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6

February 2016
www.enhsa.net/archidoct
ISSN 2309-0103

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European Observatory of Doctoral Research in Architecture

ISSN 2309-0103
www.enhsa.net/archidoct
Vol. 3 (2) / February 2016

Architectural Detailing and Energy Performance of Envelopes with Building Integrated Photovoltaics (BIPVs)

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Abstract

This study describes the potential of the photovoltaic (PV) technology in the built environment, as an alternative to fossil fuels. Building Integrated Photovoltaics (BIPVs) replace conventional building materials on the building's envelope, as a principal or ancillary source of electrical power. Architects need to have a good knowledge of the available products, relevant technologies and development processes in order to integrate the PV cells into the building envelope, with architectural criteria. Nowadays, the demand for energy efficient or zero-energy buildings is higher than ever, in order to reduce energy consumption and CO2 emissions. Designing an energy efficient building is a task which requires the combined forces of a multidisciplinary team. The architect's contribution in the design process is vital, but the addition of energy generating features, such as photovoltaics, brings performance alongside the design process. Most PV systems are installed on top of the building envelope, resulting in aesthetically poor and costly results. Architectural detailing, in the form of typical construction sections, offers a clear view of the building envelope which functions as a solar energy generator, by replacing conventional construction materials.

Keywords

Building Integrated Photovoltaics (BIPVs); architectural criteria; building envelope; SWOT analysis; architectural detailing; zero-energy buildings.

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Introduction

Current legislation aims to ensure that the European Union meets its ambitious climate and energy targets for 2020. These targets, known as the "20-20-20" targets, set three (3) key objectives:

a. A 20% reduction in EU greenhouse gas emissions (from 1990 levels).

b. A 20% improvement in the EU's energy efficiency.

c. Raising the share of EU energy consumption produced from renewable energy resources (RES) to 20%.

(http://ec.europa.eu/clima/policies/strategies/2020/index_en.htm [25 June 2015]).

According to the National Renewable Energy Laboratory (NREL) "more energy from the sun falls on the earth in one hour than is used by everyone in the whole world in one year" (http://www.nrel.gov/learning/re_solar.html [25 June 2015]). Our energy demands increase continually, while the need for new and clean energy sources makes solar the fastest-growing energy technology. The PV industry is one of the most growing and innovative industries worldwide. Despite the current energy scenario, it is estimated that over the next 30-40 years the sun will provide 25% of the global energy needs. Therefore, it is important to explore the potential of energy performance of envelopes with BIPVs, within the urban environments (Lüling, 2009).

The term 'photovoltaic' has been in use since 1849. It derives from the Greek word "phos" meaning 'light', and 'volt', the unit of electro-motive force, which in turn comes from the last name of the Italian physicist Alessandro Volta, inventor of the electrochemical cell - or battery (Smee, 1849).

Photovoltaic cells utilise the electromagnetic radiation emitted by the sun. Photons hit the photovoltaic cell and cause electrons to be ejected from the atoms of the material in the cell. The light causes other substances in the cell to accept those electrons that flow through a conductor, generating electricity (Baggs, 1996).

The use of BIPVs in the urban environment has the potential to help towards this approach. Photovoltaic energy technologies and innovation techniques for integration on the building envelopes, can help to drive growth in many levels (design, construction, industry, projects etc), while leading to the creation of thousands of new jobs.
(http://ec.europa.eu/clima/policies/strategies/2020/index_en.htm [25 June 2015]).

Smart materials and intelligent environments

Material is a universal language of culture and civilisation that carries a reciprocal relationship between the material itself and humans, affecting their psychology (Mori, 2002). It can be accessed and understood by everyone. It carries with it information about its place of origin, history, performance, economic value and its life-cycle (Mori, 2002).

Millions of years ago, stone and wood created two very different building types (stonework and timber-frame buildings). These two typical construction materials were completely opposite in their construction methods, hence created facades that were fundamentally different in terms of aesthetics and function. An integrated PV system creates a contemporary design language that has a morphic flexibility and a modest technological existence (Lüling, 2009).

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The relationship between architecture and materials had been quite clear until the Industrial Revolution during the 18th century. After this, architects began to experiment with engineering materials, with the widespread use of steel and glass. Nowadays, CAD/CAM (Computer Aided Design/Computer Aided Manufacturing) technologies allow an unprecedented range of building facades and forms. Smart materials are often considered to be a logical evolution toward a more selective and specialised performance. Smart material performances can now be engineered and perfected according to demand, while their properties can be modified in order to replace conventional building materials (Addington and Schodek, 2005).

Building as energy generator

Building envelopes are being affected by environmental factors, such as noise, wind, precipitation, air temperature and radiation from the sun. Energy-efficient building envelopes affect the amount of energy used for heating, lighting, cooling and ventilation systems, as well as the size of technical building management systems. These in turn reduce energy consumption, pollution, investment and operation costs (by reducing the payback time of the initial installation cost). Depending on its location, the building envelope provides the potential for the use of renewable energies, in order to generate energy at the point of demand (Schüco, Issue 05, 2005).

The integration of solar energy in buildings has an impact on its form. Technology affects architecture, offering a wide range of proven high-performance solutions. But there is a gap at the intersection between architecture and solar technology, in order to achieve what is known as “solar design” (Schittich, 2001). For the integration of solar energy system technologies, the building envelope is the most important interface between architecture and solar technology. To create a technical and energy-efficient design (that is also aesthetically convincing), requires a combined knowledge of the technological functional mechanisms, an understanding of building typologies and the ability to translate all the above into an executable design (Schittich, 2001). The potential of PV use in architecture is shown in Table 1.

PV generations and efficiencies

During the last decade, photovoltaic products show an average growth of around 40% per annum, while manufacturing costs decrease on a steady rate. Typical solar cells are made from silicon or other high-tech materials. Their technologies are divided into three (3) main categories, known as ‘Generations’ (Green, 2006), as shown in Figure 1.

First Generation (1G): This technology has matured and is widely used, representing approximately 80% of the worldwide solar cell production, in 2014 (NREL, 2014). They are based on silicon wafers (Figure 2), each of which can produce 2-3 Watts of solar electricity. These cells are assembled in large-area solar panels, using a single layer p-n junction (the positive/negative boundary or interface between two types of material, inside a single crystal of semiconductor). Their production costs are still relatively high compared to the overall energy output (Green, 2006).

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Advantages of photovoltaics	Disadvantages of photovoltaics
No need for fuel	Battery or grid storage required for night-time use
No pollution (after manufacturing)	
The energy source (sun) is free and available everywhere	May need to be used with another power source (or grid connected instead)
Reliability (no moving parts)	Relatively high initial capital cost for modules (though this is reducing fast)
Noiseless	
Maintainability	Toxic and corrosive chemicals used in manufacture
Long-life performance	
Short time required from planning to installing the system	Cleaning required for optimum performance
Once installed, using them costs little over their lifetime	Manufacture of cells controlled by a small number of large corporations
Safe alternative to more combustible energy sources	Legislation can sometimes become a burden for investors and stakeholders
Can be used in both new and existing building envelopes	
Visually unobtrusive (variety of products, colours and integration techniques)	
Modular and expandable	
Flexibility in terms of use or application	

Table 1. The potential of photovoltaics (author's own)

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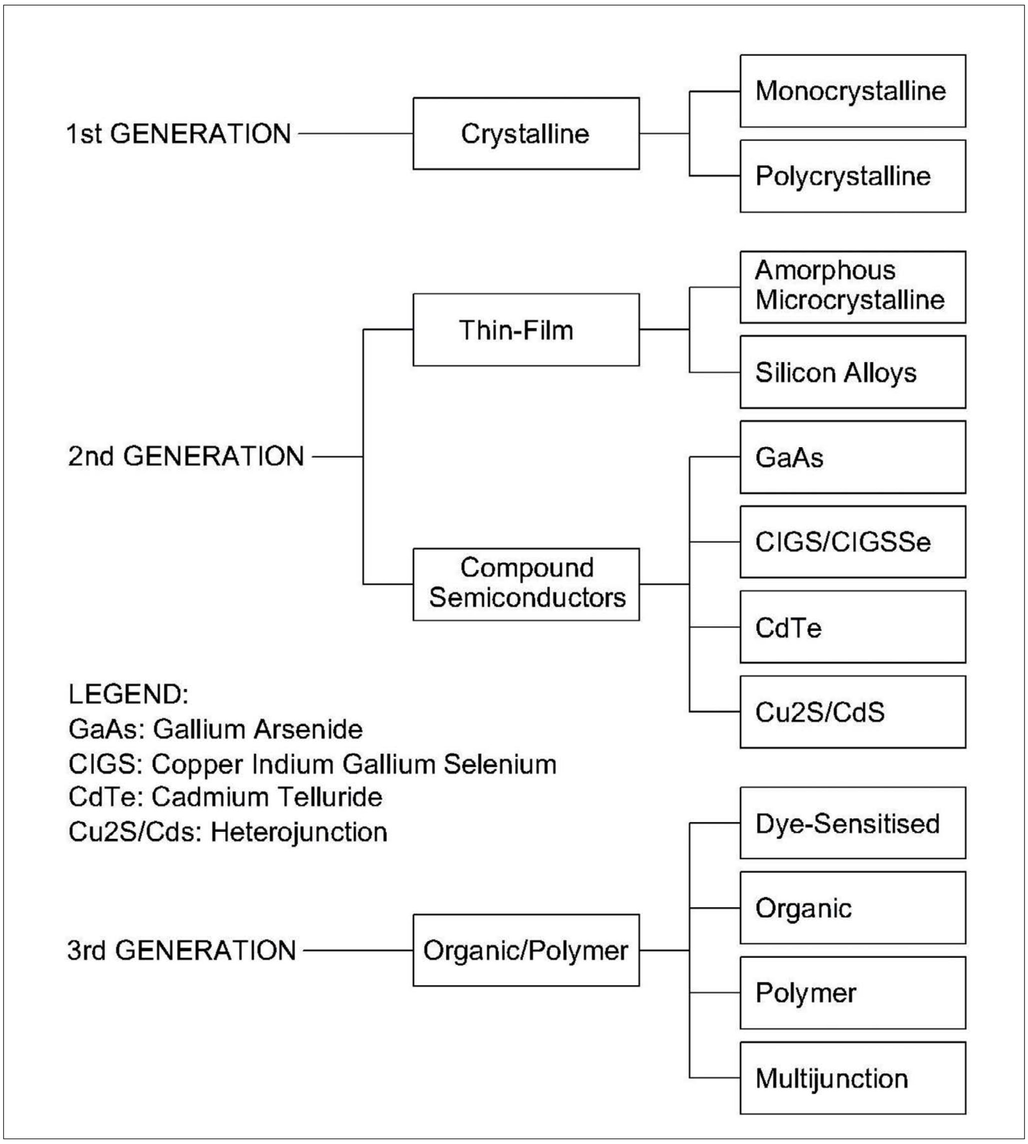

Figure 1. Main current PV technologies.
Source: Sullivan, 2013.

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Second Generation (2G): This generation of PV materials is based on the use of thin-film deposits of silicon and a wide range of compound semiconductors, minimizing the mass of material required for every cell and the total weight of solar panels. This contributes to the reduction of manufacturing costs, making this technology suitable for use on light or flexible materials, even textiles. Thin-film technology offers significant advantages, such as the increased size of the manufacturing glass sheet units, by about 100 times larger than silicon wafers. On the efficiency front, this technology steadily closes the performance gap compared to crystalline silicon cells. Second generation BIPV systems replace parts of the building envelope and partially take over its functions (Green, 2006).

Third Generation (3G): These cells are novel technologies designed as low-cost and high-performance ultrathin photovoltaic products. The new devices include photoelectrochemical, organic or polymer (Figure 3), dye-sensitized and nanocrystal solar cells. These concepts are promising, aiming to achieve high-efficiency devices by the implementation of 2G (thin film) deposition methods and the usage of nontoxic and not limited in abundance materials (Conibeer, 2007). This generation of cells is not available on the market yet, but the solar industry is working with researchers to develop prototypes which could be in-line manufactured in order to provide a cheaper alternative to typical PV systems. This expectation is feasible over the long term because alternative solar cell technologies require less material input and can be made using less expensive production methods (Lüling, 2009).

Ravi Silva (Advanced Technology Institute at the University of Surrey), recently outlined the definition for a new 4th Generation (4G) of photovoltaic technology, based on 'inorganics-in-organics'. It offers improved power conversion efficiency to current 3G PV cells, while maintaining the low-cost base and flexibility of conducting polymer organic films with the lifetime stability of novel inorganic nanostructures. (Silva et al, 2013). The efficiency range of the PV generations is shown in Table 2.

PV integration

The installed PV components are expected to become an integral part of the building envelope, to fulfil functional and structural tasks, while replacing typical building materials, in order to minimise the cost of the initial installation. The integration of PV systems must guarantee that the installation does not conflict with the requirements and characteristics of the building envelope, but complements and supports them in terms of architectural and structural integration (Figure 4). When it comes to the task of integration, many buildings display a lack of sensitivity or an absence of character, resulting in a poor adaptation into the building structure. This illustrates the necessity to consider design principles, while dealing with the more practical and technical aspects of the construction process. Decisions with regard to detail and component dimensions, design of connecting geometries and profile sections, all influence the visual appearance (Figure 5) of the building envelope and must be evaluated as to their impact on the structural layout and overall integration (Schittich, 2001).

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Figure 2. Typical silicon wafer PV cell.
Source: Lüling, 2009.

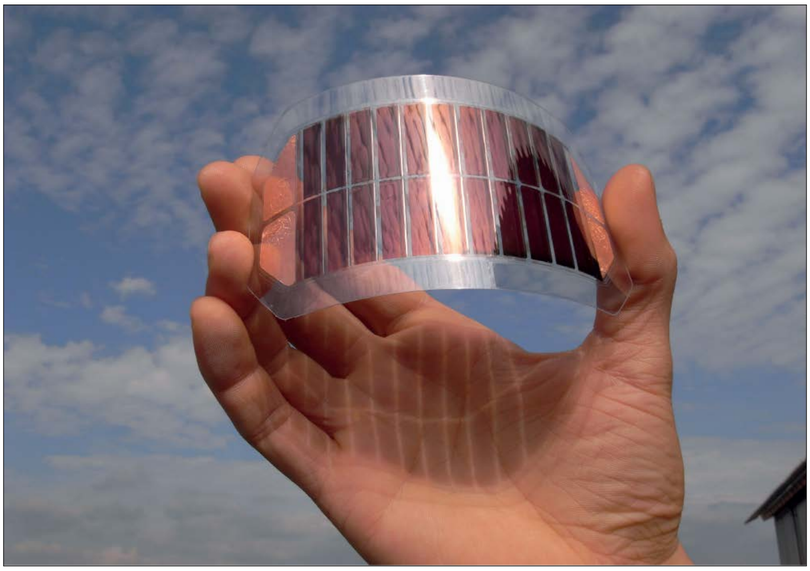

Figure 3. Third Generation (3G) organic PV cell.
Source: Lüling, 2009.

Table 2. Efficiencies of PV materials and technologies.
Source: NREL, 2014.

PHOTOVOLTAIC (PV) MATERIALS AND TECHNOLOGIES	THEORETICAL EFFICIENCY (CELL)	LABORATORY EFFICIENCY (CELL)	PRODUCT EFFICIENCY (MODULE)	AREA NEEDED per kW (MODULE)
1st GENERATION PV (Crystalline Silicon)				
Monocrystalline Silicon (m-Si or c-Si)	29%	21-28%	14-20%	~ 6m2
Polycrystalline Silicon (p-Si or m-Si)	25%	17-20%	12-17%	~ 7m2
2nd GENERATION PV (Thin Film and Compound Semiconductors)				
Amorphous Silicon (a-Si or a-Si:H)	27%	12-13%	6-10%	~ 13m2
Silicon Alloys (a-SiGe, a-SiC)	29%	13%	9-15%	~ 9m2
Gallium Arsenide (GaAs)	31%	25-26%	26-28%	~ 4m2
Copper Indium Gallium Selenium (CIGS)	29%	16-17%	12-14%	~ 10m2
Cadmium Telluride (CdTe)	31%	10-16%	10-12%	~ 10m2
Heterojunction (Cu2S/CdS)	24%	10%	N.A.	N.A.
3rd GENERATION PV (Advanced Thin-film, Organic and Polymer)				
Dye-sensitised (DSSC, DSC or DYSC)	25%	10-13,4%	2-5%	~ 30m2
Organic (OPV)	30%	10-12%	2-4%	~ 30m2
Polymer (solid or liquid)	10%	2,5%	N.A.	N.A.
Multijunction (CPV)	63%	44,7%	N.A.	N.A.
4th GENERATION PV (Inorganics-in-Organics)				
Inorganics in-Organics (HTL/ETL)	18%	5-9%	N.A.	N.A.

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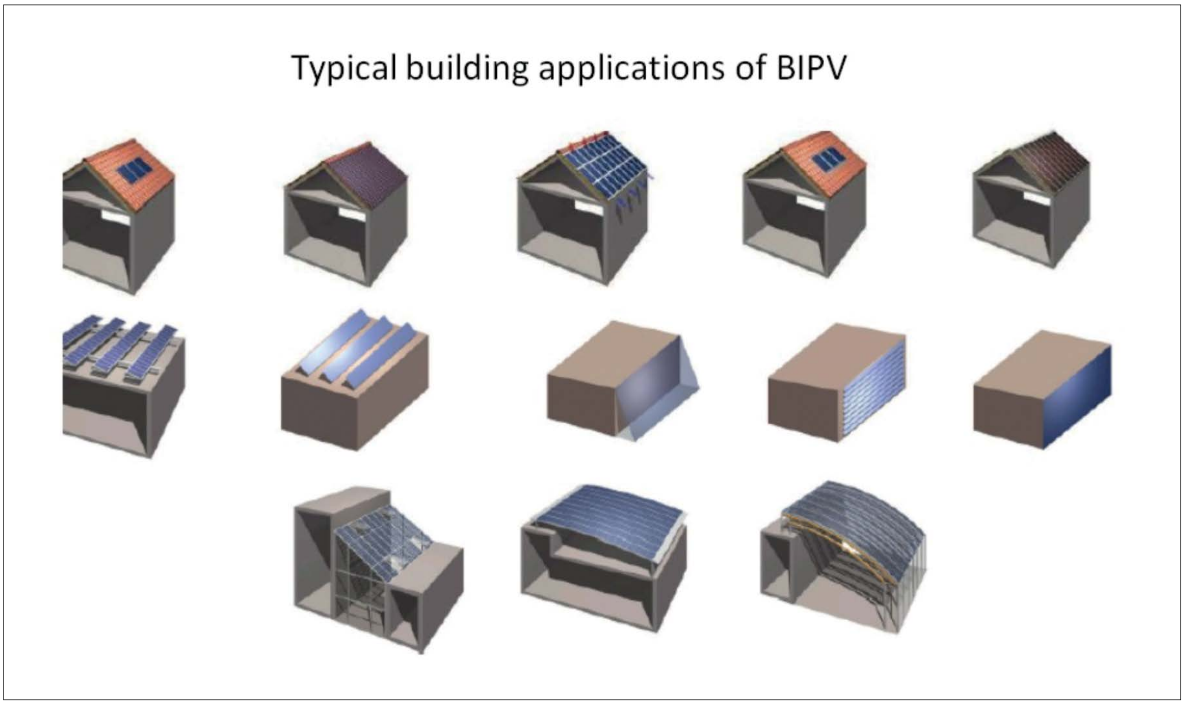

Figure 4. Typical Building applications of BIPV.
Source: Lüling, 2009.

Figure 5. Greenpix (Beijing) Zero-Energy Media Wall, with the largest color LED display and the first polycrystalline photovoltaic cells system, integrated into a glass curtain wall
Source: http://www.archdaily.com/245/greenpix-zero-energy-media-wall [27 June 2015].

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The solar cells are clean, safe and efficient devices, suitable for electricity generation on building envelopes (Figure 6). PV systems can be successfully integrated into the envelope of most building types, displacing standard building components. In retrofit applications, PV systems can also be used to camouflage unattractive or degraded building exteriors (Moyra, 2012). Photovoltaics (PV) can be used in any area of the building envelope that is exposed to direct sunlight (Weller, Hemmerle, Jakubetz and Unnewehr, 2010).

The building envelope is also known as shell or skin. The building skin plays an important role on the building itself, as it protects the occupants from the elements, defines properties and creates privacy. The building skin (especially the facade which draws more attention than any other building component) is a calling card for the building and its designer. Set into an urban environment, it characterises the face of the city. Sometimes, the facade is separated from the load-bearing structure and becomes a curtain or an artificial skin. This functions as a multi-layered system which responds to climate, affects energy consumption and additionally could be used to produce energy at the point of demand, the building itself (Schittich, 2001).

The International Energy Agency (IEA) has implemented several programs to investigate the potential application of the PVs in buildings, with the participation of many developed countries. In the program "Task 7" (2001), working groups of architects managed to identify the characteristics of a successful integration. They resulted on the criteria which set the baseline for integration of a certain architectural quality. These are:

Natural integration, referring in the way a PV system is used as an integral part of the building envelope, while the PV system completes the building.

Architecturally pleasing, relating to how the PV system highlights a good design. This is a fairly subjective matter, which can be formed over time by experience in the design process.

Good composition of colours and textures, which need to be in balance with the other external construction materials. For this reason, BIPV products are being manufactured with specific technical characteristics, in order to achieve the desired transparency, shape and colour.

Grid and dimensional composition, which should be in harmony with the proportions and grid of the building.

Contextuality, meaning that the applied PV system is in consistency with the architectural concept and the overall image of the building.

Well engineered, which refers to the elegance of the design details, but not about the watertightness of the components.

Pioneering and innovative design, asking for architectural ideas (smart products) to enhance the PV market, adding value to the buildings (Figure 7).

Along with all the theoretical considerations, the main contribution of this paper is to

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Figure 6. Multi-colored transparent PV façades.
Source: Haberlin, 2012.

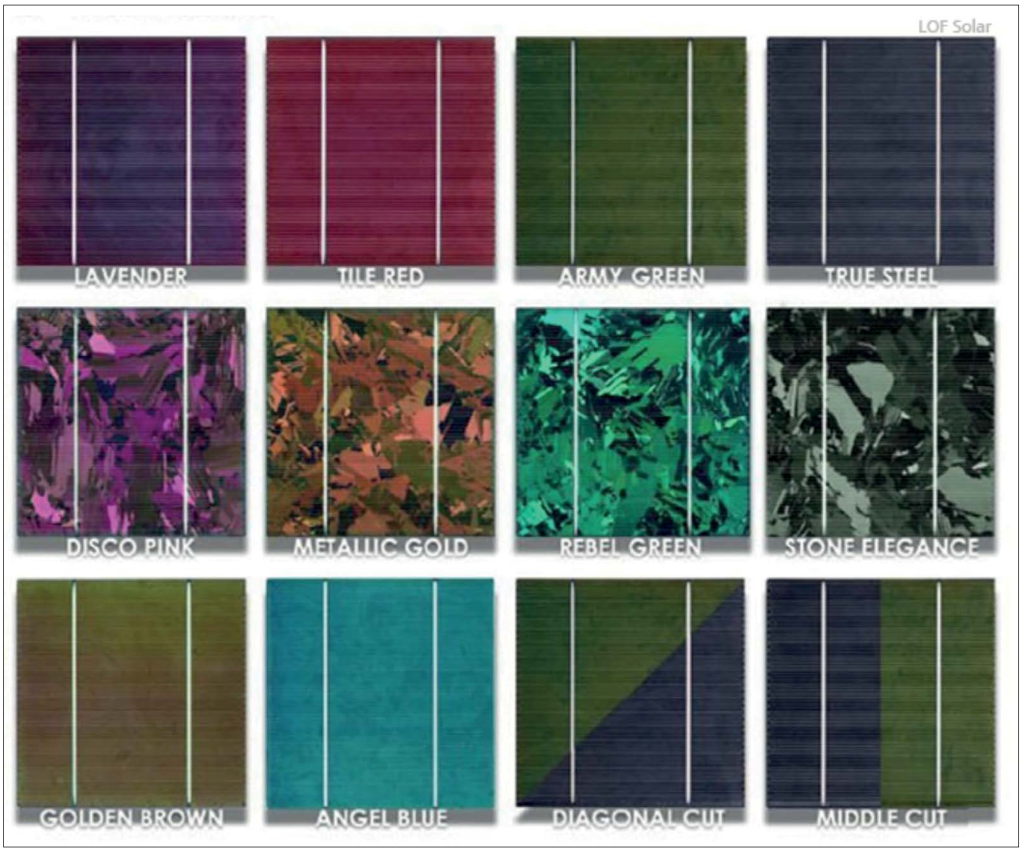

Figure 7. Color variety of PV cells.
Source: http://www.soltecenergy.com/PV.html [27 June 2015].

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understand the significance of proper installation of PV products on the building envelope, by replacing conventional materials. This helps to reduce the initial cost of installation and hence minimize the payback time of the investment. Figures 8, 9, 10 and 11 demonstrate installation detailing on a typical dwelling. A series of construction details have been created, by implementing the IEA criteria for architectural quality (author's own).

The installation of photovoltaic systems on building envelopes is a new concept in architecture. But most of the solar panels are applied on top of the building envelope (over roof tiles or external cladding etc), which is a rather expensive solution, usually without any aesthetic quality, known as Building Applied Photovoltaics (BAPVs). On the other hand, Building Integrated Photovoltaics (BIPVs), replace conventional materials on the building envelope, hence minimizing the initial installation costs. A series of typical architectural construction details is produced to assist the building industry to get it right on site. They offer the ability to design unique envelope components with integrated PVs, guide the builder on site and ensure effectiveness and optimum energy output, without any aesthetic compromise.

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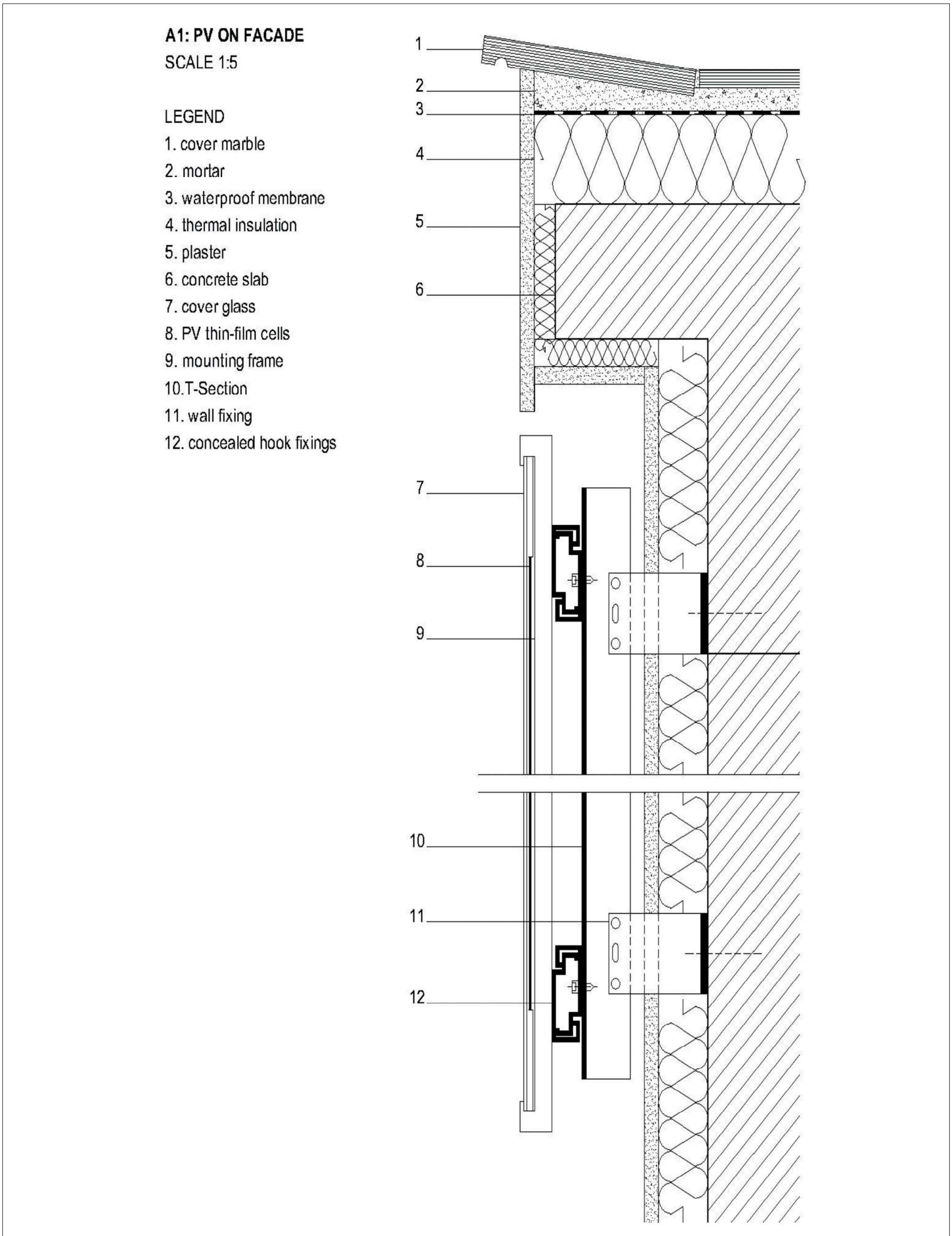

Figure 8. PV cells on a typical façade (author's own).

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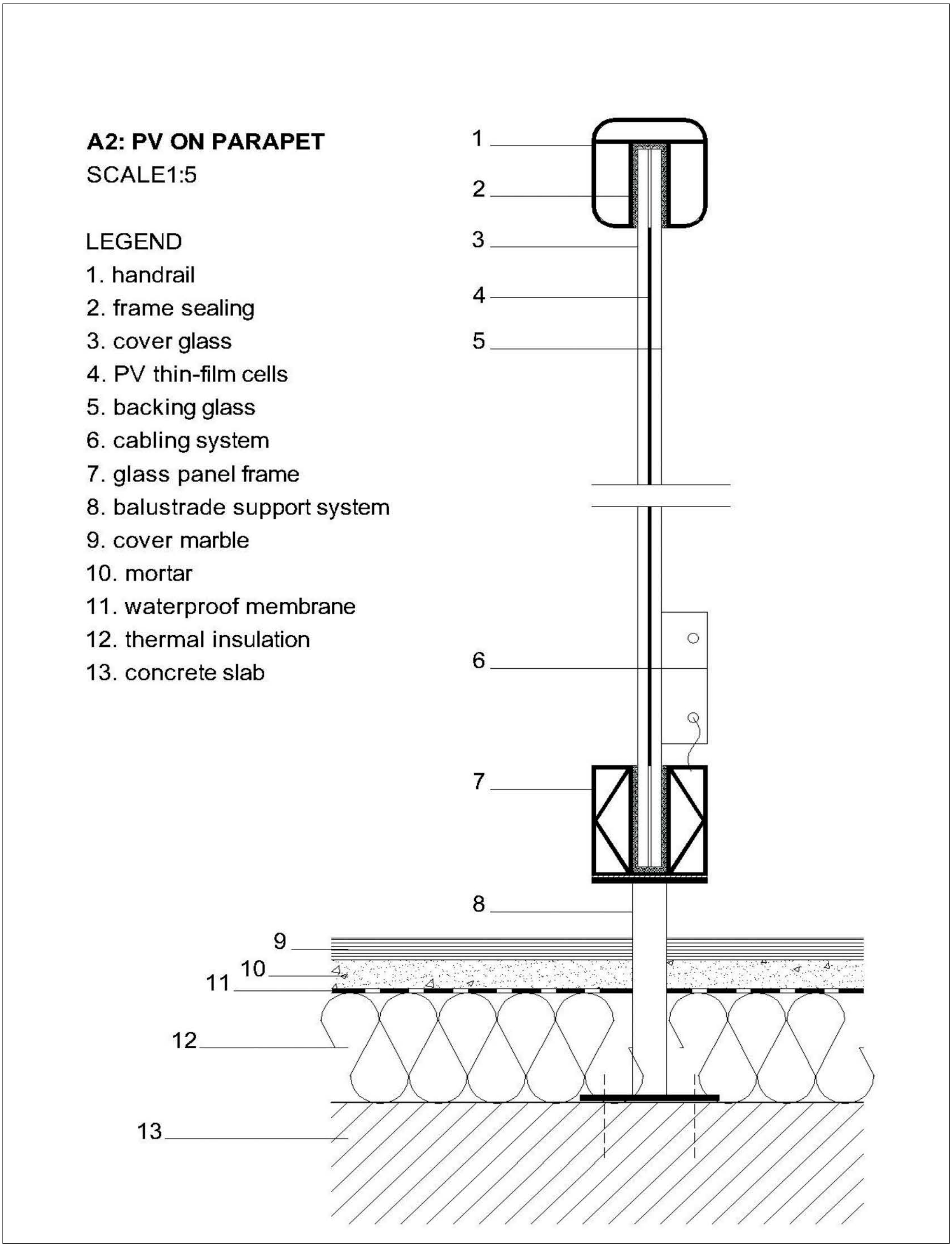

Figure 9. PV cells on a parapet (author's own).

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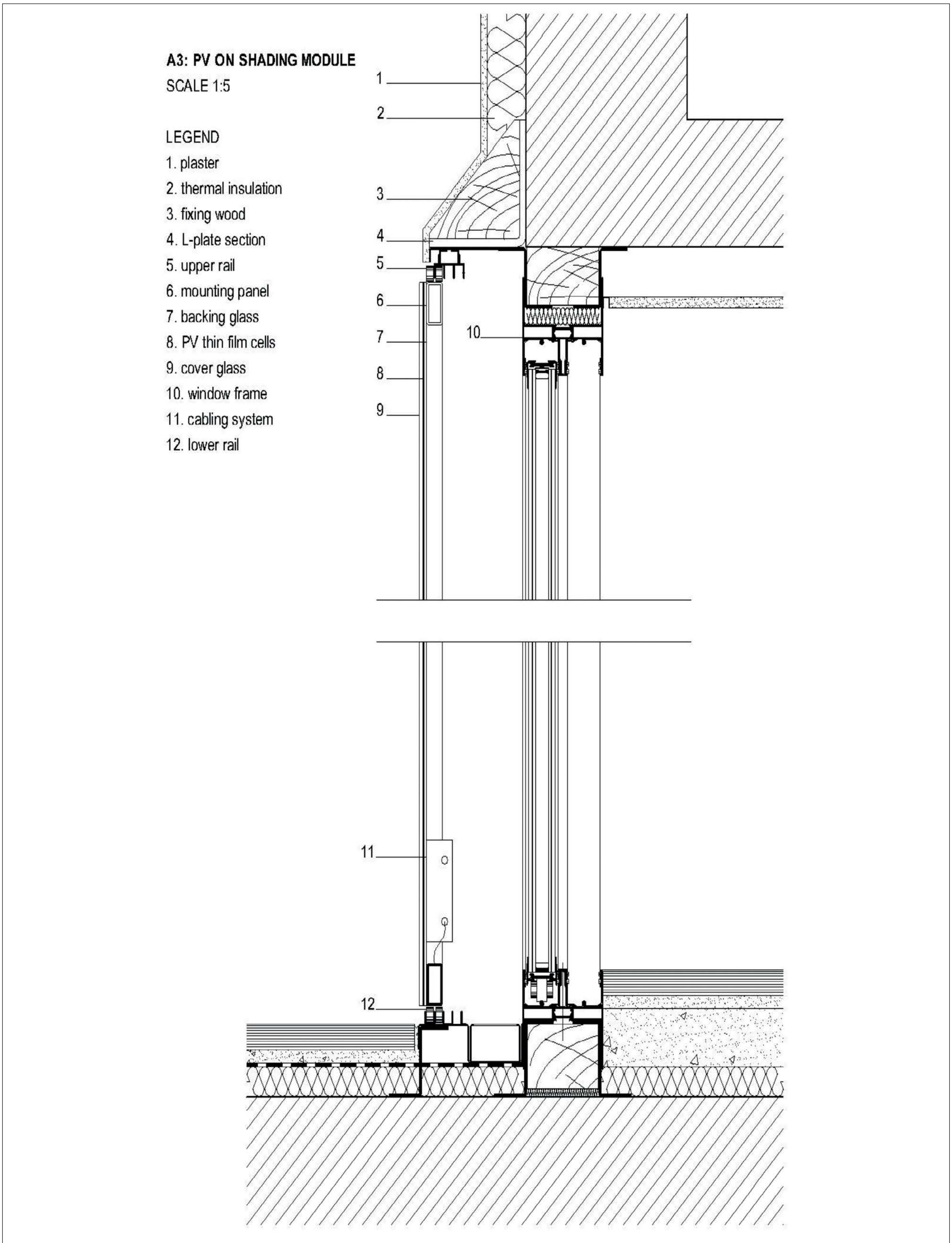

Figure 10. PV as a shading module (author's own).

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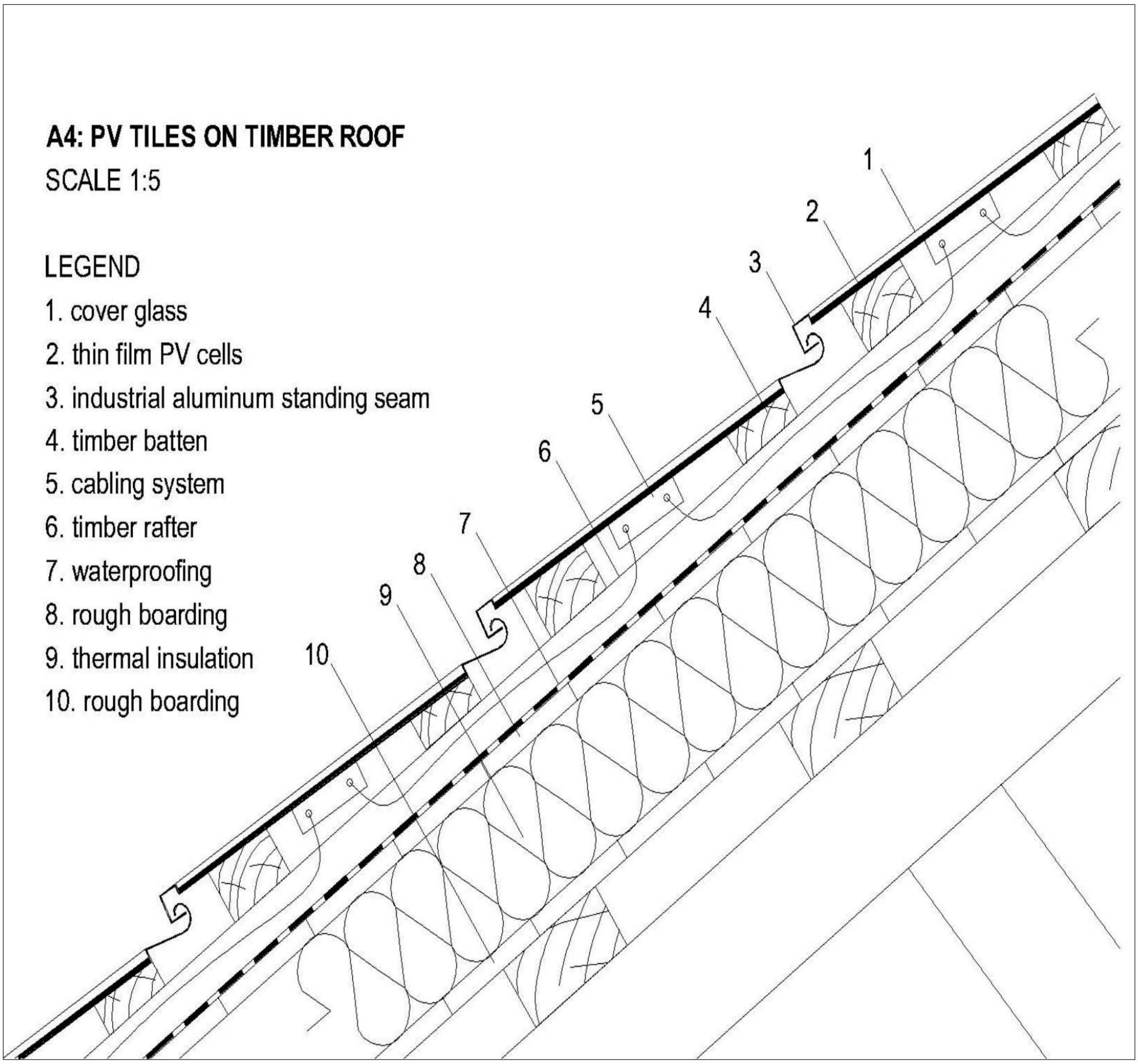

Figure 11. PV tiles on timber roof (author's own).

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SWOT analysis of BIPVs

The SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis of BIPVs, provides an effective means of evaluating the current situation, understanding the potential and identifying future development opportunities in the urban environments (Sullivan, 2013).

Strengths

• BIPV offers larger collection surfaces and allows for more building types to be suitable for solar electricity generation. The technology applications in roofs and facades in particular dramatically increase the surface area of the building envelope available for electricity generation.

• BIPV is more cost effective than conventional Building Applied Photovoltaic (BAPV) solutions, as typical building materials (and the labour costs for installation) are being replaced by suitable PV modules.

• The manufacturing costs and market prices of PV technologies decline steadily. This combined with the improved performances of PV cells and inverters could make BIPVs the most attractive option for electricity generation in the built environment.

• BIPV can be functionally and visually integrated into the building envelope, making a low aesthetic impact or even creating a new challenging architectural language. These factors can improve the perceived value of the system and increase the scope of buildings that would consider installing a PV system over that of a conventional system (Sullivan, 2013).

Weaknesses

• Currently, there are no standards and certification material to support BIPV, which leads to difficulties for practitioners to implement solutions, creating a 'grey zone' of regulatory requirements.

• BIPV presents additional complexity in building design. That is, requirement for additional materials (i.e. heat-resistant layers), design of modified conventional products (i.e. window frames) and additional design elements (i.e. the circuitry required for electrical connection).

• BIPV requires a great number of different participants to carry the process through from design to installation or integration (as it is described in the outcomes of the IEA Task 7 investigations 16 "active involvement of urban planners, architects and building engineers is required").

• BIPV systems are significantly more complex to design than BAPV systems, due to a combination of factors (except those mentioned in the point above), such as orientation and shading impacts. For instance, BAPV solutions are optimized and designed to minimize shading impacts, which reduces the power output, but this is not always achievable with PV systems integrated into the building envelope. Shading reduces energy generation because PV cells derive the majority of the energy from direct insolation. Partial shading of strings could lead to irregularities in power output and to a decreased efficiency (Sullivan, 2013).

Opportunities

• BIPV holds a small segment of the PV market at present. However, this segment is rapidly expanding, especially as a retrofit solution for existing buildings.

• BIPV can create energy generator buildings, achieve neutrality (zero-energy buildings) or transform them into net exporters of solar electricity, due to the possible increase of the system sizing, thus reducing emissions for the building sector.

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• The increased utility costs will inevitably put ongoing pressure towards the development of alternative power sources. BIPV can be installed in a way that power is delivered over a broader spectrum of the day, potentially allowing energy generation to better match on-site supply requirements and hence offset poor Feed-in-Tariffs (FiTs) scenarios.
• The parallel development of technologies may facilitate and accelerate the adoption of BIPV technology, creating tangible improvements in the financial aspects (Sullivan, 2013).
Threats
• As with any developing technologies there are many factors that may threaten the adoption of BIPV into mainstream practice. Depending on how the energy industry and government respond to the changing circumstances, there may be an increased risk for PV manufacturers and installers, with negative impacts on market development, as represented by declining FiTs.
• Failure to establish common standards in the industry for BIPVs, could result in ongoing challenges for architects and constructors to incorporate the technology into their projects. Without these standards, the users are not easily convinced about the potential of PV systems for electricity generation.
• Due to the limited standards relating to the specific conditions of BIPV, there may be as yet unrealized hazards from the integration of PVs into the building envelope.
• BIPV requires the collaboration of a number of professionals and specialties within the construction and energy sectors, a fact that raises the bar for adoption of this technology (Sullivan, 2013).
The different stages of BIPV implementation in building envelopes, involves a variety of stakeholders which face a series of challenges, as shown in Table 3.

Conclusion

Solar, as an energy source, has the theoretical potential to cover our energy demands, as it is free and available almost everywhere. Photovoltaic technology converts radiant energy into electricity (hence minimizing the dependency on fossil fuels) and is capable of reducing energy consumption and CO2 emissions in the building sector. BIPV in particular, offers the advantage of architectural integration in the building envelopes, hence minimizing the payback time of the initial installation costs, by replacing conventional building materials. Solar design transforms buildings into energy generators at the point of demand, towards a zero-energy urban environment. Detailing is crucial to understand integration techniques, while complying with the architectural criteria, set by IEA. A series of typical construction sections assists architects for best installation methods, while achieving maximum system performance

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STAGE	STAKEHOLDER	CHALLENGE	MEASURES
Design concept	Developer	Lack of knowledge for BIPV solutions and the use of relevant software	Improved communication of available products and use of easy to use software/tools
	Architect		
Detailed design	Developer	Broad range of BIPV technologies	Formalization of BIPV standards
	Architect/building engineer	Uncertainty of regulatory requirements	Creation of BIPV regulations and typical construction drawings
	Services engineer	Poor design principles	Establishment of designs to assist implementation
Building construction	Building engineer	Unclear delineation between trades in installation	Connecting BIPV technology solutions to discrete trades
	Constructors	Poor or missing skills in implementing systems	Expansion of training available for trades
	Electrician		Amendment of relevant standards
PV integration	DNSP (Distribution Network Service Provider)	Poor regulatory support for connection of large systems	Improvements to energy system regulations to streamline grid connection
	Electrician		

Table 3. Critical decision points in various stages of PV integration into building envelopes with suggesting measures to overcome any hurdles. Source: Sullivan, 2013.

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