (Jelle et al., 2012). Some architectural applications of BIPVs systems refer to semi-transparent components for fenestration and shading elements (Norton et al., 2011). Using amorphous silicon tiles, gives the BIPVs roof a standard look while, on the other hand, standard semi-transparent modules can be used in glass ceilings or facades to create distinctive visual effects (Hestnes, 2000; Farkas et al., 2009; Peng et al., 2011).

The building integrated photovoltaic systems advancement is generally correlated with the photovoltaic cells' development. Therefore, in the following sections, some PV industry aspects will be addressed firstly, before proceeding to BIPVs technology.

2. Materials used for manufacturing photovoltaic panels

The conventional PV cells are manufactured from high-grade silicon that is processed with positively and negatively charged semiconductors (boron and

phosphorous). When the sun's light energy hits the photovoltaic cells, electrons flow from negative phosphorus towards to the positive boron. The resulted current from the electric potential is harnessed through a metal grid which covers the external circuit and the cells (Prasad et al., 2005).

The silicon materials that are used to manufacture photovoltaic cells may be classified as: monocrystalline, polycrystalline and amorphous. Beside these main categories, there exist also ribbon cast polycrystalline cells that are manufactured from molten silicon by drawing, through ribbons, flat thin films. In this particular case, the production costs are lowered, as a result of silicon waste reduction (no ingots sawing is required).

The most common non-silicon based photovoltaic materials are: cadmium telluride (Cdte), gallium arsenide (GaAs), copper indium gallium selenide (CIGS) and copper indium diselenide (CIS). Fig. 1 provides an overview of the main photovoltaic technologies (silicon and non-silicone), (Dones et al., 2007).

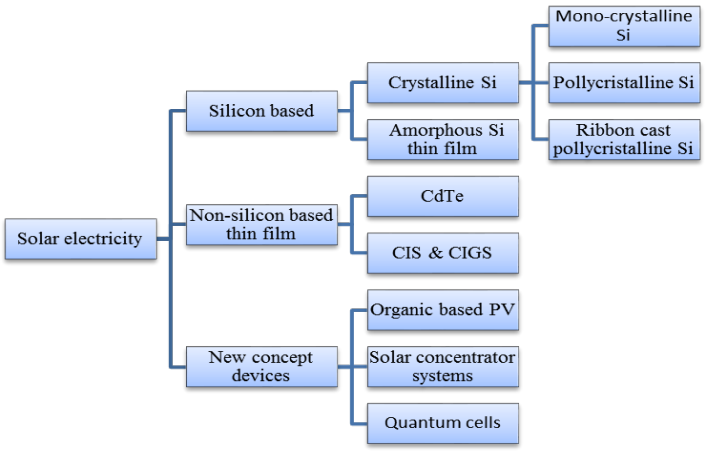


Fig. 1 − PV technologies (Adapted from Raugei and Frankl, 2009)

2. Monocrystalline silicon cells

Monocrystalline silicon cells are the most convenient and the oldest solar harvesting devices, which are made from pure silicon applied on thin wafers. Monocrystalline silicon cells consist in ordered crystal structures, with each atom located in its predetermined position. Monocrystalline silicon wafers are manufactured through slow production flow and carefully controlled conditions. Nowadays, the monocrystalline wafer capacity is around 16.6 GW, which represented 24.4% from the total market capacity in 2015 (Power and Energy Industry of IHS Technology, 2015).

Conventional efficiencies for monocrystalline solar cells are about 16-24%, and the highest efficiency for monocrystalline modules to date is approximately 20% (Dow Chemical Company et al., 2010; Ebong et al., 2010; Eiffert and Kiss, 2000; Eiffert, 2003; Eotec Energy AG Inc., 2011).

3. Polycrystalline silicon cells

The polycrystalline silicon photovoltaic cells are manufactured using multi-crystalline silicon ingots. The molten silicon is poured into blocks, which are then cut into thin plates. The solidification of the material results into cells that contain many crystals, making the surface of the polycrystalline cells less regular than the one of the monocrystalline cells. The color of the polycrystalline silicon cells is lustrous blue.

Due to an easier manufacturing process, the polycrystalline silicon photovoltaic cells are less expensive, but also less efficient. For polycrystalline cells, the efficiency is normally 14-18% (European Comitee for Electrotechnical Standarization, 2005; European Comitee for Electrotechnical Standarization, 2007).

4. Amorphous silicon cells

Amorphous silicon photovoltaic cells consist of an un-crystallized silicon thin layer deposited adjacent to a substrate. The typical color is reddish brown or brownish (Gratzel, 2003).

Amorphous silicon solar cell efficiencies are between 4% and 10% (European Comitee for Electrotechnical Standarization, 2007; European Comitee for Electrotechnical Standarization, 2008; Global Energy Network Institute, 2011; Gratzel, 1991).

5. Non-silicon based photovoltaic cells

According to Buecheler et al. (2011) the CIGS and CdTe photovoltaic cells are the most auspicious modern technologies for producing cost-effective decentralized solar electricity. CdTe photovoltaic cells are assembled on a substrate glass with a transparent conducting layer, generally produced from fluorinated tin oxide (FTO). Then, the cell is coated firstly with an n-type cadmium sulphide (CdS) window layer and then, with the p-type CdTe absorber layer (Kim et al., 2012; Knapp and Jester, 2001; Li et al., 2012). This technology has the lowest manufacturing costs (compared to other thin film modules), and also has the most encouraging wide scale application (Hammond et al., 2012). The colour is dark green with reflective properties and the usually cell efficiency

varies between 9.4% and 13.8% (EA-PVPS, Grid Connected Power Systems, 1999; IEA-PVPS, Annual Report 2000; Ishizuka, 2010).

CIGS and CIS cells are nowadays the most effective among thin-film cells with efficiencies around 11% (Javier and Foos, 2009; Jelle et al., 2012; Jelle, 2014; Jungbluth and Frischnecht, 2000; Jorgensen et al., 2008). The utmost performant CIGS/CIS modules up to date have an efficiency of approximately 13% (Khrypunov et al., 2011).

Usually, the photovoltaic cells are connected together in strings. On the other hand, the thin-film materials can be assembled directly into modules (Ebong et al., 2011). The way this is done is by sputtering the solar cell material onto a substrate of polyamide, stainless steel or glass that is interconnected to a module by laser. The solar cells in the photovoltaic module are encapsulated between a waterproof backing and a transparent cover. The cells are often laminated with a low iron content, tempered glass on the front for external environment protection. The glass is strong, inexpensive and stable and has the function to prevent penetration of water vapors, water and gasses. On the back side there is a thin polymer sheet, except the situation when semi-transparency is wanted or the module is bi-facial (glass is used). In order to provide adhesion, a layer of ethylvinylacetate (EVA) is used on each side of the photovoltaic cell. Afterwards, an aluminum frame is introduced, so that the overall strength and stiffness of the assemble are increased. Modules can be interconnected in series of strings and then for manufacturing larger units, in arrays, they are assembled in parallel. Using these arrays, the DC electricity is transported and converted into AC electricity.

6. Photovoltaic panels installation

The most practical options for building integration of photovoltaic cells are on flat roofs, sloped roofs, shading systems and facades. South facing sloped roofs is best suited for photovoltaic installation because of the advantageous angle with the sun. An option is to mount the photovoltaic modules on top of the roofing system. Another alternative is photovoltaic modules that take the place of conventional building materials in elements of the building envelopes, for instance the facades or roofs. BIPVs can work as a functional part of the building structure, or they can be architecturally integrated into the building's design (Norton, 2011). The building integrated photovoltaic system serves as power generator and building envelope material simultaneously (Nowak, 2000). This can determine savings in labor, materials and electricity costs.

A high temperature in the components decreases the performance of the photovoltaic cells, especially for polycrystalline and mono-crystalline modules. For this reason, an air gap under the module is necessary to lower the temperature. On the other hand, the thin-film products have good efficiencies at different temperatures values.

For flat roofs there are 2 installation alternatives (Kim et al., 2012):

- modules fixed mechanically to the structure of the roof;
- integrated solution.

In some cases, the photovoltaic modules might have to be inclined because of the structure's topographical position. This is more problematic with integrated solutions. The integrated modules can have the characteristics of one or several roofing elements.

Using photovoltaics in the facades can replace a tile or a glass skin. As mentioned before, geographic position is very important when design using photovoltaic cells in facades; the conversion efficiency is higher at southern and northern latitudes.

The area covered with photovoltaic modules differs from case to case. Generally, the areas that are shaded for most of the day are recommended to be avoided. In case that the project is subsidized, the payment might be given for a determined level of power produced. Thus, the photovoltaic covered area's size might depend on the needed level of power generated. If all the facades or roof should be made by PV modules a few high efficiency elements can be mounted in key areas, and several dummy models can be used for the rest of the surfaces (Breyer et al., 2010).



Fig. 2 − Curved clay looking solar tiles (Pehnt, 2010)

Building integrated photovoltaic systems offer many circumstances for avant-garde architectural design. Building integrated photovoltaics can form

semi-transparent fenestration elements and also act as shading elements (Paul, 2010; Pehnt et al., 2003). To make a building integrated photovoltaic roof look much alike a typical tiled roof, amorphous silicon tiles could be used (as shown in Fig. 2). On the other hand, for creating different visual effects, semi-transparent modules could be used in glass ceilings or facades (as shown in Fig. 3).

Some architects design the building integrated photovoltaic roof as a structure which gives a clear visual impression, although others use additional elements such that the building integrated photovoltaic roof to look as much as a classic roof as possible. Further information regarding building integration of photovoltaic systems in general, and architectural integration of photovoltaic and building integrated photovoltaic in particular, can be found in the studies performed by Farkas et al. (2007) and Hestnes and Peng (2010).



Fig. 3 − Glass ceiling with transparent BIPV modules (Kim, 2012)

7. Building integrated photovoltaics. Products and classification

There is a wide range of different building integrated photovoltaic products, which can be classified in distinct ways. The most common products are: modules, tiles, foils and solar cell glazing. Among these products, the modules are compatible to most types of roofing materials. On the other hand, the building integrated photovoltaic foil products are flexible and lightweight, which is advantageous in terms of easy installation and weight constraints (Hammond et al., 2012). Thus, as a general demand, the solar cells should be made from thin materials to provide both the required efficiency and the compatibility with the non-ventilated roof solutions.

The building integrated photovoltaic tile products may cover the entire roof or parts of the roof. They are arranged in modules with the properties and appearance of standard roof tiles and they replace a determined number of tiles. This is a convenient solution for reconstructing of roofs. The tile shape and cell type vary. A part of tile products is similar to curved ceramic tiles (see Fig. 2) and may be more esthetically pleasing, but they have lower active area due to their curved surface (Ishizuka et al., 2010).

The modern building integrated photovoltaic module products are similar to conventional photovoltaic modules in terms of efficiency. However, from the components point of view, the main difference is that they include weather skin protections. Part of these products may replace various roofing types, or can fit with a particular roof solution specifically designed (e.g. Rheinzink's ''Solar PV Click Roll Cap System'', 2011).

Another category of building integrated systems consists in the solar cell glazing products. The latter provides a variety of options for tiled or glass facades, windows and roofs (Javier and Foos, 2009). Different transparencies and colors make possible many distinct esthetically pleasing results. The units serve as sun and water protection and transmit daylight. The technology involves spraying a coating of silicon nanoparticles on to the window, which work as solar cells (Smith and Rohatgi, 2013). The distance between cells is usually in the range of 3 to 50 mm, but depends on the electricity production criteria and the level of transparency wanted. The diffuse daylight is transmitted by the space in between the cells. And so, both natural and shading lightning are provided, meantime producing electricity.

The future BIPVs research opportunities are established based on the limitations of the actual products. It is anticipated that the advances in the photovoltaic materials will lead to progress in development of the building integrated photovoltaic systems. The current target is to achieve this at a feasible cost. New photovoltaic technologies that may advance innovations, are focused on (Baetens et al., 2010):

- ✓ low cost and medium-high efficiency organic based modules;
- ✓ high and ultra-high efficiency modules;
- ✓ solar concentrator and/or solar trapping systems embedded in solar cell surface and material beneath;
- ✓ flexible lightweight inorganic thin film solar cells.

The solar cell glazing products that are currently available have an optimization potential (e.g. devices for which the solar radiation used in a photovoltaic cell can be utilized as daylight in the buildings). Other research topics are focused on incorporating solar cells or photovoltaics with electrochromic materials in completely new fenestration products (Norton, 2011). However, regardless the application area, the majority of the new material technologies are based on copper indium gallium diselenide (CIGS), crystalline

silicon on glass (CSG), hybrid solar cells (HIT), concentrating systems and micro amorphous silicon cells.

One of the latest technologies applied for harvesting solar energy more effectively is the inverted pyramid texturing of the solar cell (Fig. 4) (Liu et al., 2011). The inverted pyramid geometry great light trapping property is a result of the following effects:

- ✓ reduced front surface reflectance by providing the opportunity for a portion of the incoming solar rays to undergo a triple bounce;
- ✓ increase in path length of the solar ray through the cell, thus absorbing a larger fraction of the solar rays, which is stored in the cell before exiting;
- ✓ increase in the number 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 future inverted pyramid texture on solar cells is expected to provide approximately 24% more cell efficiencies (Khrypunov et al., 2011).

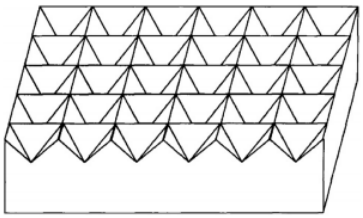


Fig. 4 − The inverted pyramids geometry used for light trapping on silicon solar cells (Adapted from Liu et al., 2011)

Easy application of photovoltaic cells in existing roof materials is crucial for further development in the solar harvesting field. According to Coons (2009), in the following years, this requirement might be achieved even by painting techniques. Thus, the future solar cell materials may consist in thin laminate or paint layers, enabling application by paint brush or spray (Breyer et al., 2010).

8. Conclusions

In the last decade, due to a continuous search to diminish the demand for fossil fuels in energy production, various experimental studies on solar energy harvesting systems have been conducted. Based on the outcomes of these studies it can be concluded that:

- ✓ the foil products have greater applicability because of the material's flexibility properties;
- ✓ the photovoltaic cell glazing products are most often predefined modules that may provide in addition to solar shading, weather tightness and natural lightning, a great esthetical appearance;
- ✓ modern building integrated photovoltaic systems have lower production costs and higher efficiencies compared to the rest of solar harvesting systems;
- ✓ even if there exists a wide range of methods of solar energy harvesting, they all fundamentally use the sun to perform work in a specifically desired way, something that traditionally rely on electricity to do;
- ✓ further increases in efficiencies and process optimizations will continue to unveil the productivity of solar harvesting efforts and may eliminate the need for fossil fuel use altogether.

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SISTEME FOTOVOLTAICE INTEGRATE ÎN CLĂDIRI STADIUL ACTUAL AL CUNOAȘTERII

(Rezumat)

Sistemele fotovoltaice integrate în clădiri sunt dispozitive modulare moderne care se încorporează în anvelopa construcției. În mod uzual, aceste dispozitive pot înlocui sistemele convenționale de acoperișuri, dar pot fi și integrate în fațadă. Integrarea acestor module prezintă un avantaj semnificativ în ceea ce privește costul total al construcției. Chiar mai mult, utilizarea sistemelor fotovoltaice integrate în detrimentul sistemelor neintegrate, nu necesită ansamble independente sau alocări de teren. Această lucrare prezintă stadiul actual al cunoașterii în domeniul sistemelor fotovoltaice integrate (SFI). De asemenea, în cea de a doua parte a lucrării sunt indicate posibilele direcții de cercetare viitoare.