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EXPERIMENTAL MANUFACTURE OF A PNEUMATIC CUSHION MADE OF ETFE FOILS AND OPV CELLS

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Key words: EFTE, Organic Photovoltaics OPV, Optical properties, Carbon Nano-tubes, Tessellation, Building Integrated Photovoltaic (BIPV).

Summary: *This paper presents the preliminary activity from which the fabrication of a new kind of ETFE foil fully integrated with a Smart, Organic, Flexible and Translucent Photovoltaic building component (named SOFT-PV) begins. A prototype of SOFT-PV cushion will be the object of optical, mechanical and thermal tests to preview all problematic aspects of the fabrication process and the environmental impact evaluation with LCA methodology.*

1 INTRODUCTION

The paper deals with the first disciplinary goals obtained by the Building Technology researchers, during the first year of a biannual research activity, co-financed by Cariplo Foundation (Lombardy, Italy) and based on the collaboration between three different research groups (fig.1): the Department of Architecture and Building Technology of Polytechnic of Milan (POLIMI-BEST), the National Chemistry Research Institute (CNR-ISMAC and the Physics Department POLIMI-FISI).

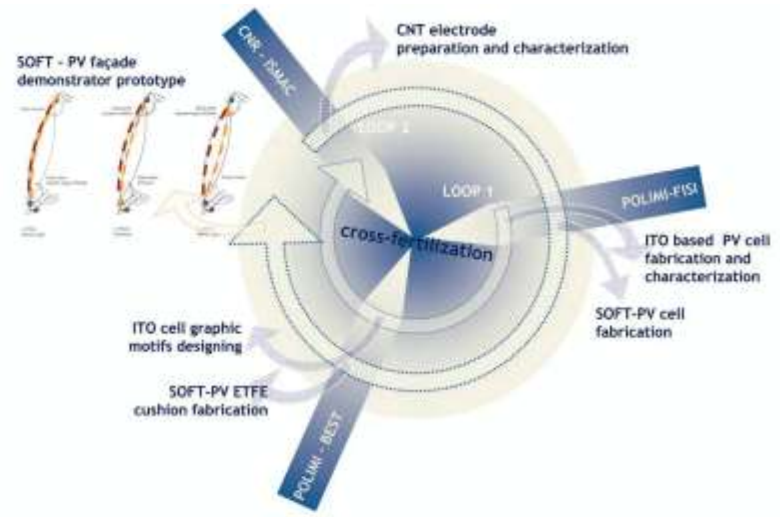

Figure 1: The main “cross-fertilisation” loops between different fields of involved knowledge

2 TOWARDS THE INTEGRATION OF PHOTOVOLTAIC INTO ETFE CUSHIONS

Actually the current use of ETFE cushion as an inflatable substrate of Photovoltaic into buildings can be considered only as an added component, not fully integrated, which is represented now by PV manufacturers. SolarNext AG has now developed a form of photovoltaic technology that enables solar cells to be added directly onto membrane materials[1]. This technology is based on extremely flexible, amorphous silicon thin-film solar cells (a-Si) laminated between two layers of ETFE foil. They can be substituted for the upper layer of pneumatically supported cushions. This process of lamination ensures the protection of the photovoltaic cells against loads and stresses, as well as against moisture and weathering. Depending on environmental aspects, they can be used in roofs or facades either in a single-layer form or as a part of a multilayer membrane cushion.

On one hand, the integration of 2nd generation PV cells into transparent ETFE foils could negatively impact the most important advantage of ETFE envelopes which is its transparency (using natural foil) or its great translucency (using printed foils). On the other hand, encapsulating PV cells into a double foil of ETFE reduces significantly the efficiency of the PV cells and the typical weight and thickness of 2nd generation PV cells are not perfectly suitable for the material properties of ETFE foils. When the photovoltaic elements are used as an intermediate layer of a cushion, they are, of course, optimally protected from the possibility of dirty. In such cases, however, the light-refracting effect of the upper film layer and the thermal gains that occur in the heat-absorbing middle layer would decrease the energy yield, but anyway the efficiency is higher than their set on the outsider layer, often easily dirty. Finally, the application of this kind of PV cell could cause problems in the management of flexibility and in the structural behaviour of pneumatic systems.

As the integration of Organic photovoltaic systems into building envelopes to replace conventional building materials has not been realized, combining two low cost technologies available on the market today - the ETFE cushion technology and the 3rd generation of organic flexible PV cells – should represent a more cost-effective solution for the creation of a new kind of smart façade employable both in renovation and new construction, overcoming the most of problems focused above on the integration between thin-film cells and ETFE foils. Moreover from an architectural perspective, photovoltaic elements don't only generate electricity, but they also provide shade, which may be often an essential design requirement.

This paper presents the preliminary activity from which the fabrication of a new kind of ETFE foil fully integrated with a Smart, Organic, Flexible and Translucent Photovoltaic building component (named SOFT-PV) begins. The origin of this idea came from the hypothesis of compatibility of the production processes of the ETFE and of the OPV: the extrusion of the film can be combined with the roll to roll OPV deposition technique.
Based on the cross-fertilization of the three research groups (fig.1), the Building Technology researches tasks are involved in the design and experimental fabrication of a prototype of the first OPV integrated ETFE cushion and to test the optical, mechanical and thermal performances of the new building component together with the LCA evaluation, while the CNR and FISI researches target is focused on maximizing the cell efficiency.

3 STATE OF THE ART

3.1 ETFE as A Shading System in Architecture

According to its numerous remarkable properties, ETFE foils offer a valid alternative to glazing in building envelopes. The reduced self weight is the most appreciated feature of ETFE structures. In comparison to equivalent glazing, pneumatic cushions achieve a comparable level of performance with less than 1% of the weight. This reduces the amount of secondary structure required to support the building envelope with consequent benefits on the primary structure and the foundations allowing unsupported spans up to 10m[2,3].
Furthermore, the high level of translucency over a wide spectrum represents the second main aspect which justifies the expectations placed in ETFE. The optical properties of ETFE foils are subjected to high variability from one producer to another due to the raw material used, the production process, the material colour and thickness[4]. In addition, the optical behaviour in the UV spectral range, with a light transmission around 70%, represents a significant benefit for structure such as solaria, swimming pools and greenhouses where the natural bactericidal and fungicidal properties of UV light reduce the demand of chemical treatments. The risk of an inadequate internal environment, due to the incorrect solar control, can be addressed by using different printing patterns which reduce the danger of glare and overheating.

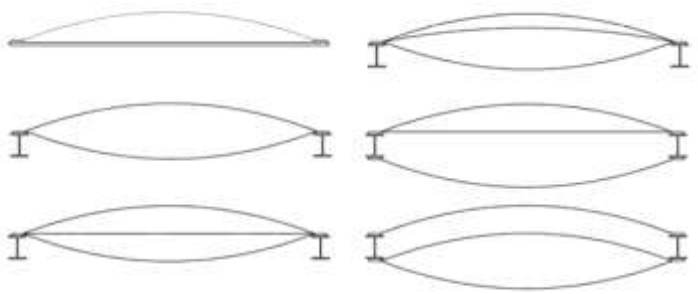

Figure 2: Common formation of ETFE layers in a foil cushion[13]

Although the material ETFE does not offer exceptional thermal insulating properties, the use of multilayer solutions allows the achievement of considerable values of thermal insulation, comparable with those obtained by means of glazed envelopes, reducing overheating, internal condensation and the energy required for air conditioning, both during summer and winter. The environmental impacts of building systems based on ETFE foils represents one of the main interesting aspects in the comparison between different covering systems based on ETFE foils, PES/PVC and PVC Crystal foils, Polycarbonate panels and double glazing. Despite the absence of comprehensive studies in this field, recent researches[5,3,6] showed the potential LCA performance of lightweight envelopes which is mainly related to the overall covering system rather than the embodied energy of the raw material, expressed in GJ per ton of material. However, side effects due to the resource consumption/savings in use, such as the pressuring system, the artificial light or the use of detergents and water, play a crucial role.

The acoustical behaviour is one of the weakest aspects of the envelopes based on this technology. The level of sound insulation provided by ETFE foil cushions is extremely low with a R_w of 8 dB[5]. However, the high transmission and the reduced reflection can have a positive effect reducing the amplification of sources of noise placed in the internal spaces. The level of noise due to the taut drum-like nature of tensioned ETFE and ETFE cushions[2] can be partially reduced by means of an addition external mesh layer.

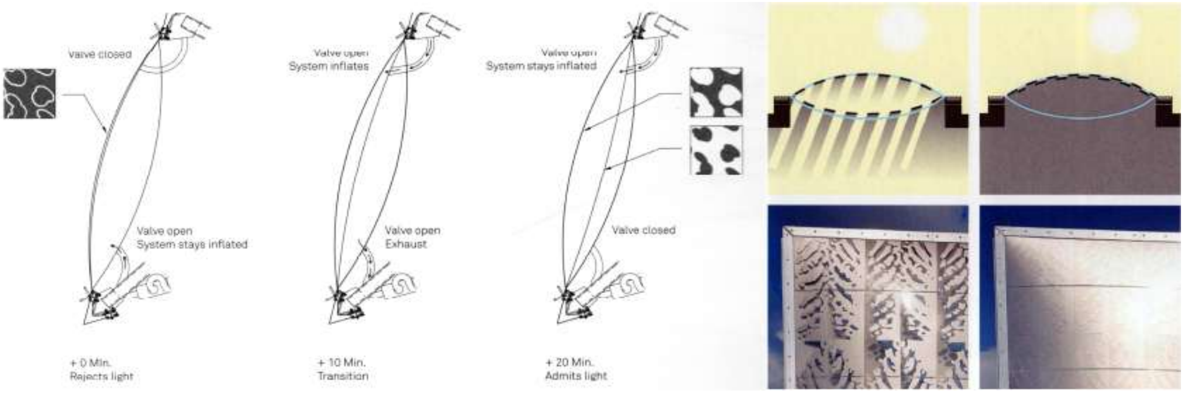

Figure 3, 4: Membrane cushion movements, Atelier Brückner& Festo Technology, Cyclebowl, 2000, Hannover[15]

The load bearing capacity of ETFE foils can be achieved through two different approaches, tensioned double curved surfaces and pneumatic cushions. Although the increasing interest in single layer envelopes[7], mainly due to the reduced maintaining costs, pneumatic cushions are the more common envelopes, especially for applications which require higher levels of thermal insulation or sun shading. The performances of the envelope can be improved increasing the number of layers and internal chambers and combining the reflectance properties of different frit patterns printed on the layers which can be moved by changing the air pressure of the chambers[8]. This solution becomes unavoidable for applications in the Mediterranean area where printed ETFE foils are necessary in order to reduce the sun irradiation and the air-conditioning loads. The high percentage of area covered with frit patterns, which increases with the amount of solar energy which have to be reflected, opens interesting prospects of applying flexible photovoltaic cells instead of reflecting patterns.
In 2000 Festo Technology[9,10] developed an interesting solution to control the daylight conditions in an architectural space enclosed by an ETFE cushion system. As shown in fig. 3 and fig. 4, a variable skin has been created by printing overlapping gestalt graphics on multiple layers, integrating the cushions with sophisticated pneumatics, and finally by moving the different graphics together and apart from each other.

There are two main production techniques that obtain flat and blown ETFE foils: the blown film extrusion, in which the melted mass comes out of the extruder and is formed by a ring die into a tube which is expanded by blowing in air. And the flat extrusion is in which the film in a roll form coming flat from the extrusion[11]. The extruded product, passing between rollers, is a 0,05-0,3mm thick and 150-220cm wide film. Then it is ready to be rolled up into cardboard tubes for storage and transportation to the cushion fabricators[3]. This part of the process, the lamination, is carried out by means of techniques with several aspects in common with the technology used during the production of OPV. The potentials of industrial applications are numerous and represent the basis of this research.

4 RESEARCH WORK

4.1 Design and Investigation Of A New Active Shading System

4.1.1 The Optical Properties of Transparent and Printed ETFE Films

The first part of the research focuses on measuring the optical behavior of ETFE films. An optical test was performed on two samples of Clear and Printed ETFE (fig. 5) with 200μm thick and resulted in the transmission values indicated in fig. 6. Spectrophotometer was used to test the transmission and reflectance values of the samples. The optical data sheets were inserted in program Optics 5 in order to conclude values with the mean light transmission for each sample as follows: a. Mean Clear ETFE Transmission Value = 0,90; b. Mean Printed ETFE Transmission Value = 0,16.

Figure 5: Clear and Printed ETFE

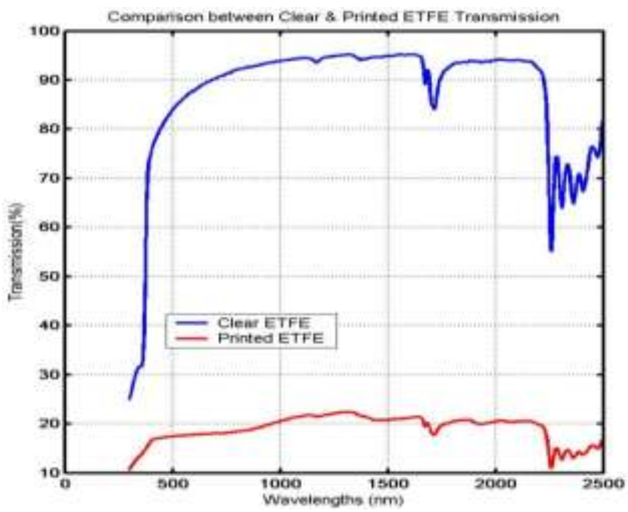

Figure 6: Clear and Printed ETFE transmission graphs

4.1.2 Printing Techniques and Corona Treatment Currently Used for ETFE

ETFE may be produced as a clear film or with printed silver pattern on the surface, usually dots and squares. These printed patterns are designed to control light and heat transmission.

By combining one clear and two printed ETFE films into a three layer pillow and moving the middle layer up and down, it is possible to control the amount of light that is transmitted to the inside environment.

ETFE is chemically inert material with low surface tensions causing it to be non-receptive to bonding with printing inks. The molecular structure of the film's very smooth surface has to be opened up, for the chemically bond adhesion between the film and the ink. Corona treatment is a safe and economical technique that uses a chemical application, electrical discharge or subjecting the film to high intensity radiation to open the surface for printing[12]. Patterns are printed with opaque or translucent fluoropolymer inks, leaving approximately 50mm not printed, along the edges of the film, for welds. The most common pigment is aluminum with the color of silver for the reflection of the solar light and heat. Also copper with its typical oxidized green colour has one time been used[13].

4.1.3 Potentials of New Printing Patterns for Controlling Light Transmission

This part of the project focuses on trying to innovate concepts for patterns that could be printed on different cushion layers in order to optimize the visual aspects of ETFE printed cushions. These patterns ideas are still under progress trying to recognize and develop their integration into the cushion and optimize their environmental impact.

4.1.3.1 Tessellations

A tessellation is a pattern of plane figures that fills the plane with no overlaps and no gaps. As indicated in fig. 7, all patterns are composed by overlapping the same two geometries, the tessellation pattern on the left, but with different distances and angles. This idea can be applied onto the multi-layer ETFE cushions in order to optimize the aesthetic value of the envelope. The more the number of printed layers increase, the more the variability of patterns are; which will reflect actually on the percentage of transmitted light to the indoor environment.

Figure 7: An example of the patterns variety out of using the same tessellation geometry (left)

In order to design and apply practically these patterns, it was necessary to calculate the total printed area for each scenario and then conclude with the percentage of transmitted light through the overlapped layers. Using Grasshopper software[19], it was easy to simulate the overlapped geometries while controlling different parameters such as the circles radiuses, the distances between circles, the displacement between the overlapped patterns in X, Y, Z coordinates. All these parameters values are controlled by a numeric slider tool. Figure 8 shows the definition used and examples of different shapes obtained by only changing the values of patterns displacement.

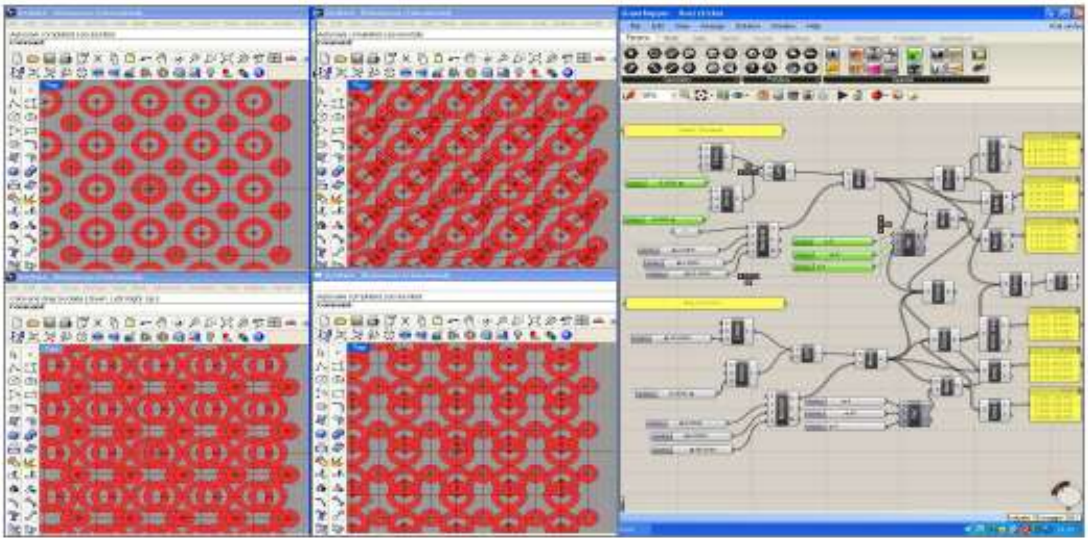

Figure 8: A screen shot for different obtained patterns using Grasshopper

4.1.3.2 Scanimation

A Scanimation is an animation technique invented by Rufus Butler that involves two layers: the bars (or "scanlines") and the background image. By splitting the frame of a potential animation up, according to the size of the bars, each image is fully revealed between the bars, in order, as the bar layer is moved horizontally over the background image. No computer chip is involved, only an acetate overlay, made up of stripes, flowed over a patented, scrambled image underneath, getting the fluidity of motion[14]. Figure 9 shows an example of this technique.

This idea is a part of the research interest but it's still in progress, trying to apply it on ETFE layers replacing the horizontal movement of the two layers (to get the fluidity of motion) by the movement of users themselves, walking under or in front of the cushion. In order to get the motion effect, specific distances should be kept between the two layers: it can be represented by the air chamber of the cushion. Specific distances, pattern area and number of frames should be recognized in a formula in order to get the clearest motion of the scene.

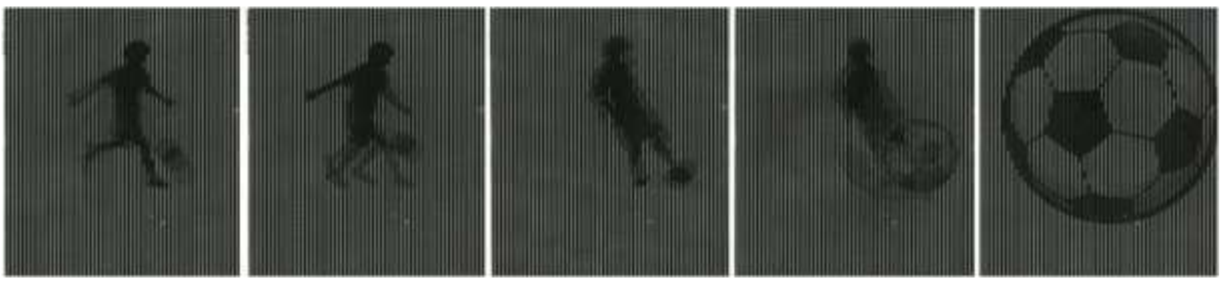

Figure 9: some shots for a scanimation pattern[15]

4.2 Sun-shading envelopes based on Organic Photovoltaic

4.2.1 Flexible Organic Photovoltaics

Due to the international orientation towards the use of renewable energies and the fact that harvesting solar energy using a photovoltaic panel costs more than burning fossil fuels pushed the researches to focus more on the organic solar cells. The OPV cost savings come from the possibility of using flexible substrates, printable organic inks for the active layers, low temperature and ambient pressure fabrication, and reduced materials costs[18]. However, the efficiency of the fabricated cell is not the target of the research. The research innovative idea is using fluoropolymers as substrate and encapsulating material and also replacing the typical ITO cathode with Carbon Nano-tubes (CNT).

As indicated in fig. 10, organic solar cells function as follows: the light absorption produces excitons, electron-hole pairs that are bound together and hence not free to move separately. To generate free charge carriers, the excitons must be dissociated. This can happen in the presence of high electric fields at the interface between two materials that have a sufficient mismatch in their energy levels. Thus, an organic solar cell can be made with the following layered structure: positive electrode/electron donor/electron acceptor/negative electrode. An exciton created in either the electron donor or electron acceptor layer can diffuse to the interface between the two, leading to electron transfer from the donor material to the acceptor, or hole transfer from the acceptor to the donor. The negatively charged electron and the positively charged hole is then transported to the appropriate electrode.

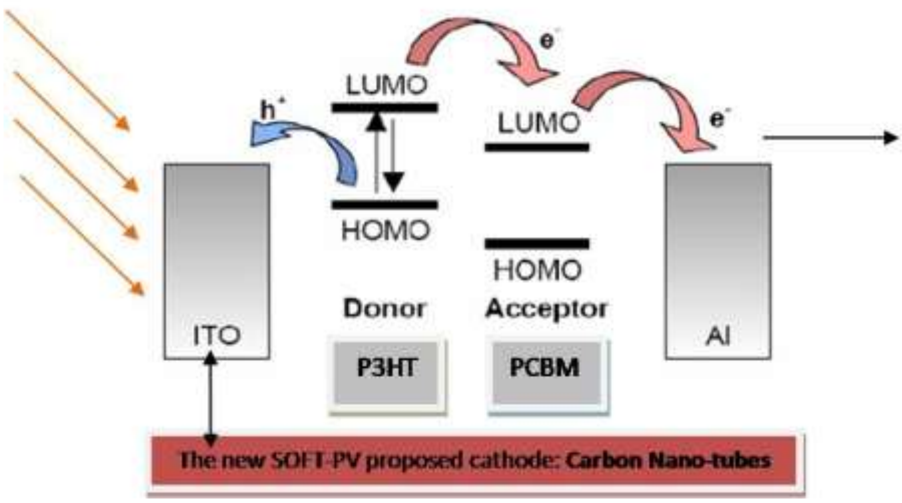

Figure 10: a graph indicates how the Organic Solar Cell is functioning and the SOFT-PV contribution

4.2.2 Fabrication of an OPV Cell based on CNT on ETFE Substrate.

The fabrication of the OPV cell is passing by three different phases. The first is the deposition of the Carbon Nano-Tubes and the PEDOT:PSS, the second is the deposition of the organic active layer PCBM/P3HT and the third is the deposition of the Aluminium electrode. These three phases are explained as follows:

a. First Phase - Deposition of the CNT & PEDOT:PSS:
Continuous CNT network in a film could offer a new class of transparent conducting materials which complements ITO for applications such as organic light-emitting diodes and organic photovoltaic (OPV) devices. CNT films are superior to ITO in terms of flexibility because the former can be bent to acute angles without fracture. In addition, although carbon is the most abundant element in nature, the worldwide production of indium is limited, which may soon find difficulty meeting the ever-increasing demand for large-area transparent conductive electrodes. The decreasing resources of crude indium induced a ten-fold price increase between 2003 and 2007[16]. Furthermore, CNT films may offer additional advantages such as tuneable electronic properties through chemical treatment and enhanced carrier injection; moreover CNT coatings can be produced at room temperature and do not require vacuum procedures. In this project we aim to create by electro spinning a 2D network of fibers deposited onto glass substrate. The same procedure will be tried using fluoropolymer substrates and CNT will result to be embedded into the electros pinned polymer. Polymeric lattices prepared by radical copolymerization of the monomer could offer the possibility to obtain the nanotubes directly embedded into the ETFE material. After this layer, a coating with Poly(3,4 ethylendioxythiophene- poly(stryrenesulfonate) (PEDOT:PSS) is applied.

b. Second Phase - Deposition of the active layer (PCBM/P3HT):
The realization of the flexible PV cell using P3HT and PCBM as donor and acceptor materials respectively, follow standard procedures, since the goal of the present project is not the specific performance and efficiency of the PV cell, but its fabrication using fluoropolymers as substrate and encapsulating material and its integration into the building component. Deposition of the active layer is based on the bulk heterojunction concept where the donor material (typically a polymer) is mixed with an acceptor (a soluble fullerene) in an organic solvent and then deposited in a spin coating device (fig.11).

c. Third Phase - Deposition of the Aluminum Electrode:
Finally, the Aluminum electrode is deposited using a vacuum evaporation device (fig.11) by putting the cells in a metal perforated template which is pre-designed according to the cells dimensions. The machine should be air-vacuumed before the evaporation starts then the process begins by increasing the temperature till the Aluminum evaporates and the molecules stick to the whole entire surface including the cells samples. After the deposition finishes, the final action is to stabilize the air pressure again.

Figure 11: Spin-Coating device (left) and Metal Evaporation Device (right)

4.2.3 Experimental data concerning the optical properties of the fabricated cell

The optical and optoelectronic characterization targets all the intermediate steps and the final product of the research. Transmission, absorption and reflectivity is measured on the new thin film electrode, on the organic active layer, on the final PV cell and will be measured on the final integrated structure. The goal is to assess the optical and consequently the optoelectronic performance of the device structure. In particular: The transmission, front and back reflections of the new flexible fluoropolymeric ETFE substrate deposited with the modified electrode, Carbon Nano-Tubes using a standard Spectrophotometer.

The light transmission is measured for three samples: each corresponds to a specific phase of the previous three deposition steps. As indicated in fig. 13, the first sample represented by the blue line corresponds to the deposition of the Carbon Nano-Tubes + PEDOT:PSS. Sequentially, the second sample represented by the red line corresponds to the deposition of the CNT + PEDOT:PSS + the active layer PCBM/P3HT. The third sample is not included in the transmission measurements as the aluminium layer has a transmission of zero value.

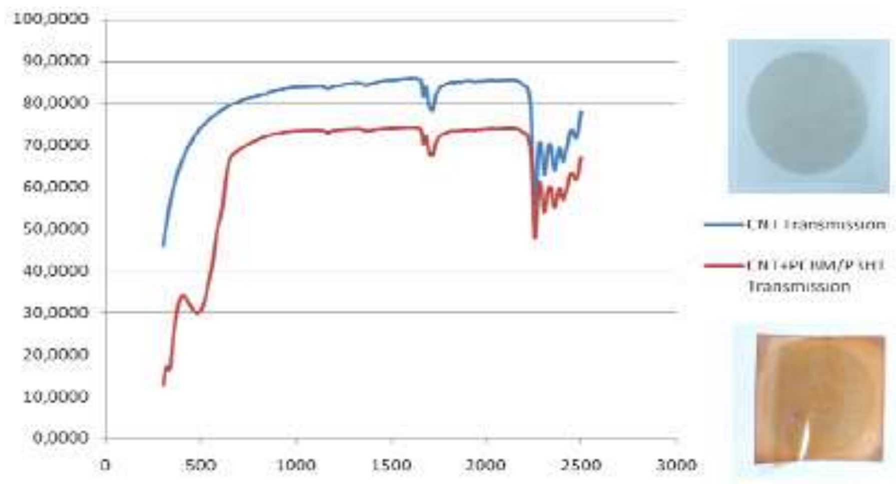

Figure 13: light transmission graph of the two samples; above: ETFE+CNT, below: ETFE+CNT+PCBM/P3HT

5 SOFT FUTURE WORK

5.1 The approach to design an innovative facade component

This part of SOFT research will focus on the creation of printable graphic motifs by integrating a CNT based organic cell into different ETFE layers of a building component, to preview all problematic aspects of the fabrication process. A demonstration prototype of this new kind of smart façade will be created by the integration of the new kind of SOFT-PV cells into an air-supported multi-layer fluoropolymeric building component trying to study the degree of flexibility of integrating OPV cells as units for various patterns.

5.2 Mechanical, environmental and LCA evaluation of the final prototype

First, this model of a new active building envelope (smart façade, smart transparent roofs) will be tested to investigate the mechanical behaviour of the new prototype. Second, the thermal and the optical behaviour of the cushion will be simulated for different scenarios (orientation, time & season) of a building model. Finally, the life cycle assessment of the SOFT cushion with the integrated OPV has to be evaluated. On material scale, the life cycle analysis of all materials involved in this manufacturing process will be developed: the material inventory of the full process for a module production, the accountability of the energy embedded both in the input materials and in the manufacturing processes. Also, a computation of the energy payback time will be evaluated in order to compare this technology in progress with the current ones. At the scale of the cushion system the analysis of the environmental profile of the envelope technology will be carried out on the whole life cycle. The durability of the involved material and of the efficiency of the OPV cells has to be considered and compared.

6 CONCLUSION

Going through the research different phases, some problems and constraints were investigated by the researchers. Parts of them are related to the technical properties of used technologies such as The Spin-Coating device. Since the device technique is based on spinning the substrate while pouring the active layer, there are some restrictions regarding the maximum area to be covered as the more the substrate area the less homogeneous the deposited layer is.

During the service-life of a SOFT cushion some aspects would be deepen and previewed: the durability of the involved material and component and the efficiency of the OPV cells have to be considered and compared, in order to define the management and substitution cycles. In the design phase the compatibility of the durability between the involved materials and components has to be taken into account, in order to design the easy reversibility of each part, especially the OPV cells.

In the life cycle approach the end of life aspects has to be considered also in the design phase: actually the substrate ETFE is recyclable and a recycling chain is just operating. In Germany and in Italy commercial opportunities already exist to take the production waste or the “old” used ETFE and then to re-process them and close the cycle[17]. Actually one limit of the recycling practice of the ETFE is related to the printed foils, a technology to separate ETFE from ink has to be found. The same limit belongs to the SOFT cushion: how would be the end of life cycle scenario of the ETFE with the encapsulated OPV cells? Huge work has to be carried out, in order to improve the system during all the life cycle phases.

7 ACKNOWLEDGEMENTS

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