The integration of selected technology to energy activated ETICS - theoretical approach

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Abstract. The main goal of this study is to develop the new external thermal insulation composite system (ETICS) by integration of flexible photovoltaic (FPV) and encapsulated phase change materials (PCM). This work is the first step of the international project En-ActivETICS and concerns mainly material selection and systems integration issues. The paper presents a complete solution of façade component which integrates thermal insulation, heat storage and electricity generation - En-ActivETICS that combines ETICS technology with a self-supporting flexible photovoltaic elements. This system will be applicable for both masonry or concrete constructions and it is a new step in the development of building facade technology allowing to achieve a component classified to the group of functional material. In the paper, the formulation of basic principles of En-ActivETICS as well as an overview of existing materials and technologies is presented. Finally, the initial concept of the system is described. The main features of that system is using an elastic, high heat capacity and frost resistant adhesive joining flexible PV with thermal insulation.

1 Introduction

Nowadays, buildings are increasingly expected to meet higher and more complex performance requirements: they should be sustainable; use zero-net energy; foster a healthy and comfortable environment for the occupants; be grid-friendly, yet economical to build and maintain [1]. A better building energy performance is one of the EU priorities from the beginning of the 21st century [2]. To boost the energy performance of buildings, the EU has established a legislative framework that includes the Energy Performance of Buildings Directive and the Energy Efficiency Directive. The completion of this new energy rulebook – called the Clean energy for all Europeans package - marks a significant step towards the implementation of the energy union strategy, adopted in 2015. This strategy leads directly to the development of nearly-zero [3,4], net-zero [5] or plus-zero [6] buildings even in moderate, cold or severe climatic conditions. This goal is possible to be met by the decrease of the energy demand but also by the usage of the renewable energy sources on-site [7].

In net-zero energy building, the electricity is commonly used to cover energy demand for heating (cooling), ventilation and domestic hot water [8]. Moreover, in modern buildings, it is also necessary to cover an auxiliary energy demand making electricity a dominant form of energy. One of the efficient and justified technology to provide clean, renewable electricity to cover primary energy consumption in buildings is

photovoltaics [9]. As an application of the photovoltaic (PV) technology, building integrated photovoltaic (BIPV) systems have attracted an increasing interest in the past decade, and have been shown as a feasible renewable power generation technology to help buildings partially meet their load [10]. The BIPV are usually performed as a roof or façade integrated systems depending on the size and shape of the building. Although roof photovoltaics are easier adjustable to the optimal slope angle, its application is limited by roof area and other technical issues caused by e.g. presence of HVAC units and/or watertightness of roof junctions. Therefore, especially in the city centres, the façade integrated PV became more and more popular. The existing systems are based on the rain screen cladding system using different cells technology [11]. In addition to the less favourable angle of inclination, facade systems are also exposed to temporal overheating. As it is well known, an increase of panel temperature adversely affects their performance [12]. Therefore, in the case of systems integrated with walls, it is necessary to use intensified ventilation [13] or other thermal stabilization methods [14]. The application of thin phase change material layer on the inner side of PV cells is one of the promising solutions to effectively decrease their temperature [15,16]. As it was revealed by Curpek et al. [17] the influence of the phase change material layer on the PV operating temperature can be even more than 10 K in daytime hours. The combining of aluminium fins integrated with phase change material container was

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considered in [18] giving temperature reduction higher than 30 K when compared with single flat aluminium plate.

The main goal of this study is to develop the new external thermal insulation composite system (ETICS) by integration of flexible photovoltaics (FPV) and encapsulated phase change materials (PCM). This work is the first step of the international project En-ActivETICS (TRL 2-5) and concerns mainly material selection and systems integration.

The motivation for energy activation of ETICS is still a huge potential of the existing façade renovation as well as thermal requirements for a new constructed buildings in EU. In Poland, more than 70% of existing buildings do not meet the criteria of the thermal insulation and should be energy renovated in the nearest future. Nowadays, façade integrated PV panels are less than 20% of current BIPV market [19] and are based only on the ventilated, cladding technology which is expensive and inflexible solution, having multiple restrictions due to inherent design limitations. Innovative En-ActivETICS that combines ETICS technology with a low cost, self-supporting flexible photovoltaic element will offer a complete façade solution integrating thermal insulation, heat storage and electricity generation. This system will be applicable for both masonry and concrete external walls in a need for energy renovation.

The main objectives of the study is to formulate basic principles of En-ActivETICS as well as an overview of existing materials and technologies in photovoltaics and phase change materials to be implemented in the future developed En-ActivETICS.

2 En-ActivETICS requirements

The rule of thumb is that façade of a building should be rain tight and in cold climates vapour tightness of building envelope should decrease in moving indoor to outdoor. PV panel is vapour tight comparing with other material layers in ETICS that is contrariwise to previous rule. It means that combination of ETICS with BIPV is a great challenge from moisture safety point of view.

Hygrothermal performance of ETICS is mainly determined by its robustness against hygrothermal loads such as temperature and humidity from indoor and in addition to latter, solar radiation, wind and precipitation from outdoor. Therefore, vapour diffusion from indoor, built-in moisture as well as water leakages from outdoor are the main sources for excess moisture. ETICS is declared to be an acceptable solution in terms of reinforcement corrosion although vapour tight thermal insulation e.g. PIR/PU(R) in combination with high levels of built-in moisture should be avoided [20]. Concerning defacement of ETICS, surface condensation depending mainly on the orientation of the wall might be a preponderant factor [21] in addition to wind-driven rain (WDR), drying process of the wall and pollutants in the surrounding environment. In general, ETICS performs quite well in cold and moderate climates when the detailing of joints and openings are well done, i.e. there is no rainwater leakage [22]. In the comparative

analysis of field studies against dynamic calculations, it was discovered that convective moisture transfer between the concrete wall and thermal insulation covered with ETICS might appear [23]. Drying out of the constructional moisture from the original wall could cause an increase of the moisture content in the structures above the critical level [24–26]. It is shown that drying out only by diffusion might take up to eight years [27]. Concerning high WDR for instance in Norway it is concluded that one frequent cause of the defect is the incorrect assembly of the components of the ETICS [28]. Each layer of ETICS needs to fulfil specific requirements while the performance of the layer can be altered by material selection, design, and on-site construction activities [29]. Therefore, the proposed concept must be specified, studied and further developed by theoretical study, calculations and laboratory tests in technology readiness levels (TRL) to come. Special requirements will be set on the materials and workmanship.

Based on the selected articles [30,31] reviewing the properties, requirements and possibilities of future thermal insulation materials it can be observed that there is a strong need for the new, smart technologies on thermal insulation market. There is no doubt that thermal insulation materials of the future will have to be still characterized by excellent insulating properties but simultaneously should reveal the ability of its properties adjustment to dynamic thermal conditions. There are different concepts of achieving those assumptions [32]. One of the most promising ideas is to utilize the effect of latent heat accumulation induced by the phase transition of material caused by natural, diurnal temperature fluctuation.

The proposed Energy Activated External Thermal Insulation Composite System is a realization of the concept of functional building component with alternate and self-regulating physical properties and on-site energy production. The idea of how to develop smart, self-regulated and energy active building component is based on the combination of ETICS with phase change material and FPV cells. The external, traditional based cement plaster is substituted by the thin-film FPV layer. The FPV panels are placed externally and any sensitive parts, e.g. joints should be protected against weather conditions. Especially it should be watertight and mechanically resist. For better temperature stabilisation the additional layer incorporated selected and encapsulated PCM is applied directly behind the FPV. Taking into account the limited area of a single FPV panels, electrical connection will be placed in the adhesive layer. Additionally, the main cables should be routed by the specially designed duct to the building interior.

3 Flexible PV technology

Integration of the photovoltaic panels with a building envelope allows to produce electricity for on-site requirements. Building integrated photovoltaic (BIPV) systems applicable at the roofs, facades or balconies are

wide and dynamically growing branch of technology in recent years. BIPV is characterized by various efficiency depending on the type of photovoltaic cells [10,33]. Two different types of PV panels are mainly used – wafer crystalline silicon panels or thin-film flexible modules. Wafer crystalline silicon PV cells, 1st generation of the PV cell, have many advantages like high efficiency and wide availability on the market [34]. However, these PV panels are characterized also by high manufacturing cost and high weight, which determine the requirement of subconstruction to integrate with the building envelope. Therefore, high potential in the BIPV market reveals thin flexible film photovoltaic panels that have many advantages such as low production cost, lightweight, suitability for curved surfaces or installation without additional subconstruction. The most popular flexible thin-film solar cells are CIGS, CdTe, and a-Si. However, the thin layer of crystal silicon can be also produced as a flexible module as well as emerging solar cells like Perovskite or Quantum Dots [35].

Manufacture of thin-film solar cells is based on the deposition of thin layers of photovoltaic materials on selected substrate to establish a heterojunction barrier. Thin-film solar cells have lower temperature coefficients and better sensitivity to diffused radiation than crystalline silicon PV [36,37]. The substrate of the thin-film solar cell define the shape and mechanical parameters of the final PV panel. Many researchers were performed to analyse different flexible substrates materials over the years including metal foils (Mo, Ti), polymers (PI, PET), paper or ultra-thin glass [38]. Type of substrate and deposition technology have significant influence on the final efficiency and temperature dependency of a flexible photovoltaic cell.

Mentioned thin-film solar cells have individual advantages and disadvantages. CIGS panels have the highest efficiency, about 20.4% (polyimide substrate), while the CdTe maximum efficiency is at the level of 16.4% (flex glass substrate) and for a-Si only 11.2% (PEN substrate). However, the manufacturing of CIGS is the most sophisticated in comparison with CdTe and a-Si. Subsequently, the stability of a-Si is low because of the degradation of its efficiency under light impact (Staebler-Wronski effect). Moreover, the CIGS contain toxic Cadmium while the component of CdTe Tellurium is scarce raw material [39].

At the market, there are also available thin flexible crystalline silicon solar cells characterized by high efficiency of about 20%. They are produced from very thin silicon wafers to obtain flexibility. However, the thin crystalline silicon solar cells flexibility is limited by the radius of curvature [40]. Furthermore, the manufacture costs of these PV panels are significantly higher compared to flexible thin-film panels.

The flexible solar cells are a promising technology, especially for BIPV application because of their low weight and possibility to fit to curved surfaces. At the market, there are available CIGS, CdTe, a-Si and flexible crystalline silicon. All of the proposed above seems to be useful for further consideration as an external coating of energy activated ETICS. However, many research activities are still ongoing to improve

existing technology or develop novel materials, therefore new products are expected to be on the market in the nearest future.

4 Thermal stabilization technology

Mechanism of thermal accumulation can be classified as sensible, latent or chemical energy storage. Due to high density, small size of the system and narrow operating temperature range, the latent heat storage became the most important among other systems in building application [41,42]. During the phase transition from solid to liquid materials absorb heat in the endothermic process [43]. Due to the greater freedom of movement, material molecules have higher energy in the liquid state than in a solid form [44]. When the temperature drops below the melting point, PCM returns to the solid state and releases heat in the exothermic process.

In 1983, the classification of PCM based on the chemical composition was proposed by Abhat [45] and acknowledged by many authors till present time [43,46,47]. The three main groups of compounds can be distinguished: organic, inorganic and eutectic PCM.

The most commonly used PCM for thermal stabilization of PV is paraffin [48,49] composed of saturated hydrocarbons with various lengths of straight chain alkane mixture ($\text{CH}_3\text{-(CH}_2\text{)-CH}_3$). Due to the large amount of latent heat released during the crystallization process of alkane chain, the latent heat of fusion and melting point of specific paraffin increase with the length of the alkane chain [50].

Other organic PCMs that can be considered for building application are fatty acids, described by the general formula $\text{CH}_3(\text{CH}_2)_n\text{COOH}$. As in the case of paraffin, the higher carbon number results in the higher both latent heat and melting point. Other properties significantly depend on the purity of fatty acids. This group of PCM is not as popular as paraffin due to low flashpoints of fatty acids, instability at high temperatures, a varying level of toxicity, unpleasant smell and around 2-2.5 times higher cost [50].

The group of inorganic PCMs suitable for building applications is represented by salt hydrates with the general formula $\text{M}\cdot n\text{H}_2\text{O}$, where M is the inorganic compound. During the melting process, salt hydrate decomposes, forming water and lower hydrated salt. Due to the difference in density of these two compounds, solid salt settles down in the bottom and is not available for recombination with water in the subsequent freezing process. This phenomenon is called an incongruent melting and is irreversible. The second main drawback of salt hydrates is sub-cooling during the solidification process. This means that latent heat is released not at the melting point but at a lower temperature when crystallization begins. This phenomenon is caused by a low nucleation rate at the fusion temperature but can be overcome by adding an appropriate nucleating agent with a crystal structure similar to that of the considered salt hydrate.

PCMs can be combined with building materials in different forms: micro- or macro-encapsulated, shape-

stabilized, or as direct impregnation of a porous material [51–53]. Depending on the form of PCM, it can be used as an independent component or may be integrated with other materials. In some cases, it limits the application of the amount of PCM in the wall. In the literature, the most frequently investigated form is a micro-encapsulated PCM integrated into a drywall panel as the interior layer of the external wall [54].

Another group of PCM applications is characterized by macro-encapsulation. Nevertheless, this solution requires integration with the insulation or construction material and, in most cases, cannot be used in every desired configuration. The application of PCM as an independent component is more flexible and offers the possibility of implementing a larger amount of PCM. One of the techniques makes it possible to incorporate PCM in thin, sealed polymer pouches, arranged in sheets laminated with aluminium foil on both sides, known as a PCM thermal shield (PCMTS) [55]. Another possibility for the PCM's incorporation into the wall is the application of a shape-stabilized PCM (SSPCM) [56]. A component with a PCM content of 80% can be obtained by mixing low-density polyethylene with paraffin [51].

5 System integration

5.1 PCM encapsulation

The easiest and probably the most economical way for implementing the PCM into the insulating panel consists of simple mixing the paraffin into a suitable carrier matrix. The important advantage results in easy adjusting the phase change temperature to any desired value by selection of the appropriate paraffin and simple mixing the basic materials with additives, what allows to select the temperature with the precision to 0.1°C as well as to prepare the PCM with absorbing or releasing the heat within desired, even rather broad, temperature range.

However, two problems appear when applying the encapsulation method. First, while the two-phase system, i.e. carrier material and immiscible but compatible solid PCM (below its melting temperature T_m) is stable, at the temperature over T_m , the PCM turns to liquid state and starts to flow slowly out from the carrier. This can be solved by coating the PCM droplets into appropriate capsule preventing the escaping the PCM out. However, this created another problem consisting in thermal expansion of the PCM, especially by different density of solid and liquid material even at the same temperature, and the density change with changing temperature might be dramatic. Therefore, rather sophisticated system must be developed to design the suitable encapsulated PCMs with desired ultimate physical properties but also acceptable considering the expenses of high-volume production.

Thus, the optimization of the PCM encapsulation composition and processing will be one of the important partial steps regarding the construction of the En-ActivETICS panel. The procedure will consist of the determination of the parameters of ultimate PCM properties, such as thermal capacity, melting temperature

and the optimal temperature range of melting, as well as the material from which the capsule will be produced. The consequent task is aimed at the production technology to achieve the effective production from both technical as well as economical points of view.

5.2 Coupling of selected components

As BIPV is directly exposed to outdoor temperature and solar radiation, it has a large range of thermal expansion as well as sub-zero temperatures (°C) in cold climates between BIPV and PCM. Hence, elasticity, adhesion and frost resistance of the glue used to attach BIPV determine the durability of the system. In addition, glue should have high thermal conductivity and limited thickness in order to conduct heat between BIPV and PCM. In addition to regular joints of ETICS, there are joints of electric cables in En-ActivETICS and transition between different materials of the façade – dark coloured BIPV against rather light coloured plaster.

En-ActivETICS wall system consists of seven main layers, see graphically Fig. 1 in chapter 6:

- Mineral substrate (concrete or brick wall);
- Adhesion mortar;
- Thermal insulation (rigid);
- Reinforced adhesive sub-plaster / drainage layer;
- PCM;
- Glue;
- Flexible PV.

In façade sections without PV-s, finishing plaster replaces PCM, glue and flexible PV. In their thorough study about on-site degradation factors carried out in Estonia, performance and failures were presented layer by layer [29] (reference applies to all until the same reference appears again – still, referred sections are upgraded by the authors of current paper).

Starting with a mineral substrate, it should be able to resist the additional loads caused by ETICS as well as assuring sufficient bond between the wall and the rest of the layers. It is advised that substrate irregularities should be pre-treated (filling gaps and crack as well as evening bumps) and the minimum bond strength is 0.08 N/mm². In case of substrate is very smooth, rubbing treatment should be applied. Substrates with biological growth, dirt, oil or similar create an adhesion prohibiting layer while old paint can create a chemical reaction between the layers. Temperature and RH of the outer layers of the wall should not be too dry or too wet.

A layer used to attach thermal insulation to the substrate is adhesion mortar or PU foam alternatively. Mortar can be applied as bead-point method or by using a notch towel to cover a full area. The bead-point method foresees that the insulation plate's border zones and the middle section are covered with adhesion mortar in a reach of 40-100% depending on the type of mixture and thermal insulation used. The middle adhesion dots in case of a bead-point method prevent the arching out, which can cause a crack formation near the edges. The adhesion on the borders prevents the bending out of the sides, which causes crack formation directly on the edge of the plate. The mortar must stay only on the given area

of thermal insulation and not incur on the sides. On the other hand, mortar must not stay away from the edge, causing air leakage along the façade and being a risk in terms of fire safety. The amount, i.e. thickness of adhesion mortar must be in a range given by the producer. In case of mineral wool, mortar must be rubbed into the surface of thermal insulation. As applying adhesion mortar is related to properties of mixture, its ingredients, storage conditions and application process must fulfil the requirements such as amount of kneading water, pureness of water, duration and method of mixing, the amount of aggregate (sand), binder (cement), and other admixtures (including winter-time admixtures), temperature and humidity conditions in the time of applying as well as drying of adhesion mortar.

Coming to thermal insulation, its hygric shrinkage due to production process must have ended by the time of issuing and its dimensions must be within the given tolerance. It must arrive at the building site inside a sound package and temporarily stored while being protected by moisture, UV radiation and mechanical damage. Thermal insulation plates must be installed without cross joints, including corners of windows and doors. Plates must be mounted tightly side-by-side, aligned vertically as well as horizontally. Use of small plates or remainings is not allowed. In addition, fire regulations must be followed, e.g. mineral wool is used instead of EPS in order to limit the spread of fire. Application of the thermal insulation to the wall must be carried out with enough pressure to the adhesion mortar. Thermal insulation plates must be placed in not more than one layer in thickness according to requirements of most producers of plastering systems.

In general, thermal insulation is attached to substrate by using the mechanical fasteners in addition to adhesion mortar (or PU foam alternatively). The key finding in order to prevent failures due to mechanical fasteners are a suitable type and length of an anchor considering the material of substrate, diameter, depth and cleanness of the hole, amount and location of anchors, depth of anchor plate inside the thermal insulation.

The stresses caused in the system are transmitted to the reinforcement mesh in the applied mortar. During the installation, the layer should be applied in wet to wet conditions and the mesh should be pressed into the mortar, followed by the installation of covering mortar shortly. Proper mesh must be used in a mortar having a required thickness. Mesh must be free of folds, not broken and without hollow areas. Sufficient overlapping is necessary as well as additional diagonal nets on the corners of openings, installed together with the main mesh. The surface of the thermal insulation must not be too smooth in order to achieve sufficient bonding.

In façade covered with regular ETICS, finishing plaster is beside aesthetic function responsible for weather protection. To prevent cracks having a thickness of 0.2 or 0.3 mm, a primer should be applied if the system producer requires it. The application process must be carried out in acceptable climatic conditions (moderate temperature, cloudy weather, no strong wind) by ensuring the required thickness of the plaster.

Mineral, silicone and silicate are the preferred types of plasters, advisably with low liquid water conductivity and high vapour permeability.

In addition to layers of regular ETICS handled, detailing tends to determine the overall performance of the system. Therefore, the following aspect should be deeply evaluated during design, development and construction - structural expansion joints, window sills, rainwater drainage, fixed frames, roof edge covers, plinth details, penetration through the system and solutions for shock resistance (i.e. no double reinforcement mesh where need, corner details etc.) [29].

When it comes to façade covered with En-ActivETICS, analysis and development of the concept will be carried within the project out in order to bring the proposed technology from TRL-2 to TRL-5. Therefore, following relevant material properties as well as functions of hygric environment are needed for reliable hygrothermal analysis to come:

- bulk density,
- porosity,
- water vapour permeability,
- liquid water conductivity,
- sorption curves,
- thermal conductivity,
- specific heat capacity,
- air permeability.

Other properties to be analysed and tested but not simulated:

- thermal expansion,
- hygric expansion,
- frost resistance,
- tensile strength,
- adhesion,
- elasticity.

6 Initial concept of En-ActivETICS

The proposed concept (Fig. 1) is a novel expansion from wide-spread ETICS wall, where building facades oriented to east, south or west in the northern hemisphere are covered with PCM and flexible BIPV instead on regular plaster. PCM will be attached to the rigid thermal insulation by using adhesive mortar that has vertical gaps $\geq 5 \times 5$ mm. Gaps enable to i) drainage of the water (condensation, built-in or leaked from the cracks) and ii) vapour diffusion along with vapour tight BIPV. Similarly to glue for BIPV, the adhesive mortar between thermal insulation and PCM must have sufficient elasticity, adhesion and frost resistance in sub-zero temperature climates. In order to achieve architecturally preferred plane façade and controlled runoff of the droplets, the thickness of thermal insulation in zones with En-ActivETICS is diminished.

Fig. 1. Vertical cross-section of the first prototype concept of En-ActivETICS solution (based on the technical documentation of Sto company).

7 Summary

The characteristics and basic principles of En-ActivETICS were formulated in the article. Firstly, the deep analysis of possible technical solutions, as well as an overview of existing materials and technologies were done. Then, the possibly system integration was investigated and defined. Finally, the existing concept of the first prototype was developed. The prototype drawings have been enriched with a detailed description of the technical solution.

The main objective of the En-ActivETICS (2019-22) project is to develop, test and validate the advanced, functional component with a new physical properties, leading to advances in the area of smart thermal insulations and building integrated photovoltaic. This objective will be fulfilled by the execution of 7 workpackages (from TRL 2 to 5) including a theoretical and experimental study in a laboratory and real building scale.

This research was supported by the project En-ActivETICS: in a framework of M-ERA.NET by ETAG (grant No. 3-4/MOBERA1719029), NCBiR (grant No. M-ERA.NET2/2018/2/2019) & SAS (grant No. M-ERA.NET 2 /2018 /786/En-ActivETICS), by Estonian Centre of Excellence ZEBE (grant TK146), by the personal research funding (grant PRG483), and by European Commission through the H2020 project Finest Twins (grant No. 856602).

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