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Advanced Integrated Facades: Concept Evolution and New Challenges

Fabio Favoino **Marco Perino** **Valentina Serra**

ABSTRACT

The exploitation of RES at the building scale, the possibility to perform the energy demand management and the ability to take the advantage of the opportunities offered by the outdoor environment are, today, key issues for achieving a satisfactory energy efficiency in buildings. It has been demonstrated that all these goals can be achieved through the adoption of the so-called Responsive Building Elements (RBEs). Among various concepts, Advanced Integrated Façades (AIFs) are probably one the most promising RBE technology, due to the important role that the building envelope plays in controlling the energy and mass flows between the building and the outdoor environment. In this paper the most significant outcomes of a twenty year long research activity, done on different types of AIF, will be presented. They are the results of both numerical and experimental investigations performed on various types of AIF, namely active double skin facades with various ventilation strategies (mechanical, natural, hybrid) and smart glazing systems. Morever, the present and future evolution of the AIF concept toward more comprehensive, up-to-date and visionary technological solutions will be discussed. They are the so-called Multifunctional Façade Module (MFM), like the ACTRESS prototype (ACTive, RESponsive and Solar) or the POWERSKIN$^+$ system (Highly advanced modular integration of insulation, energising and storage systems for non-residential buildings). The ACTRESS prototype integrates high performance insulation systems (opaque and transparent) with energy storage capabilities (by using PCM latent heat). It hosts PV cells and the opaque submodule can be ventilated with various strategies. It is has been conceived and a prototype was built for monitoring its energy performance and its capability in providing optimal indoor environmental quality. POWERSKIN$^+$ is an off-site prefabricated modular system, glazed and opaque, integrating smart material solutions to renovate existing facades of both double skin and advanced integrated curtain walls. It will be developed in a recently funded Horizon 2020 EU project.

INTRODUCTION

The centrality of the building envelope in providing adequate comfort levels and improving the energy efficiency of buildings has long been established. Its importance grew over the time and has been recently strengthened by the European legislative framework and by the need to satisfy the "Nearly Zero Energy Building" (nZEB) and ZEB targets.

However, attaining such high performance levels is not thrivial, implies a revolution of the traditional constructive habits and imposes a radical change of the paradigms adpted so far for the design of façades and building envelope components.

For decades the mantra, supported by the so-called "energy conservation approach", was to improve the thermal insulation of the building enclosure. This way of thinking derived from the idea that the "energy efficiency in buildings" ment, practically, to just reduce the energy demand for space heating and DHW production (see e.g. Energy-Efficient

Fabio Favoino is Assistant Professor, **Marco Perino and Valentina Serra** are Professors in the Department of Energy, Politecnico di Torino, Corso Duca degli Abruzzi n° 24, 10129 Torino, Italy.

Green Homes with Green Building – US, PEW Centre – Global Climate Change, US DoE NREL - National Renewable Energy Laboratory). Under this perspective, the design strategies were then focused in strengthening the shielding and barrier effects of the building envelope. The goal was to push the separation between the indoor and the outdoor environment (in a wider sense, thermal and for the air/water vapour exchange) to the maximum. The façades and the walls were seen just as a problem to counteract and to solve. Indeed, the application of these policies has allowed, in the last 20 – 30 years in Itay and Europe, to significantly improve the energy performance of buildings as far as the heating demand is concerned, but on the other hand, has created other serious issues related to the Indoor Environmental Quality (IEQ) and the cooling and lighting energy consumptions. In fact, having focused the attention for decades mainly on optimizing the space heating and domestic hot water production, caused the other items of the thermal balance of a building (summer cooling, artifi-cial lighting and plug-loads) to increase their influence. It is well-known that today many modern office buildings must be cooled even during the winter season and that the ventilation losses are becoming comparable (or higher) than the transmission losses. Besides, having pursued the same approach over and over again for years has led us to the point at which any further improvement will allow to only obtain marginal improvements, with ever growing costs. That is, we are clashing with the constraint introduced by the so called "law of diminishing returns" (Shepard, 1974). It was demonstrated by Torcellini et al., 2007 how pushing the optimization of the traditional solutions to their limit could only lead to an improvement of the current energy performance of buildings of 50%, which is well far from the target imposed by the European directives (that asks for more than 100%).

There is undoubtedly still space for a further optimization in relation to the thermal insulation of façades, as testified by the research and technological develoment of new and better performing materials for buildings, like SIM (Super Insulating Materials) (IEA, Annex 65, 2019) and TIM (Transparent Insulation Materials). SIM are opaque thermal insulating material having a nominal thermal conductivity lower than 15 mW/(mK); examples of technological solutions are the VIP (Vacuum Insualtion Panels) and the Advanced Porous Materials (like AMP) (Pisello, 2017). Nevertheless, even such highly sophisticated solutions, derived from aerospace applications, do not change the base design concept (that is, to increase the thermal insulation of walls) and cannot provide that significant "jump forward" that is mandatory to do today.

We are at such a point in which the BAU approach is not any more effective and we must aim for a totally new viewpoint, where the opportunities offered by the local climate and by the natural resources are exploited and not fighted, as endorsed in the past by the energy conservation approach (e.g. the shield/barrier effect). The envelope should not be intended anymore as a "problem", a "difficulty", to fight, but as an "opportunity" to exploit and a "potentiality" (Perino, Serra, 2015). The building envelope, more than a "construction component", will have to be seen as a spatial location and an interface that can effectively be used to dynamically manage the mass and energy balances of the built environment. A place where to host the technologies for the exploitation of renewable (non-carbon) sources and/or low quality energies (low exergy) and to store energy and water. Therefore, the way towards the innovation of the building envelope, that today appears far more promising, consists in passing from the concept of "insulation" to that of "integration and multifunctionality". This requires the transition from a "passive" to an "active" component, able to play various roles. How it can be easily imagined, the practical implementation of this vision – which represents a revolution in the way of conceiving and developing the building envelope components – is everything but easy. To be able to solve such a complex problem, a systemic approach is needed (Goia, 2013). As of today, the technological solution that seems to offer the better perspectives is represented by the so-called: Advanced Integrated Facades (AIF)

ADVANCED INTEGRATED FACADES: FACTS AND CONSIDERATIONS

What an AIF is, where it comes from and why they may help in implementing the new vision outlined in the previous section?

In order to answer these questions a little historical background is needed. At the beginning of the XX century, with the theories of Modernism, a new architectural school of thought established, and both the attitude towards the building form and the envelope technologies deeply changed. The era of the unconfined confidence in technology and mechanical systems started. Thanks to the industrial innovations and the introduction of the curtain-wall, the use of completely transparent façades became very popular since the early 1950s. The influence of the "international" architecture and the superficial mimicry of the style proposed by the 'trend setter' architects had the consequence of a flourishing of fully glazed buildings, whose poor thermal and environmental performance were counterbalanced by the introduction of oversized HVAC systems. A fashion that is still exerting its influence today. Along with the universally recognized beauty of such buildings, unacceptably high transmission losses during the heating season, huge cooling loads during the summer period, problems of glare and local thermal discomfort invariably aroused. These issues forced the researchers to look for solutions able to mitigate such disadvantages.

The first and most straightforward solution was to pass from simple clear glazing systems to double façades, where the solar shading device was located in the protected environment constituted by the air cavity between the inner and outer layers. This configuration revealed to be able to improve the daylighting control and to reduce significantly the heating losses. The maintenability and durability of the façade were also enhanced, thanks to the protected position of the solar shading device. However, though a clearly perceptible upgrade of the thermal comfort during the cold periods was achieved, the serious overheating of the glazed surfaces still severely compromised the comfort during the warm seasons (due to the strong radiative exchanges) and did not introduce any substantial benefit as far as the reduction of the cooling load was concerned.

Based on these achievements, and in order to takle the still present limitations, the second measure was to ventilate the cavity between the two skins, thus creating a Double Skin Façade (DSF). The airflow made it possible to remove part of the thermal energy that otherways would be buffered in the cavity and in the solar shading device, causing the overheating of the façade. At the beginning, the ventilaton of the cavity was done with the sole purpose of getting rid of the solar loads during the cooling season, and the hot air was exhausted towards the outdoor environment (Outdoor Air Curtain ventilation – OAC). But soon, under the push of the ever growing consciousness towards the environmental sustainability and the increasing price of energy, it was realized that many more opportunites could have been exploited working around this first concept. Moving away from the idea that a ventilated DSF was just a solution able to compromise the architect dream towards a total transparency and the engineering urgency of making these dreams compatible with a decent energy efficiency of the building and with the occupants comfort, new concepts and configurations were conceived. Playing with the ventilations strategies/paths and integrating the DSF with the HVAC systems, it became possible to exploit the façade as an element of the mechanical system.

Now the façade can act as an air intlet/outlet, as a sort of solar collector (to exploit the solar radiation for preheating the ventilation air) and can tune its thermal insulation and air tightness capacities: the AIF are born and new horizons open. The AIF were the first seed that allowed to start translating into practice the keywords that describe the new vision for the building envelope outlined in the introduction, that is: responsivity, adaptability, dynamic behaviour, integration/interactivity, harmonization (tuning) with the indoor/outdoor environment, multi-functionality (Van der Aa, Heiselberg & Perino, 2011). This evolution over time, that has seen the passage from DSF to AIF, is also testified by the thread of research experiences that the TEBE research group has carried out and that will be brievely presented and discussed in the next section

RESEARCH EXPERIENCES AND EVOLUTION

Figure 1 shows the various typologies of AIF that has been conceived and/or analysed during an almost twenty year research activity carried out at the Department of Energy – Politecnico di Torino (Italy).

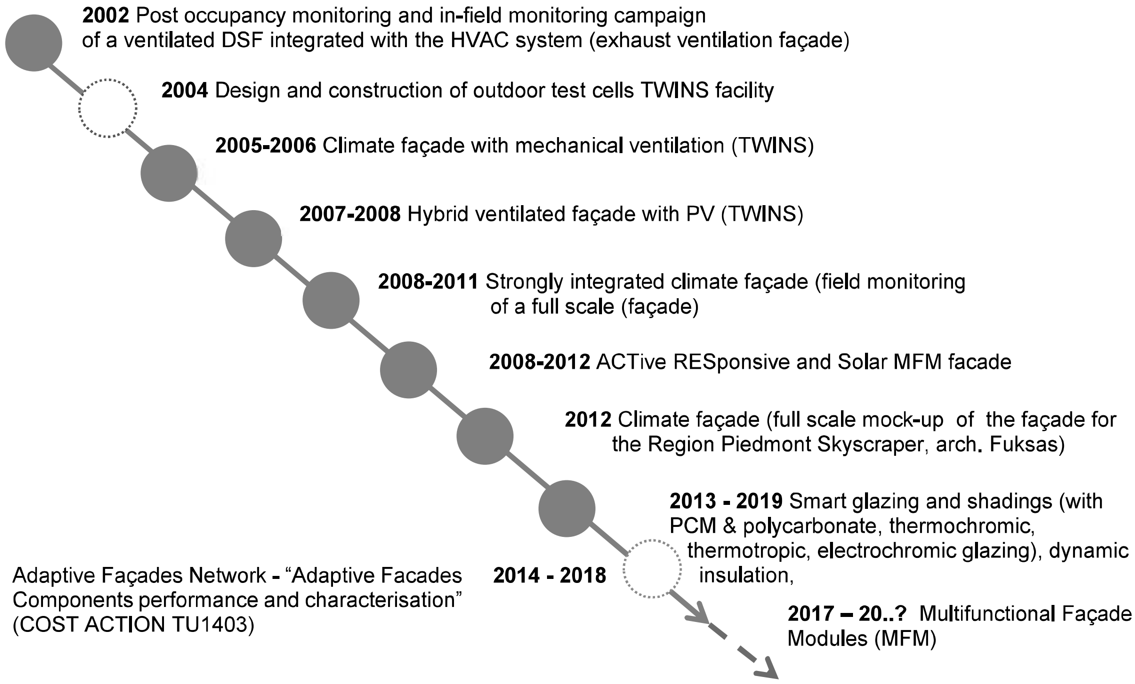

Figure 1 Research trend and studies on AIF at Politecnico di Torino.

This two decade long research activity has focused on the development, characterisation (through experimental and numerical methods) and integration of different AIF concepts in the built environment. Particularly, it evolved from the development of different kind of transparent Double Skin Facades (DSF) and single skin components, differentiated by: i) air flow configuration (thermal buffer or so-called Closed Cavity Facades, exhaust air, supply air, outdoor and indoor air curtain); ii) air movement (natural, mechanical or hybrid); iii) integration of active solar control by means of cavity solar shadings (roller and venetian) and/or smart glazings; integration of energy generation (different kinds of BIPV) and storage (PCM); integration of high performance insulation (i.e. aerogel, vacuum insulation and ventilative active insulation systems). This research has always been carried out by means of two complementary paths, on the one hand an experimental activity (either in outdoor test facilities or on site) aimed at the characterization of the above mentioned technologies and of their performance and on the other hand, as a development, validation and test of the numerical models.

The research was initially devoted to improve the energy efficiency for heating and cooling. Nevertheless, due to the dynamic and integrated characteristics of these technologies and systems, and to the multifaceted nature of the building performance (i.e. different energy uses including lighting and ventilation, thermal and visual comfort etc.) a performance based and holistic design approach has become necessary.

In this context, it is difficult to quantify the performance of such technologies with traditional performance metrics and indicators (such as U-value, g-value, and so on) which would allow instead a direct comparison with traditional building envelope technologies. In fact, building envelope performance indicators are intrinsically static (i.e. not representing the capability of dynamically controlling the energy flow across the façade) and they are able to quantify the performance of the system only partially (e.g. the capability to reduce a certain energy demand). Therefore, the research activity has also aimed at providing new methods to quantify the performance of AIFs and in general of dynamic building envelope components by means of simulation and experimental testing, and by conceiving novel more comprehensive performance metrics. These studies were carried out in the framework of the European COST Action TU1403 "Adaptive Facades Network" (Favoino et al., 2018). In particular, the performance metrics conceived in this two decade long research are oriented towards the quantification of the achievement of a certain performance objective (i.e. pre-heat supply air, reduce heat losses or gains, delivered solar radiation through an opaque component to the adjacent room etc.). As a result, most of these metrics are dimensionless efficiencies or ratios over known quantities, with an analogy between AIFs and Heating Ventilation and Air Conditioning (HVAC) systems (Bianco et al. 2018).

THE FUTURE BEYOND ADVANCED INTEGRATED FACADES

The AIF has been indeed a significant step forward in the building envelope innovation, however, new and more challenging requiremements emerged (and are emerging) that push for even more effective, flexible and multifaceted functions. This is compelling the evolution of the AIF towards a new scheme. In fact, the idea to switch from a building that is only a consumer of energy to a builing that becomes a "prosumer" (e.g. producer and consumer) and the aim of reaching not only ZEB but also Positive Energy Buildings, asks for:

- an energy efficiency that is far more higher than the one achievable through AIF.
- an holitstic approach where all the energy demands (i..e for heating, cooling and lighting) are cumulatively and simultaneously optimized.

The consequence is that, in practice, it will be hardly possible to fulfill such requirements with a fully glazed assembly. The reasons lies in the fact that even adopting the most sophisticated galzing, coatings and shading systems available on the market, the themal insulation of a transparent component is far lower than that of an opaque element. Besides, transparent materials are characterized by a very low thermal inertia; therefore, the AIF do not offer sufficient opportunities to implement thermal energy storages and to perform effective demand side management.

This means that the future evolution of the concept has necessarily to shift toward configurations where the transparent part is coupled with an opaque part, whose their relative size (Window to Wall ratio – WWR) has to be carefully otpimized on the basis of the local climate conditions and of the façade orientation (Goia et al., 2013) .

Such envelope components have been called: "Multi-functional Façade Modules" or MFM. An MFM integrates many different technologies (such as: SIM, PCM, ventilated cavities, PV cells, solar thermal harvesting elements with different fluids, coatings,….) and "smart" sensors and controllers, thus allowing to obtain a façade module practically self-sufficient as far as the energy is concerned. One of the earliest examples of MFM was the ACTRESS façade prototype developed at the Department of Energy – Politecnico di Torino.

The ACTRESS prototype

The ACTRESS (ACTive RESponsible and Solar) Multifunctional Façade Module (MFM), developed within an Italian national research project (2008-2012), was primarily aimed at overcoming drawbacks of current DSFs and AIFs solutions, highlighted in the previous section. The ACTRESS concept was framed in order to implement capabilities/functions pursuing the vision of a façade for Zero and Plus Energy Buildings, that is: i) embed technologies (e.g. PV and solar panels) to increase the exploitation of solar energy, directly at the façade level; ii) possibility of selectively activating thermal storage layers within the building envelope, to store the surplus solar thermal energy; iii) possibility of increasing the management of the solar gains both in the transparent and in the opaque sub-modules.

The ACTRESS MFM is made of two different sub-systems: an Opaque Sub-Module (OSM) and a Transparent Sub-Module (TSM), as shown in Figure 2:

- the OSM is an opaque ventilated façade, which exploits the active control of the cavity ventilation to manage solar heat gains (removing them in summer or pre-heating the ventilation air flow in winter). The air cavity is located between an outer BIPV integrated glazed skin and a rear lightweight sandwich wall panel. This last is a highly insulated system composed of 50 mm of VIP panels (R=10 m^2K/W), embedding on the indoor side a solar LHTES (Latent Heat Thermal Energy Storage System). The LHTES enables to shift the exploitation of thermal solar gains towards times where they are most needed, thanks to the presence of an electric heated foil directly powered by the PV panels. The heated foil is positioned between two layers of Phase Change Materials (PCMs) with different melting temperatures (27 °C and 23 °C) to address both the summer and winter requirements;

- the TSM is made of two glazing systems, a larger triple glazed unit (Argon filled and with lowE coatings, U-value 1.0 W/m²K). The outer cavity of the triple-glazing hosts a high reflective, low-e coated venetian blinds, for solar and light transmission control. The upper part of the TSM is made of a triple-glazing, whose outer cavity is filled with granular, translucent, aerogel (with a nominal thermal conductivity: λaerogel = 0.009-0.012 W/mK), while the inner cavity is filled with Argon.

This MFM was conceived to play different roles during the year, by continuously adapting its thermo-physical behaviour in order to either maximise or minimise insulation and/or solar gain. The performance can be adapted to different boundary conditions. In summer, the control of the MFM would be aimed at reducing the solar gain (by means of cavity ventilation and integrated shading devices) and at promoting a time shift of the cooling load profiles (peak shift), thanks to the passive exploitation of the PCM layers. In winter, the goal is to achieve a high level of insulation and solar energy harvesting (i.e. by means of the LHTE, the control of the cavity ventilation and the solar shading).

The ACTRESS prototype demonstrated to have good performance and potentialities, especially in terms of present day needs, but it also highlighted some limitations. First of all, it was conceived as a module to be used for new constructions (specifically office, and commercial buildings). However, today in Europe the rate of new constructions per year is very low (1 % of the existing stock or less), while there is a growing request for solutions purposely designed for retroffiting existing buildings. The energy efficiency measures, in fact, can be better fostered and faster implemented by interventions on the existing bulding stock. Moreover, in the near future the buildings, together with electric vehicles, can play a key role in the development of the so-called "smart grids". In these networks the high share of electricity produced by RES poses a lot of challenges for the control and stability of the network itself; large and distributed thermal and electric energy storages are therefore required. The possibility of using, on the one hand, the building itself

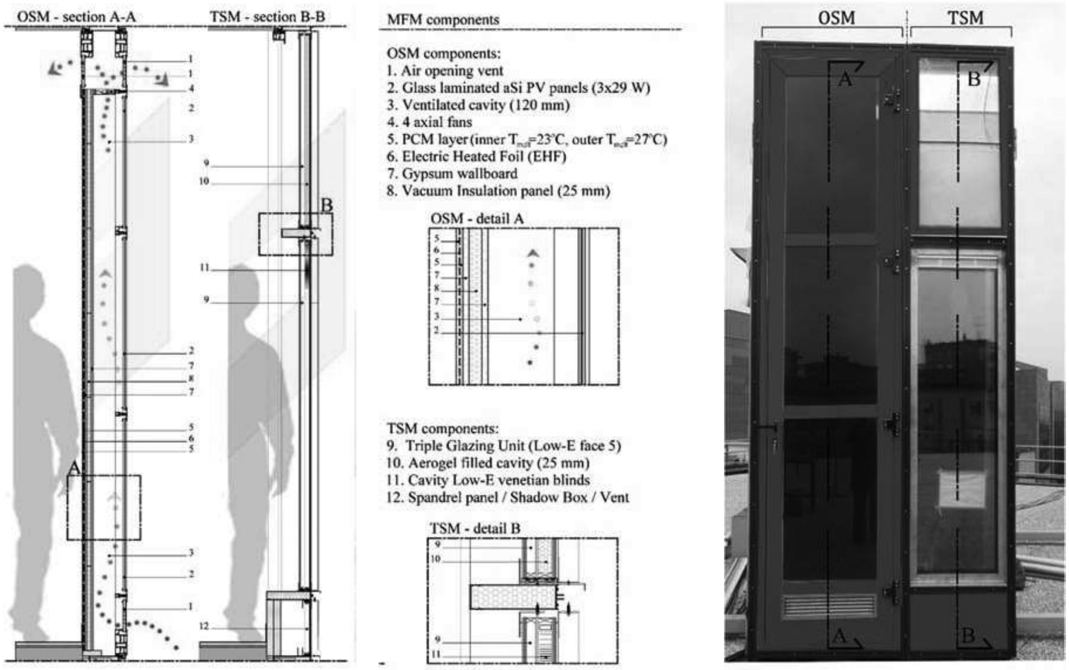

Figure 2 Scheme of the ACTRESS MFM components (left) and vertical details (centre), picture of the mock-up for the experimental investigation (right) (Favoino et al. 2016).

and its structure as a "passive thermal energy storage" and on the other to eventually implement the energy storage capabilities at the façade level (e.g with high thermal mass or PCM and with purposely optimized electric batteries), represents indeed a promising perspective. In this regard the storage capabilities of the ACTRESS module revelead not to be sufficient as, at the same time, it appeared appropriate to further increase its solar harvesting capacity.

The POWERSKIN$^+$ project

Based on the ACTRESS experience and its limitations a new concept of MFM is going to be developed in a H2020 EU project recently funded: the POWERSKIN$^+$ project (Figure 3). The technology proposed in this project represents the last advance of the MFM and is specifically aimed at tackling the challenges introduced in the previous section. POWERSKIN$^+$ will develop and scale-up eco-innovative, cost-effective and smart material solutions to renovate existing facade systems of both double skin and advanced integrated curtain walls. This MFM will integrate highly performing insulations and renewable energy technologies, with breakthrough features based on nano-formulated VIP, PCM, flexible thin glass, integrated solar cells and multi-functional nano-enabled coatings. This portfolio of technologies will be included into an off-site prefabricated plug-and-play system combining glazing and opaque elements, with a sustainable ecodesigned connecting framings and a dedicated large capacity electric building storage system.

Taking advantage of its modular nature, different combinations of POWERSKIN+ modules and add-ons can be set to match any specific need and refurbishment budget. In its full package, the POWERSKIN+ Upgrade, the system targets the deep renovation market and accelerates the transition to plus energy ranks, while providing a unique all-in-one envelope retrofit solution by combining 3 objectives: insulation/climate control, energy harvesting and storage, in the least invasive exterior building refurbishing way, with minimum adaptation and skilled installation required.

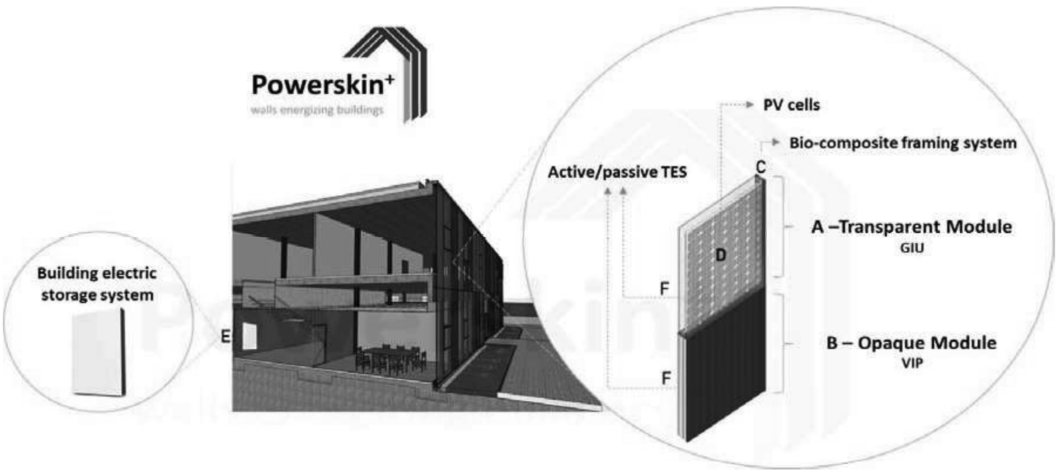

Figure 3 The POWERSKIN+ Concept .

The standard module (for nZEB buildings) will include:

- A prefab, low-e superinsulation glazing (A), which eventually exploits active thermal storage materials and heat exchange and thermal transport elements and HVAC components which are turning the façade into an organic component of the building (F);
- A prefab sandwich opaque module (B) with an incorporated novel generation of advanced nano superinsulation vacuum insulating panels (VIP) and an outer functional protective biopolymer sheet (C). PCM-driven latent heat storage elements for the opaque systems can be included (F), working with similar principles to the ACTRESS module.

- An innovative low cost and lightweight bio-composite smart framing system to integrate both modules on-site with superior installations cost reductions to replace conventional systems and designed for easy disassembly at the end of service, allowing full recycling and recovery of the modules.
- Finally, functional coatings will be applied to the transparent sub-module (self-cleaning, anti-reflective, photocatalytic properties and wavelength control for PV power generation, etc.) and opaque sub-module (UV weatherability, fire resistance, etc.) where appropriate.

The POWERSKIN+ *Upgrade* system, instead, is aimed at plus-energy buildings. With respect to the standard solution, it adds: a novel generation of flexible and highly efficient semi-transparent Photovoltaic Cells (PV) (D), to be integrated either on the transparent or opaque modules as solar energy harvesting solution and combined with a dedicated autonomous building electric storage system (E). Apart from module fabrication, smart controls will be designed and operated to control the active balancing of the cells/modules in terms of both capacity equalisation and heat generation management.

ACKNOWLEDGMENTS

POWERSKIN PLUS "Highly advanced modular integration of insulation, energising and storage systems for non-residential buildings ", Horizon 2020, Call: H2020-NMBP-ST-IND-2018-2020 (INDUSTRIAL SUSTAINABILITY), Topic: LC-EEB-01-2019. This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 869898.

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