Thermal performance of ETICS, energy activated with PCM and PV

Martin Talvik1, Simo Ilomets1, Targo Kalamees1,2, Paul Klõšeiko1, Dariusz Heim1, Anna Wieprzkowicz3 and Dominika Knera1

1 Tallinn University of Technology, Department of Civil Engineering and Architecture, Ehitajate tee 5, 19086 Tallinn, Estonia
2 Smart City Center of Excellence (Finest Twins), Tallinn University of Technology, Ehitajate tee 5, Tallinn, Estonia
3 Lodz University of Technology, Department of Environmental Engineering, ul. Wolczanska 213, 90924 Lodz, Poland

Abstract. Installing photo-voltaic (PV) panels on building façades is a growing tendency that helps to achieve both newly built and renovated nearly zero energy buildings. A novel approach to building active facades is to use a phase change material (PCM) behind the flexible PV. The PCM stabilises the PV’s temperature which can lead to an increase in energy production and cuts down the temperature peaks to avoid damage. In this study, the thermal performance of an En-ActivETICS wall was modelled in three different locations across Europe. The model was validated against on-site temperature measurements. The efficiency of the PV was calculated and an optimal PCM thickness and melting temperature were selected. The results show that annual energy production of the PV panel could increase between 2% (in Lodz) to 5% (in Madrid) using a 40mm-thick PCM. The optimal PCM melting temperatures for a certain climate should be chosen as 0 to 10 degrees below maximum air temperature in summer. The maximum peak PV temperatures could be reduced by ca. 20 K (from ~90 to ~70°C). Reasonable way to fix the stainless steel casing to the wall would be with four stainless steel anchor bolts – that gives 78% or 93% efficiency in case of EPS or PIR thermal insulation, respectively.

1. Introduction
1.1. Demand for facade PV solutions
To meet future needs, buildings have to meet strict energy efficiency norms and should produce energy on site. One of the easiest ways to enable a building to produce energy is to integrate PV panels. But because of poor aesthetics and the need for air flow behind the Building Integrated PV Panels (BIPV) for today’s solutions [1] [2], often only the roof surface is used for mounting PV panels. When PV panels overheat, the PV performance will normally fall around 0.3%/K to 0.7%/K [3,4], depending on the PV panel type, and the risk of physical damage will increase. So the temperatures of PV should be stabilized to avoid overheating. If there is no cooling air flow to the rear, another cooling method should be applied. One passive cooling method is using Phase Change Material (PCM), which would melt during the daytime, due to solar radiation, and then solidify at night, also keeping the outer layer of the facade a little bit warmer. It was revealed in [5] that with a ventilated façade, the maximum temperature of the external surface for a standard insulation layer was around 20 K higher than for the case modified by PCM.

1.2. Research need and potential problems
There have been many different solutions to integrate PV panels into buildings. But many of those need air flow behind the PV panel to cool down the panels. Many researchers have found that it is possible to cool down the panels with PCM instead of airflow to the rear [6] [7] [8]. Therefore, calculation models are needed to study the thermal performance of such a novel wall system before testing a full size wall
in the laboratory, especially if there is no acknowledged methodology [9] to determine whether the wall is in line with the essential requirements set out for a building according to [10].

1.3. Purpose of the study
The purpose of this paper is to determine the suitable PCM-s temperature range and the most reasonable variants for encapsulating the PCM in three different climates by calculating PV panel maximum temperatures and efficiency. Also, to find thermally efficient solutions for different PCM fixings.

2. Methods

2.1. Thermal modelling
Coupled heat, air, moisture and matter transport software Delphin 6 [11,12] was used to model the thermal performance of the wall assemblies. PCMs can be modelled in Delphin using the thermal storage \( u(T) \) function (figure 1d). However, only one of those functions could be added, thus the differences between melting and solidification processes were averaged.

2.2. Calculation models for optimal PCM selection
For selecting the optimal PCM solution, 1D simulation model with standard ETICS, PV panel glued straight to insulation layer, was used as base model (figure 1a). It was compared with 2D model of En-ActivETICS with PCM encapsulated in stainless steel casing (figure 1b) and with 1D model with PCM encapsulated in small granules, mixed in plaster (figure 1c).

Figure 1. Example of Delphin 6 calculation models and PCM functions used for PCM selection process. Reference model (a) and En-ActivETICS models with stainless steel casing (b) and with PCM granules encapsulated in façade plaster (c). Optimising the PCM content allows us to move the final material \( u(T) \) function (d) between the two material \( u(T) \) functions.
2.3. Calculation models for analysing PCM and PV fixing solutions

For evaluating the intensity of heat exchange through thermal bridges, the simulation model was set up in Delphin 6, with constant outside and inside temperature, and the simulation was carried out for 21 days, for temperature stabilisation. For calculations the overall thermal transmittance (U-value) of a cross section combining traditional and En-ActivETICS in 2D was modelled. The dimensions of cross sections were selected using the principle that 50% of the total façade surface would be covered with En-ActivETICS elements. For five different fixing solutions (table 1), 12 characteristic cross sections (figure 2) were modelled. Thermal transmittance was compared with the base model of standard ETICS.

Table 1. Selection of different PCM+PV fixing solutions simulated in Delphin 6.

| Fixing solution                      | Description                                                                                                                                 |
|--------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------|
| 1 Base Model, without PCM            | 200mm concrete (1)*, 10mm adhesive mortar (2), 200mm insulation - EPS Silver (3) or PIR (11), 6mm facade plaster system (8).                |
| 2 Without mechanical fixings**       | 200mm concrete (1), 10mm PU foam (9) with air gaps, 150mm insulation (3 or 11), 40mm PCM (7) in 1mm thick stainless steel core (6).        |
| 3 Exposed mechanical fixings         | 4 stainless steel (6) M12 anchor bolts in corners. Rubber sleeves between bolts and PCM core. Bolts are exposed to outside climate.      |
| 4 Covered mechanical fixings         | 4 bolts are covered with 37mm high-density XPS or PIR [e.g Linirec (12)] covering frame.                                                 |
| 5 Watertight stainless steel casing***| Whole prefabricated element (insulation + PCM) is encapsulated in 1.5mm stainless steel (6) casing. Mechanical fixings (6) behind insulation. |
| 6 Watertight aluminium casing***      | Same as solution 5, but 1.5mm casing is made of aluminium (13) instead of stainless steel (6).                                         |

* Italic number in brackets is the number of the material in table 2
** Solution without any mechanical fixings could be dangerous in real life.
*** Solutions with fully closed metal casings could be dangerous if there is any leakage inside the capsule during the whole lifetime of facade.

Figure 2. Typical cross-sections used for calculating the thermal transmittance of fixing solutions.
2.4. Material properties

Thermal properties for materials used in calculations (table 2) were taken from material data sheets as well as the Delphin 6 database. The porosity of plaster system was measured in TalTech [13]. The bulk density and heat capacity of PCMs were replaced with the $u(T)$ function in thermal calculations (figure 1d). Materials were used in various calculation models (figure 1 and 2).

|        | Absorption coefficient $\alpha$, - | Bulk density $\rho$, kg/m$^3$ | Porosity $\theta$, m$^3$/m$^3$ | Heat capacity $c$, J/(kg*K) | Thermal conductivity $\lambda_{dry}$, W/(m·K) |
|--------|-------------------------------------|------------------------------|-------------------------------|----------------------------|----------------------------------|
| 1. Concrete | -                                   | 2320                         | 0.143                         | 850                        | 2.1                              |
| 2. Adhesive mortar | -                                   | 707                          | 0.733                         | 945                        | 0.21                             |
| 3. EPS Silver      | -                                   | 35                           | 0.935                         | 1500                       | 0.034                            |
| 4. Silicone glue   | -                                   | 2590                         | -                             | 1000                       | 1.53                             |
| 5. PV panel        | 0.84                                | 1515                         | -                             | 1000                       | 0.8                              |
| 6. Stainless steel | -                                   | 7900                         | -                             | 500                        | 15                               |
| 7. PCM (RT HC series) | - Solid 880                         | -                             | According to $u(T)$ function* | 0.2                        |                                   |
| 8. Plaster system  | 0.6                                 | 1365                         | 0.42                          | 1000                       | 0.7                              |
| 9. PU foam         | -                                   | 45                           | 0.92                          | 1500                       | 0.029                            |
| 10. Mineral wool   | -                                   | 67                           | 0.92                          | 840                        | 0.035                            |
| 11. PIR            | -                                   | 35                           | 0.95                          | 1500                       | 0.022                            |
| 12. Liinerec rigid insulation | -                                  | 550                          | 0.94                          | 1500                       | 0.083                            |
| 13. Aluminium      | -                                   | 2700                         | -                             | 900                        | 235                              |

*Example $u(T)$ function is shown in figure 1d.

2.5. Climate

The Typical Meteorological Test Years (TMY) [14] from three locations were used:
- Tallinn, Estonia. TMY 2004-2018
- Lodz, Poland. TMY 2004-2018
- Madrid, Spain. TMY 2004-2018

In all the locations, a southern facade (azimuth 180°) with three different PCM products (RT25HC, RT28HC and RT35HC all produced by Rubitherm Technologies GmbH) were analysed. PCM product name RT25HC means that its phase change peak temperature is approximately 25 °C. Two different encapsulation methods (encapsulation in stainless steel casing and PCM encapsulation into small granules, covered with PU and mixed into plaster) and two different thicknesses (30 mm and 40 mm) were simulated.

2.6. Post-processing

PV electricity production efficiency was calculated in MS excel, according to information provided by the PV panel producer [4], and temperatures obtained from the simulation. After selection of PCM, the thermal efficiency analysis for different fixing solutions were conducted for PCM stainless steel casing. For evaluating the point thermal bridges caused by bolts and steel cases, relative weight of cross sections shown in figure 2 were calculated and a simplified methodology for converting 2D model results into 3D thermal bridges was used. The solutions 3 and 4, where PCM and PV were fixed with bolts, were double checked for point thermal bridge influences with methodology from [15].

3. Model calibration based on field measurements

A 7-hour experiment was carried out in Lodz on the 6th of October 2020 to calibrate the PV temperature calculation models. There, a 2mm-thick flexible PV panel was glued on an 8mm-thick facade plaster system, applied straight to a 50 mm EPS insulation panel, which was fixed to an 18mm OSB panel. The
test panel was placed on the roof with azimuth 188 degrees. Solar irradiance, outside temperature, wind direction and velocity were measured, as well as the temperature between the PV panel and the EPS insulation board. Coefficients for calculating the air velocity-dependent surface heat exchange coefficient were determined by changing them iteratively and then comparing the measured and modelled temperatures. The best fit was achieved using parameters given in figure 3 and were also used in further modelling.

Figure 3. PV back surface temperatures modelled in Delphin 6 and measured in experiment.

4. Results
4.1. Selection of best-performing PCM solution
To find out the suitable PCM nominal melting temperatures, the dynamic thermal simulations were conducted with different PCM solutions. To evaluate them, two main criteria were considered:

- each hourly average electricity production was corrected with PV temperature efficiency function and production was summarised for the whole test year.
- the highest hourly average temperature of different PCM products was compared, as the physical deterioration of PV panels tends to happen with high peak temperatures.

Three different PCM products (RT25HC, RT28HC and RT35HC), two different encapsulation methods (stainless steel casing with 90% PCM content and 45% of PCM content for granules mixed into plaster) and two different thicknesses (30mm and 40mm) were simulated. The results were compared with the solution where there was no PCM and the PV was glued directly on the thermal insulation layer. It was found that the optimal PCM that can be recommended for Tallinn and Lodz should be RT25HC or RT28HC and for Madrid, it should be RT28HC or RT35HC (table 3). For other locations, the optimal PCM melting temperature should be chosen around maximum hourly air temperature (or few degrees below) in summer. This way, the PCM would effectively attenuate the warming effect of solar irradiance during the daytime and is able to cool down entirely at night, see figure 4 and 5.

Encapsulating the PCM into a stainless steel casing is more effective than mixing PCM granules into plaster, because there will be a higher PCM content in a more limited volume. However, the stainless steel casing is technologically more challenging and therefore could be more expensive to produce. A final solution should be selected after hygrothermal and economic analysis.

To avoid the damage caused by overheating, the most effective PCM solution could drop the peak temperatures in Tallinn by 20.0°C (from 82.7°C to 62.7°C), in Lodz by 15.0°C (from 81.0°C to 66.0°C) and in Madrid by 26.5°C (from 91.2°C to 64.7°C).

When analysing the daily temperature fluctuations during different months (figure 6), it is clearly seen that PCM succeeds in buffering the temperature peaks. However, the PCM effect is much more significant in summer than in winter, especially in Tallinn and Lodz.
Table 3. Energy production efficiency increase and peak maximum temperatures with different PCM solutions. Green cells stand for best performing PCM solution using stainless steel casing and yellow cells mark the best performing granules mixed into plaster solution for each location.

| Type of PCM | Thickness (mm) | TALLINN | | LODZ | | MADRID | |
|---|---|---|---|---|---|---|---|
| PCM | Max temp* (°C) | Annual energy production (kWh/m²) | Increase in efficiency % | Max temp* (°C) | Annual energy production (kWh/m²) | Increase in efficiency % | Max temp* (°C) | Annual energy production (kWh/m²) | Increase in efficiency % |
| Without PCM | 0 | 83 | 39.3 | 0.0% | 81 | 35.6 | 0.0% | 91 | 53.7 | 0.0% |
| RT25HC 45% | 30 | 73 | 40.1 | 2.2% | 73 | 36.2 | 1.6% | 82 | 55.2 | 2.9% |
| | 40 | 68 | 40.3 | 2.7% | 70 | 36.3 | 1.9% | 77 | 55.6 | 3.6% |
| RT28HC 45% | 30 | 71 | 40.2 | 2.2% | 70 | 36.1 | 1.8% | 81 | 55.3 | 3.1% |
| | 40 | 64 | 40.3 | 2.7% | 67 | 36.2 | 1.8% | 74 | 55.7 | 3.8% |
| RT35HC 45% | 30 | 67 | 40.1 | 2.1% | 67 | 36.1 | 1.3% | 79 | 55.4 | 3.2% |
| | 40 | 59 | 40.2 | 2.4% | 61 | 36.1 | 1.5% | 71 | 55.7 | 3.8% |
| RT25HC 90% | 30 | 67 | 40.6 | 3.4% | 69 | 36.4 | 2.3% | 74 | 56.1 | 4.6% |
| | 40 | 63 | 40.7 | 3.7% | 66 | 36.5 | 2.4% | 69 | 56.3 | 5.0% |
| RT28HC 90% | 30 | 61 | 40.6 | 3.4% | 66 | 36.3 | 2.1% | 69 | 56.2 | 4.8% |
| | 40 | 57 | 40.7 | 3.6% | 63 | 36.4 | 2.2% | 65 | 56.4 | 5.1% |
| RT35HC 90% | 30 | 51 | 40.4 | 2.9% | 53 | 36.2 | 1.7% | 63 | 56.2 | 4.7% |
| | 40 | 44 | 40.5 | 3.1% | 44 | 36.3 | 1.9% | 56 | 56.3 | 4.9% |

Figure 4. PV panel back surface temperatures during one test year without PCM and with best performing PCM (40mm RT25HC in stainless steel casing) in Tallinn.

Figure 5. PV panel rear surface temperatures during three high solar irradiation days in March with 40mm RT28HC in stainless steel casing, in Madrid. Daily peak values could be reduced by as much as 35°C.
4.2. Different solutions for fixing stainless steel PCM casing to the structural layer.
Because the U-value was calculated in a stationary situation, it is worth noticing that this method does not include the u(T) function as a dynamic calculation or the PCM’s ability to buffer the heat, so the thermal insulation performance in a real building should be somewhat better.

Figure 6. Daily temperature fluctuations in all three locations with PCM and without in January (left) and in July (right).

It can be stated from the table 4, that most reasonable way to fix the stainless steel casing would be with 4 stainless steel anchor bolts with rubber sleeves between the PCM core and the bolts (fixing solution 3). The calculation was made with M12 bolts, to be on the safe side. This solution is relatively easy for prefabricated elements and for fixings to apply on site. With EPS insulation, efficiency is 78% of a standard wall, but 93% when using PIR insulation behind the active element. However, the PCM stabilising effect would compensate for some of the weaker performance of the active element.

Table 4. Thermal transmittance of different PCM+PV fixing solutions shown in figure 2. Efficiency is determined in comparison to the base model. It is assumed that façade area consists of 50% of active elements and 50% standard ETICS.

| Fixing solution               | EPS Silver ($\lambda=0.034$) | PIR ($\lambda=0.022$) |
|------------------------------|-------------------------------|-----------------------|
|                              | Thermal transmittance U [W/(m²K)] | Efficiency | Thermal transmittance U [W/(m²K)] | Efficiency |
| 1 Base Model, without PCM    | 0.161                         | 100%                      | 0.106                      | 152%        |
| 2 Without mechanical fixings | 0.185                         | 87%                       | 0.151                      | 107%        |
| 3 Exposed mechanical fixings | 0.207                         | 78%                       | 0.173                      | 93%         |
| 4 Covered mechanical fixings | 0.195                         | 83%                       | 0.162                      | 99%         |
| 5 Watertight stainless steel casing | 0.221                       | 73%                       | 0.189                      | 85%         |
| 6 Watertight aluminium casing | 0.253                         | 64%                       | 0.223                      | 72%         |

5. Discussion and need for future research
The appropriate PCM materials could be selected with these simulation tools, based on maximising the energy production. However, the exact amount of PCM content and the encapsulation method should be selected after conducting an economic analysis. PCM gives a more significant temperature reducing effect in climates with year-round intense solar radiation (+5.1% efficiency in Madrid and +2.4% in Lodz with the same encapsulation solution) because in colder climates, during winter months the PCM is not melting into liquid state due to lower levels of temperature/solar radiation. The 20°C reduction in PV peak temperatures could increase the lifetime of PV panels, but quantifying the exact effects of physical deterioration of facade integrated PV panels due to high surface temperatures would need
Further experimental research. The thermal insulation thickness of En-Active elements must be decreased by 50mm to keep the same facade level. Therefore, replacing EPS with a more effective thermal insulation material, e.g. PIR, should be considered. However, the exact insulation material should be selected after hygrothermal analysis. As a future research project, hygrothermal performance of En-ActivETICS should be studied in terms of moisture dry out around the En-Active element. Furthermore, appropriate joint design for putting a plaster and PV panel together in the outer layer of the facade must be developed, to avoid cracking and water penetrating the joint.

6. Conclusions
It could be concluded that adding a PCM layer behind the PV panel should make it possible to integrate flexible PV panels with ETICS systems which could significantly increase the amount of building surface available for energy production. A PCM layer 40 mm in thickness could reduce PV panel surface temperatures by 20°C in order to extend the service life of PV panels. Annual energy output of PV panels increases 2 to 5%, depending on the PCM encapsulation technology and location. A relatively low increase in PV’s annual electricity production could be caused by a rather short time period in which the PCM is able to go through full melting cycles, especially in a boreal climate.

Acknowledgements
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).

References
[1] Knera D, Heim D. Application of a BIPV to cover net energy use of the adjacent office room. Manag Environ Qual An Int J 2016;27:649–62. doi:10.1108/MEQ-05-2015-0104.
[2] Knera D, Heim D. A heat transfer model of a PV panel integrated with a “rainscreen cladding system.” WIT Trans. Eng. Sci., vol. 83, 2014, p. 157–68. doi:10.2495/HT140151.
[3] Radziemska E. The effect of temperature on the power drop in crystalline silicon solar cells, Gdansk: 2003. doi:10.1109/ICMLC.2004.1380410.
[4] Flisom Flexible Solar Modules. eFlex 1.6m FF60 data sheet.
[5] Heim D, Wieprzkowicz A. Attenuation of temperature fluctuations on an external surface of the wall by a phase change material-activated layer. Appl Sci 2017;8. doi:10.3390/app8010011.
[6] Heim D, Wieprzkowicz A. Positioning of an isothermal heat storage layer in a building wall exposed to the external environment. J Build Perform Simul 2016;9:542–54.
[7] Huang MJ, Eames PC, Norton B. Phase change materials for limiting temperature rise in building integrated photovoltaics. Sol Energy 2006;80:1121–30.
[8] Jun Huang M. The effect of using two PCMs on the thermal regulation performance of BIPV systems. Sol Energy Mater Sol Cells 2011;95:957–63. doi:10.1016/j.solmat.2010.11.032.
[9] Ilomets S et al. A method to develop energy activated ETICS 2020; NSB 2020 Tallinn.
[10] CPR EU 305/2011. Construction Products Regulation. Off J Eur Union Regul No 305/2011.
[11] Nicolai A. Modeling and Numerical Simulation of Salt Transport and Phase Transitions in Unsaturated Porous Building Materials 2008:251. doi:10.13140/RG.2.1.2016.2088.
[12] Grunewald J. Diffusiver und konvektiver Stoff- und Energie- transport in kapillarporen Baustoffen. Diss TU Dresden 1996:220.
[13] Volkova K et al. The effect of temperature, humidity and mechanical properties on crack formation on external thin plasters of ETICS; IBPC 2021.
[14] Climate.OneBuilding.Org. Repository of free climate data for building performance simulation 2019. http://climate.onebuilding.org/WMO_Region_6_Europe/.
[15] EN ISO 6946. Building components and building elements - Thermal resistance and thermal transmittance - Calculation method. Brussels, Belgium: 2017.