Schweizerische Eidgenossenschaft
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Federal Department of the
Environment, Traffic, Energy and Communications DETEC

Swiss Federal Office of Energy

Final report 21.08.2014

ARCHINSOLAR

Innovative PV products for better aesthetical integration of green energies in the built environment

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SFOE Contract number: SI/500474 / SI/500474-01

Abstract

The ArchinSolar project aimed at designing new low-cost PV products for building integration in urban environment with a higher level of acceptance thanks to colors and shapes matching the traditional roofing materials, while maintaining low costs. In order to achieve this goal, a highly multidisciplinary approach had to be used, combining the competences of architects, specialists of buildings physics, professionals of the PV engineering and design, material sciences engineers and thin-films physicists. Over three years, the five academic partners from EPFL, ETHZ and EMPA went together through a complete product development cycle from lab research to pre-industrialization, finally delivering three innovative products to the market.

1. Which product for which market?

The first task addressed by the ETHZ and EPFL partners including architects and engineers was to define the characteristics of the perfect PV product for aesthetical building integration. Thanks to a market survey performed by the Solar Energy and Building Physics Laboratory (LESO-PB, EPFL) in collaboration with the Photovoltaics and thin-film electronics laboratory (PVLAB, EPFL), it was soon detected that a single product would not be able to match the different demands of the market, due to the high discrepancies of expectations in terms of shape, color, weight, price and efficiency. Therefore, in order to maximize the chances of market penetration, three different specialized products were designed and produced, all based on the thin-film silicon technology which brings already more freedom in terms of final products shape and colors as compared to standard c-Si technologies, while keeping decent efficiencies and of course low production prices. A state of the art description of the Building Integrated Photovoltaics (BIPV) market and challenges was also published[1].

A) Full-size glass/glass terra-cotta PV modules for standard low-cost on/in-roof integration

- Perfect terra-cotta color with high angular stability and homogeneity
- Based on a standard technology allowing low manufacturing costs
- Standard on/in-roof integration
- Perfect for large size installations
- The developed product is now commercialized by the Swiss company ÜserHuus[2]

B) Multifunctional colored PV tile with composite material backing for aesthetic building integration

- More appealing aspect ratio matching architects demands
- Design matching standard tiles allowing both partial and complete roof coverage
- Tunable color thanks to high-end interferential filters
- Multifunctional composite backstructure providing structural rigidity, quick mounting, roof water-tightness and lightweight product

[1] P. Heinstein, C. Ballif, L.-E. Perret-Aebi “Building integrated photovoltaics (BIPV): Review, potentials, barriers and myths” *Green*, 3, 2, (2013).

[2] www.userhuus.ch

C) Pre-fabricated building elements using combined solar-thermal (PVT) collector

- Hybrid collector able to provide low temperature heat for heat pumps and thermal regeneration of geothermal probes
- Pre-fabricated element enabling easy and rapid mounting of very large structures
- Already industrialized by the Swiss company 2Sol[3] in collaboration with the Meyer-Burger group

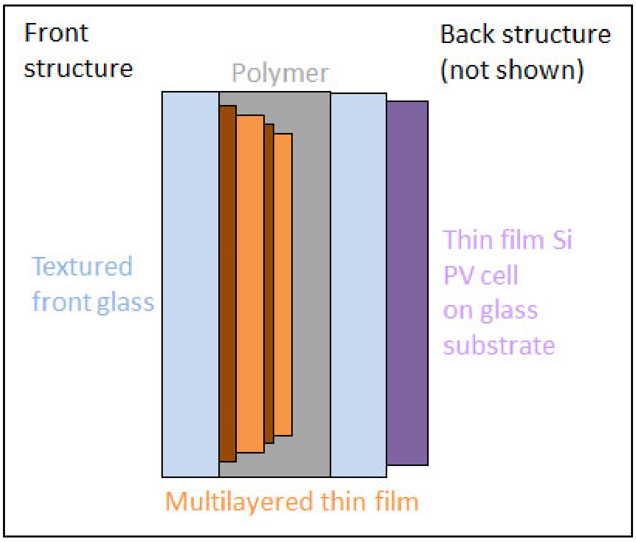
2. Changing the PV module color

The first and the most important element pointed out by the market survey was the need to change the PV module color from the blue-purple tones of standard technologies toward a more terra-cotta like color matching the traditional roofing materials. If this could be achieved, a large part of the market actors would agree to lose up to 10% of power production and even accept to suffer a slight cost increase.

Taking advantage of the knowledge in materials for PV encapsulation of the PV-Lab engineers and in functional thin-films of the LESO-PB physicists, two different approaches were explored to tune the PV modules appearance.

2.1 Adding an interferential filter above the active layers

The advantage of this technique, depicted in figure 1, is that the active device structure is left untouched, benefiting thus from the very high reliability of the PV packaging in terms of active layers protection. However, the challenge to be addressed is the need to reduce as much as possible the reflection losses induced by the color generation.



- **Figure 1 : Schematic representation of the colored Archinsolar PV module by mean of multilayered interference filters**

A very promising first generation of interferential filters based on TiO_2/SiO_2 stacks deposited by magnetron sputtering were developed by the LESO-PB and tested by the PV-Lab at the device scale. Unfortunately, the angular stability of the obtained color was not high enough, as shown on figure 2.

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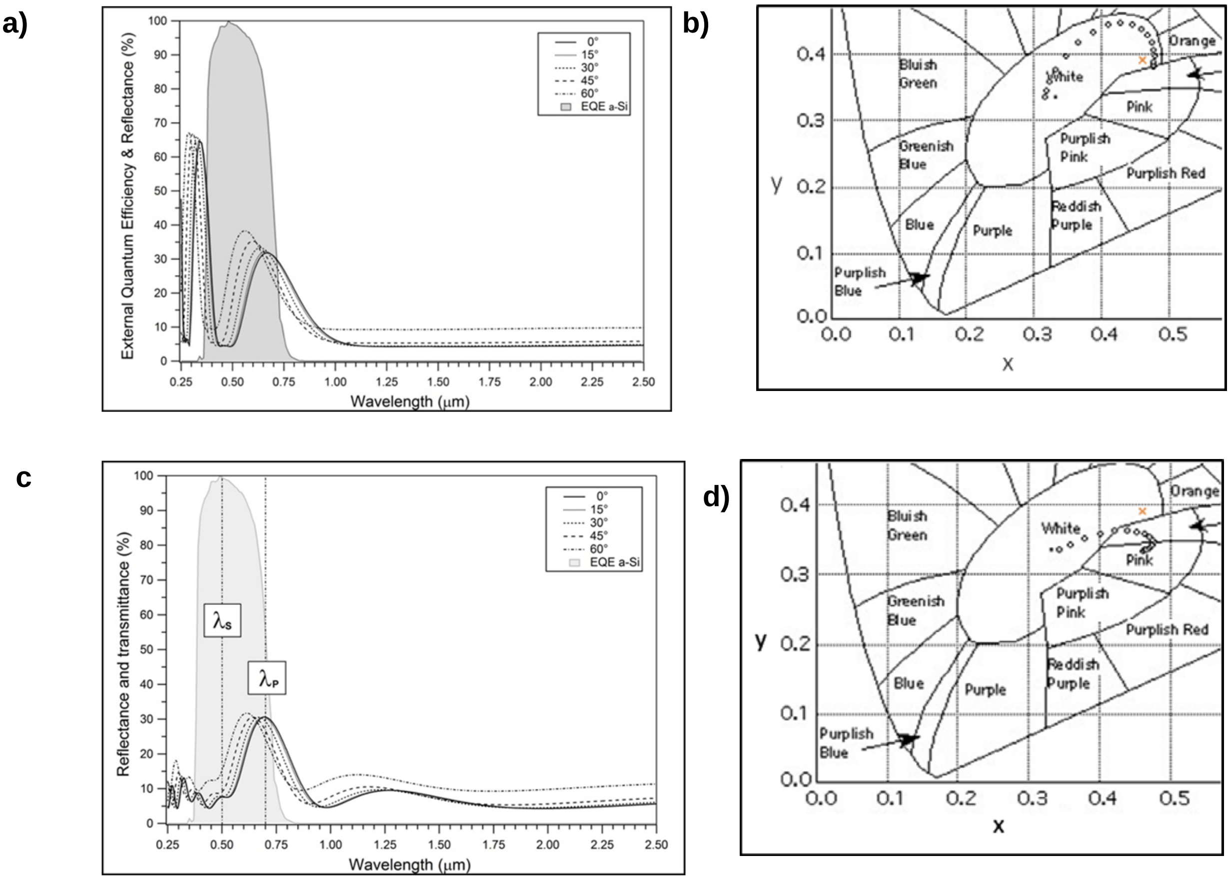
[3] www.2sol.ch

Moreover, the presence of a second reflection peak in the blue light lead to unwanted power loss by light reflection with no color gain in the orange tones.

- **Figure 2 : First generation interference filters produced by magnetron sputtering technique laminated with amorphous PV module. The color rendering changes as a function of the incidence angle**

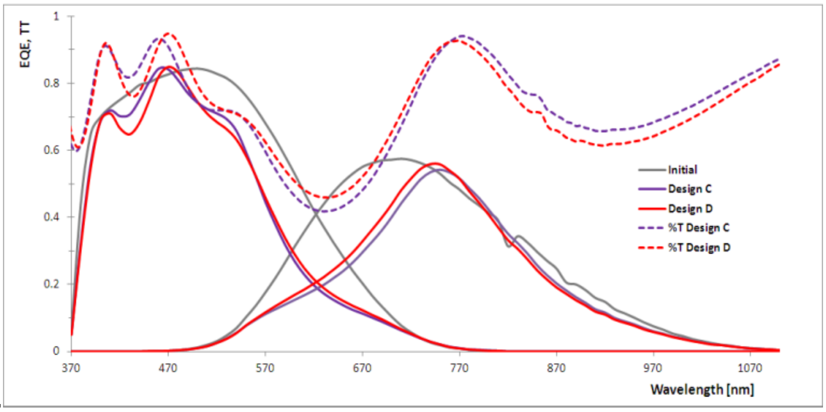
Shifting from the initial "two-peaks" architecture (one reflection peak in the blue and one in the orange) to a "peak and shoulder" architecture (see fig.3) and changing from TiO_2/SiO_2 to Ta_2O_5/SiO_2 lead to the production of second generation filters with a much higher color stability and improved performances at the device level with less than 10% of power loss when applied on a-Si PV modules. This result leads to a PCT application[4].



- **Figure 3 : a) First generation filters wit a 2-peaks architecture (left image) leading to poor color stability (right image). The grey area shows PV device quantum efficiency. b) Second generation Ta2O5/SiO2 filters with "shoulder-peak" architecture (left) and improved color stability (right).**

[4] n°PCT/IB2012/054998 : "*Interference filter with angular independent orange color of reflection and high solar transmittance, suitable for roof-integration of solar energy systems*"

The only disadvantage of the second generation of interferential filters was to lead to high power loss when applied to the micromorph technology, due to the uneven current loss in the top and bottom cells. Therefore, a last adjustment of the peak position was performed to produce a third generation minimizing the power loss when applied to the micromorph technology. In those filters, the main reflection peak is shifted towards the EQE overlap of the two cells involved in the micromorph technology (see fig.4). The resulting color is a little bit shifted towards reddish tones, but the power loss could be reduced by a factor 2 from 40 to 20%.

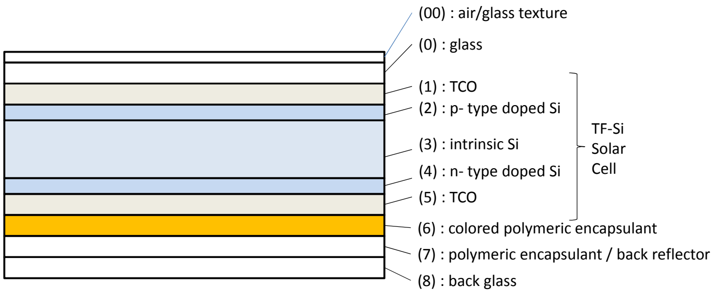


- **Figure 4 : total transmission spectrum (dashed lines) of generation 3 filters and correlation to the external quantum efficiency (solid lines) of the micromorph cells**

The fabrication process was successfully transferred from a magnetron sputtering to a sol-gel dip-coating equipment, enabling large scale production of the filters at low cost. Finally, a special chemical etching has been developed by the LESO-PB and applied to the opposite side of the filter in order to further homogenize the color rendering and suppress unwanted specular reflections. The company SwissInso already commercializes these products.

2.2 changing the module backside: colored encapsulation

Another way to tune the module color is to play on its encapsulation and on the active layers thickness. By reducing the absorber layer thickness, it was possible to produce semi-transparent devices which color could be tuned by laminating colored polymers behind the active layers, as shown on fig.5a. Using at the back of the semi-transparent device a multilayer structure made of white and colored PVB encapsulants, the PV-Lab could produce industrial size a-Si modules with terra-cotta color matching perfectly existing roofing elements (see fig.5). Thanks to the addition of a very high transparency textured glass on top of the device, it was even possible to match the "feeling of diffusivity" of the tiles appearance. This innovative coloration process resulted in a PCT application[5].



- **Figure 5 : addition of a colored encapsulant at the back of semi-transparent a-Si cell enables device color tuning**

This approach holds two advantages. First, as compared to the interferential filter solution, no additional layer is added in front of the PV cell, except a high transparency solar-grade textured glass, and, therefore, the reflection losses are minimized. Second, the lamination process stays identical to the

[5] PCT application,"*Manufacture of colored PV modules*" L.-E. Perret-Aebi and al., deposited in 09.2013

one used in standard modules and no costly materials are needed (only a colored polymer layer and a commercially available textured glass). Therefore, this product enables terra-cotta tones matching at low price and maximum reliability. The only disadvantage was shown to be the slight efficiency reduction as compared to standard opaque (purple tones) a-Si due to the introduction of the colored polymer layer between the cell and the white back reflector. Tuning the colored polymer layer thickness, it was possible to reduce the power loss to 8%, below the acceptable threshold of 10% defined during the market survey.This market survey was sent to more than 1,800 architects, in order to characterize architectural sensitivity regarding freedom in choosing module size, colors and texture, and the willingness to pay for these features. The survey showed that architects are very interested in installing PV but are looking for specific characteristics rarely available on the market: the possibility of choosing dimensions, color, type of surface and jointing. This study also showed that they were ready to pay the price (extra cost or reduced efficiency) for a suitable product.

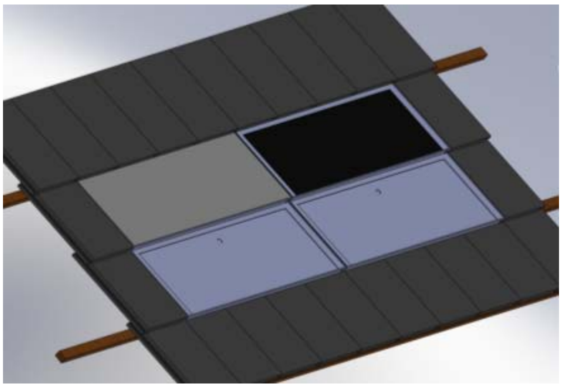
Discussions are on-going now with two private landlords for a possible installation / demonstration on roofs in Neuchâtel. Some simulations of power output and performance on the terra-cotta modules installed on these roofs were performed using the PV-SYST software and showed the nice generation potential of those roofs. This procedure is still ongoing and the installations should take place in 2014.

3. Designing a multifunctional structure for easy and aesthetical building integration

The second challenge, after the module color, was the wish of the architects to dispose of a PV product with a high aspect ratio (in landscape format) that could be easily installed, matching existing tiles, while staying lightweight.

In order to match this demand, it was needed to design a structure in composite materials in order to obtain the wanted lightness while keeping stiffness high enough to ensure the product mechanical stability. The design of this structure was done jointly by the Laboratory of Polymer and Composite Technology (LTC, EPFL), the LESO-PB, EPFL and the PV-Lab, EPFL and allows:

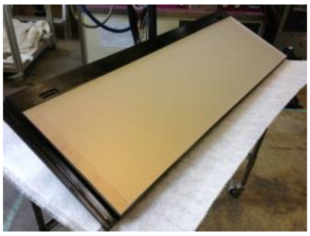
- Quick and easy in-roof integration thanks to its light weight (15kg per complete tile of ½ squared meter) and simple screw fixation system
- Roof water tightness through an optimal horizontal and vertical overlap
- Compliance to all roof pitches from 15° to 60° thanks to the tunable vertical overlap (see fig.6, right)
- Compliance with the Tegalit tiles from the company Braas, allowing highly aesthetical solutions for both complete and partial roof covering with the PV elements (see fig.6, left)
- Structural integrity thanks to the stiffness of the composite material (compliance to IEC 61215 checked by the mean of FEM)
- Excellent weathering capability of the well-known PVC material
- Tunable color to adapt different PV technologies and to meet customer requirements
- Easy and safe storage, transportation and handling through additional features on the backside



- **Figure 6 : Left: Complete integration of four ArchinSolar PV tiles matching with Braas Tegalit tiles. The composite back-structures are represented in blue, the active PV element in black, the textured front glass in light grey and the Tegalit tiles in dark grey. Right :** ***vertical alignment with the tunable overlap ensuring both vertical water-tightness and compatibility with roof pitches ranging from 15° to 60°***

Once the design ready, a material selection step was undertaken at LTC by the mean of a product cycle analysis in which the balance "cost / production rate / environmental impact" was optimized. The selected solution consists of a glass fiber reinforced PVC (GFR-PVC) processed by glass-mat thermoplastic (GMT) (preheating in IR Oven then direct molding by pressure). This process leads to a product that is recyclable, highly UV and corrosion resistant and which color can be tuned using pigments. Some prototypes were produced in collaboration by the PV-Lab and the LTC using the colored filters presented in §2.1 to tune the PV element appearance, as shown in fig.7

a)



b)

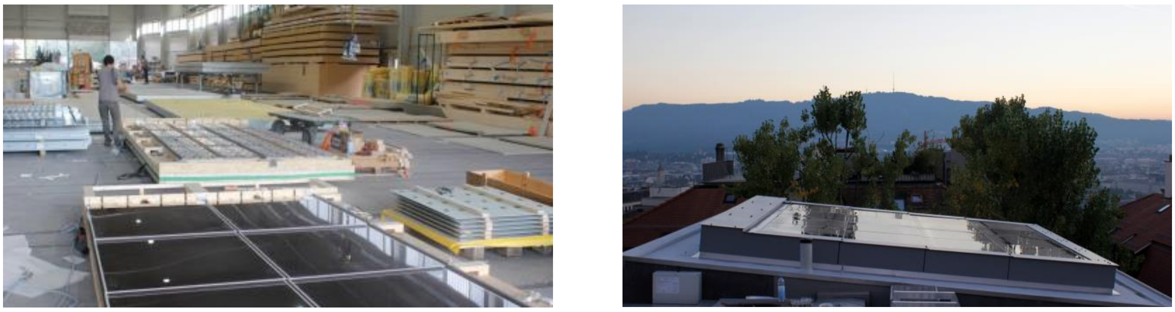
- **Figure 7 : a) all black tile-like BIPV product, b) colored-tuned tile-like BIPV product, thanks to the previously developed interferential filters. Note that the composite backing color can be tuned to match the filter color.**

4. Designing a PV/T product for integration in pre-fabricated roofing elements

The last product development challenge consisted in answering the will of architects to dispose of prefabricated roofing elements that can at the same time produce electricity and low-temperature heat to be used in synergy with heat pumps. These elements are intended to be used both in new constructions aiming low energy impact as well as in building refurbishment.

To do so, a special heat absorber was designed at the ETHZ and applied on the back side of large size colored modules (presented in §2) to create a PV/T product. The PV/T module was then integrated in a prefabricated design consisting of a wooden frame acting as supporting structure, an insulation layer with low U-value and water vapor permeability to prevent water condensation behind the PV/T collector. The water-tightness system is ensured by the thermal collector that also acts as a mounting structure for the PV module.

After a series of outdoor tests needed to assess the water-tightness and electrical/thermal performances of the developed concept, the ETHZ could start the production of real size prefabricated roofing elements that were applied on a real roof in the city of Zürich (see fig.8). The developed solution is now industrialized by the Swiss company 2Sol in collaboration with the PV industry leader Meyer Burger.



- **Figure 8 : left) manufacturing of the prefabricated elements using black micromorph modules, right) a roof realized with the developed prototypes in Zürich**

5. Ensuring high reliability

The introduction of new materials and changes in the module encapsulation architecture lead to the evident need to check that the end products reliability was still as high as possible. To do so, the PV-lab conducted extended studies including potential induced degradation (PID, high voltage test under hot and humid environment), adhesion tests before and after degradation in damp-heat (85°C/85%RH) using a specially developed procedure[6] and moisture ingress tests.

a) b)

- **Figure 9 : corrosion of the ZnO electrode due to application of high voltage under hot and humid environment (a) couls be suppressed using a moisture blocking polymer applied on the edges of the PV module (b)**

It was observed that the new architectures developed showed an increased sensitivity to moisture penetration, which lead to high adhesion loss and potential induced corrosion on the ZnO back electrode of the PV cells (see fig.9). In order to mitigate this effect, a dedicated protective tape made of moisture-blocking technical polymer was applied at the product level around all interfaces (either during the lamination or during the framing processes, depending on the design). Addition of the protective tape was then shown to decrease the moisture ingress to similar level as observed in standard and certified commercial products.

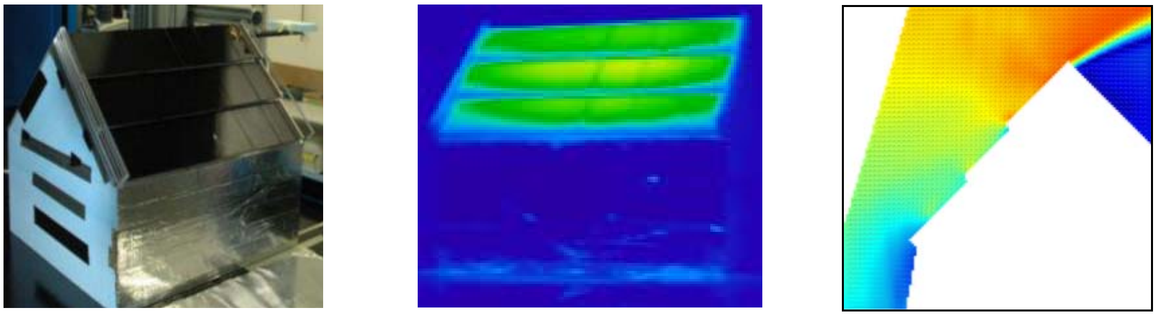
The realized reliability study and the addition of the moisture blocking polymer ensure that the developed product can be safely commercialized and if needed certified according to the existing PV standards (EN61646)

6. Studying cavity ventilation to overcome the overheating of BIPV solutions

Even though BIPV solutions are preferable from an aesthetic point of view, the proximity of the active layers to roofing insulation material usually induces overheating of the PV module resulting in efficiency losses.

A study was then conducted in collaboration between the PV-Lab and EMPA in order to evaluate the influence of different mounting designs on the PV modules temperature. Therefore, a mock building on which small PV modules can be installed in different configurations was realized (fig.10a) and placed in a wind tunnel under a sun simulator. The PV modules temperature was monitored by thermography (see fig.10b), while the airflow was observed using particle image velocimetry (see fig.10c).

[6] Chapuis, V., Pélisset, S., Raeis-Barnéoud, M., Li, H.-Y., Ballif, C. and Perret-Aebi, L.-E. (2012), Prog. Pho-



a) b) c)

- **Figure 10 : a) the mock structure placed in wind tunnel, b) example of thermography imaging of the mini PV modules, c) image of the air velocity around the PV installation**

The conducted study evaluated six different PV modules mounting schemes and the impact of the airflow regime on removal from the PV panel was clearly demonstrated for both open and closed mounting architectures. It was moreover shown that a stepped arrangement of the PV modules, such as realized with the tile-like product presented in §3, had a significant advantage in cooling the modules than standard flat constructions. This study resulted a scientific publication[7] and in guidelines for the mounting of BIPV that strengthened the design choices made for the BIPV tile and the pre-fabricated elements developed during this project.

7. Conclusions

ArchinSolar has been a three years long success story in which the well established close collaborations between academic partners from highly different research fields was shown to be the key in overcoming the proposed innovation challenges from lab scale research to pre-industrialization of prototypes. Thanks to the high personal investment of each collaborator involved, ArchinSolar is now able to propose innovative BIPV products to the market that will surely contribute to make photovoltaic energy more accessible and more attractive, particularly in built-environments or protected areas. This project also demonstrated the possibility to manufacture innovative BIPV elements by working on the “packaging”, functionality, aesthetic and mounting aspects of the modules and not only on the core of the PV modules (the solar cells). This “transformative” strategy of modifying existing PV elements is the only way, today, to allow sufficiently low costs to give a chance to BIPV elements to be successful on the market.

tovolt: Res. Appl. doi: 10.1002/pip.2270

[7] Mirzaei, P. A., Carmeliet, J. (2013) ,in "*Progress in PhotovoltaicProgress in Photovoltaics: Research and Applications"*, DOI: 10.1002/pip.2390.