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Adaptive facades, developed with innovative nanomaterials, for a sustainable architecture in the Mediterranean area

Paola Gallo[a], Rosa Romano[a *]

[a]*University of Florence, Department of Architetcture DIDA, via S. Niccolò 93, Firenze 50125, Italy*

Abstract

To respond at the European Directive 2002/91 on the energy performance of buildings, so to build a new generation of nearly zero energy buildings and, at the same time, to reduce the high emission and tiny air pollution particles, a challenging input is developing a new generation of multifunctional, adaptive and dynamic facades. These novel envelope systems allow answering the necessity to improve the indoor environmental quality and to facilitate the exploitation of renewable energy sources at the building scale. Adaptive building envelopes can be considered, in fact, the next big milestone in façade technology because they are able to interact with the environment and the user by reacting to external influences and adapting their behaviour and functionality.
The paper presents the research SELFIE that is focused on design, testing and construction of a smart façade system where will be possible to integrate new technological components of envelope. The innovative "SELFIE system" will be built, in fact, with smart materials and novel technologies to produce clean energy and decrease total consumption of the new and/or existing buildings. Furthermore, the components of the “SELFIE system” will be designed as preassembled elements that will be possible to compose in a modular façade to make new buildings envelope or replace the wall and windows in the existing ones.
In detail, the work introduces the research methodology used to develop the first design concept of the “SELFIE system”, with the objective to improve the knowledge in the field of adaptive facades and innovative technologies, able to increase the energy performances of the buildings located in the Mediterranean area.

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Keywords: Energy Saving, Adaptive Facade, nZEB, Renewable Energy

* Corresponding author. Tel.: +39-055-2755332; fax: +39-055-2755399.
E-mail address: paola.gallo@unifi.it, rosa.romano@unifi.it

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Nomenclature

SELFIE	Smart and Efficient Layers for Innovative Envelope
nZEB	nearly Zero Energy Buildings
PCM	Phase Change Materials
MFG	Mesopourous Foam Glass
IR	Infrared Reflective
LCA	Life Cycle Analysis
DSSC	Dye-Sensitized Solar Cell
PVB	Poly Vinyl Butyral
TiO2	Titanium Dioxide
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
PEFP	Product Environmental Foot Print

1. Introduction

Several key factors influence the evolution of building energy consumptions and emissions, including population growth, which increases demand for residential buildings and services. Building sector energy consumption grew 18% between 2000 and 2015, to reach 117 EJ – around one-third of global final energy use, producing about one-sixth of end-use direct CO_2 emissions. Furthermore, the buildings are responsible for the largest share of energy consumption and associated greenhouse gas emissions.

The challenge of the future efforts of the construction sector should be properly addressed by policies in order to mobilize the market towards a low carbon society and trigger multiple benefits (such as the independence from energy imports from politically unstable areas, job creation, improved air quality and indoor comfort, reduced fuel poverty etc.).

Near-zero energy consumption in new and existing buildings and communities is possible. Designing a carefully chosen research and development strategy will enable the building industries to move from incremental – to substantial – energy savings and reductions in greenhouse gas emissions. The aim of the implementing agreement for a program of research and development on energy in buildings is to take advantage of energy-saving opportunities to remove technical obstacles to market penetration of new energy conservation technologies for community systems and residential, commercial and office buildings.

To implement this strategy, research activities have to focus on building systems, decision-making and dissemination strategies. When buildings are constructed or renovated, a whole-building perspective is preferred, which involves considering all parts of the building and the construction process to reveal opportunities to improve energy efficiency.

In these perspectives, detail the building envelope's impact on energy consumption should not be underestimated. While whole building approaches are ideal, every day building envelope components are upgraded or replaced using technologies that are often less efficient than the best options that will be available if we invest in the innovation. These advanced options, which are the primary focus of the future in the construction, are needed not only to support whole-building approaches but also to improve the energy efficiency of individual components:

- High levels of insulation in walls, roofs and floors, to reduce heat losses in cold climates, optimized through life-cycle cost assessment
- High-performance windows, with low thermal transmittance for the entire assembly (including frames and edge seals) and climate-appropriate solar heat gain coefficients
- Highly reflective surfaces in hot climates, including both white and "cool-colored" walls and roofs, with glare minimized
- Properly sealed structures to ensure low air infiltration rates, with controlled ventilation for fresh air

- Minimization of thermal bridges (components that easily conduct heat), such as high thermal conductive fasteners and structural members, while managing moisture concerns within integrated building components and materials.

Analysis of building envelopes is complicated by the extreme global diversity of building materials, climates, and standards and practices of building design and construction, but it is vital to ensure for new and retrofit buildings, the use of the most efficient envelope technologies. Furthermore, the suitability of energy-efficient technologies depends on the type of economy, climate and whether the materials are being used for new buildings or retrofits. To achieve the large energy savings that efficient building envelopes can offer, full market saturation of high-priority, energy-efficient building materials is essential. [1]

2. Experimental program: the applied research work

In this frame what is the role of the innovation for systems and components in the future? Will we be able to change the existent technological systems and to develop innovative products in order to influence the building market or create new ideas capable of change to the life style of the people? The answer to this questions is achieve a sustainable good quality construction as a continue process starting from the new characteristics and new opportunities for the enterprises and develop new components, as the adaptive envelopes, with high efficiency in order to satisfy the construction market and to meet the demand for high-performance by the users. Market barriers preventing the adoption of energy-efficient buildings or building materials can be real or perceived. As well as simple failures such as a lack of knowledge about alternative options, they can include concerns about the performance, expected energy savings, reliability and service life of a new product. Some new construction materials and solutions oblige builders to completely change the way a building is erected.

For decades, architects and building scientists have envisioned the possibility that future buildings will possess envelopes that replicate our skin's adaptive response to changing environmental conditions. [2, 3] Advances in material technology and building automation systems are making these parallels drawn between adaptive envelopes and the intelligent response of human behavior and our own skin, to environmental stimuli, increasingly feasible for regulating energy flow through a building's thermal barrier in a controlled manner that benefits energy reduction and occupant comfort.

Static envelopes have limits to how much energy savings can be realized [4] as they are unable to take advantages of favorable outdoor conditions that would benefit the indoor environment consistently, as well as hinder occupant's abilities to modify the envelope to their needs. With seasonal variations, shifting weather patterns, and occupants' ever-changing comfort and energy needs, static envelopes cannot provide consistent climate control without HVAC assistance due to hourly changes in the weather, suggesting the need for dynamic controls [3]

Single variable adaptations (e.g. moveable and dynamic insulation, envelope daylighting control, operable windows, etc.) have been shown to provide energy savings and improved comfort [5, 6] alone and in combination under a variety of conditions.

Moreover, the target of the Energy Performance Directive of Buildings 2010/31/UE [7] and the Energy efficiency Directive 2012/27/UE [8] on the energy performance of buildings, the rising cost of fossil fuels in recent years, the high emissions and tiny air pollution particles, led us to the development of new façade systems. An appropriate envelope is, in fact, the main element in the field of sustainable building design, but in mild temperate and mesothermal climates, the rapid changing of outdoor conditions, additionally requires a dynamic response of building envelope parameters to allow the maintenance of good adaptive interior comfort. [9]

In this legislative and cultural contest, in Italy to overcome these barriers and stimulated by the scenarios provided by the European Community, the Italian Ministry of University and Research and the regional administration of Tuscany, has funded a research project SELFIE. It aimed to develop synergy between industrial companies, builders and research centers, to increase competitiveness in building sector and meet European and Italian standard requirements. The project aimed to increase the energy saving in Mediterranean climate, focusing on summer comfort, developing and testing innovative envelope solutions with national companies. The research, in fact, is mainly focused on the design, test and prototype of innovative components for adaptive building envelope, able to decrease the energy consumptions in line with nZEB target for existing and/or new buildings located in South Europe.

Furthermore, the research SELFIE aims increasing the knowledge on energy performances and technological features of these typologies of innovative building envelopes. The adaptive envelopes have showed a significant technology evolution in the last decade thanks to the possibility to integrate smart materials and building management systems. The adaptive facades are able, in fact, to change their architectural configuration and their energy features in order to answer in real time to the climatic conditions. [2]

Indeed, adaptive technologies embedded in the building envelope systems are considered to have the largest potential to minimize the energy consumption of buildings [10]. In particular, Double Skin Facades or Advanced Integrated Façades [11] and, smart glazing [12], movable solar shading [13], phase change materials [14] and multifunctional facades [15] are identified among the most promising adaptive façade systems and components in terms of energy reduction potential. [16]

For these reasons the SELFIE concept is foreseen like an adaptive system and SELFIE consortium gathers skills and expertise which cover three distinct research domains: design (conceived and engineered for flexibility and modularity targeting full customization to specific refurbishment requirements), materials (use of emergent micro and nano-materials and processing techniques in the functionalization of building parts for improved technical and functional performance), and engineering systems (i.e. integration of advanced control and monitoring systems for a smart behavior of the building envelope). Particular attention is paid also to architectural aspects, considering that the aesthetical acceptance constitutes an important barrier against a broad implementation of some energy efficient technologies in refurbishment projects.

3. Methodology

3.1. The approach

The research SELFIE will be developed by adopting an inductive and systemic methodological model that allows organizing the research work for consequential steps: from the definition of the macro-theme (focused on the issues related to the dynamic building envelope and the energy efficiency of the building) to the design and prototyping of an innovative adaptive façade. All the working phases are characterized by the energy performance analysis of materials, technological components and facade system, developed by simulations in virtual and real environment.

3.2. Work Packages

The work is divided in six Work Packages, organized as follows:

- Work Package 1 sets the design requirements of the façade SELFIE and its components (SELFIE model 1-2-3) through the analysis of technological features and functional, physic-chemical, energy and operational characteristics. In this phase will be analyzed all adaptive envelopes currently used in nZEB around the world, evaluating their architectural features and energy performances.
- Work Package 2 and 3 are focused on the characteristics setting of smart materials in order to guarantee energy storage, self-cleaning, anti-bacterial and anti-pollution and on the capacity of the innovative technologies integrate in the components to produce renewable energy. In the same phases will be produced small mock-ups of semi-finished smart materials substrates.
- The aim of the Work Package 4 is to develop a façade concept with the modular SELFIE components (model 1, 2 and 3). Moreover in this phase of project will be held an assessment of thermo-hygrometric potential (conducted with dynamic simulations) and environmental impact of the facade system.
- During the Work Package 5, a recognition of building management systems will be make to integrate in the SELFIE components, to control all internal comfort parameters.
- In the Work Package 6 will be realized a prototype of the facade SELFIE and it will be evaluate in the Test cell of University of Florence with the aim of assessing its thermal-hygrometric performances to reduce the energy consumption of buildings, located in the Mediterranean area. In the same time, during this operational phase, will

be start a market analysis to assess the commercial potential of these innovative technological solutions, as well as a campaign of scientific dissemination of the results, to spread the knowledge on a national and international level.

4. SELFIE components performance

4.1. The prototypes

The three prototype of facades components SELFIE will be realized how modular elements with a size of 90.0 cm x 140.0 cm, that can be assembled, with different geometric configurations in the SELFIE facade system (280.0 cm x 280.0 cm).

The concept of the three SELFIE components foresees several functionalized layers that could be separately assembled depending on the architectural design of the building where they will be installed. In the integrated solutions, the layers will be considered all together and performances will be tested as a whole. Among the different layers, two will be mainly devoted to the energy saving/storage. The first is a PCM loaded MFG. The second is a special innovative-coupled glass with an internal IR treatment. Other layers comprise functionalities such as visible photoactivable ceramic and/or metals and/or special paints devoted to the treatment of the air.

4.2. The performances

All three prototypes SELFIE will provide the following performances:

- *Reduction of energy consumptions and CO_2 gas emission.*

The Components will be designed to decrease the energy losses during the winter and overheating phenomena during the summer, thanks to the integration of innovative nano and smart materials in the transparent and opaque elements. All materials used are choose for their LCA performances so to decrease also the environmental impact of the whole system.

- *Wellness and health*.

The possibility to use photocatalytic paints and nano materials within the opaque panels, allows reducing internal air pollution due the presence of occupants or for the use of toxic glue, formaldehyde or other harmful materials.

- *Energy production*.

Innovative DSSC PV cells will be integrated in the SELFIE facade, to produce and use renewable energy in situ with the aim to decrease the whole energy consumptions of the building.

- *Reduction urban pollution*.

The use of photo catalytic paints and nano materials to realize also the external surfaces of the SELFIE components, will actively contribute to the CO_2 and/or other chemical pollutants reduction.

- *Management of buildings consumptions*.

An integrate energy management system will be embedded in the SELFIE components frames, so to guarantee a smart control of energy flows inside the building envelope and to ensure a “dynamic configuration” of the panels that allows changing their energy performance; in function of the external climatic conditions and of the indoor comfort required. Consequently the multiple combination of the SELFIE panel components, assure an aesthetic modulation of architectural envelope. Sensors and the equipment for data management will be integrated in all three SELFIE panel taking into consideration the accessibility for maintenance, the exposition to temperature and the easiness for electrical connection.

4.3. The experimental test

In order to analyze their energy performance, the SELFIE components, will be tested:

- *In the concept phase*, with simulations carried out under dynamic conditions through a virtual model able to evaluate the energy performances of the façade system in three climatic zones and with different assembly configurations and orientation;

- *In the executive phase*, monitoring the façade prototype in the test cell "ABITARE Mediterraneo" ownership Florence University.

5. The modular components

5.1. SELFIE 1 component

The component SELFIE 1 is an opaque panel composed of following layers from outside to inside:

a. A glass layer coupled by two simple glass sheets coupled through a PVB film compose the layer. Glass coupled sheets have a wide use in building façades, because coupling confers a higher resistance compared to a single sheet. In the SELFIE project the PVB will be merged with nano-materials, particularly nano-oxides and nano-metals able to maintain the transmittance of the visible light and to reflect in the IR zone.

b. A first internal layer realized with a panel of honeycomb, in the form of a porous ceramic charged with TiO2 material able to be activated with visible light to activate a purification effect of indoor air. This layer is a half-element of a system that allows the circulation of forced or natural air. The wide surface area of this material enables for a homogeneous distribution of the photo catalytic material that comes in direct contact with the air.

c. A second internal layer realized with a panel of mesoporous foam glass, loaded with polymeric PCM. It enhanced building components would have the ability to reduce energy consumption for space conditioning and reduce peak loads as well as improving occupant comfort, compatibility in comparison with traditional wood and steel framing technologies, and the potential for application in both new and retrofit applications.

d. A final layer realized with sealant that will be studied for coupling the foam glass with the materials from the inner lining. For this purpose, more sealants will be examined including glass based and polymeric sealants. SELFIE aims to produce a reliable MFG joined structure with high reaction to fire performance and high durability in environmental relevant conditions. The novel adhesives developed will ensure the absence of critical materials (i.e. rare raw materials, toxic compounds), an increase of the life-time of products, high moisture resistance, thermo-mechanical properties compatible to the new envelope system and the use of materials with small environmental footprint.

f. A panel of closure applied on a support frame in aluminum thermal break. This panel will be made with light materials with good mechanical properties able to ensure the mechanical safety performance needed for the interior space features.

The panel SELFIE 1 will be equipped with grid vents in correspondence of internal and external surfaces. These ventilation systems will allow:

- To reduce the energy consumptions for heating in winter months (when the internal grid vents are opened and external grid vents are closed) thanks the possibility to direct the pre-heating air inside passively
- To reduce overheating phenomena in summer months (when the internal grid vents are closed and external grid vents are opened) thanks the possibility to re-direct the heating air outside by air gap, reducing the internal temperature

The choice to place in this configuration a porous layer inside with phase change polymers will allow achieving good thermo-hygrometric performance, using materials with limited thicknesses.

5.2. SELFIE 2 component

The component SELFIE 2 is an opaque panel composed by following layers:

a. An outer layer in photovoltaic panels DSSC, to produce renewable energy, ensuring a good architectural integration. If will be necessary to increase the percentage of energy produced from RES this layer can also be realized with polycrystalline PV cells.

b. An insulating layer in phase change material.

c. An heat exchanger system in order to reduce building energy consumptions in the winter months and increase micro-ventilation inside the panel in the summer months.

d. A closure panel, operable for the maintenance of the heat exchanger system. This panel will be made with light materials with good mechanical properties able to ensure the mechanical safety performance needed for the interior space features.

5.3. SELFIE 3 component

The component SELFIE 3 is a transparent panel composed by following layers:

a. A window with thermal break frame with transmittance values of 1.2 W/m2K and a layer with a glass laminated sheet, with self-cleaning external treatment, coupled with PVB and nanomaterials in order to maintain the transmittance of the glass visible light and to reflect in infrared.

b. An air cavity, containing an electric shielding system designed to optimize daylighting inside the building and to reduce thermal overheating phenomena in the summer months.

c. A window with thermal break frame with transmittance values of 1.2 W/m2K and a layer with an external low emissivity glass.

In the external layer of SELFIE 3 it is possible also integrating DSSC photovoltaic cells, with the aim to produce electricity and shade interior spaces.

The SELFIE 3 should ensure the following energy performances:

- U value of 1.2 W/m2K, with a consequent reduction of thermal transmittance of the transparent parts of the buildings envelope
- Control of solar radiation thanks the possibility to regulate the shading device placed inside the air gap between the two glasses
- Improvement of acoustic performance of internal spaces of the building.

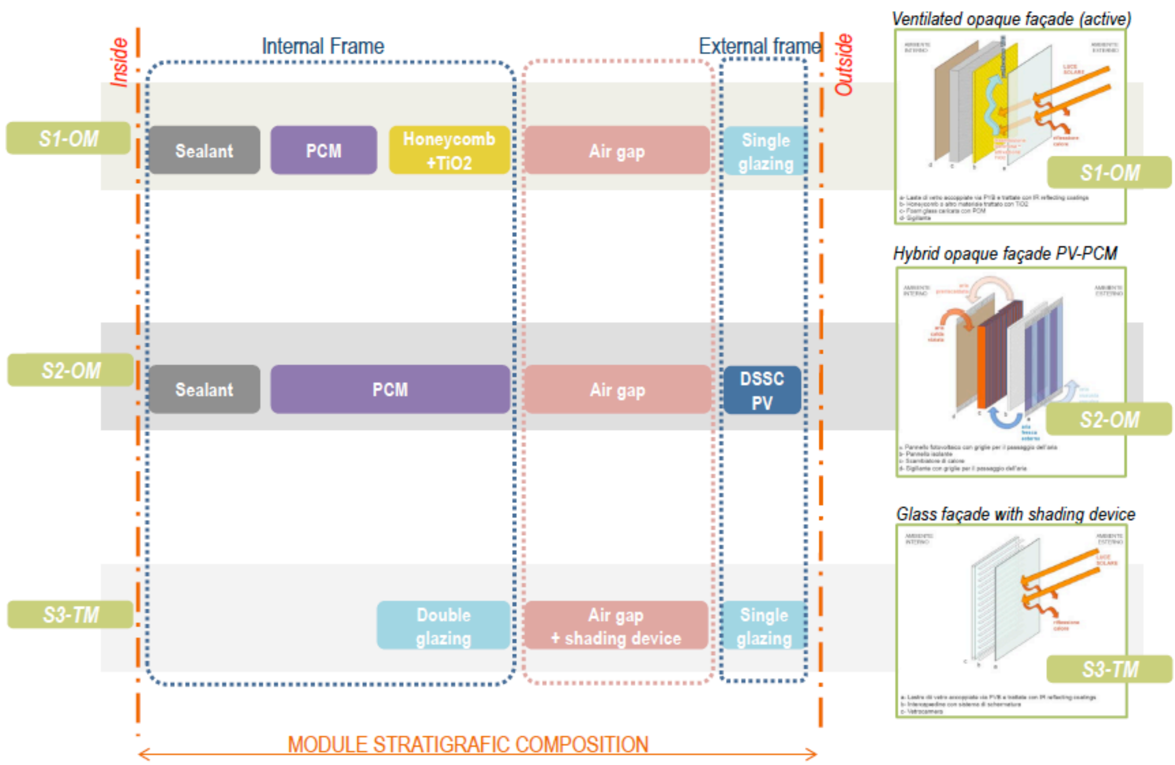

Fig. 1. Scheme with the stratigraphic composition of SELFIE Modules.

6. The SELFIE facade

The adaptive SELFIE facade will be realized as a unitized curtain wall system that allows an easy installation on building site. The SELFIE modular components can be placed in this technological frame with different geometric configurations, different types of materials and different colors in order to guarantee the customization of all façade system.

The SELFIE facade consists of fixed and mobile parts (opaque and transparent), which can be operated through automatic or manual controls to regulate the air temperature and air quality inside the building during all year.

Furthermore, the dynamic façade SELFIE will be designed to achieve good performance in the terms of:

1) Structural safety, ensuring:
   - Mechanical Resistance to static, suspended and dynamic (the wind and/or seismic actions) loads;
   - Shock resistance;
   - Fire resistance;
   - Deformation resistance;
   - Contact safety.
2) Indoor comfort, thought the control of the following parameters:
   - *Air permeability*, providing a good implementation of sealing layers, finish coatings and vapor barriers.
   - *Water tightness*, planning adequately junction points to avoid water infiltrations inside the panels
   - *Thermal transmittance*, decreasing thermal bridges and monitoring the temperature of the indoor surfaces. In particular the transparent SELFIE modules will have a U value at list of 1,2 W/m2K and the opaque SELFIE modules will have at list a U value of 0,20 W/m2K
   - *Hygrothermal insulation*, choosing materials and technological solutions to control the interstitial and superficial condensation phenomena that can reducing the thermal and mechanical proprieties of the façade system.
   - *Thermal inertia*, choosing materials and technological solutions to decrease the overheating inside the building during the summer months.
   - *Daylighting and solar protection*, guarantying integration of shadings device and nanomaterials in the glass panels to regulate the incident rays on the transparent surfaces.
   - *Acoustic insulation*, selecting insulating materials characterized by various density and bounding the presence of acoustic bridges in correspondence of the joints. The objective is to build a façade with an acoustic insulation of at list 50dB
3) Maintainability: the choose to use modular elements will be enable to repair (with isolated action of maintainability) the facade system without changing the global performance of the façade
4) Functioning, guarantying to the users to manage the façade also in absence of an automated system of control.

To achieve the objective to define the energy performances of the adaptive façade SELFIE, will be done dynamic energy simulations during the first year of the research. In this research phase will be developed at list three virtual model of the façade configurations analyzing their energy performance in an virtual adiabatic test cell located in three geographical area (Milan, Florence and Palermo) with three climatic conditions. The results of these simulations (energy saving for heating and cooling and thermal comfort index quantified by PMV and PPD will allow knowing which is the better façade configuration and the better orientation to reduce the energy consumption of the building.

In the same time will be developed a contribution analysis to define the LCA and PEFP of the three-façade configurations with the aim to choose the one with less environmental impact in terms of Kg/ CO_2.

After these steps, the best façade solution will be realized by the enterprise involved in the research. The prototype will be then tested for six months in the Test Cell Abitare Mediterraneo to evaluate:

- Thermal energy for heating
- Thermal energy for cooling
- Primary energy consumption for heating and cooling (assuming that inside the test cell is applied a ventilation system powered by electric heat pump)

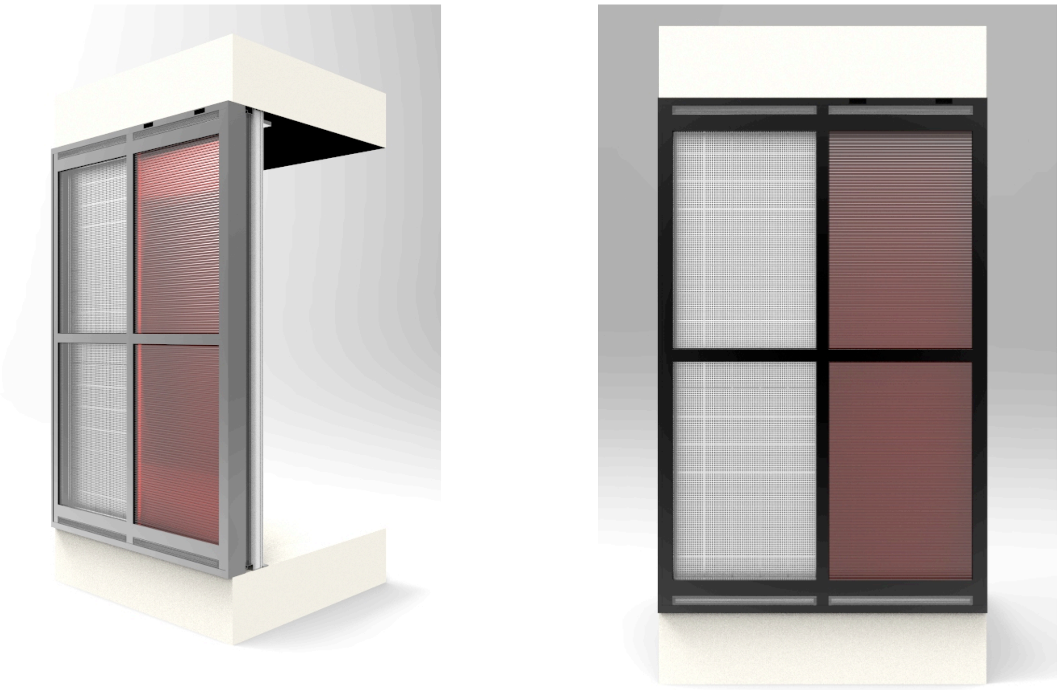

Fig. 2. Selfie façade. Architectural Configuration with the combination of Selfie 1 and Selfie 2

The measurements carried out will allow defining in detail also the thermal transmittance values and thermal inertia value of the three SELFIE panels.

Moreover, costs for ventilation system (heating - cooling) and the amount of kg of CO_2 produced from ventilation system in the management phase, will be evaluated.

7. Conclusion

Innovation in the construction industry may take place at a lower rate compared to other industries due to the structure and characteristics of the industry and projects, but it does, and must, occur in a competitive market.

Product innovation is, in fact, an important activity in corporate entrepreneurship and technology management. The successful introduction of new products into the market is a critical factor for the survival and growth of companies. However, the increasingly dynamic and turbulent environment in which firms compete makes the commercialization of new products not only a necessary, but also a risky venture.

Anyway, to unleash the full potential of energy savings related to buildings, the additional value of improved energy efficiency (e.g. improved indoor climate, reduced energy cost, improved property value, etc.) must be recognized, and the lifetime costs of buildings have to be considered rather than just focusing on investment costs. Over the last decade, building policies in the European Union increased in their scope and coverage; they are moving towards an integrated approach taking into account the energy, environmental, financial and comfort related aspects.

In this frame SELFIE project research show as the innovation within a project, company and occupational industry provides the opportunity to realize significant benefits and, in a competitive market, is a requirement for continued existence.

In addition, in an effort to catalyze innovation in environmental building performance, the impetus for SELFIE will be not to simply create new building products for architects, but to develop enabling technologies that both architects and engineers, could engage with in seeking a balance between aesthetics and efficacy.

The research project activities (skill up of smart materials the mockup of SELFIE components and the prototype of SELFIE façade) are started in March 2016. After the first phase of the research will be possible to launch the energy analysis to investigate the energy performances of these innovative technological solutions in real conditions. Moreover during the preliminary activity a database with 50 cases studies of adaptive envelopes will be realized an shared by official SELFIE research web site, to increase the knowledge in this field of the smart buildings.

The right number and the elevate professional expertise of partners involved (research centers and enterprises), will guarantee the success of the research and the effective possibility to develop new conceptual and operational tools to support the process of innovation in the field of adaptive envelope able to promote the NzEB buildings as request from EU directive.

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