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Nanomaterials and smart nanodevices for modular dry constructions: The project “Easy House”

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Abstract

This paper reports the preliminary experimental results of a research project aiming at applying innovative materials and devices to a new modular construction system, named Easy House. The goal of the project is to use specific enabling nanotechnologies to achieve a significant enhancement of thermal performances of the building envelope as well as visual comfort indoor. With this aim, we perform a synthetic chemical route to obtain stable and monodispersed amorphous silica nanocapsules containing phase change materials (PCMs). The first results deriving from *in vitro* toxicological analyses, here reported, showed that such structures are not harmful and they can be adopted as suitable capsules to host a PCM, typically used in finishing materials, acting as thermal buffers. Moreover, the paper reports the possible advantages deriving from the integration of chromogenic devices, able to ensure energy saving and optimizing the use of daylighting.

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Keywords: Sustainable housing; innovative building envelopes; nanomaterials; dry construction

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1. Introduction

The progressive depletion of fossil energy resources and the growing attention towards environmental issues, requires innovative building technologies enabling energy saving and exploitation of renewable energy sources.

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The research on nanomaterials has experienced, in the past years, a growing interest, with a specific focus on technologies used to mitigate energy demand. [1] Innovative materials and devices, deriving from the huge research effort in the cross-disciplinary field of nanotechnology, show several undisputable advantages: reduction of raw materials and of energy used in production processes, unlimited customization of shape, size, morphology and features.

The development of new construction techniques showing higher energy performances and the chance to reuse materials in buildings represent, nowadays, relevant quality indexes within the construction sector, which is spurred by relevant challenges involving the improvement of its manifold performances. Moreover, the environmental sustainability of future housing will be strictly connected to social and economical aspects. This conundrum inherently involves design aspects, relating the complex equilibrium between design tendencies, new technologies and available materials.

The project "Easy House" [2] is founded upon these premises, disclosing an innovative construction system aiming at the design of energy efficient and highly performing green buildings, with low costs and short completion time, fulflilling the requirements of safety, energy efficiency and percentage of recyclable materials (70%).

The here presented research project is based on the effort of a multidisciplinary team of researchers and designers, allowing the design of residential and commercial buildings with a modular and dry-mountable construction system based on lost formworks in composite materials. The structure is composed of shells and simple modular blocks easy to assemble, complete with special brackets and steel tie-beams allowing quick dry mounting, also easy to be disassembled and recycled/reused. The blocks' shape has been designed in order to take advantages of shape resistance principles (based on folded structures) and on special interlocking systems. Fig.1 includes an overview of the system and of its components.

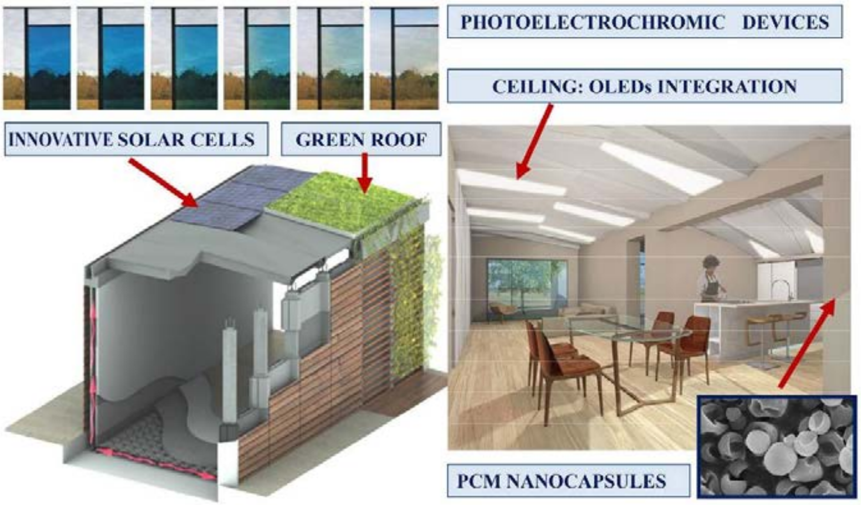


Fig. 1. Overview of Easy House system. Source www.gesimat.de.

The structure is then easily completed by mounting brackets, prefabricated reinforcing frameworks and pouring concrete in predisposed sections. This procedure dramatically decreases the execution time, and it is estimated that a 100 m^2 house can be fully assembled and finished within three working weeks. Then, the Easy House system allows to significantly reduce cost/m^2 and construction time, compared to any other building system. It would be ideal for social housing, retrofitting extisting buildings, urban regeneration purposes, consolidations and elevations, energy retrofit of existing envelopes and even industrial applications, like warehouses, large roofings, gyms and hangars, boat shelters, depots and roofings.

The research activities in progress for Easy House will focus on the potential building integration of specific nanomaterials, (aerogel, PCMs), and nanodevices (chromogenic devices, semitransparent photovoltaic glasses and OLEDs). In this paper, we illustrate the results of the very first steps of such research work. In particular, we show the highly customized synthesis of semiconductor nanoparticles, hosting specific classes of PCMs in their core. Moreover, we will show the current state of the art and the advantages deriving from the integration of electrochromic devices in glazings. Dynamic tintable glazings (electrochromic and photoelectrochromic devices) [3,4] are very promising technologies, allowing variable energy throughputs in windows, which are normally considered as thermal weak points in constructions but during the hot season, may conversely cause excessive solar loads that require HVAC systems, with an increase in energy consumptions. Then, controlling the transmitted energy fraction may contribute significantly to energy savings in buildings. The aim of this paper is to show the opportunities coming from innovative technologies in terms of energy savings applied to both new and existing buildings. In particular, most of the investigated technologies could be suitable for refurbishments and energy retrofitting, also in historical and cultural heritage buildings. In fact, as reported by Ascione et al. [5] new buildings are only 1% of the total European stock, while significant renovations regard about the 1.8% of the existing buildings.

2. Design philosophy

The innovation of the system is based upon seven fundamental points:

- simultaneous performances of the components;
- reuse of materials from excavation and/or demolition;
- form-resisting structures, with folded surfaces and stiffening ribs;
- implementation of high-performance and smart materials, through the integration of nanomaterials and nanodevices;
- implementation of high-performance building components, such as green facades, green roofs, microventilated facades, building-integrated photovoltaics, in order to achieve Nearly-Zero Energy (NZE) standards;
- building services fully integrated in the modular components and integrated with solar energy systems;
- Assembling easiness, through the adoption of a dry-mountable modular system.

Multidisciplinary Design Optimization (MDO) has been adopted as primary methodology, in order to reduce resource exploitment and to improve construction phases. As an example, techniques for stacking and compacting of modular components have been explored in order to reduce storage and transportation costs. Moreover, components' shape has been defined according to architectural and structural requirements, resulting in form-resisting spatially-corrugated geometries.

A validation of the theoretical approach has been carried out by means of digital and physical modelling. This phase has been essential in order to check the integrity of surfaces in the space. By means of 3D printing and laser cutting of Aluminium foils, 1:50 and 1:20 scaled prototypes have been produced in order to test geometry and assemblage. Once the final geometry has been identified, the production has been further implemented and metal formworks have been created in order to create prototypes in fiberglass reinforced plastic. Figure 2 includes the abovementioned design and fabrication process.

Fig. 2. Design and prototyping of roof elements.

Fig. 3. Roof elements’ components.

Fig. 4. Assemblage and finishing of roof elements.

Figure 3 shows the division of the roof element in its three major components: the upper shell, the bottom shell and the joining flange. The three components are made of the same material (fiberglass reinforced plastic) and are glued on site in order to create a monolithic component (Fig. 4). It is worth noting that the joining flange is designed in order to connect each roof element with the adjoining one. Steel cross bracings are finally used in order to stabilize the overall system. Design and fabrication of the wall shells has followed a similar procedure. In particular, wall shells have been ribbed and folded on three sides in order to create a shape with symmetricity around the horizontal median axis. In this way, rotating the panel around the symmetricity axis, it is possible to create the finished wall block using two identical shells. In this way the wall shells can be easily transported and their assemblage can happen on site (Fig. 5).

Fig. 5. Geometry and assembling scheme of wall shells.

Wall blocks and roof elements can either work as self-sufficient structural members or, in case of high horizontal or gravitational loads a steel or concrete frame can be added in order to reinforce the structure, as shown in figure 6. Once the external structural envelope has been created, further finishing layers can be added. Also in this case, the principle of dry assemblage has been adopted (Fig. 7). The building yard is, therefore, converted into an assembling factory, reducing the errors, typical of traditional wet construction techniques. Another undisputable advantage is the decrease of materials’ wastage, thus resulting in an increase of the sustainability of the intervention.

Fig. 6. Implementation of the system with additional structural components

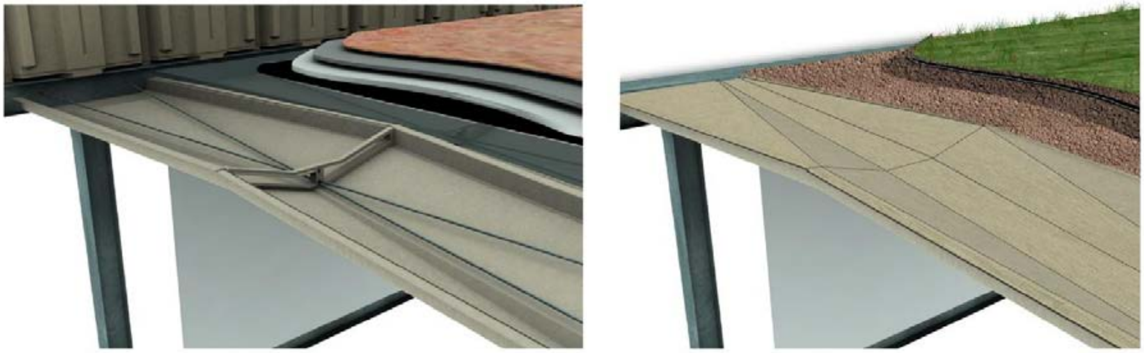


Fig. 7. Dry assemblage of wall finishes.

3. Role of materials

Nanoscale design of materials can dramatically improve their inherent properties, surprisingly, with several fallouts on processing, fabrication, costs of raw materials used, environmental impacts and, eventually, performances. These new opportunities in the filed of materials design, allow unprecedented design possibilities.

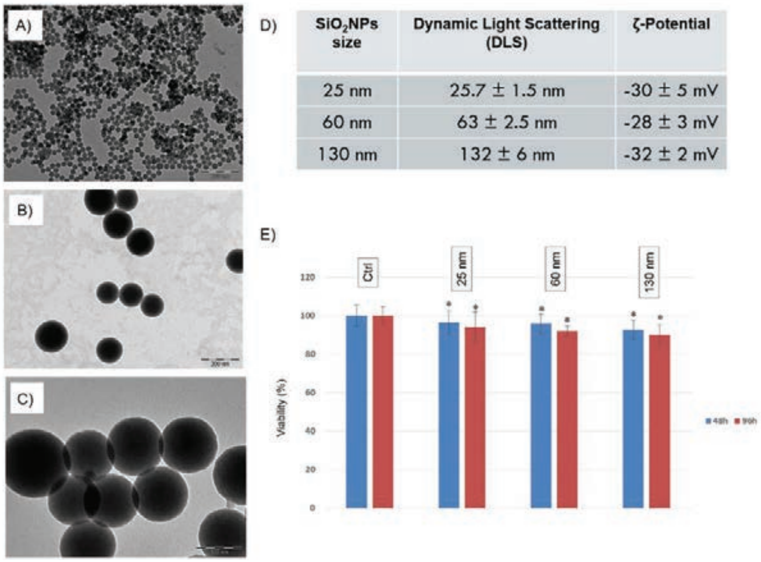
Starting from these assumptions, the project “Easy House” will investigate the manifold advantages deriving from two relevant enabling technologies: PCMs and electrochromic glazings, in order to improve the performances of both opaque and transparent envelope. The integration of PCMs encapsulated in nanoshells could improve energy efficiency of "Easy House". These materials show thermal buffering function due to their unique properties to retain and accumulate heat during day and subsequently release it when the temperature during night is low, with high melting enthalpy values. Nanoscale design of core-shell nanostructures will result in serveral advantages, respect to the state of the art and will be part of the scientific activities. The PCMs will be suitably chosen on the basis of their safety and their melting temperatures. In addition, this approach offers the chance to assess the effect of innovative nanomaterials in lightweight constructions like "Easy House", where PCMs are ideally embodied in order to make up for their low thermal inertia. Their use is ideal in building envelopes if embedded in cements, mortars, concrete and resins. The encapsulation of the PCM inside metal oxides as silica (SiO_2) nanocapsules could increase both the heat capacity and the diffusivity. In this way, these nanoenhanced PCMs are eligible candidates to address the application limits of already-on-market microcapsules (e.g. the use of flammable materials or plastic shells). Another relevant aspect, for the activities in progress, is to be the biocompatibility of novel nanostructures. In most instances, the commercial products employ capsules of polymers and paraffins, which could be toxic to human health. In the Easy House Project, we aim at designing biocompatible materials, even assessing their toxicity by means of "in vitro" specific assessments. On the other hand, electrochromism is considered a "green" nanotechnology [1], investigated worldwide among available chromogenic technologies. It has been reported that "smart windows" could effect an energy saving of 340 kWh/m^{2}y, due to the controllability of energy throughput. [6] Windows are multifaceted building components, affecting visual interaction with the surrounding environment, the use of daylighting as well as energy consupmtion, with non negligible concerns both in winter and in summer conditions. Granqvist et al. have reported that, in European climates, the energy annually used for cooling could be reduced by 50% adopting dynamic control of glazing transmittance instead of conventional glazings equipped with static solar control films. [7]

In the last decade, some of the authors of this work have gained experience and skill in the design of chromogenic devices and, for this reason, this project will represent, indeed, an interesting test. [8]

3.1. Nano-sized core-shell structures hosting PCMs

3.3 PCMs are a class of materials capable of absorbing, storing and releasing a large amount of heat at given, constant temperatures. In recent years, several researches have investigated the integration of latent thermal energy storage systems in building envelopes, with the objective of improving energy savings in buildings. The use of PCMs can be considered a valid alternative to storing large amounts of energy in small volumes at a constant temperature. They can absorb, store and release heat in the form of thermal energy. It is stored in PCMs during a melting process which is recovered, reversibly or with limited hysteresis, during freezing processes. [9] The heat of fusion of the PCM represents the change of internal energy during the phase transformations. The use of these materials reduces oscillations in air temperature; besides, it shifts the cooling loads in off-peak periods in order to decrease the electricity consumption and optimizes redistribution of the thermal loads in buildings. Inorganic and metallic PCMs show higher melting temperatures while salt hydrated, organics, solids-solids and eutectics PCMs are characterized by low melting temperatures. [10] Moreover, the first group also shows low heat storage capacity. The suitable phase transition temperature is the principal factor that influence the effectiveness of PCMs. In addition, the rapid melting and solidification of the PCM is desirable. Other relevant factors are high latent heat of transition per unit weight, high thermal conductivity and large specific heat capacity. The most used organic solid-liquid PCMs are paraffins. Paraffins of type C_nH_{2n+2} are saturated hydrocarbons with similar properties while paraffins between C_5 and C_{15} are liquids and the rest are waxy solids. In commerce, the paraffin wax is the most widely used organic PCM having melting temperatures between 23°C and 67°C. Among non-paraffin organic PCMs are fatty acids, i.e. compounds of carbon (C), hydrogen (H) and oxygen (O). Among inorganic PCMs, salt hydrates are the most studied group. They consist of a salt and water that combine in a crystalline matrix when the material solidifies. There are many different salt hydrates having melting temperature ranges between 15 °C - 117 °C. The thermal characterization of PCMs is essentially based on differential scanning calorimeter (DSC) and thermogravimetric analysis (TGA). As reported by Baetens et al., [11] the principle at the basis of PCMs, latent heat storage, can be applied to any porous building materials. Microencapsulation of PCMs is technically feasible especially for organic materials: it consists of core–shell structured particles, which have a liquid core surrounded by a polymer shell that prevents the interior PCMs from leaking during the solid–liquid phase change. [12] Products already on market tend to use paraffins. For example, the company BASF produces paraffin confined in microcapsules. In general, the microencapsulation is more functional to increase the heat transfer in comparation with macroencapsulation. Therefore, the closing the PCM inside a microcapsule, prevents the leakage of the material in its liquid phase. They studied lime plaster modified with Micronal PCM and pozzolana based on calcined kaoline mixed with milled mudstone. In the plaster, the introduction of paraffin capsules enhances the apparent specific heat capacity, if compared to reference materials. The heat flow in PCM-enhanced plaster reached about 0.6 W/g at 26.27°C (it was roughly 0.22 W/g in the reference plaster). The use of micro-PCMs shows limitations because the polymeric shells is flammable and the chemical stability and heat conductivity is low. [13] The size of the additives can be reduced to a nanometer scale; this reduction can enhance the suspension performance, specific surface area, and heat transfer performance of the additives. [14] Several studies were focalized on the application of silver nanoparticles or carbon nanofibers. [15] Tun-Ping Teng et al. [14] analyzed the effect of addition of alumina (Al_2O_3), titania (TiO_2), silica (SiO_2), and zinc oxide (ZnO) into paraffin to analyze the enhancement of PCM performance. The authors concluded that the TiO_2 NPs are more suitable than other nanoparticles type to enhance heat storage and thermal conduction. Therefore, they succeeded in reducing the temperatures of melting and increasing the solidification temperature. Ho and Gao [16] showed the modification of thermo-physical properties of paraffin, when added with Al_2O_3 nanoparticles. The mass fraction of Al_2O_3 nanoparticles increased the thermal conductivity and dynamic viscosity of the mixture, in non-linearly manner. Another study [17] investigated the effect of magnetite nanoparticles dispersed in paraffin wax obtaining an increase of thermal energy storage capacity corresponding to 20% after the addition of 10% of magnetite nanoparticles. This works showed that the dispersion of nanometer-sized materials in paraffin increases the thermal conductivity, though the toxicity of these materials on human health and environment has not yet been investigated.

Another approach reported in literature is represented by the nano-encapsulation of PCMs, having the advantage to increase thermal conductivity and mechanical stability especially in inorganic materials respect to organic materials. [18] Nano-enhancement of PCMs can also follow a different approach, consisting in the encapsulation of a PCM in a nano-shell [19] or a nanofiber, [20] with different preparation techniques, like electrospinning or miniemulsion. The choice of a suitable inorganic material as a shell for the PCMs is an interesting approach with the aimi of enhancing their properties. Among them, amorphous SiO_2 presents a stable structure and a defined surface. Therefore, it is safe, [21] biocompatibile, [21] promotes a high storage capacity, shows exceptional thermal conductivity and inert characteristics. For example, Zhang et al. [22] concluded that thermal conductivity of the encapsulated n-octadecane can be significantly enhanced by a silica shell. In addition, the heat storage and release during melting and solidification cycles is improved by core shell structure. Sari et al. [23] studied the thermal porperties of n-octacosane incapulated in a shell of PMMA (poly (methyl methacrylate): during their phase change, these nanomaterials reported energy storage and release capacity of 86.4–88.5 kJ/kg. Moreover, Kwon et al. synthesized nanocapsules of n-octacosane with a size lower than 100 nm [24]. In all cases studied so far, the size distribution was not specifically controlled.



SiO_2NPs size	Dynamic Light Scattering (DLS)	ζ-Potential
25 nm	25.7 ± 1.5 nm	-30 ± 5 mV
60 nm	63 ± 2.5 nm	-28 ± 3 mV
130 nm	132 ± 6 nm	-32 ± 2 mV

Fig. 8. A-B-C. TEM images of SiO2NPs (A-25 nm, B-60 nm, C-130 nm); D. DLS and Zeta Potential of 25-60 130 nm of SiO2NPs E. Viability assay of 25-60-130 nm SiO2NPs. Data are reported as mean ± SD from three independent experiments; *P < 0.05 compared with control (n= 8).

The analyses of studies reported above, emphasize the importance of encapsulation of PCMs to integrate them in building system “Easy House” in order to enhance energy efficiency by improving the thermal properties of its lightweight envelope.

As a starting point of our experimental activietes, we carried out “in vitro” toxicological assessments for the materials adopted. Consequently, we synthesized stable and monodisperse silica (SiO_2) nanocapsules with different sizes (25, 60, and 130 nm) by microemulsion method [25]. Nanoparticles were characterized by transmission electron microscopy (TEM) (Fig. 8 A-B-C) and Dynamic light scattering (DLS) in order to analyze the size distribution; zeta potential was performed to measure the surface charge (Fig. 8D).

As shown in Fig. 8, all the three sizes of nanoparticles were monodispersed and showed smooth surface. After this careful characterization of nanomaterials, we performed a viability test (MTT) following the procedure described in De Matteis et al. [26] in order to investigate the cytotoxicity of SiO_2 nanoparticles synthetized at different size (Fig. 8 E). This step was crucial to understand the safety of these materials which should be integrated in building envelopes, then in contact with humans everyday. The analysis was conducted on A549 cell lines (adenocarcinomic human alveolar basal epithelial cells): the choice of lung epithelial cells is strategic because the major exposure of nanoparticles in buildings is due to inhalation. We used a NPs concentration of 3 nM for 48 and 96 hours. As reported in Fig. 8D, the three sizes of SiO_2NPs, did not induce a perturbation of viability. Further experimental work will involve incorporation of biocompatible PCMs in SiO_2 shells, after a careful choice of suitable materials having a specific melting temperature and enthalpy of fusion.

3.2. Chromogenic devices for building integration

The EC behavior has been observed in a plethora of materials from the largely explored transition metal oxides, to conjugated polymers, and small molecules. EC oxides are typically subdivided into two main kinds: cathodic and anodic [27]. The former color under ion insertion, whereas the latter undergo an optical transition upon ion extraction, in a complementary fashion.

The most investigated cathodic EC material is tungsten oxide (WO_3). On the other hand, a typical anodic inorganic EC oxide is nickel oxide (NiO). The basic redox reactions of cathodic (and anodic) electrochromism can be simplified with the elementary reactions (1) and (2), regarding WO_3 and NiO [28]:

$$\left[WO_3 + H^+ + e^-\right]_{bleached} \leftrightarrow \left[HWO_3\right]_{colored} \tag{1}$$

And

$$\left[Ni(OH)_2\right]_{bleached} \leftrightarrow \left[NiOOH + H^+ + e^-\right]_{colored} \tag{2}$$

Since the 80s, EC devices [7] containing transition metal oxides consist have been investigated [29]. An EC device generally shows multilayered battery-like architectures, containing substrates, transparent conductive oxides, an ion conductor and one or two EC materials. As reported in equations (1) and (2), the chromic state varies when electrons are inserted (extracted, in case of anodic EC materials) into the cathodic EC material from the transparent conductive oxide and charge balancing ions enter from the electrolyte (or exit, in the case of anodic ECs).

On the other hand, photoelectrochromic (PEC) devices represent an intriguing class of “smart” devices [30], capable of sensing even small changes in external irradiation, acting as a stimulus to activate persistent changes in visible and infrared transmittance. PEC devices represent a relevant chance to design “intelligent” building envelopes, and to manage the complex energy flows passing through them. Like electrochromic smart windows, dynamic tintable PEC windows could achieve a consistent attenuation of energy consumption, cooling loads, and of the demand for electric lighting [31].

Since the first seminal letter to Nature, by Bechinger et al. [32], who described the first PEC device, embodying a ruthenium sensitized nanocrystalline titanium dioxide photoelectrode and a tungsten oxide layer, deposited by thermal evaporation on the counter electrode, several architectural modifications were proposed for such devices. Hauch et al. [33], from Fraunhofer-ISE, proposed a new PEC cell, showing some novelties in the mutual disposition of materials layers. In 2009, Wu et al. [34] disclosed the first ever photovoltachromic (PVC) devices, i.e. solar cells combining the photovoltaic properties of dye-sensitized cells and PEC properties. Such devices colored in short-circuit conditions under light irradiation, showing very fast coloration (4 s), and fair photovoltaic characteristics (η=0.50%). A fast bleaching time was also demonstrated (about 40 s), due to the presence of the platinum catalyst. It was the first demonstration of a glass showing smart coloration and photovoltaic characteristics as well.

An innovative design for PVCDs was proposed by some of us in 2010 [35], with a specifically designed counter electrode, ao as to allow distinct operations on the two available external (photovoltaic and photoelectrochromic) circuitries. We obtained smart control of optical transmittance modulation and the highest photovoltaic efficiency reported in literature for PEC cells (η=6.55%). A different approach was demonstrated in 2014, with highly transparent organic dyes sensitizing full-area mesoporous TiO_2 photoelectrodes and a suitably designed comb-like pattern for bi-functional counter electrodes, consisting of two physically separated series of stripes made of tungsten oxide and platinum, respectively, resulting from the combination of physical vapor deposition and lithography-based microfabrication processes [36]. Recently, for the first time, a semi-transparent perovskite photovoltaic film was used to smartly activate solid polymer electrolyte-based electrochromic, in a newly conceived solid PVC device [3]. The photovoltaic layer showed high transmittance, due to the customized dewetting of the perovskite islands, allowing the formation of discrete micron-sized islands.(η=5.5% and ΔT=26%) Since only a part of the energy produced by the semitransparent PV film was required to activate the smart tinting, it offered the chance to deliver external power.

It was also demonstrated that a dynamic tinting gradient of glazings can increase indoor visual comfort, though allowing visual interaction with the surrounding environment, even when operating as a shading system. Effectiveness of the integration of PVC devices in windows was also studied [4] predicting an increase of UDI of up to about 72% as an average value in a standard office room. An additional demonstrated benefit was the reduction of intolerable glare to less than 12% of occupied hours. Model simulations and experimental investigations will be carried out in order to assess the manifold beneficial effects of smart windows in Easy House envelopes.

4. Conclusions

An innovative system for dry prefabricated construction of modular homes has been here presented. The project is the result of an international collaboration involving three universities and a small-medium enterprise (SME). Extensive laboratory activities have been carried out in order to characterize smart nanosystems based on PCMs and chromogenic devices. The final aim was to assess the potential benefits due to the integration of these nanosystems in the prefabricated construction in order to improve its energy performance and sustainability. The preliminary results demonstrate positive characteristics of both nanoencapsulated PCMs and chromogenic devices to be integrated in building envelopes. Further experimental and simulation works will then quantify the benefits of the adoption of these materials in the Easy House envelope.

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