

DOCTORAL THESIS

Hygrothermal Performance of Energy Activated External Thermal Insulation Composite System

Martin Talvik

TALLINN UNIVERSITY OF TECHNOLOGY
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Declaration:

Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for doctoral or equivalent academic degree.

Martin Talvik

signature



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TALLINNA TEHNIKAÜLIKOO
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Integreeritud päikesepaneelidega soojusisolatsiooni liitsüsteemi soojus- ja niiskustehniline toimivus

MARTIN TALVIK



Abstract

Hygrothermal Performance of Energy Activated External Thermal Insulation Composite System

The integration of renewable energy technologies into building envelopes is essential for achieving decarbonisation goals and reducing Europe's dependence on imported energy. While rooftop solar panels are already widely used, facade-integrated photovoltaic (FIPV) solutions would allow electricity generation to be better aligned with peak demand periods. However, most of the FIPV solutions still require a ventilated cavity. So far, there is no good solution for PV integration into External Thermal Insulation Composite Systems (ETICS), which are dominant in the Eastern European renovation market. This thesis addresses the hygrothermal challenges associated with integrating vapour-tight photovoltaic panels into ETICS facades without a ventilated air cavity and employs phase change materials (PCMs) for temperature control.

In this study, a novel PV-ETICS facade system with PCM was developed as a Technology Readiness Level (TRL) 5 product. Its hygrothermal performance was evaluated using an interdisciplinary approach combining experimental investigations and numerical modelling. After small-scale laboratory measurements were conducted to determine the material properties of the novel PCM mortar, full-scale test walls were constructed and monitored under both controlled climate-chamber conditions and real outdoor exposure. A hygrothermal model was developed and calibrated using climate chamber data and subsequently applied to predict long-term performance under real climatic conditions. In addition, building-scale energy simulations were carried out to assess the impact of the facade system on indoor overheating in a typical Soviet-era apartment building renovation.

Hygrothermal measurements were performed using temperature and relative humidity sensors, heat flux plates and calibrated soil moisture sensors (SMS) capable of operating in the overhygroscopic range. Custom-made equations for calculating volumetric moisture content (MC) based on SMS voltage readings were developed using gravimetric calibration. In addition to isothermal calibration, which has been studied previously for various construction materials, temperature correction functions for measuring MC of porous materials containing PCM under non-isothermal conditions were developed.

The results demonstrate that the PV-ETICS system can be designed to maintain PV temperatures below critical limits, with maximum measured temperatures remaining significantly below the critical threshold of 85 °C. Moisture measurements and simulations showed no long-term moisture accumulation in the PCM mortar when diffusion channels were incorporated into the design. Even in scenarios with water leakage behind the vapour-tight PV, moisture was able to dry out effectively. The calibrated hygrothermal model proved capable of reproducing measured behaviour with sufficient accuracy, confirming the validity of the combined experimental and modelling approach. The contribution of PV-ETICS to indoor overheating was found to be rather small in case of well-insulated facades, although it should still be considered in energy design.

During the destructive opening of the facades, the design for disassembly (DfD) joint was tested in practice as service life of PV panels is typically shorter compared to the rest of the building envelope. It was confirmed that PV panels can be replaced without

damaging the surrounding facade plaster. Several minor shortcomings in product design were identified after the destructive opening and are listed for improvement in the next stages of development.

The research contributes to new knowledge in several areas, including the application and calibration of soil moisture sensors for PCM-containing construction materials in non-isothermal conditions. A methodology for the experimental validation of a novel facade system that challenges traditional hygrothermal design principles was developed. The final prototype achieved TRL 5 and demonstrated reliable performance under real conditions during the two years. The calibrated hygrothermal model showed promising long-term performance.

In conclusion, the PV-ETICS concept is a viable solution for introducing solar energy production into ETICS facades in cold climates, provided that appropriate design principles (see Appendix 5) are applied. The novel methodology developed in this thesis offers a framework for evaluating similar innovative building envelope systems. Overall results support further development of the PV-ETICS system towards scaling up to industrial implementation, supporting the mass renovation of ageing housing stock in Europe.

Lühikokkuvõte

Integreeritud päikesepaneelidega soojusisolatsiooni liitsüsteemi soojus- ja niiskustehniline toimivus

Laialdasem elektri tootmine taastuenergia allikatest hoonetes on oluline nii Euroopa energiajulgeoleku suurendamiseks kui ka heitmevaba hoonefondi saavutamiseks. Katustele paigaldatud päikesepaneelid (PV) on tänaseks laialt levinud ning sageli ei suudeta suvepäevadel kogu toodetud elektrit hoones ära kasutada. Seevastu fassaadi integreeritud päikesepaneelide lahendused võimaldavad ajastada tootmist paremini tarbimise tiputundidele. Tänaused lahendused nõuavad valdavalt päikesepaneelide tagust tuulutusvahet ning turul ei ole veel olemas head lahendust päikesepaneelide integreerimiseks soojusisolatsiooni liitsüsteemiga (SILS), mis on Ida-Euroopa renoveerimisturul laialt levinud lahendus. Käesolevas doktoritöös uuritakse ja lahendatakse soojus- ja niiskustehnilisi väljakutseid, mis on põhjustatud veeaurutihedate päikesepaneelide paigaldamisest SILS fassaadile ilma ventileeritava õhkvaheta, kasutades paneelide ülekuumenemise piiramiseks faasimuutusmaterjali (PCM).

Uurimistöö käigus töötati välja uudne fassaadisüsteem, mis saavutas tehnoloogia valmidustaseme TRL 5. Süsteemi toimivust hinnati interdistsiplinaarselt, kombineerides väikese- ja suuremõõtmelisi katseid numbrilise modelleerimisega. Materjaliomaduste määramiseks viidi esmalt läbi laborikatsed uudse faasimuutuskrohvi. Seejärel ehitati täismõõdus katsesein kliimakambrisse ning seal teostatud katsete põhjal kalibreeriti dünaamiline arvutusmudel. Seejärel ehitati testhoone lõunafassaadile teine katsesein ning kliimakambris kalibreeritud mudelit kasutati fassaadisüsteemi mitmeaastase toimivuse prognoosimiseks tegelikes kliimatingimustes. Lisaks hinnati energiasimulatsioonide abil fassaadisüsteemi mõju siseruumi ülekuumenemisele suveperioodil tüüpilise nõukogudeaegse korterelamu renoveerimisel.

Soojus- ja niiskusklikku toimivust mõõdeti temperatuuri ja suhtelise niiskuse andurite ning soojusvooplaatidega. Lisaks kasutati ka kalibreeritud pinnaseniiskuse andureid, mis võimaldavad mõõta materjali niiskussisaldust ülehügroskoopes piirkonnas. Nende andurite pingeväljundi põhjal mahulise niiskussisalduse määramiseks töötati gravimeetrilise meetodiga võrreldes välja kalibreerimisvalemid. Lisaks arendati välja temperatuurikorrektsooni valemid, mis võimaldavad mõõta pinnase niiskuse anduritega faasimuutusmaterjali sisaldavate poorsete materjalide niiskussisaldust ka muutuva temperatuuri tingimustes.

Tulemused näitavad, et PV-SILS süsteemi on võimalik projekteerida ja ehitada nii, et päikesepaneelide temperatuur jääb ohututesse piiridesse. Maksimaalsed mõõdetud temperatuuri olid oluliselt alla kriitilise 85 °C piiri. Nii mõõtmised kui ka simulatsioonid kinnitasid, et faasimuutuskrohvis ei teki pikaajalist niiskuse akumulereerumist, kui päikesepaneelide taga on difusioonikanalid. Ka olukorras, kus vesi lekkis päikesepaneeli taha, oli niiskusel võimalik konstruktsioonist välja kuivada. Kalibreeritud mudel suutis anduritega mõõdetud niiskustaseme rahuldava täpsusega jälgendada. Samuti selgus, et PV-SILS fassaadisüsteemi mõju siseruumi ülekuumenemisele on hästi soojustatud fassaadide korral pigem vähene, kuid seda tuleks siiski energiatõhususe modelleerimisel arvesse võtta.

Fassaadide purustaval avamisel kontrolliti ka PV-paneelide demonteeritavuse võimalikkust fassaadikrohvi ja päikesepaneeli liitekohas, kuna päikesepaneelide kasutamisega on üldjuhul lühem ülejäänud välisseina omast. Tõestati, et PV-paneeli on

võimalik välja vahetada ilma ümbritsevat krohvikihiti kahjustamata. Avamise käigus tuvastati ka mitmeid väiksemaid kitsaskohti, mille parandamise ettepanekud on välja toodud fassaadisüsteemi tulevaste arendusetappide jaoks.

Doktoritöö annab uut teadmist mitmes valdkonnas. Käsitletakse pinnaseniiskuse andurite kasutamist ja kalibreerimist faasimuutusmaterjali sisaldavates ehitusmaterjalides muutuva temperatuuri tingimustel. Samuti esitatakse metoodika uudse fassaadisüsteemi eksperimentaalseks valideerimiseks olukorras, kus süsteem ei järgi traditsioonilisi piirdetarindite projekteerimise põhimõtteid. Lõplik prototüüp saavutas tehnoloogia valmiduse taseme TRL 5 ning demonstreeris kaheaastase perioodi jooksul usaldusväärset toimivust reaalsetes tingimustes. Kalibreeritud niiskustehnilise mudeli abil tõestati ka uudse tarindi pikaajalist toimivust.

Kokkuvõttes on PV-SILS fassaadi kontseptsioon sobiv lahendus päikesepaneelide integreerimiseks SILS fassaadidesse eeldusel, et järgitakse sobivaid projekteerimispõhimõtteid ja ehitustehnoloogiat (vt Lisa 5 (*Appendix 5*)). Käesolevas töös välja töötatud metoodika loob aluse sarnaste innovaatiliste piirdetarindite toimivuse hindamiseks. Töö tulemuste põhjal on põhjendatud PV-SILS fassaadisüsteemi edasiarendamine kõrgematele TRL tasemetele. See võimaldab liikuda eksperimentaalselt skaalalt edasi tööstusliku rakenduseni ning panustada Euroopa kasvava renoveerimisvajadusega hoonefondi jätkusuutlikkusse.

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List of publications

The list of the author's publications on which the thesis is based:

- I **Talvik, M.**, Ilomets, S., Klõšeiko, P., Kalamees, T., & Heim, D. (2022). Construction Process and Measuring Initial Dryout of PCM Mortar in Energy Activated ETICS Facade. Buildings XV Conference, Clearwater Beach, FL, December 5–8, 2022. ASHRAE, pp. 757–764. <https://www.scopus.com/pages/publications/85163701291>
- II **Talvik, M.**, Ilomets, S., Klõšeiko, P., Kalamees, T., Põldaru, M., & Heim, D. (2023). Hygrothermal performance of thick PCM mortar behind PV panels in energy-activated ETICS facades. Buildings, 13(6), Article 1572. <https://doi.org/10.3390/buildings13061572>
- III **Talvik, M.**, Kalamees, T., & Ilomets, S. (2025). Measured hygrothermal performance of energy-activated facade in cold climate. Journal of Building Physics, 49(2). <https://doi.org/10.1177/17442591241312415>
- IV **Talvik, M.**, Ilomets, S., & Kalamees, T. (2025). Indoor overheating risks of PV-ETICS and dark-coloured facades: Experimental and simulation-based assessment. Sustainable Energy Technologies and Assessments, 82. <https://doi.org/10.1016/j.seta.2025.104452>

Author's contribution to the publications

Contribution to the papers in this thesis is:

Pub.	Author	Contribution
I	Martin Talvik	Concept of the study, construction of the test setup, installation of the measurement devices, data collection and analysis, modelling, writing of the paper
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	Paul Klõšeiko	Concept of the study
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III	Martin Talvik	Concept of the study, construction of the test setup, installation of the measurement devices, data collection and analysis, modelling, writing of the paper
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	Simo Ilomets	Editing, acquisition of funding
IV	Martin Talvik	Concept of the study, construction of the test setup, installation of the measurement devices, data collection and analysis, modelling, writing of the paper
	Simo Ilomets	Writing of the paper, editing
	Targo Kalamees	Concept of the study, writing of the paper, editing, acquisition of funding

Abbreviations

AAC	Autoclaved aerated concrete
BIPV	Building-integrated photovoltaics
CPR	Construction Products Regulation
DfD	Design for disassembly
EAD	European Assessment Document
EN	European Standard
EPS	Expanded polystyrene
ETAG	European Technical Approval Guideline
ETICS	External thermal insulation composite system
EU	European Union
EVS	Estonian standard
FDR	Frequency-domain reflectometry
FIPV	Facade-integrated photovoltaics
GB/T	Chinese national standard
HAM	Heat, air, and moisture
HVAC	Heating, ventilation, and air conditioning
IDA ICE	Indoor climate and energy modelling software
MC	Moisture content of material (m^3/m^3)
MC4	Multi-Contact 4 photovoltaic connector
MW	Mineral wool
NASA	National Aeronautics and Space Administration
PCM	Phase change material
PU	Polyurethane
PV	Photovoltaic
PV-ETICS	ETICS with integrated photovoltaics
RH	Relative humidity
RQ	Research question
SHGC	Solar heat gain coefficient
SMS	Soil moisture sensor
SILS	<i>Soojusisolatsiooni liitsüsteem</i> (external thermal insulation composite system in Estonian)
TDR	Time-domain reflectometry
TRL	Technology readiness level
TRY	Test reference year
UV	Ultraviolet
WDR	Wind-driven rain
WWR	Window-to-wall ratio

Symbols

α	Solar absorption coefficient, –
$\alpha_{plaster}$	Linear thermal expansion coefficient of facade plaster, $m/(m \cdot K)$
α_{PV}	Linear thermal expansion coefficient of PV panel, $m/(m \cdot K)$
A_w	Water absorption coefficient, $kg/(m^2 \cdot s^{0.5})$
c	Specific heat capacity, $J/(kg \cdot K)$
d	Thickness, m
ϵ	Dielectric constant, –
g	Solar heat gain coefficient of glazing, –
K_l	Liquid water conductivity function, $kg/(m \cdot s \cdot Pa)$
K_v	Water vapour conductivity function, $kg/(m \cdot s \cdot Pa)$
λ	Thermal conductivity, $W/(m \cdot K)$
λ_{dry}	Thermal conductivity of dry material, $W/(m \cdot K)$
μ	Water vapour diffusion resistance factor, –
μ_{dry}	Dry-cup water vapour diffusion resistance factor, –
μ_{wet}	Wet-cup water vapour diffusion resistance factor, –
ρ	Density, kg/m^3
ρ_{dry}	Dry density, kg/m^3
ψ	Volumetric moisture content, m^3/m^3
S_d	Relative water vapour diffusion resistance of a layer, m
t	Temperature, $^{\circ}C$
Δt	Temperature difference, $^{\circ}C$
U	Soil moisture sensor output voltage, V
U_{20}	Soil moisture sensor output voltage corrected to 20 $^{\circ}C$, V
U_{wall}	Thermal transmittance of wall, $W/(m^2 \cdot K)$
$u(T)$	Temperature dependent heat storage function of PCM, J/kg
x	Spatial coordinate, m
y	Spatial coordinate, m

Introduction

As Europe still relies heavily on imported energy, the deployment of local renewable technologies such as solar and wind power has become essential for contributing to energy sovereignty, climate resilience and decarbonisation. One of the most efficient ways to produce solar energy is through building-integrated photovoltaics (BIPV), as it allows electricity production and demand to occur at the same site, optimising the use of electricity grids. While rooftop PV installations are common, rooftop space is often limited, especially in taller buildings where it must be shared with technical service systems and terraces. Complementing rooftop PV with facade-integrated PV (FIPV) systems can increase total generation capacity and improve grid stability by aligning electricity production more closely with morning and evening peak electricity prices, using southeast- and southwest-facing FIPV systems. Several FIPV solutions already exist on the market, but nearly all of them incorporate a fully ventilated air cavity behind the panels.

On the other hand, in the Eastern European market, External thermal insulation composite systems (ETICS) are among the most widespread facade solutions for both new construction and energy renovations. Despite the popularity of ETICS, viable FIPV solutions based on ETICS have not yet been widely commercialised, partly because of challenges related to thermal performance and moisture management.

Research problem

This research aims to address, through a combination of experiments and simulations, the thermal and moisture-related challenges associated with integrating PV panels into ETICS facades without relying on a fully ventilated cavity.

Previous studies have shown that applying PV panels directly onto insulation layers is not a viable option, as the PV panels would overheat to the extent that critical performance limits (PV temperature $>85^{\circ}\text{C}$) are exceeded. One possible solution is the use of phase change materials (PCM) behind the PV panels, allowing PCM to function as a passive heat sink due to its high thermal capacity.

A relatively cost-effective way to employ PCM as a passive heat sink is by incorporating encapsulated PCM granules into a thick mortar layer behind the PV panel. However, this approach introduces new challenges. In cold climates, the water vapour resistance of materials in the external building envelope should typically decrease from the inside towards the outside. Applying vapour-tight PV panels as the outermost facade layer violates this principle. The risk is further increased by the presence of porous cementitious mortar just behind the PV panel, which can absorb moisture and accumulate it over time.

Therefore, it is essential to identify a reliable method for measuring the moisture content of the PCM mortar, which is expected to remain in the overhygroscopic range for a substantial proportion of the time. Then the hygrothermal behaviour of the PCM mortar should be studied both experimentally and numerically.

The architectural concept of the proposed FIPV solution is illustrated in Figure 1. Particularly in the Eastern European renovation market, there are many typical post-World War II buildings with large opaque end walls, many of which are oriented favourably for solar energy capture. A significant number of these buildings need renovation, and alongside prefabricated mass renovation approaches, ETICS remains an affordable and widely adopted solution. The PV-ETICS system offers an opportunity not

only to visually enhance these end walls but also to generate electricity on-site from renewable sources, particularly during peak demand hours.



Figure 1. Architectural concept of the PV-ETICS facade on an opaque end wall of a renovated typical apartment building in Tallinn, Estonia.

The potential applications of the PV-ETICS system are not limited to end walls alone. It is also not designed only for the renovation market but also for new buildings, residential as well as non-residential.

Aim and research questions

This research aims to develop a reliable PV-ETICS facade system incorporating PCM, and to evaluate its long-term hygrothermal performance through extensive testing under controlled and real-world conditions and hygrothermal modelling.

The main research questions of the thesis are:

- RQ1** How to design and build a durable PV-ETICS facade system with a dark and vapour-tight PV surface on top of thick PCM mortar in a cold climate, in a way that overheating and moisture accumulation in the system are avoided, and the PV replacement process is considered?
- RQ2** Which scientific methods and sensors are suitable for measuring the hygrothermal performance of thick PCM mortar, including within the overhygroscopic moisture range?
- RQ3** Can the hygrothermal performance of the facade system in real outdoor conditions be predicted using a hygrothermal model calibrated in a climate chamber?
- RQ4** How to determine the hygrothermal performance of the PV-ETICS system with scientific methods when the system is not in line with the traditional rules of hygrothermal design for building envelopes?
- RQ5** To what extent do the dark facade surface of the PV modules and the external thermal mass of the PCM mortar contribute to indoor overheating?

Hypothesis

According to the research questions, the following hypotheses were stated:

- H1** It is possible to design a buildable system that keeps peak PV temperatures within durability limits (below 85 °C) and avoids long-term moisture accumulation.
- H2** Moisture content of PCM mortar, measured using calibrated soil moisture sensor corresponds with gravimetrically measured values.
- H3** A hygrothermal model, calibrated using climate chamber measurements, will reproduce the measured moisture content of PCM mortar during a real facade experiment with sufficient accuracy.
- H4** The long-term hygrothermal performance of the PV-ETICS system can only be evaluated using an experimentally calibrated dynamic hygrothermal model, as traditional dew-point methods are not suitable for assemblies featuring vapour-tight external surfaces without a ventilation cavity.
- H5** Dark PV-ETICS surfaces contribute significantly to indoor overheating and should therefore be considered in overheating risk and cooling demand design.

Research methods and the scope of publications

The following methods were chosen to answer the research questions:

- **Developing and constructing** several variations of PV ETICS **facade system** as one-storey-high test walls.
- **Hygrothermal measurements** inside test walls both in the climate chamber and outdoor conditions using **calibrated soil moisture sensors**.
- **Development of a hygrothermal model** in *Delphin*, using measured material properties.
- **Calibration of a hygrothermal model** using data from climate chamber experiments.
- **Using the calibrated hygrothermal model to predict the moisture behaviour** of the PV-ETICS facade under real climatic conditions.
- **Destructive opening** of the test facades to **gravimetrically determine moisture content** and validate both measured and modelled results.
- **Long-term hygrothermal modelling** using critical test years to assess durability and moisture safety.
- **IDA ICE energy model calibration** based on measurements during a real climate experiment
- **Energy simulations** of a typical renovated apartment building with PV ETICS, using a **calibrated energy model**.

Publication I describes the development and construction process of the PV-ETICS facade system incorporating thick PCM mortar. It presents the calibration process of soil moisture sensors specifically for this PCM mortar and gives the equations to calculate moisture content from voltage readings under non-isothermal conditions. Measurement results from the initial dry out process of the test walls are provided. Additionally, the preliminary hygrothermal model in Delphin 6.1 was developed to simulate the initial drying phase before the installation of the PV panels.

Publication II outlines the experimental setup in a climate chamber. The characteristics of the different testing cycles are described, and the corresponding results

are presented. In addition to solar radiation, wind-driven rain (WDR), freeze–thaw cycles and possible water leakage through cracks were imitated by directly injecting water into the PCM mortar. A more advanced hygrothermal model was developed, incorporating both diffusion channels and a PV panel installed over the PCM mortar. All experiments were replicated in the model for model calibration.

Of the three wall configurations constructed in the climate chamber, one was selected for long-term testing on a real facade. **Publication III** focuses on the full-scale outdoor experiment, analysing both exterior and interior climatic conditions. Results from a 20-month monitoring period are presented, covering two summers and two winters. Maximum PV and PCM temperatures are reported, and the long-term moisture content of the PCM mortar is modelled using ten condensation test years to assess the risk of moisture accumulation. The previously calibrated model from the climate chamber was applied directly, without modifying any parameters.

Publication IV was initiated based on findings from the experimental wall studied in Publication III. During data analysis, it was observed that overheating occurred in the test room, and noticeable heat flux was measured from the PV-ETICS facade into the structural layer, despite the presence of relatively thick thermal insulation. This observation raised a concern about how significant this additional heat flux might be in a real building. Since the PV-ETICS system is also intended for the renovation market, even small additional heat gains from the facade could cause indoor temperatures to exceed acceptable overheating thresholds, as mechanical cooling is generally not installed during typical apartment building renovation.

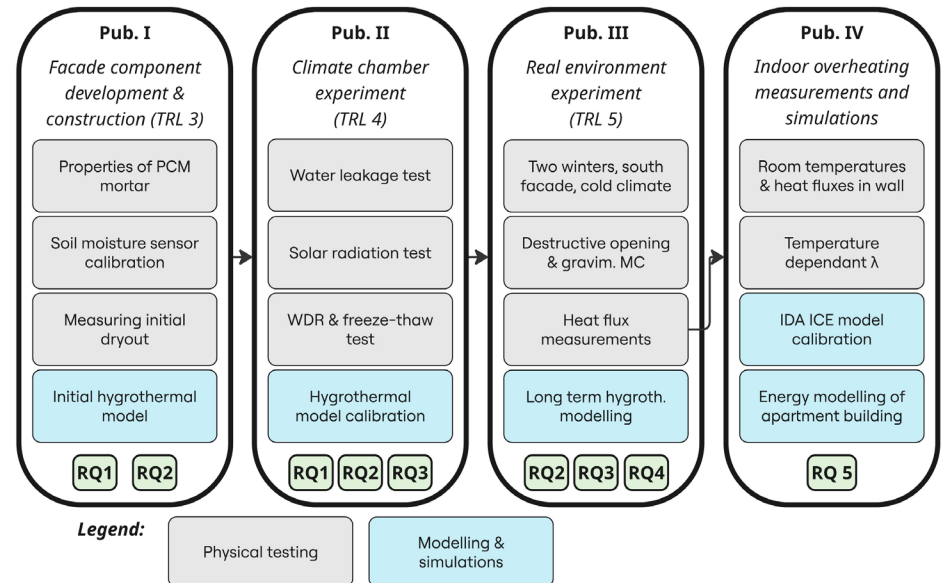


Figure 2. Contents of the publications included in the thesis

Scientific novelty

Traditionally, PV facades have been developed based on principles established separately in the fields of electrical engineering and building physics: PV panels are applied to an otherwise fully functional external wall, with an additional air cavity provided for ventilation. In the case of a PV-ETICS facade, however, the PV panels also

serve as a functional layer of the external wall. The novel methodology for experimental testing and product development presented in this study is grounded in an interdisciplinary approach by combining building physics, electrical engineering and material science.

PCMs are often studied in terms of latent heat storage and thermal comfort. Hygrothermal performance of PCMs encapsulated in porous cementitious materials represents a novel aspect of this study.

The use of soil moisture sensors to measure overhygroscopic moisture content in thick, porous materials has been explored for several construction materials. The available studies consistently indicate that material-specific calibration is required for each substrate. However, based on the scientific literature reviewed in this study, this method has not been applied to the measurement of moisture content in cementitious materials containing phase change materials (PCM). Because PCM undergoes phase transitions between liquid and solid states during thermal cycling, the readings of soil moisture sensors are likely influenced by changes in the dielectric properties of the material associated with the phase change. To the best of the authors' knowledge, the use of soil moisture sensors to measure the moisture content of construction materials containing PCM has not previously been reported in the literature.

New knowledge gained from this research includes:

- **A novel method** for testing ETICS facade systems with a **vapour-tight external layer** was developed and applied.
- A methodology was developed for deriving custom **calibration formulas** for measuring **overhygroscopic moisture content** at non-isothermal conditions in thick (>30 mm) porous materials containing PCM, using **soil moisture sensors**.
- The accuracy of **temperature correction graphs** for soil moisture sensors was evaluated during long term experiments.
- An optimal hygrothermal modelling approach was applied to simplify the complex PV-PCM mortar cross-section with diffusion channels into a **2D model**, neglecting micro-convection and gravity effects inside the channels and avoiding complex 3D simulations. The model was **calibrated in climate chamber** tests and demonstrated **sufficient accuracy in predicting** the hygrothermal behaviour of a real facade during a **long-term experiment**.
- The final prototype of the novel facade system was selected and applied based on its resistance and robustness against **water leakage behind the finishing layer**. This represents a **fundamentally new approach to moisture safety in the design of ETICS facade**, which traditionally assumes that water must not penetrate behind the plaster surface.
- **Linear deformations** of the PV panel, facade plaster, and connecting joint were measured, and two alternative joint designs were proposed, including one based on design-for-disassembly principles.

Overall, the model calibration techniques conducted in the thesis could be recommended to be applied to other applications in the future, as calibration in the climate chamber is less time consuming than conducting long-term outdoor model calibration

Practical applications

A novel facade system, including all its components, joints, and detailing, was developed, constructed, and experimentally tested by the author of this thesis. The **facade system exists in the real world as a physical TRL 5 prototype** resulting directly from this PhD research. It is producing solar electricity and performs as designed in terms of hygrothermal behaviour, under extreme conditions, including leaked-in moisture and freezing while being wet. The system has demonstrated reliable performance beyond the two-year guarantee period, with modelling indicating continued functionality over the long term.

The final prototypes tested experimentally achieved Technology Readiness Level (TRL) 5, and most of the critical performance principles were solved during the research. It is possible to mature the technology relatively quickly into a marketable product at higher TRL levels.

For the successful development of a mass-producible PV-ETICS facade system, the following key factors identified in this research should be taken into account:

- Diffusion/drainage channels must be incorporated behind the vapour-tight PV panels to allow any leaked-in moisture to safely dry out.
- A minimum drying period of two weeks (at 20 °C / 50 % RH) should be allowed between the application of PCM mortar and the installation of PV modules. The facade must be protected from environmental exposure during this period. At lower ambient temperatures, the drying time should be extended accordingly.
- The dark surface of the PV facade should be considered in energy performance calculations, particularly for walls with thinner insulation ($U > 0.20 \text{ W/m}^2\text{K}$).
- In accordance with design-for-disassembly principles, stainless steel ribbons should be used at the interface between the PV panel and the facade plaster to enable replacement of the PV panel without damage to the surrounding plaster surface.
- Cabling with MC4 connectors should be installed before the application of the insulation layer to enable PV replacement. Connectors should not be placed in a cavity filled with PU foam.

Key construction steps for the facade system are presented in the application guidelines provided in **Appendix 5**. Proposals for the further development of the facade system are provided in **Appendix 7**.

Limitations of the work

The main limitations of the research are:

- Electrical output and economic analysis were outside of the scope of the thesis.
- The exact latent heat storage capacity of the PCM before and after the long-term experiment was not measured directly; therefore, potential degradation of PCM efficiency was assessed only indirectly through temperature data.
- While the hygrothermal performance of traditional ETICS was monitored during the experiments, the precise deterioration mechanisms of the traditional facade plaster were not investigated. However, at the scale of the test walls, the presence of a PV-PCM section did not make traditional ETICS less durable.
- Thermal expansion related deformations between the PV modules and facade plaster were studied on test walls with a relatively small surface area compared to full-scale buildings.

1 Background

1.1 Need for renovation-compatible vertical PV solutions

Europe's energy sector is vulnerable, largely because of its limited domestic energy resources and continued dependence on imported energy (Mróz, 2021; Vošta, 2023). To reduce this dependence, European Union's energy policy has strongly promoted the expansion of renewable electricity production in member states (Relich, 2024).

However, the rapid growth of solar power has also created new challenges for the electricity grid, including the so-called duck curve, where midday overproduction from south-facing solar panels coincides with lower electricity demand. Several studies have addressed the duck curve phenomenon and different strategies for mitigating it (Kaji Esfahani et al., 2021; Krietemeyer et al., 2021). One approach is to increase solar electricity production at times that better match building energy demand, particularly during the morning and evening peak hours. (Doroshenko et al., 2018) demonstrated that optimising PV panel angles can increase electricity production during peak hours by 25–30% without significantly reducing total annual output. In residential buildings in particular, south-east and south-west oriented facade PV can be better aligned with demand patterns than conventional south-oriented rooftop systems.

Increasing on-site electricity generation using PV facades is mainly being done, using widespread rigid PV panels, with a ventilation cavity behind (Figure 3). In these conventional BIPV facades, a ventilated air cavity is used to improve both hygrothermal safety and PV performance.

On the other hand, there is a strong need for energy retrofit of the post-Second World War building stock in Estonia, and indeed throughout Eastern Europe. The indoor climate, energy efficiency, and hygrothermal performance of the envelopes of these buildings need improvement (Ilomets et al., 2017). Many of these buildings suffer from the need for renovation due to mould growth on the internal surfaces at the thermal bridges, insufficient ventilation, and high heating costs. Facade deterioration may accelerate reinforcement corrosion from the exterior, that results in residual service of facades within three to six years (Ilomets et al., 2016). Therefore, adding external insulation and improving ventilation, thermal comfort, and facade performance are recommended. Such renovation measures can reduce heat losses, mitigate moisture and mould risks, improve durability, and enhance both the appearance and long-term performance of the buildings (Ilomets, 2017).

External Thermal Insulation Composite System (ETICS) is one of the most common and cost-effective facade renovation systems in Europe and is unlikely to disappear from the market in the near future. The system is flexible in terms of facade geometry, widely known in construction practice, and relatively lightweight and cost-effective to apply. Although more advanced renovation approaches, such as prefabricated elements, are gaining market share, ETICS is still expected to play a significant role in the Renovation Wave for Europe (European Commission, 2020). For this reason, there is a need for a space-efficient way to energy-activate plastered facades. Current PV facades are generally based on rear-ventilated principles, where the weatherproof wall remains behind and the PV layer is mounted separately in front of it (Figure 3).

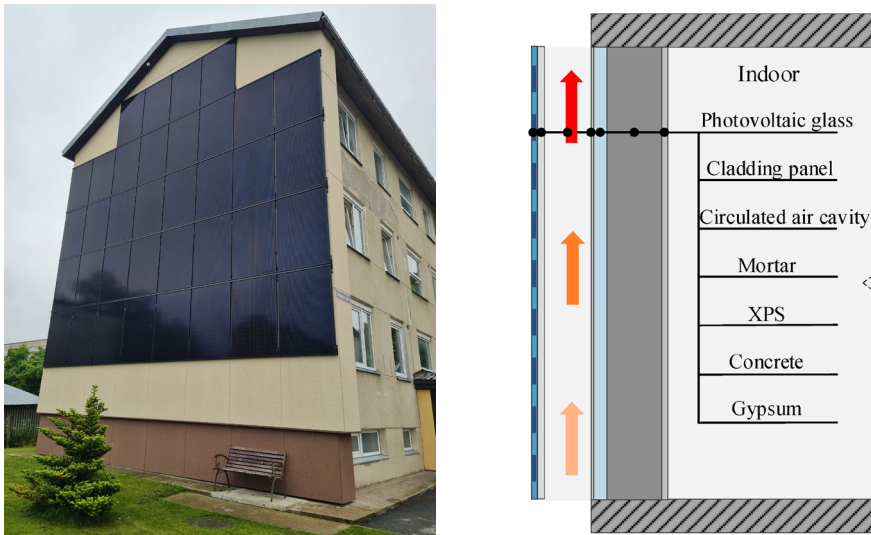


Figure 3. An example of ventilated PV panels installed on top of a ventilated fibre cement board facade in Türi, Estonia (left) and an example cross-section of a ventilated PV double-skin facade studied by Y. Li et al. (2026) (right)

1.2 Development of the PV-ETICS concept

Several studies have investigated the combination of PV and PCM (Abdelrazik et al., 2022; Čurpek et al., 2022; Čurpek & Čekon, 2020; González-Peña et al., 2020; Hasan et al., 2015; Tao et al., 2019) in a variety of applications. However, at the start of this study, the integration of a PV+PCM cross-section into ETICS and its development to a relatively high TRL remained largely unexplored in the literature.

The PV-ETICS concept was developed within the En-ActiveETICS project (M-ERA.NET, 2022), to integrate PV panels into a traditional ETICS facade without a full ventilation cavity. The product development process was based on the Technology Readiness Level (TRL) framework, which was developed by the National Aeronautics and Space Administration (NASA) in the 1970s as a standardized tool for assessing technology maturity in complex system development (Mankins, 1995; Olechowski et al., 2020).

The framework uses a nine-point scale, ranging from TRL 1, where basic principles are observed and reported, to TRL 9, where the system is complete and has been proven in operational conditions. This ranking scheme has been widely adopted in many fields, including construction (Ma et al., 2022). The aim of the En-ActiveETICS project was to develop the PV-ETICS facade system from TRL 2 to TRL 5. The present thesis begins from the point at which TRL 2 had already been achieved (Ilomets et al., 2020) and covers TRLs 3, 4, and 5 (Figure 4).

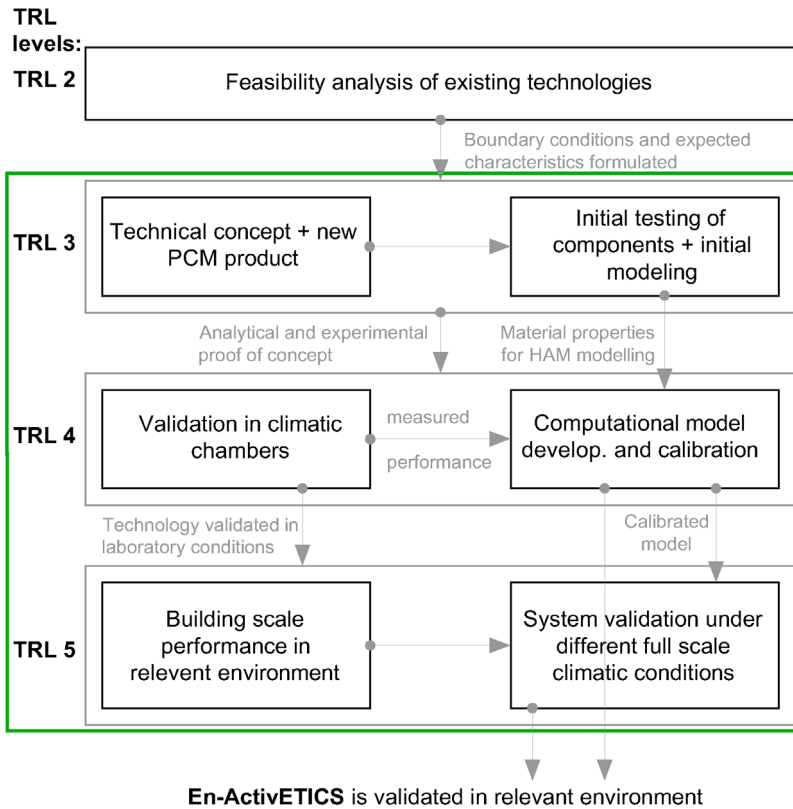


Figure 4. Planned work stages of PV-ETICS development process. Published before the start of the current thesis by (Ilomets et al., 2020). The scope of the present thesis is marked with a green rectangle.

At TRL 2, (Ilomets et al., 2020) presented the initial cross-section (Figure 5), which differed considerably from the version later used in the experiments of this thesis, but defined the main functional layers and outlined the main hygrothermal, mechanical, and energy-related challenges of combining photovoltaics and phase change materials with ETICS.

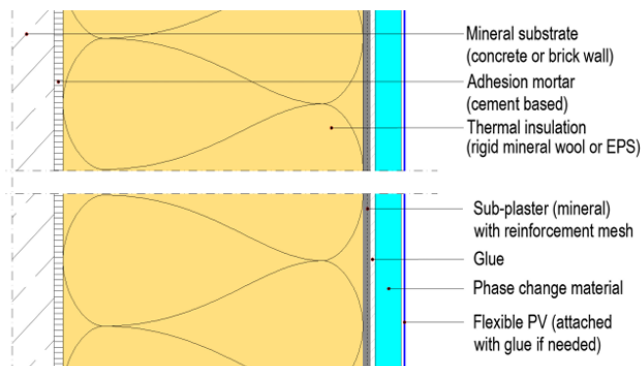


Figure 5. Starting point for the PV-ETICS development. Overall concept of the cross-section by (Ilomets et al., 2020).

The key idea behind PV-ETICS was to prevent PV panel overheating by placing PCM behind the PV panel to absorb heat. The PCM had to be dimensioned so that it could melt effectively during the day and solidify again at night. The initial concept did not define exactly how the PCM would be encapsulated or which melting temperature would be optimal. This issue was examined in a numerical study conducted by the author of this thesis (Talvik et al., 2021), which analysed two options: PCM encapsulated in a metal case and PCM granules mixed into a cementitious mortar. The study showed that a 30 mm PCM mortar layer could reduce peak PV temperatures by about 10–16 °C, depending on the PCM used, and increase electricity production by about 2% compared with a solution without any thermal sink behind the PV.

For economic reasons (Heim, Talvik, et al., 2023), the cement-based mortar solution was selected, as it required less PCM, which is one of the most expensive components in the system. In addition to the PCM content, the thermal mass of the thick mortar in which the PCM granules are encapsulated could also be used to the system's advantage.

From a hygrothermal point of view, there is a risk caused by the PV panel, which is, unlike traditional facade plaster, vapour tight. Because the PCM mortar solution was selected, this issue became more critical, since the porous cementitious material was now enclosed behind a vapour-tight PV layer. In cold climates, indoor moisture excess and built-in moisture tend to migrate outwards, while adjacent ETICS is also known to allow rainwater ingress, due to cracking. Therefore, an additional outward drying path was needed to allow moisture to escape from the thick PCM mortar and thereby avoid freeze-thaw damage.

The initial idea that diffusion channels should be used to mitigate the risk of moisture accumulation was presented in a master's thesis by the author of this thesis (Talvik, 2021). Based on Delphin simulations carried out midway through the model calibration process, hygrothermal performance of the system with and without diffusion channels was evaluated in five different climates (Heim, Talvik, et al., 2023) and it was numerically confirmed that the diffusion channels are necessary. This study also included an economic analysis and highlighted the system's high market potential in Europe.

The electrical performance of the system was investigated by (Heim et al., 2020; Heim, Knera, et al., 2023; Heim, Talvik, et al., 2023). No significant problems were identified in terms of electrical output, and therefore, electricity production is not examined further within the scope of this thesis. As emphasised in Talvik et al. (2021), the primary role of the PCM layer should be to prevent damage of the PV from overheating beyond the manufacturer's declared temperature limit. The increase in electricity yield due to lower PV operating temperatures is too small to provide meaningful economic benefit. It has been calculated in (Talvik et al., 2021) that applying PCM behind PV increased annual electricity production by just 2.1–3.7% at the Tallinn location.

As the PV-ETICS facade combines two different finishing materials into one system, it should be considered that PV panels typically have a service life of 25 years, whereas external wall assemblies should be designed for a service life of 50 years. Therefore, when the PV-ETICS concept is being developed, it is important to allow the PV panels to be replaced without damaging the facade plaster, and vice versa. Separating the building components is also important at the end-of-life stage of the system. For this reason, Design for Disassembly (DfD) principles were implemented to some extent during the development of the facade.

The core objective of DfD is to enable the reuse of products, components, and materials from buildings at the end of their service life, thereby facilitating a shift from

the current linear use of construction materials to a more circular model (Ostapska et al., 2024; Salama, 2017). The DfD approach promotes the design of buildings and systems in such a way that materials and components can be easily separated, recycled, and potentially reused during renovation, transformation, or demolition processes (David et al., 2024). Key strategies for implementing DfD in construction include the use of mechanical or otherwise reversible connections, modular design, clear separation of material layers, avoidance of hazardous or composite materials, and the preparation of deconstruction plans already during the initial design phase (Ostapska et al., 2021, 2024).

Unfortunately, conventional ETICS facade systems perform poorly when evaluated against DfD principles. The layers in ETICS are typically bonded using adhesives, creating strong chemical connections between insulation, base coat, reinforcement, and finishing layers. As a result, dismantling generally causes both the plaster and insulation to fragment into small pieces, which are then discarded as mixed construction waste. Therefore, ETICS disassembly without material degradation is generally not feasible, and reuse of components is practically impossible, despite the systems having relatively low environmental impacts during the production phase (Devos et al., 2023).

Some alternative solutions exist in which the insulation layer is mechanically fixed rather than adhesively bonded, allowing for potential removal. They have been tested out in scientific studies (Talvik et al., 2025) and some solutions are also available on the market (*ETICS Weber.Therm Circle*, 2022). However, such systems are still not widely adopted. They typically require a structurally even, level, and smooth substrate, which limits their applicability in renovation projects. Additionally, ETICS systems using mineral wool insulation are generally more expensive than those based on expanded polystyrene (EPS).

1.3 Sustainability relevance and regulatory framework of PV-ETICS

The relevance of this work can also be framed through the United Nations Sustainable Development Goals (Genders, 2023). A PV-ETICS facade contributes to several of these goals. By generating renewable electricity at building level, especially during peak demand hours, it supports the transition towards cleaner and more accessible energy systems (Goal 7) while also reducing CO₂ emissions (Goal 13) (Valencia G. et al., 2026). By improving both the thermal performance and energy-generation capacity of the building envelope, PV-ETICS can contribute to a more sustainable and resilient built environment (Goal 11) (B. Li et al., 2026). In addition, the possibility of replacing PV panels without damaging the facade plaster, together with the introduction of DfD principles and improved outward drying through diffusion channels, supports more resource-efficient construction and longer material service life (Goal 12) (Sanchez et al., 2020).

The research can also be related to the EU Construction Products Regulation (EU Regul. No. 2024/3110, 2024). Annex I of the CPR sets out eight Basic Requirements for Construction Works: structural integrity and durability (1); fire safety (2); hygiene, health, and the indoor environment (3); safety and accessibility (4); noise protection and acoustic properties (5); energy efficiency and thermal performance (6); emissions into the outdoor environment (7); and sustainable use of natural resources (8). In principle, the PV-ETICS system developed and tested during this thesis relates to all of these requirements, but the main focus is on requirements 1, 3, 6, and 8 (Ilomets et al., 2020).

To address the requirement concerning the durability of the system (1), it is necessary to control the maximum temperature of the PV panel and the moisture content of the

PCM mortar to ensure long-term durability. The requirement concerning hygiene, health, and the indoor environment (3) is addressed by applying additional external thermal insulation, which reduces the risk of mould growth on the interior surfaces of the building envelope, and also by including diffusion channels behind the PV panel, to reduce the risk of moisture damage caused by water leakage through the facade system. To address the requirement concerning energy efficiency and thermal performance (6), in addition to an appropriate insulation thickness and renewable energy production, the risk of overheating of the indoor environment was considered. With respect to the sustainable use of natural resources (8), the system incorporates some DfD principles.

1.4 Durability and moisture-related risks of ETICS facades

External Thermal Insulation Composite System (ETICS) is a facade system in which insulation boards are adhesively bonded and mechanically fixed directly to a masonry or concrete substrate, after which a plaster system is applied directly on top of the insulation, without any ventilation cavity (EAD 040083-01-0404, 2024). Its performance is based on the principle that liquid water should not penetrate behind the plaster layer. Although the facade plaster system is designed to remain watertight but vapour-open, its water vapour diffusion resistance (S_d in the range of 0.1 m to 2.0 m) is still noticeably higher than that of typical wind barrier membranes ($S_d = 0.02 - 0.1$ m). Compared with a ventilated facade, ETICS is more sensitive to defects (Liisma et al., 2016; Sulakatko et al., 2017), because it relies on a single outer layer for weather protection: the plaster system must simultaneously function as primary rain protection, secondary rain protection, and an air and wind barrier.

ETICS has become one of the most widely used facade insulation systems in Europe because of its improved thermal performance, low installation cost, and ease of application (Künzel et al., 2006). Compared with ventilated facades, ETICS has a lower embodied carbon footprint (A1-A5), but this advantage decreases when maintenance and service life are considered (Baptista et al., 2024; Kertsmik et al., 2023). Computational models for service life prediction of ETICS lead to an average estimated service life of 21 years, considering 378 ETICS samples located in Portugal (Tavares et al., 2020). However, numerous examples indicate that the service life of ETICS in the cold climate of Estonia could be shorter (Olak et al., 2026; Sulakatko, 2019; Sulakatko et al., 2017).

Numerous field studies in various climates show that ETICS defects are common in practice and are closely linked to weaknesses in design and workmanship (Amaro et al., 2014; Kvande et al., 2018; Sulakatko, 2019). The risk of on-site degradation in ETICS is found to be high and cracking of the facade plaster is a frequent problem, especially in cold climates. The mechanisms of crack formation in facade plaster have been described in detail by (Cecconi et al., 2020; Liisma et al., 2015) and deformations of different plasters have been measured by (Volkova et al., 2021). A comprehensive review by (Parracha et al., 2023) identifies recurring anomalies and concludes that most could be avoided through proper design and execution. However, careful execution is often a challenge because ETICS is intended to be a relatively low-cost solution for insulating buildings, which creates strong demand for inexpensive low-skilled labour for installation, despite the fact that it is technically a complicated system to install properly because of its many complex joints and details (Parracha et al., 2023).

The aim of the PV-ETICS development is not to make traditional ETICS inherently different than it is today or to increase the durability of the ETICS section. However, the

concept may improve moisture safety by introducing diffusion/drainage channels that provide an additional route for moisture to escape, not only when water enters through joints between PV and plaster, but also when it originates from other sources such as construction moisture, leakage at window interfaces, or defects in parapet details.

Another aspect addressed in this thesis is the potential effect of dark ETICS on indoor overheating, which requires defining the maximum solar absorption coefficient of dark facade plasters. Dark ETICS finishes are associated with higher solar absorption, higher surface temperatures, and a greater risk of early degradation (Pasek, 2014; Ramos et al., 2020), which is why most plaster manufacturers specify a maximum surface absorption coefficient of $\alpha = 0.8$.

1.5 Measuring MC of construction materials with soil moisture sensors

Originally, soil moisture sensors (SMS) (Figure 6) were developed to determine moisture content (MC) by measuring the dielectric constant (ϵ) of the medium using capacitance/frequency domain technology. They are primarily used in agricultural research and greenhouse applications (Yu et al., 2021).

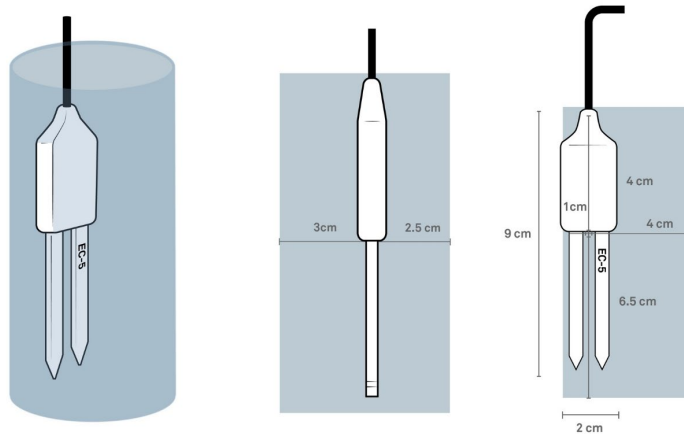


Figure 6. Example of soil moisture sensor with visualisation of its measurement area. Source: (Edaphic scientific, 2026)

One possible technology for measuring moisture content in soil is the capacitance-based frequency domain principle (FDR), which is used in dielectric soil moisture sensors. This method determines volumetric water content by measuring the dielectric constant of the surrounding medium, which is strongly influenced by the presence of free water (Yu et al., 2021). Dielectric soil moisture sensors based on capacitance principles estimate water content by measuring changes in the dielectric constant of the surrounding medium. In such sensors, the probe and the material form part of an RC circuit, where variations in moisture alter the equivalent capacitance (Figure 7). These changes affect the electrical response (e.g., voltage), which is converted into an output signal, using a high-frequency oscillator and a detection circuit. Output from this detection circuit is proportional to the volumetric water content of the soil (Yu et al., 2021).

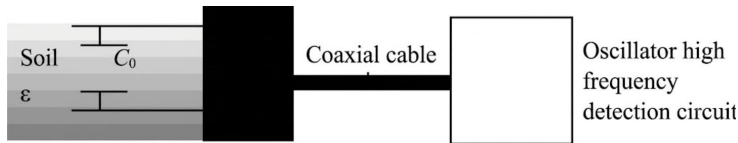


Figure 7. Schematic representation of a capacitance-based (FDR-type) dielectric soil moisture sensor. Source: (Yu et al., 2021)

Karoglou et al. (2024) applied capacitance-based sensors to monitor the full drying process of various building materials under controlled laboratory conditions. The study covered a representative range of mineral building materials commonly used in both historic and modern construction, including two types of bricks, two types of natural stones, and four types of mortars. The results showed that the relationship between moisture content and sensor signal voltage can be described using linear functions for all tested materials. However, all experiments by (Karoglou et al., 2024) were conducted under controlled environmental conditions (temperature 21 ± 1 °C, RH $50 \pm 5\%$), and it was stated that future work should include temperature-dependent calibration models.

(Karoglou et al., 2024) states that the 70 MHz frequency of EC-5 probes minimises salinity and textural effects, making this sensor accurate in almost any soil or soilless media, and the sensor is described as follows: “*Delivers research-grade accuracy at an economical price.*” The manufacturer provides both written and video guidelines for sensor calibration (METER Group, 2026). The recommended calibration method for soil is, in principle, based on gravimetric measurements. The calibration equation presented in the manufacturer’s data that best fits the measurements is a cubic polynomial.

Among other technologies used for measuring soil moisture content, the Time Domain Reflectometry (TDR) technique has also been tested for construction materials. For example, Mollo & Greco (2011) used TDR to measure various cement mortars and clay bricks, and Freitas et al. (2020) used TDR to measure the moisture content of limestone walls. Instead of measuring capacitance between two probes, TDR measures the travel time of an electromagnetic pulse along a probe to determine the apparent dielectric permittivity ϵ . These studies have also concluded that each material requires custom-made semi-empirical calibration equations and that equations developed for soils cannot be directly applied.

Very little research has been conducted on the use of SMS of any type within larger-scale wall assemblies where the measured construction material is embedded between other materials. Additionally, no research was found on the use of SMS for measuring moisture content in construction materials containing PCMs. There is also limited knowledge regarding the temperature dependence of these sensors, beyond general observations that this factor should be considered in future studies (Karoglou et al., 2024).

Phase-Dependent Dielectric Permittivity of PCM-Containing Materials

A phase change material (PCM) is a substance capable of storing and releasing large amounts of thermal energy through a reversible phase transition, typically between solid and liquid states, at nearly constant temperature. This latent heat storage mechanism makes PCMs highly suitable for thermal energy storage applications in buildings and energy systems. PCMs are generally classified into three main categories: organic, inorganic, and eutectic materials (Kannan et al., 2022).

If soil moisture sensors are intended to be used for measuring thick, porous materials that also contain PCM, the calibration process may become more complex when the

material is exposed to temperatures at which the PCM can exist in both liquid and solid states. Some PCMs are specifically designed to exhibit large differences in dielectric permittivity between liquid and solid phases (Tu et al., 2019).

However, Mira-Hernández et al. (2025) showed that non-polar (paraffin-based) PCMs behave as low-loss dielectrics, with only a minor contrast in dielectric constant between phases, where the solid phase typically exhibits slightly higher relative permittivity (approximately 3–8%) than the liquid phase.

Mira-Hernández et al. (2025) also showed that for PCMs RT28HC and RT35HC (both paraffin-based; nominal melting temperatures 28 °C and 35 °C respectively), there is a decrease in high-frequency relative permittivity ϵ_{∞} in the phase change region. This change is significantly smaller than that observed for polar organic PCMs or for sodium acetate trihydrate.

Dielectric parameters of PCM composites combined with other construction materials have not been extensively studied in the literature. To the best of the author's knowledge, no studies have been published on measuring moisture content with SMS in porous construction materials containing PCM. However, existing literature provides strong indications that calibration should be conducted separately for both solid and liquid states of the PCM composite material.

1.6 One-storey-scale testing of ETICS

Climate chamber testing of ETICS for commercial certification in EU

For industrial application and product qualification within the European assessment, conventional ETICS are assessed according to (EAD 040083-01-0404, 2024). Among other experiments, durability-related climate-chamber testing is an important part of the evaluation of watertightness and long-term robustness of ETICS.

For hygrothermal assessment, the EAD uses a test area of at least 6 m² (width > 2.5 m, and height > 2.0 m). After installation, the specimen must cure for at least 4 weeks at 10–25 °C and RH ≥ 50%.

The climatic programme of EAD consists of 80 heat-rain cycles followed by 5 heat-cold cycles (Figure 8). These tests are intended to reveal defects such as blistering, peeling, detachment, and cracking.

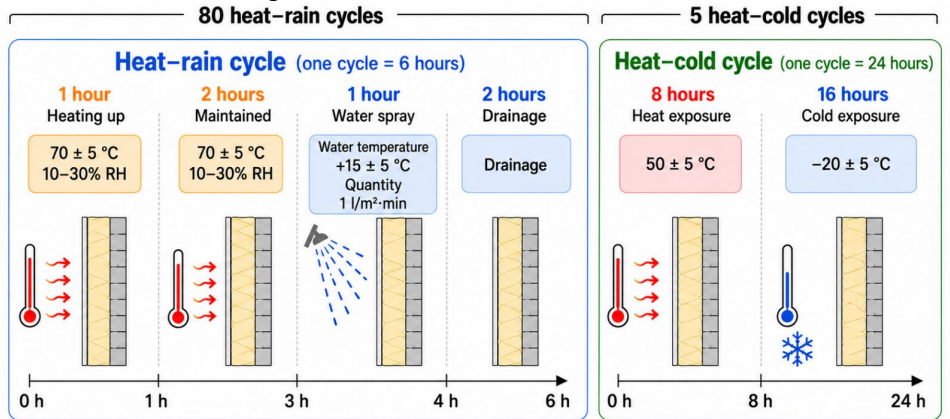


Figure 8. Climate cycles for testing ETICS kits in climate chamber according to (EAD 040083-01-0404, 2024). Visualisation created with OpenAI ChatGPT GPT-5.4 Thinking.

A key point is that the EAD treats heat-rain and heat-cold exposure separately. It does not define a large-scale test in which freezing occurs directly after facade exposure to the wind-driven rain. This is important for the present study, because freeze-thaw after wetting may be highly relevant when cold-climate performance and model calibration are considered. Freeze-thaw performance according to the EAD is assessed separately on 500 × 500 mm samples.

Another important aspect of the EAD is the way the facade is heated. In the standard test, the required surface temperature is achieved by adjusting the air temperature in the chamber, not by applying solar radiation to the facade surface. If only plasters are evaluated, this is appropriate, especially as light-coloured plasters, which could be preferred for the tests, would be difficult to heat to 70 °C using radiation. However, for a PV-ETICS facade, where light-coloured plaster and dark PV panels are located side-by-side, radiative surface heating is preferred, especially as a proportion of the radiation hitting the PV is converted into electricity instead of heat.

To pass the EAD tests, there should be no blistering, peeling, or detachment of any layers. There should also not be any cracks at the end of the experiment bigger than 0.2 mm, which is considered wide enough to allow water to penetrate behind the finishing plaster. If cracks do not appear during the experiment, there is no leaked-in moisture considered in any of the EAD tests. ETICS systems are designed to be water-tight, and therefore these climate-chamber rain tests without leakage are used. However, research has shown that leaks do occur; therefore, for scientific studies, a water leakage experiment should be included.

The EAD climate-chamber tests are designed mainly for product qualification, not for scientific model development. They provide pass/fail criteria for certification, but they do not require detailed measurements inside the wall. The EAD does not prescribe monitoring of temperature, relative humidity, or heat flux inside the ETICS assembly. Only chamber temperature, RH, and surface temperature are measured. Current research aims not only to prove the durability of a PV-ETICS system, but also to investigate the hygrothermal behaviour of the facade system in a broader sense and to calibrate a hygrothermal model using measurements from the test assemblies. Therefore, the EAD test concept is a useful reference, but it should not be copied directly.

Climate chamber testing of ETICS in scientific studies

In scientific studies, accelerated climate-chamber tests are mainly used to reproduce degradation actions such as heat-rain, heat-cold, freeze-thaw and, in some studies, UV or simulated solar-radiation exposure in a relatively short time. However, outdoor exposure and real-building monitoring remain important for verifying long-term natural degradation mechanisms and failure modes, including biological growth, cracking, changes in material properties, effects of pollutants, and defects related to design, execution or assembly of ETICS systems (Parracha et al., 2023).

Climate chamber experiments are conducted often with the aim to obtain measurement data for numerical modelling. This combined approach is significantly more reliable compared to modelling alone, as measurements provide insight into real physical behaviour and make it possible to verify the reliability of the hygrothermal model.

Jerónimo et al. (2023) tested an innovative light steel frame wall incorporating ETICS as part of a hybrid wall solution in a climate chamber using first steady state conditions to measure thermal transmittance of wall assemblies. This was followed by heat-rain and freeze-thaw cycles that were conducted according to EAD. In addition to this, they found

it necessary to also conduct 5 solar radiation cycles using (1100 ± 100) W/m² for 5 hours. Temperature, heat flux and humidity sensors were installed in the test wall.

Landolfi & Nicoletta (2022) adopted accelerated ageing cycles inspired by the EAD/ETAG durability framework to test the performance of ETICS with six different insulation materials, including heat-rain, heat-cold and freeze-thaw actions. But the number of cycles, temperatures, durations and conditioning phases were modified compared with the standard EAD procedure. Surface temperatures were measured during the dynamic thermal performance test, while moisture-related performance was assessed through gravimetric water absorption tests before and after ageing, rather than through continuous moisture monitoring during the cycles.

Parracha et al. (2021) tested six commercial ETICS variants in a climate chamber to complement findings from outdoor exposure and visual inspection studies (Parracha et al., 2022) in Portugal, where urban and maritime exposure in a relatively warm climate makes surface deterioration particularly relevant. The ageing programme included the EAD heat-rain and heat-cold cycles, but its main contribution was to go beyond standard temperature, humidity and rain exposure by adding UV-A/condensation cycles and SO₂ pollutant exposure, which better reflect urban facade conditions. The study therefore focused mainly on surface degradation, including colour change, gloss loss, increased roughness, reduced hydrophobicity and biological susceptibility, rather than on cold-climate durability mechanisms typical of Nordic conditions, such as repeated severe freeze-thaw loading leading to cracking.

Sun et al. (2025) studied ETICS in the context of a severe cold climate, but their climate-chamber experiment was mainly used to validate a coupled heat-moisture-mechanical numerical model rather than to perform a full accelerated durability assessment. An ETICS wall specimen with EPS external insulation was placed in a dual-sided steady-state environmental chamber, where high- and low-temperature regimes were applied while temperature, relative humidity as well as plaster deformations were measured at the surfaces and internal interfaces. The test procedure followed the Chinese (GB/T 29906, 2013) standard rather than EAD cycles, and no full heat-rain or freeze-thaw ageing sequence was implemented. The novelty of the study lies less in the chamber exposure itself and more in combining measured chamber data with a COMSOL model that includes dynamic wind speed and wind pressure as boundary conditions for a severe cold region.

Overall, the reviewed studies show that climate chamber testing of ETICS provides valuable information on different deterioration mechanisms and helps calibrate models. Scientific studies often go beyond standard EAD testing, and modifying the standardised cycles is common to obtain better data for model calibration. Calibrated models enable analysis of the long-term performance of building envelope components and parametric variations that are difficult to achieve experimentally.

Several prementioned climate chamber studies, as well as studies on other materials and wall assemblies (Dang et al., 2023; Klößeiko & Kalamees, 2022), consistently show that reliable HAM modelling depends on using accurate material properties. When necessary, these properties should be measured in the laboratory, especially in studies involving novel or experimental materials. Although hygrothermal models are powerful tools for analysing heat and moisture transport, their accuracy depends strongly on the quality of the input data, model assumptions, and boundary conditions. Experimental validation is therefore crucial for identifying model limitations, improving calibration, and ensuring that simulation results reflect real-world behaviour.

Most studies combine only two or three methods, for example climate chamber testing and hygrothermal modelling, to go beyond standard EAD cycling. However, it is relatively rare to find work that includes small scale measurements of material properties, climate chamber experiments, outdoor measurements, and hygrothermal modelling in one comprehensive study.

1.7 Energy modelling of dark facades and wall assemblies with PCM

Summer overheating has become an increasingly important issue in cold climate of Estonia, particularly in highly insulated non-residential (Raide et al., 2015) and residential buildings (Simson et al., 2017). Windows are generally the dominant source of indoor heat gains, and parameters such as window-to-wall ratio (WWR), glazing Solar Heat Gain Coefficient (SHGC / g-value), shading, and orientation strongly influence overheating prevalence (Simson, 2019; Thalfeldt, 2016). However, heat gains through opaque facade surfaces can also become relevant, especially in the case of dark-coloured surfaces.

The overheating effect of dark, non-ventilated facades remains poorly addressed in the literature. One early example is the simulation study by Yao & Yan (2011) which found that a higher facade solar absorption coefficient increases cooling demand and decreases heating demand approximately linearly in a hot-summer, cold-winter climate. However, their model used an external wall with a thermal transmittance of $U = 1.5 \text{ W}/(\text{m}^2 \cdot \text{K})$.

Numerous studies have examined the surface temperatures of dark-coloured roofing materials and their impact on indoor temperatures in rooms situated beneath the roof (Fabiani et al., 2019; Kalamees et al., 2020). It has been shown that the net cooling demand reductions between dark roofs and cool roofs are significantly greater for poorly insulated roofs than for those with higher levels of insulation (Synnefa et al., 2007).

The PV-ETICS system has potential for application in the renovation of residential buildings, particularly given the widespread use of traditional ETICS in the regional renovation markets of Northern and Eastern Europe. However, in Estonia and neighbouring countries, cooling systems are generally not installed during apartment building renovation projects, which could make even a slight increase in interior heat gains from the dark-coloured facade a potential concern. In the case of the PV-ETICS system, an additional thermal consideration arises from the 35 mm thick PCM mortar layer situated behind the PV panels. While PCMs effectively store excess heat during the day and release it at night, a portion of this heat is transferred into the interior through the insulation layer.

Integrating PCM material on the external side of the facade has been covered rarely in scientific literature, especially for well-insulated walls. In hot climates and for uninsulated walls, external PCM has shown a decrease in cooling demand by around 40% (Dardouri et al., 2023; Kumar et al., 2021). PCM installed on the external side of uninsulated roof assemblies in hot climate has shown a reduction of interior temperatures up to 9 °C in a hot climate (Al-Yasiri & Szabó, 2021).

Unlike the aforementioned studies conducted for warmer climates, the current study focuses on the colder climate of Estonia, where typical 200 mm of insulation may correspond to approximately $U \approx 0.12 \text{ W}/(\text{m}^2 \cdot \text{K})$, or in Finland where the required thermal transmittance of walls is $U < 0.12 \text{ W}/(\text{m}^2 \cdot \text{K})$ for small residential buildings and $U < 0.14 \text{ W}/(\text{m}^2 \cdot \text{K})$ for larger apartment buildings. In colder climates, the effect of dark facade finish and externally placed PCMs has not been extensively investigated.

2 Methods

To address the research questions posed in this study, a combination of physical measurements as well as hygrothermal and energy simulations was employed. The methodological approach prioritised empirical validation, ensuring that simulations were grounded in measured data. Over the course of the research, the PV-ETICS facade system was developed into a fully functional and buildable facade system (TRL 5), enabling larger building scale experimental investigations.

2.1 Methods for designing the functional layers and joint details of PV-ETICS [RQ1]

The PV-ETICS system was initially conceptualised as a one-dimensional (1D) multilayered wall assembly, with each layer fulfilling a specific function (Figure 5). After defining the 1D structure and recognising the intent to apply PV panels and traditional facade plaster on the same surface, joint solutions between traditional ETICS and PV-ETICS with PCM were developed.

2.1.1 Functional layers of PV-ETICS

Structure

Autoclaved aerated concrete (AAC) was selected as the load-bearing material for all experiments (Appendix 5, step 1) due to its high initial built-in moisture content and low vapour diffusion resistance. Its relatively low density also facilitated construction in the climate chamber by limiting structural loads to the chamber floor. In practical applications, all stone-based materials such as concrete, bricks, or different blocks may be used.

The internal surface of AAC was left unfinished to enhance vapour diffusion from the indoor environment into the wall and to eliminate interior finishing as an additional variable in hygrothermal modelling.

Initial moisture content of AAC was determined gravimetrically using AAC blocks stored in the same climate chamber conditions. These measured values were used as initial conditions in the simulation model, while other material properties were adopted from Delphin material database, correcting some basic properties according to the manufacturer's data (Bauroc Classic, 2026).

Glue mortar

A thin layer of glue mortar was applied between the insulation and the structural layer. A commonly used glue mortar (Webertherm 310, 2026) from Estonian ETICS construction practice was selected. As its thermal and hygric impact on the overall performance of the wall system is minimal, hygrothermal properties were not measured directly. Default material parameters of glue mortar were adjusted based on manufacturer data.

Insulation

Expanded polystyrene (EPS) and mineral wool (MW) were both used as insulation materials. Graphite-enhanced EPS (EPS 60 Silver Facade, 2026) was predominantly used, with MW (Paroc Linio 10, 2026) included in the climate chamber experiment to explore the differences in hygrothermal behaviour. The primary insulation thickness was 200 mm, consistent with standard practice in heating dominated countries of Eastern and

Northern Europe. To accommodate the PCM mortar, cavities matching the dimensions of the PV panel product were created using specially ordered insulation boards with a thickness of 160 mm (Appendix 5, step 2). Insulation was bonded to the AAC substrate with full-surface coverage to ensure homogeneity, and mechanical fixings were installed in accordance with wind load requirements for Estonian ETICS facades.

PCM mortar

The PCM mortar was composed of a cement-based mortar (Sto-Faserputz, 2026) mixed with microencapsulated PCM granules. The granules were coated with polyurethane (PU) to ensure water resistance and to encapsulate the PCM wax, particularly in its liquid phase. The PCM mixture included RT25HC, RT28HC, and RT35HC granules in equal proportions (Heim, Talvik, et al., 2023), yielding a composite latent heat profile suitable for northern climates. Mixing of PCM granules, cement-based mortar (dry mix), and water was performed on-site immediately prior to application (Appendix 5, steps 7-9).

Initial tests assessed the feasibility of applying PCM mortar to vertical surfaces. Due to a tendency for the mortar to slump, reinforcement was deemed necessary. A steel wire mesh was incorporated to provide structural integrity, and special anchors were used to secure the mesh directly to the structural layer through the insulation, ensuring mechanical stability (Appendix 5, steps 5-6).

PV panel

A thin, flexible PV panel used in the experiments was a monocrystalline silicon product. Electrical parameters and product specifications are detailed in (Flisom AG, 2021). The manufacturer declares the performance limit temperature of 85°C, a common threshold also for many other flexible PV panels.

A PV panel was glued directly onto the PCM mortar, using cementitious glue mortar with high polymeric content. Polymeric primer, mixed with cement according to the manufacturer's guidelines, was applied on the back side of the PV panel before glueing to improve adhesion (Appendix 5, step 11).

2.1.2 Concept of diffusion/drainage channels behind vapour tight PV panel

Triangular diffusion channels were formed in the fresh PCM mortar (Figure 9) to facilitate moisture dry-out from behind the vapour-tight PV panel. These channels were connected to the external environment at the lower end via a double steel sheet joint detail (Appendix 5, step 13). The upper ends of the channels were sealed, thereby eliminating convective airflow and the chimney effect. Consequently, only micro-convection was permitted. These single-ended diffusion channels also functioned as drainage paths in critical scenarios involving moisture ingress, effectively directing liquid water and condensate out of the wall. This dual functionality was verified through experimental testing.



Figure 9. Four diffusion channels were grooved into PCM mortar during application for all but one experimental cross-section.

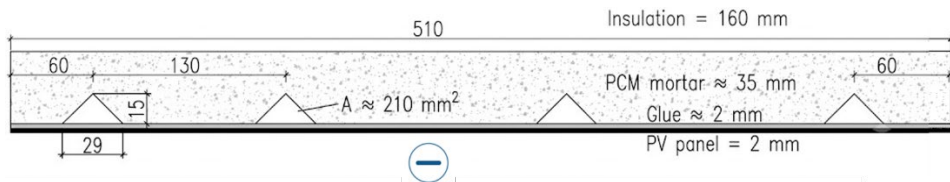


Figure 10. Horizontal cross-section of the PCM mortar showing diffusion channels. The dimensions indicated in the figure represent average values. The depth of the channels varied between 12 and 17 mm.

2.1.3 Design principles for PV cable connections

The existing PV cable connectors were rewired to modify the geometry of the cable outputs. These reconfigured outputs were sealed using layers of waterproof sealant with high temperature tolerance and enclosed on the front side with a steel sheet (Appendix 5, step 14). For future industrial-scale applications, custom made PV panels with rear side outputs and appropriately sized cables should be used. MC4 connectors were employed in the installation, consistent with standard PV industry practices (Figure 11).



Figure 11. MC4 connectors in cavity during demo application before insulating the whole facade (left) and filling the cavity during the application of PV panel (right). Lengthening cables between PV panels are attached to the AAC structure and would stay in place even after replacing the PV panels.

Extension cables were installed on the AAC structure prior to insulation (Appendix 5, step 1). In the experimental setup, electricity was consumed on-site using a simple 24 V truck bulb. As the electrical output of the PV panels was outside the scope of this research and had already been verified in previous measurements (Heim et al., 2021; Heim, Knera, et al., 2023), a basic switch was sufficient to either consume all generated electricity or disconnect the circuit to simulate an electrical fault condition. This fault condition was relevant for assessing overheating risks under critical conditions, as the solar radiation absorption coefficient of PV panels increases when electricity is not actively produced.

In the experimental setups, separate bulbs and cables were used for each PV panel. In real building applications, multiple PV panels would be connected in strings, with inverters installed in a technical room. Cabling for all strings must be installed prior to insulation, with each cable terminated at the correct length to enable rapid connection and replacement of individual PV panels over the building's lifetime, without necessitating the removal of extension cables or insulation. Cable locations must be documented, and during insulation installation, their positions should be marked on the insulation boards to prevent mechanical fixings from damaging the cables.

2.1.4 Joints between PV-PCM section and traditional ETICS

The joint between the PV panel and the adjacent traditional ETICS plaster was designed to be elastic, accommodating the differing thermal expansion of the dark-coloured PV panel and the light-coloured facade plaster. The bottom joint incorporated open diffusion channels shielded by overlapping steel sheets, while the top joint was sealed and connected to the plaster system using an elastic facade profile with water drip nose to divert rainwater away from the facade (Figure 12). Vertical side joints were also flexible, utilising elastic self-adhesive sealant (Figure 13 and 14). These profiles were adapted from existing ETICS window profiles, with modified geometry. The sealant enables minor multidirectional movement between the PV panel and the plaster.

Supplementary waterproofing between the plaster profiles and the PV panel was achieved using an elastic, UV-resistant, weatherproof PU sealant (Appendix 5, step 18).

The movement between the two facade materials was measured during the experiments and the condition of the sealant was evaluated after the long-term experiment in real climate.

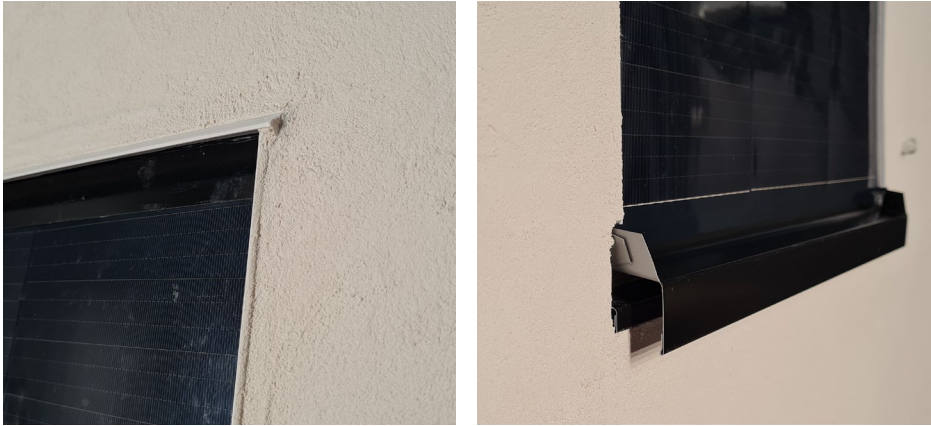


Figure 12. Upper joint between PV-PCM section and traditional facade plaster with water droplet nose (left) and lower joint with double steel sheet solution to enable air contact for diffusion channels.

Two versions of elastic joints between PV-ETICS and traditional ETICS were tested:

Version 1 – business as usual

Elastic deformation profiles were applied directly onto the PV panel. This configuration allows for replacement of the facade plaster without damaging the PV panels, but it does not enable replacement of individual PV panels without requiring extensive repair works of the facade plaster.

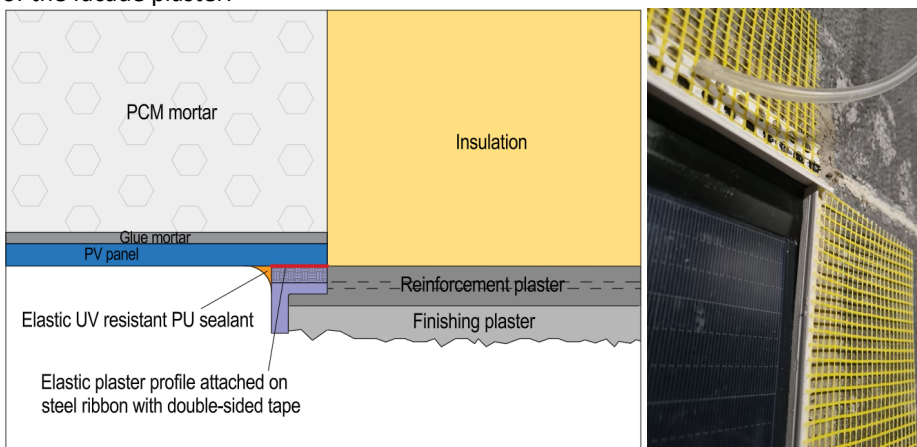


Figure 13. Business as usual joint design between PV-PCM section and traditional ETICS facade. Facade plaster profiles are attached to the PV panel surface.

Version 2 – design for disassembly

Overhanging steel ribbons were installed behind the PV panel edges prior to panel application (Appendix 5, step 10). After the PV panel was installed, elastic facade plaster

profiles were applied adjacent to the panel on the surface of the steel ribbons rather than directly on the PV panel. The ribbons were bonded to the PV panel using adhesive with moderate bonding strength, enabling removal of the PV panel from the steel ribbon without damaging the ETICS facade plaster.

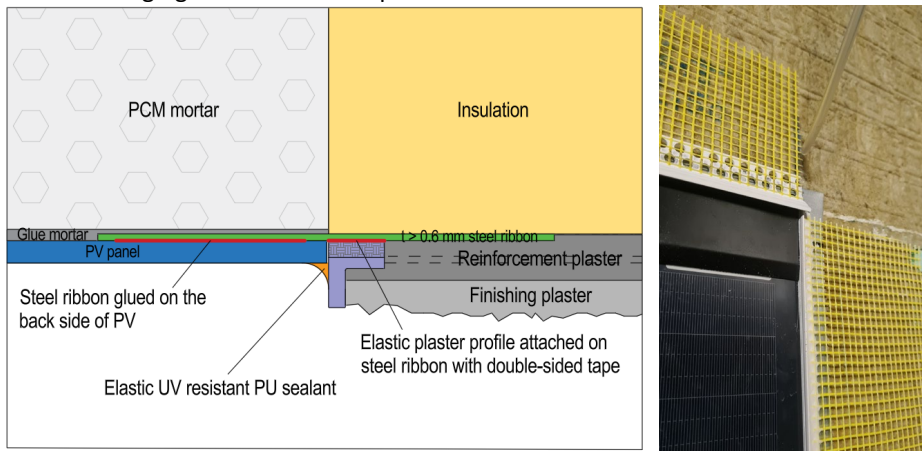


Figure 14. Advanced joint design between PV-PCM section and traditional ETICS facade. PV panels could be removed without damaging the facade plaster surface.

The PV panel removal technique was experimentally tested following the completion of the climate chamber experiments (Appendix 6).

2.1.5 Cross-section of PV-ETICS facade

The final cross-section of the PV-ETICS facade system integrates all functional layers and joint details described above. Vertical and horizontal cross-sections are illustrated in Figure 15 and Figure 16.

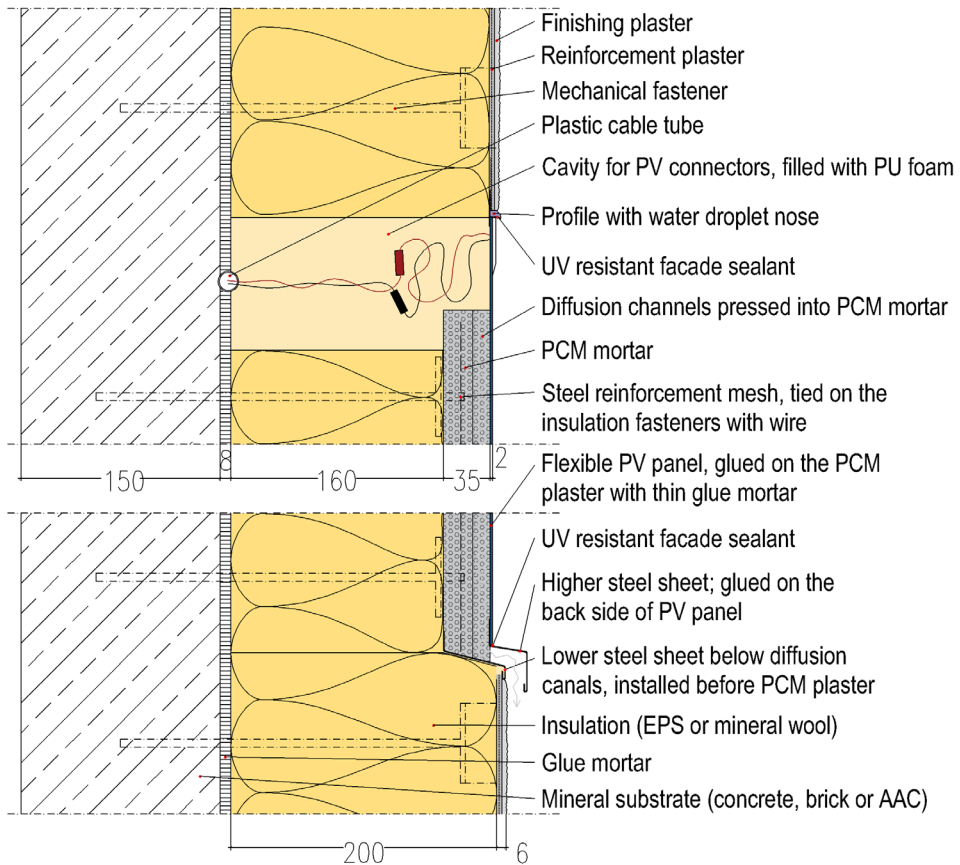


Figure 15. Vertical cross-section of PV-ETICS facade system

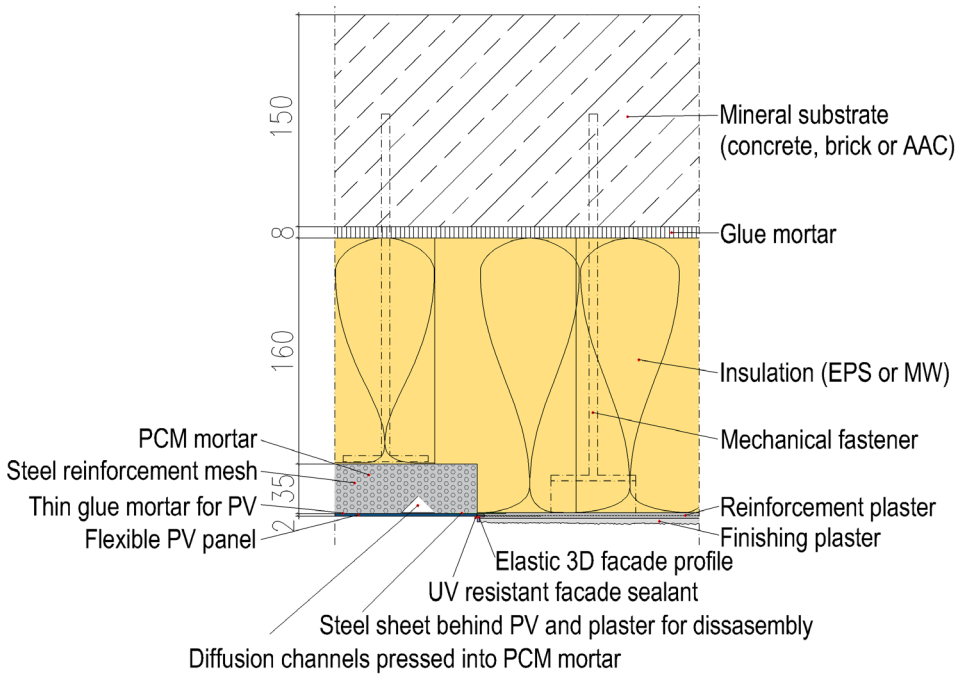


Figure 16. Horizontal cross-section of PV-ETICS facade system

2.2 Experimental set up for measuring overhygroscopic MC in PV-ETICS [RQ2]

This section outlines the experimental framework from small scale experiments to climate chamber and real environment experiments to assess the hygrothermal performance of the PV-ETICS facade system.

2.2.1 Initial experiments with PCM mortar

Preliminary tests were conducted with a small volume of PCM mortar applied to the EPS insulation to measure the temperature behaviour. Solar radiation screens were used to heat in the climate chamber to evaluate the thermal behaviour of PCM mortar, potential PCM wax leakage and melting process of the EPS and whether the melting point could be crossed in case of severe radiation through the PCM mortar. These tests helped to define safe application boundaries and work out application techniques of PCM mortar to a vertical surface.

2.2.2 Soil moisture sensor calibration for PCM mortar

EC-5 Soil moisture sensors with HOBO loggers were used throughout all the following experiments to measure overhygroscopic moisture content of PCM mortar. The EC-5 were calibrated specifically for this novel construction material. The calibration process was performed by embedding soil moisture sensors in two small scale mortar specimens and curing the specimens for 28 days in a closed environment. Cured samples were then kept under isothermal conditions (+20°C) and moisture content of the samples was monitored during drying process, calibrating the voltage readings with gravimetric measurements.

During the latest stages of drying, samples were put also in an oven at +60 °C, then stored in a plastic bag to cool down to +20 °C to obtain the low moisture readings. After drying, samples were introduced to the water contact, sealed hermetically in plastic containers for moisture levels to stabilise. After a stable voltage reading was reached, gravimetric measurements were conducted. The cycle was repeated 2 times.

After isothermic calibration was finished, samples with two different moisture levels were put under different temperatures and temperature correction formulas were developed for two moisture contents.

During these experiments HOBO temperature sensors were used to measure temperature inside PCM mortar. Additional cavities, sealed with porous membrane capsules (Figure 17, left) were added to the test samples to obtain RH readings at hygroscopic conditions, using temp-RH sensors Rotronic Hygroclip HC2-C05 and Sensirion SHT35.



Figure 17. Small-scale sample set up for calibrating SMS for measuring PCM mortar volumetric moisture content. Besides SMS, Hobo temp sensors were used to ensure isothermal conditions of the measurements and SHT35 were used to measure RH in hygroscopic conditions.

2.2.3 Sensors used in the test walls

Inside the test walls of both the climate chamber and the outside facade, the same EC-5 soil moisture sensors ($\pm 0.02 \text{ m}^3/\text{m}^3$ for porous materials) were used. Temperature and relative humidity were measured using Sensirion SHT35 ($\pm 0.1 \text{ }^\circ\text{C}$; $\pm 1.5 \text{ \%RH}$), Hobo Onset TMC20-HD ($\pm 0.15 \text{ }^\circ\text{C}$) and Rotronic Hygroclip HC2-C05 ($\pm 0.3 \text{ }^\circ\text{C}$; $\pm 1.0 \text{ \%RH}$) sensors. Temperature on the back side of the PV panels was measured with small Littelfuse KS103J2 NTC thermistors ($\pm 0.1 \text{ }^\circ\text{C}$). Heat flux was monitored using Hukseflux HFP01 plates (uncertainty $< 3\%$ ($k = 2$)).

Data from the HOBO and EC-5 sensors were recorded using a HOBO UX120-006M datalogger, while data from the Littelfuse and Hukseflux sensors were recorded using a Grant Squirrel SQ2020 logger. Data from the Sensirion sensors were recorded using custom-built dataloggers based on the Arduino platform and data from the Rotronic sensors were recorded with a logger integrated into the climate chamber.

Temperature and RH sensors were new and factory-calibrated. Additionally, the calibration of all sensors was additionally checked in the laboratory before the experiment using a small chamber maintained at constant temperature and relative humidity. Where possible, calibration was checked again after the sensors were removed from the wall.

Sensor placement was carefully planned to capture gradients across the wall layers and multiple sensors from different brands were used to ensure redundancy in case of sensor failure. For most temp-RH sensors in the external layers of the facade system, where high moisture conditions were expected, plastic measuring tubes were installed with porous measuring capsules at the end of the tube. This method follows the principles of the continuous RH measurements in the concrete floors (RT 103333-et, 2021). RH sensors were inserted after the initial dry-out period to avoid keeping them in 100% RH conditions for long periods of time. Sensors were removed from the wall periodically during longer experiments to recalibrate the sensors or, if necessary, replace them.

2.2.4 Equipment for measuring boundary conditions

Boundary conditions in the climate chamber were monitored using integrated chamber sensors. In addition, pyranometers were used to calibrate artificial radiation screens and air velocity near the wall surface was measured to validate convective heat transfer assumptions.

Outdoor conditions at the test house were monitored using a rooftop weather station, including temperature, humidity, wind speed and direction, and solar radiation. Indoor conditions in the test building were monitored with temperature and RH sensors to define the internal boundary conditions for modelling. The indoor environment in the test house was heated and humidified, but neither cooled nor dehumidified.

2.2.5 Gravimetric measurements

Gravimetric measurements were used to determine the moisture content of PCM mortar specimens, and they were performed during initial sensor calibration and at the end of the long-term experiment. A precision scale ($d = 0.001 \text{ g}$) was used to weigh samples before and during the drying process. Final dry mass was defined after weight stabilisation of less than 0.1% over two consecutive measurements, taken at least 24 hours apart.

Because PCM granules were occasionally damaged on the edges of cut samples, there was a risk of PCM loss if dried at elevated temperatures. To mitigate the risk of PCM wax vaporisation and associated mass reduction, a preliminary test drying was conducted at the initial phases of the study on eight samples:

- 1) Measurement of wet mass
- 2) Drying under indoor conditions at $+20 \text{ }^{\circ}\text{C}$ and $<40\% \text{ RH}$ for 30 days
- 3) Drying in a sealed box with silica gel granules and a small ventilator at $+23 \text{ }^{\circ}\text{C}$ for 42 days
- 4) Drying in an oven at $70 \text{ }^{\circ}\text{C}$ for 7 days
- 5) Drying in an oven at $105 \text{ }^{\circ}\text{C}$ for 4 days

The difference in calculated volumetric moisture content between step 3 and step 4 was approximately $0.005 \text{ m}^3/\text{m}^3$ ($0.124 \text{ m}^3/\text{m}^3$ after silica gel drying vs $0.129 \text{ m}^3/\text{m}^3$ after oven drying at $70 \text{ }^{\circ}\text{C}$) which aligns with the expected change when moving along the sorption isotherm of PCM mortar from 35% RH (balance RH of silica gel) to 0%. However,

transitioning from 70 °C to 105 °C resulted in an additional increase of 0.023 m³/m³ (0.129 m³/m³ to 0.152 m³/m³ after drying at 105 °C), indicating probable PCM loss through damaged sample edges.

Considering that the expected peak temperatures of PCM mortar were around 70 °C and the manufacturer's declared maximum operating temperature is in a similar range (Rubitherm Technologies GmbH, 2020), all gravimetric measurements presented in this thesis were obtained using an oven drying process at +70 °C until weight stabilisation.

2.3 Methodology for hygrothermal modelling [RQ3]

The model calibration and validation process in this research followed the sequence below:

1. **Direct measurements, small scale (Pub. I):** Measuring material properties, using small-scale experiments.
2. **Replicate small-scale tests in the model (Pub. I):** Creating hygrothermal models that reproduce the small-scale experiments to verify material properties.
3. **Climate chamber experiments for calibration (Pub. II):** Measuring the hygrothermal behaviour of the full facade assembly at controlled boundary conditions.
4. **Replicate climate-chamber tests in the model (Pub. II):** Reproducing the chamber experiments, using measured boundary conditions from the climate chamber experiments.
5. **Hygrothermal model calibration (Pub. II):** Adjusting material properties and boundary-condition inputs iteratively within realistic limits to improve agreement between measured and simulated results.
6. **Back-check key transport functions (K_v , K_l):** Revisiting the small-scale models to confirm that updates to vapour and liquid conductivity functions remain realistic
7. **Parameter freeze:** After obtaining the Pub. II results, no further changes were made to model parameters.
8. **Field validation under real climate conditions (Pub. III):** Using the calibrated hygrothermal model from Pub. II with measured climate conditions to predict hygrothermal behaviour of the facade system during a prolonged period.

One aim of the study was to demonstrate that long-term hygrothermal performance of a complex facade system under real climate conditions can be predicted using a model calibrated only with small-scale and climate-chamber data. This workflow is far less time-consuming than re-calibrating to long-term field data, while still offering substantially higher credibility than modelling based solely on generic material properties (Figure 18).

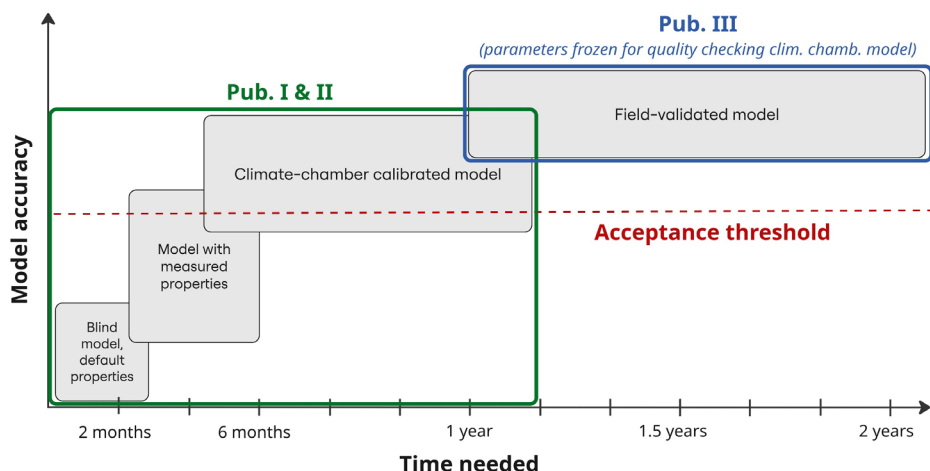


Figure 18. Schematic overview of the progression from blind modelling to field-validated modelling, showing how model accuracy increases with the time and resources invested.

The following chapters describe, in detail, all material properties and parameters used in the Delphin 6 models, together with the specific methods used to obtain each parameter or function and the calibration and validation steps applied as well as the test wall set up in climate chamber that was used for model calibration.

2.3.1 Material properties of PCM mortar

Thick cementitious mortar incorporating PCM granules is a novel construction material that was developed within the En-ActivETICS research project (M-ERA.NET, 2022). To enable reliable hygrothermal modelling, its material properties had to be measured. This section details each property required by the numerical models, outlines the methods used to determine them, and reports the resulting values.

Bulk density and porosity

The dry bulk density and open porosity were determined with a vacuum-saturation procedure (EN 1936, 2006). The results are presented in Figure 19.

Thermal conductivity

Thermal conductivity of the PCM mortar was first estimated from manufacturer data for the cementitious mortar and the aluminium-rich filler/PCM mixture using a dedicated small-scale thermal model that reproduced a realistic cross-section with PCM granules embedded in mortar. A theoretical value of $\lambda = 0.78 \text{ W}/(\text{m}\cdot\text{K})$ was obtained in (Talvik, 2021).

This preliminary estimate was then verified in the climate chamber (Pub. II) by measuring temperatures on both faces of the PCM-mortar layer under steady artificial solar radiation, together with the rear-side heat flux. The measured boundary conditions were imposed on the thermal model while varying λ until simulations matched the measurements. A moisture-dependent correction of thermal conductivity was obtained, and the simultaneously measured moisture content (from embedded SMS) was added as initial moisture content to the model. The resulting value, $0.63 \text{ W}/(\text{m}\cdot\text{K})$ (Figure 19), is the thermal conductivity of dry material, with moisture corrections applied in all subsequent models.

Heat capacity

The latent-heat function of PCM-containing building materials is the principal reason for employing them. The sensible specific heat of the cementitious mortar and fillers was taken from manufacturers’ data (Rubitherm, 2023; Sto-Faserputz, 2026). The latent contribution of the PCM was superposed using supplier curves for the three paraffin fractions (RT25HC, RT28HC and RT35HC) (Rubitherm, 2023). Using the known mass fractions of the composite (Figure 19, upper-right corner), a heat-capacity function $u(T)$ was developed, that rises across the melting range ($\approx 21\text{--}35\text{ }^{\circ}\text{C}$). In Figure 19, $u(T)$ of the composite material is shown as a solid black line, and it is compared with the dotted line representing the cementitious mortar without any PCM content. The difference between the two, $\approx 30\text{ MJ/kg}$, corresponds to the additional latent enthalpy provided by the PCM.

The magnitude and shape of $u(T)$ were validated by comparing simulated PCM-layer temperatures with climate-chamber measurements under controlled solar-radiation cycles (Pub. II) and with outdoor measurements on the south facade (Pub. III & IV). The hygrothermal model reproduced the daily melt–solidify behaviour and phase lag with relatively good agreement. No significant reduction in PCM heat capacity was observed between the initial months of monitoring and measurements taken in the second (Pub. III) and third summer (Pub. IV).

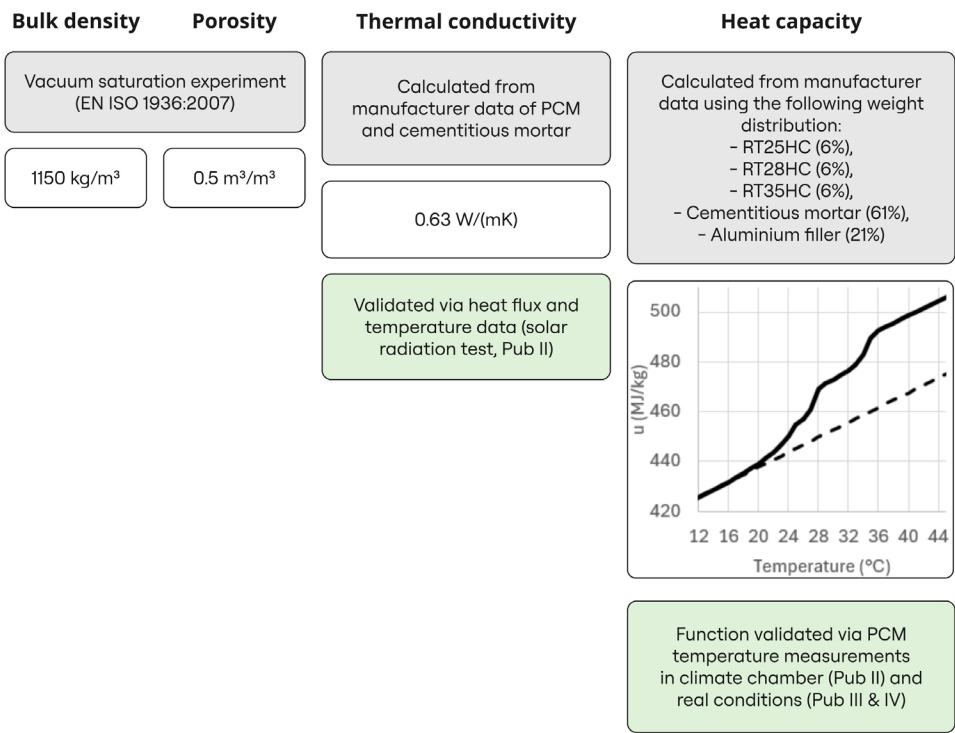


Figure 19. Overview of methods used to determine PCM mortar basic properties

Moisture storage (sorption isotherm)

The moisture storage function was determined by salt-solution conditioning (Greenspan, 1977), covering 11–97% RH. Small specimens were placed in a conditioning box with continuous air movement under isothermal laboratory conditions according to (ISO

12571, 2021). Both adsorption and desorption curves were measured and the mean of the two (Figure 20) was used in the modelling.

The adopted curve was further validated using embedded RH sensors in small-scale PCM-mortar specimens, alongside SMS to capture moisture content, during the experiments reported in Pub. I. Both RH and volumetric moisture content readings were compared with gravimetrically measured moisture content of the PCM mortar.

Water-vapour diffusion resistance

Water-vapour diffusion resistance was measured using wet- and dry-cup tests (ISO 12572, 2016). The resulting μ -values were $\mu_{dry} = 450$ and $\mu_{wet} = 154$. As wet conditions are more relevant for evaluating the long-term durability of the whole facade system, the wet-cup value, measured at 85%/97% RH, was used to do the initial scaling of the vapour-permeability (K_v) function. According to the already defined sorption isotherm, the average moisture content for the samples in the wet-cup test was around $0.08 \text{ m}^3/\text{m}^3$.

For more precise validation, climate-chamber data from the period before PV installation were used to calibrate both K_v and K_i , with minor iterative adjustments to each. The wet-cup and dry-cup tests were then replicated in Delphin using the revised K_v to derive modelled μ -values.

Final validation was conducted during the first weeks of the real-climate experiment (Pub. III) – during the initial dry-out phase prior to installing the PV panels. K_v function was confirmed against these measurements.

Liquid-water conductivity

Capillary liquid-transport parameters were initially derived from water-uptake tests in accordance with (ISO 15148, 2002). The measured capillary uptake coefficient was $A_w = 0.045 \text{ kg}/(\text{m}^2 \text{ s}^{0.5})$ (Talvik, 2021).

In addition to the uptake test, instead of a traditional small-scale drying test in a wind tunnel, an alternative drying experiment was performed on the same PCM mortar samples ($\approx 200 \times 100 \times 35 \text{ mm}$) that were also used to calibrate the SMS (Pub. I). Specimens were left to dry under laboratory conditions while mass, RH, and volumetric moisture content were recorded, together with the overall drying time.

During the climate-chamber experiment (Pub. II), in the initial dry-out phase, drying of uncovered PCM mortar was also monitored on three PCM sections (each $1150 \times 510 \times 35 \text{ mm}$) using multiple temp and SMS sensors. Based on these drying responses, the liquid-conductivity function was iteratively refined. The final K_i function (Figure 20) is expressed as a moisture-dependent, “r-shaped” function, with the junction between the two linear segments occurring at approximately 80% RH ($\approx 0.017 \text{ m}^3/\text{m}^3$ moisture content).

This function was further validated in the later stages of the climate-chamber test (after PV installation) and used to model the initial dry-out phase and long-term hygrothermal behaviour of the facade system in real conditions (Pub. III).

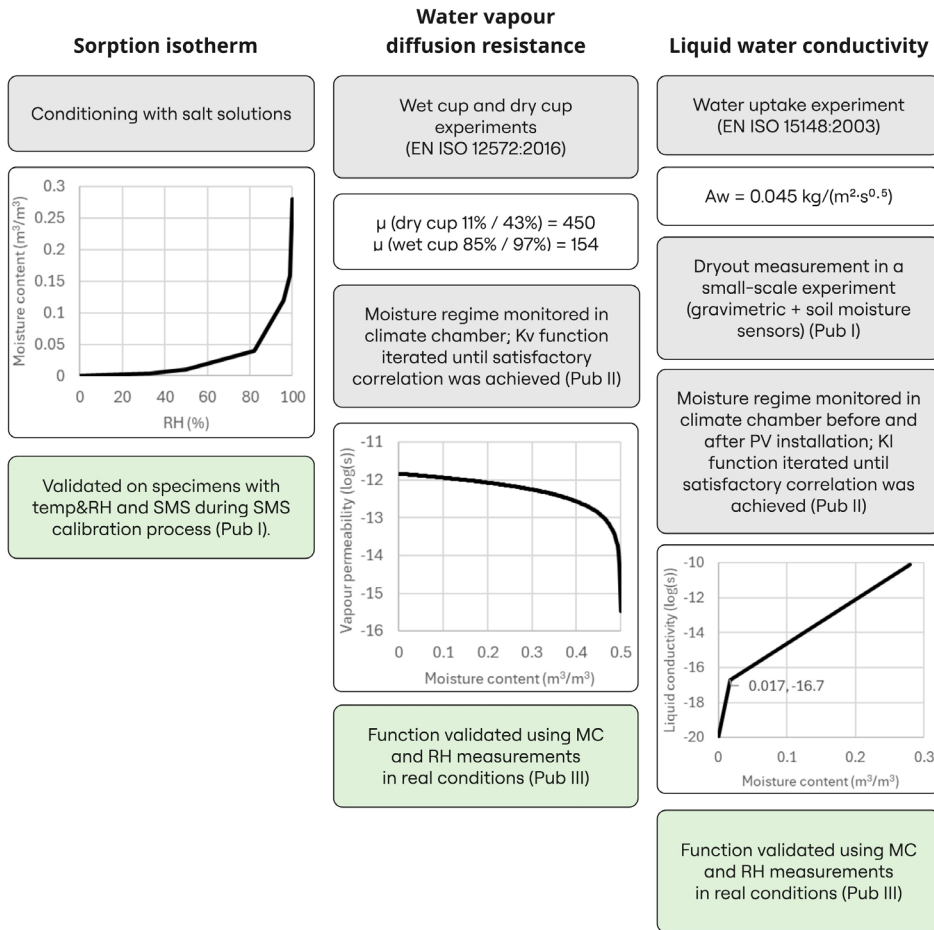


Figure 20. Methodology for defining hygrothermal functions of PCM mortar.

2.3.2 Material properties of other construction materials

Other construction materials in the system were conventional, with more data available for hygrothermal modelling. The facade plaster system used in the experiments had its hygrothermal properties previously measured by (Volkova et al., 2021), and these values were used in the simulations. For the insulation and structural layers, Delphin 6 material files from the database were used as the baseline, with only a few manufacturer-declared parameters adjusted.

A comprehensive table of material properties is provided in Pub. II, Table 1. The same properties were also used for modelling in Pub. III.

The first three publications focus primarily on the outer layers of the facade system and used established properties for the insulation and AAC. However, during the energy modelling with IDA ICE for Pub. IV, it became clear that the heat-flux accuracy through the insulation was insufficient when using the declared thermal properties. Consequently, an additional round of measurements of thermal conductivity and specific heat capacity was carried out later in the research. These refinements proved critical when modelling the internal layers and indoor environment, but they were less influential for the overall hygrothermal performance of the facade, which depends more on external climate loads and the properties of the PCM mortar.

A material-properties table for thermal calculations for energy simulations is available in Pub. IV as Annex 1 (supplementary materials). Relative to the table in Pub. II, the density, thermal conductivity, and specific heat of AAC and EPS are specified more accurately, based on measurements (using “Hot Disk” method in accordance with (ISO 22007-2, 2022) conducted on samples taken from the real test wall three years after its construction.

To reproduce the measured summer heat flux through the EPS insulation with sufficient accuracy, temperature-corrected thermal conductivity values for EPS were required. These were measured using the TA Instruments FOX 200 heat-flow meter in accordance with EN 12667, on pieces of insulation from material purchased at the same time as that used for construction three years earlier. The temperature-corrected λ -values for carbon-enhanced EPS are presented in Annex 2 of Pub. IV.

2.3.3 Test wall set up in climate chamber experiment

A one-story test wall was constructed inside a climate chamber to evaluate the hygrothermal performance of the PV-ETICS system under controlled and extreme conditions. The wall consisted of three sections: a reference PV-ETICS section with PCM mortar without diffusion channels on EPS insulation, a similar section with diffusion channels, and a third section also with diffusion channels, but on mineral wool insulation. The exact layout of the test wall and sensor locations is presented in Pub. II.

The climate chamber allows precise control of temperature and relative humidity. Rain sprinklers were used to simulate extreme wind-driven rain. Artificial solar radiation screens equipped with halogen lamps were built for this experiment and calibrated using a pyranometer (calibration results available in Pub. II). Artificial water leakage was introduced through dedicated injection points to mimic water ingress behind the PV panels through potential cracks.

The experimental programme consisted of four stages: room-temperature drying (before PV application), water leakage simulation, solar-radiation drying, and WDR freeze-thaw cycling (Figure 22).

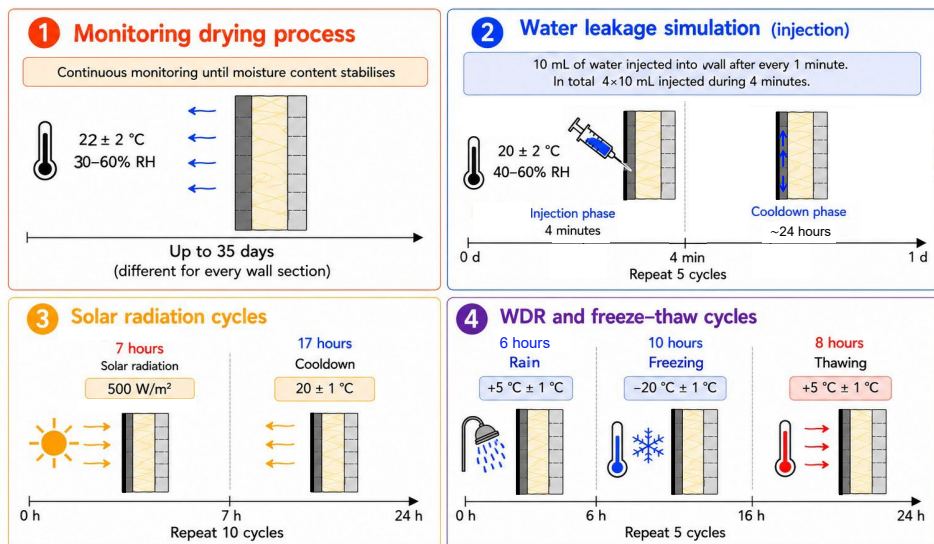


Figure 21. Climate cycles used for testing PV-ETICS in climate chamber. Visualisation creation aided by OpenAI ChatGPT GPT-5.4 Thinking.

In contrast to the procedures outlined in (EAD 040083-01-0404, 2024), the experimental programme, presented above, was designed primarily for model calibration rather than solely for durability assessment of facade plaster after EAD climatic cycles. The objective was not only to evaluate the standard durability of an ETICS system, but to investigate the performance of a novel PV-ETICS facade system, which represents a considerably more complex assembly.

The experimental design deviated from the EAD procedure in several important respects. First, the number of cycles applied in the present study was lower than in the EAD. Second, the wind-driven rain (WDR) exposure was combined with freeze-thaw cycling, whereas the EAD does not propose a large-scale climate chamber test in which freezing occurs after rain exposure. Third, instead of heating the facade by heating up the climate chamber, artificial solar radiation was used. This approach provides a more realistic representation of facade surface heating, particularly in the case of facades incorporating PV panels and both dark and light surfaces side-by-side.

A more detailed description of the climate chamber test methodology is provided in Pub. II.

2.3.4 Temperature deformation measurements in climate chamber

In addition to the previously described experiments, supplementary solar radiation cycles were conducted in the climate chamber after completion of the main test programme to determine the temperature deformations of the PV and the adjacent facade plaster. Measurements were performed only on the mineral wool cross-section configuration, as this specimen incorporated removable steel-sheet joint details.

Prior to the deformation measurements, the specimen had undergone several solar radiation cycles. The relative humidity (RH) behind the facade plaster system was confirmed to be low (approximately 30% RH at 22 °C), ensuring that the measured deformations could be attributed predominantly to temperature effects. The temperature range during the measurements was –25 °C to +50 °C for the facade plaster and –25 °C to +70 °C for the PV panels.

Relative displacements were measured using a digital calliper MarCal 16 EWRI by Mahr with a resolution of 0.01 mm. Six stainless steel reference tabs were fixed to the surface of the facade plaster and PV panel, using a two-component epoxy adhesive. The calliper was kept at room temperature and taken into the climate chamber only for the duration of each measurement, to minimise thermal influence on the measuring device.



Figure 22. Measurement of relative deformations between the facade plaster and PV panel at the joint. Similar stainless steel reference tabs were used to determine the deformations of the facade plaster and the PV.

2.3.5 Model geometry and boundary conditions

The hygrothermal performance of the PV-ETICS wall assembly represents a fundamentally three-dimensional (3D) phenomenon. Excess moisture can dry out both through the diffusion channels and sideways through the facade plaster. Although initial attempts were made to construct a 3D simulation model, it was ultimately found to be more efficient to use a 2D horizontal cross-section, to optimise both computational resources and modelling complexity.

To compensate for the accuracy loss associated with simplifying the 3D situation into a 2D model (Figure 23), the model was calibrated based on measured results from the climate chamber and real environment experimental data. The water vapour resistance of the diffusion channels was defined using a trial-and-error method and satisfactory correlation was obtained with $S_d = 0.5$ m. This value also reflected the observed moisture behaviour of PCM mortar at both the mid-height and upper parts of the mortar behind the PV panel during the long-term real environment experiment.

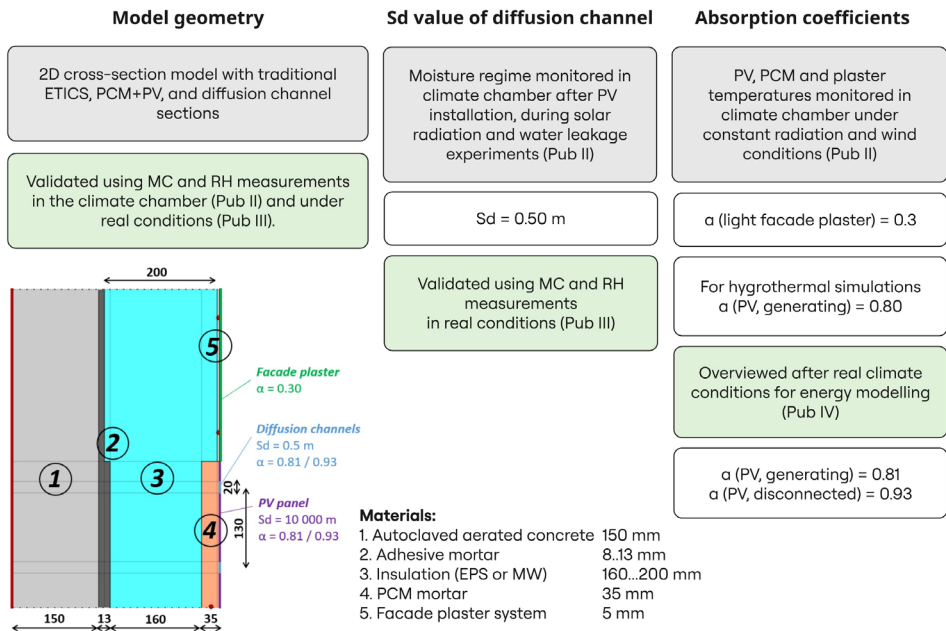


Figure 23. Methodology for defining the boundary conditions for the final 2D numerical model in Delphin 6.1.

One important simplification in the 2D model involves treating the air channels purely as diffusion channels, excluding microconvection and the ability to drain condensate. In reality, although the diffusion channels are open only at the bottom, they facilitate not only diffusion but also a certain degree of microconvection due to temperature differences in the channel. When the PV panel cools down, condensate may form on the rear side of the PV panel. At a certain point, condensate starts to drip down through the channels and exit the system as liquid water between the steel sheets. However, convection and gravity-driven condensate transport were not explicitly modelled in this study. Instead, these effects were accounted for indirectly through the diffusion channel water vapour resistance. The final value, $S_d = 0.5 \text{ m}$, is significantly lower than the theoretical S_d value for the most critical point, which corresponds to the full physical length of the drainage channel (1.1 m).

The model incorporates all external climate conditions, including temperature, relative humidity, direct and diffuse solar radiation, wind direction and velocity, as well as wind-driven rain. The model assumes, however, that the facade is watertight, meaning that driving rain does not penetrate through cracks. This simplification is considered justified, as the PV–PCM sections of the facade were shown to be less vulnerable to water ingress compared to traditional ETICS systems thanks to the diffusion channels. This was demonstrated through a water leakage test conducted in a climate chamber. In cases where water was deliberately introduced behind the PV panel into the PCM mortar, imitating the cracks in the joints between PV and facade plaster, the diffusion channels began to act as drainage paths. The drying behaviour of such leakage scenarios with and without diffusion channels was modelled in Pub. II, and the results confirmed the necessity of these channels. Since the system is designed with built-in diffusion channels acting as secondary protection against water leakage, hygrothermal simulations did not account for water ingress scenarios.

The equivalent vapour diffusion thickness (S_d) of the air channels was determined during controlled laboratory testing in a climate chamber. After the PV panel installation, the PCM mortar was able to dry out only sideways through the facade plaster in test section 1 that did not have the diffusion channels. Sections 2 and 3 were drying out through diffusion channels and also sideways. During solar radiation, WDR and freeze-thaw experiments, the measured results were replicated with hygrothermal models with and without diffusion channels. The case without diffusion channels was used to calibrate the PCM mortar liquid conductivity function and after reaching satisfactory correlation with the model without diffusion channels, diffusion channel S_d value was calibrated using measured data from sections 2 and 3. This allowed identification of an S_d value of 0.50 m. The results from both measured and modelled results during these experiments are covered in Pub. II.

To refine this estimate, further validation was performed by comparing measured moisture content and RH with modelled results from the long-term experimental data under real climate (Pub. III). The $S_d = 0.5$ m was proven to be a valid parameter for the long-term experiment, corresponding also well to the gravimetrically measured moisture content.

Solar absorption coefficients (α) for the facade materials were initially determined in controlled conditions in a climate chamber. Surface temperatures were measured using multiple small sensors placed behind the facade plaster and behind the PV panel during a solar radiation experiment in climate chamber. Solar radiation on the wall was monitored with a pyranometer, and it remained relatively stable at approximately 500 W/m² throughout the 7-hour test. Air movement, generated both by the climate chamber's ventilators and by the heated facade surfaces, was measured using an anemometer positioned near the facade. Solar radiation and air velocity inputs were applied in the simulation model, and the absorption coefficients for the plaster and PV surfaces were iteratively adjusted until agreement was achieved between the measured and simulated temperatures.

These coefficients were later refined using data collected under real environmental conditions. Although the initial estimates were already highly accurate, adjustments were made in Publication IV, which focused specifically on energy modelling. The α -value for the PV panel was increased from 0.80 to 0.81. Additionally, a separate α -value was introduced for cases in which the PV panels are not actively generating electricity, which is critical for assessing overheating risk in indoor spaces. In such scenarios, an absorption coefficient of $\alpha = 0.93$ was defined. While this elevated absorption coefficient was not relevant for estimating hygrothermal performance of the system as higher surface temperatures lead to more rapid drying, it is crucial for evaluating the long-term overheating risk of the PV panel itself. This includes ensuring that the critical surface temperature limit of +85 °C is not exceeded, even when the panels are inactive.

2.4 Overall performance evaluation framework for PV-ETICS [RQ4]

2.4.1 Test wall set-up under real climate conditions

The experimental wall for long-term monitoring was installed on the south-facing facade of the test facility. Of the three sections tested in the climate chamber, only the second one (on EPS with diffusion channels) was selected for this experiment, as it was considered the most relevant for real facade applications.

The test wall was measured under real outdoor conditions for 20 months (May 2022 - January 2024). Indoor conditions were controlled: the room was heated in winter (setpoint +23 °C) and not cooled in summer, with relative humidity maintained at 50% using a humidifier. The average indoor moisture excess during the heating season was 6 g/m³. This corresponds to the critical 10% design value for indoor moisture excess in the Estonian building stock (Ilomets et al., 2019; Kalamees, 2006). The AAC surface remained unfinished to increase vapour diffusion toward the wall. PV panels generated electricity throughout the test period, simulating real operating conditions.

Temperature, heat flux, RH, and volumetric moisture content were measured inside the wall. The exact layout of the test wall and sensor locations is presented in Pub. III.

Outdoor climate conditions were measured on the roof of the building, approximately 2 m above the test wall. On-site climate data was cross-checked against national weather station data.

Local shading from trees and nearby buildings occasionally reduced solar exposure during low sun angles in winter, which was considered when comparing measured and modelled results.

2.4.2 Evaluating long term overheating risk of PV panel

Long term thermal durability was evaluated alongside the hygrothermal analysis in Pub. III by focusing on PV panel temperatures relative to the 85 °C service limit for flexible thin PV panels. First, the full 20-month dataset (PV rear-side and PCM temperatures and local climate) was analysed and then the measured local climate data was compared against long-term Estonian climate statistics from Tallinn-Harku and Tõravere weather stations. Cumulative solar radiation and ambient temperatures were analysed statistically to find out whether much more critical days could be expected in Estonian climate.

The thermal performance of PV-ETICS system in other European climates has also been evaluated, using test reference years and these results have been published in (Heim, Talvik, et al., 2023).

2.4.3 Evaluating long term hygrothermal performance of PCM mortar behind PV panel using hygrothermal modelling

Following the 20-month monitoring of the test wall, the Delphin 6 model that was calibrated during climate chamber experiments was used to project long-term hygrothermal behaviour (Pub. III). The measured outdoor (air temperature and RH, direct & diffuse solar radiation, wind speed & velocity and vertical rainfall) and indoor (temp and RH) boundary conditions were first applied exactly as recorded within the duration of the measurement period. To assess durability beyond the measurement period, the simulation was extended with an Estonian condensation test year. This year was repeated 7 times, together with a high indoor moisture excess (≈ 6 g/m³) and WDR loads on an uncracked facade surface. The condensation test year is designed to be harsh.

Simulating seven of these in a row, creates intentionally severe boundary conditions that are not expected every year in reality, but are suitable for testing robustness.

Apart from the long-term durability assessment under an extreme climate, preliminary long-term hygrothermal simulations were conducted for several European locations (Heim, Talvik, et al., 2023), using the model created during the process of model calibration in the climate chamber. In this study, five consecutive moisture reference years were simulated for Bergen, Trondheim (both Norway), Vantaa (Finland), Potsdam (Germany), and Väike-Maarja (Estonia).

2.4.4 Assessing the moisture content of PCM mortar gravimetrically at the end of experiment

At the end of the long-term experiment, the PV-ETICS facade was destructively opened to extract samples (Figure 24). Samples were collected in January. Internal temperature of the PCM mortar was -5°C , therefore most of the moisture inside the PCM mortar was in a solid state during the opening. Holes were cut into the PV panel with an angle grinder, and PCM mortar sample pieces were removed, using a chisel. Samples were sealed in an airtight plastic bags and volumetric moisture content was measured, using an oven drying process at $+70^{\circ}\text{C}$ until weight stabilisation. Results were compared with sensor data to validate the SMS after 20 months. Similar samples were also taken from the test wall in climate chamber for comparison of PCM moisture content.



Figure 24. Destructive opening of the outdoor facade after 20 months of measurements (left) and similar opening conducted in the climate chamber (middle). PCM mortar pieces removed from each sample slot were sealed in plastic bag until first weighting (right).

2.4.5 Assessing the facade system after destructive opening

After the PCM mortar samples were collected from the test wall, all sampling holes were filled with PU foam and covered with climate-proof tape. Two years and eight months after construction, additional samples were collected to measure the thermal properties of the aged insulation and AAC. Three years after construction, the PV connectors were removed to evaluate their condition. Three years and eight months after construction, the remaining PV-panel components were dismantled to make room for new

installations. At each stage, a visual assessment of the physical condition of the critical layers was performed.

The test wall in the climate chamber was opened in the same manner as the outdoor test wall to compare the gravimetric moisture content of the PCM mortar between the test wall located outdoors and the test wall in the climate chamber. The climate-chamber wall was fully dismantled four years after construction, during which a visual evaluation of the connectors and the backside of the PV panel was carried out.

2.5 Energy modelling: IDA ICE model set up and calibration [RQ5]

After the overall concept of PV-ETICS with PCM and diffusion channels had been proven to be hygrothermally viable, indoor overheating risk was assessed to determine the system's suitability for apartment-building renovation. Extensive in-wall measurement data was collected during the hygrothermal experiments and during the long-term real-environment measurements, a notable heat flux from the wall system to the indoor environment was observed. Given ongoing concerns in Estonia about increased cooling demand and the potential of dark-coloured facades to exacerbate overheating, a more thorough investigation was undertaken.

2.5.1 IDA ICE calibration model set up

An additional experimental setup was implemented in the test facility: existing in-wall sensors were complemented with temperature sensors in the test room and in adjacent spaces to characterise the indoor climate more accurately. Internal free heat gains were also monitored.

In contrast to all the aforementioned modelling that was conducted with Delphin, energy modelling was done using IDA ICE software. First, an IDA ICE model of the test facility was established using the measured indoor and outdoor boundary conditions. The test-wall build-up was discretised in the IDA expert level interface, allowing comparison of modelled temperatures and heat-fluxes at the same interfaces as in the measurements. Agreement was checked against the measured dynamics (temperature and heat-flux). To improve the initial agreement between measured and modelled values, additional measurements were carried out to determine the thermal conductivity and specific heat capacity of the aged insulation and structural layers, as described in chapter 2.3.2.

2.5.2 Modelling overheating of renovated soviet era apartment building with PV-ETICS

Once the IDA ICE model reproduced the inward heat-flux behaviour observed in the measurements, a representative post-war concrete apartment with a large, windowless end-wall was simulated. Scenarios included PV-ETICS (50% of south facade coverage), dark versus light plaster, variable insulation thickness, window-to-wall ratio (WWR), and glazing g-values. The national TRY weather file was used, and overheating degree-hours were evaluated according to (EVS-EN 16798-1, 2019).

3 Results

During the experimental and modelling phases of the study, numerous results were obtained, with the key findings published in Publications I–IV. Rather than repeating the results presented in the individual papers, this chapter addresses the overarching research questions of the thesis. It highlights the most relevant findings and synthesises insights obtained from the climate-chamber experiments, real environment measurements and simulations.

3.1 Defining the design rules for PV-ETICS facade with PCM mortar [RQ1]

3.1.1 Initial dry-out of built-in moisture before PV application

The initial estimate provided by the plaster manufacturer for the required drying time prior to PV panel installation was 1 mm per day. This would result in a waiting period of approximately 35 days between the application of the PCM mortar and the installation of the PV panels. However, the environmental conditions assumed for this drying period were not specified.

The initial drying process of the PCM mortar was monitored both in a climate chamber and under real outdoor conditions (Figure 25). Climate chamber tests indicated that, under ambient air temperatures between 20 °C and 25 °C and relative humidity ranging from 30% to 60%, a period of approximately two weeks was sufficient for the PCM mortar to reach a stable moisture level before PV panel installation. For the outdoor test wall, the drying rate was similar. Although the conditions fluctuated more, the outdoor environment was generally favourable during the dry-out phase, with an average air temperature of 10.7 °C (ranging from 0.7 °C to 22.4 °C) and an average relative humidity of 67% (ranging from 13% to 100%). The installation was protected from direct solar radiation and precipitation. For both cases, at a volumetric moisture content of 0.12 m³/m³, the rapid initial drying slowed and therefore PV application could be recommended.

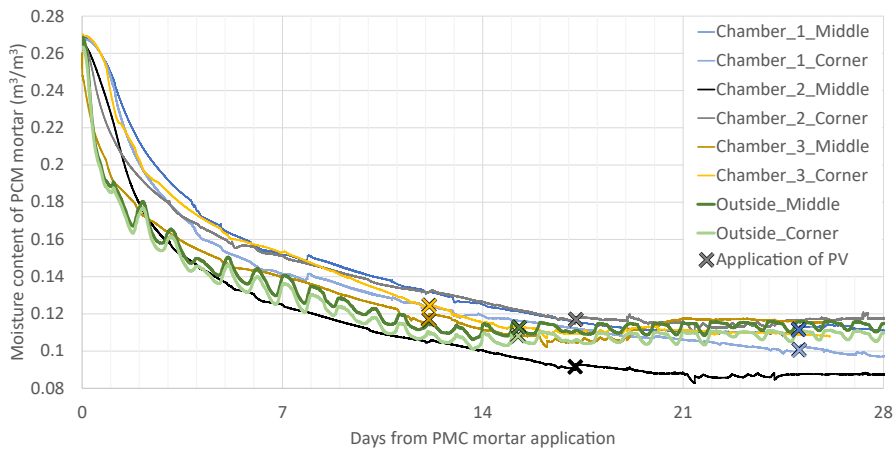


Figure 25. Initial drying of PCM mortar in three climate-chamber sections (from Pub. I) compared with drying in the outdoor test wall (data obtained during Pub. III).

Although PV panels were applied to the test walls after this initial dry-out phase and moisture content seems to stabilise after PV application, long-term measurements demonstrated that moisture reduction continued through the integrated diffusion channels.

3.1.2 Diffusion channels as an additional layer of defence against leaked-in moisture

During the climate chamber experiments (Pub. II), a water injection test was performed to simulate leakage behind the PV panel through potential cracks that may develop over time in real ETICS facades. Sections with and without diffusion channels were compared side-by-side. The results clearly demonstrated that diffusion channels functioned as drainage channels, allowing leaked water to exit the wall assembly (Figure 26). For the cross-sections with drainage/diffusion channels, only the sensor near the leak area was affected by the leaked water.

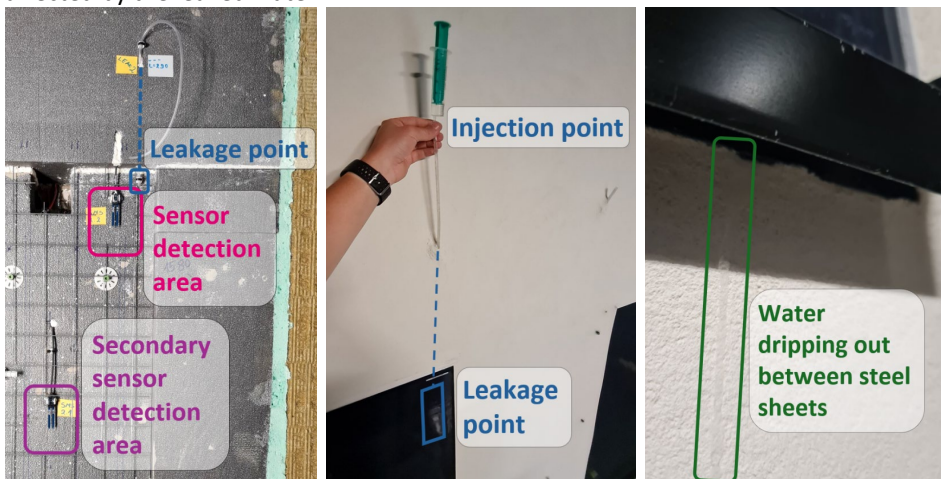


Figure 26. Water tubes for injecting water into the PCM mortar and soil moisture sensors before the mortar application (left); injecting the water behind the PV, using a syringe (middle); water dripping out from the system between the bottom steel sheets (right).

In sections without diffusion channels, there was no visually detectable drip out from the facade system and SMS readings became higher than in the case of the cross-sections with diffusion channels (Figure 27). Even the sensor in the middle of the PCM section was affected by the leaked-in moisture after ca 12 hours if there were no diffusion channels. After repeated solar radiation cycles, the drying out was very slow, as expected. Sections equipped with diffusion channels exhibited significant drying, with excess moisture drying out after several solar cycles.

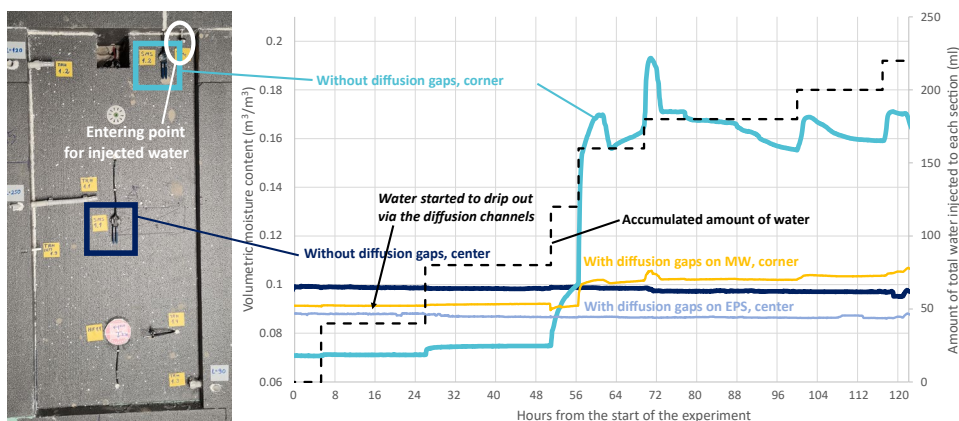


Figure 27. Measured moisture content of PCM mortar during water leakage simulation

Considering that cracking occurs relatively frequently in ETICS facades and that the vapour-tight PV panel prevents outward drying, moisture would migrate laterally toward the plaster layer. This increases the hygrothermal load on the plaster, potentially accelerating its deterioration. Therefore, diffusion channels behind PV panels are essential. The dimensions used in this study (Figure 10) proved effective and can be recommended as a baseline for future research.

3.1.3 Testing the replacement procedure of PV panels

In total, four PV panels were installed across the two facade assemblies. Two panels were built using the Business-as-usual version of the PV–plaster joint (Figure 13), and two were built using the Design for Disassembly version of the joint (Figure 14).

As expected, in the case of Business-as-usual joints, it was necessary to remove the adjacent facade plaster around the PV panels to enable their removal. According to “Localised Repair Guidelines of the ETICS in the Damaged Area” from (ET-2 0404-1010, 2017), the plaster removal procedure after PV detachment requires cutting away at least 10 cm of the facade system around the PV panel to remove the joint profiles together with their integrated mesh. For the next 10 cm, all of the plaster on top of the reinforcement mesh must be removed in a way that preserves the mesh, allowing it to be anchored into the new reinforcement layer. In the following 5 cm, only the finishing coat should be removed. After completing these steps, all layers must be reinstated according to (ET-2 0404-1010, 2017) and the plaster system manufacturer’s instructions.

Even with careful reinstatement of all layers, a visually detectable difference will remain around the PV perimeter within a band of approximately 25 cm. Overall, the PV replacement procedure using Business-as-usual joints is time-consuming and costly due to the extensive facade plaster removal required.

In contrast, the Design for Disassembly joints performed as intended. The PV panels were successfully removed without damaging the facade plaster. The adhesive joint between the PV module and the steel sheet ribbons proved sufficiently strong to hold the panel in place, yet weak enough to allow removal without harming the surrounding plaster. The removal procedure should follow the instructions provided in Appendix 6.

Overall, the use of Design for Disassembly joints (Figure 14) is clearly recommended. However, some minor design modifications to their design are suggested, which are described and explained in Appendix 7.

It was also confirmed experimentally that, in both joint configurations, full removal and replacement of the facade plaster system around the PV panel is possible, without damaging the PV panels.

3.1.4 Bond between PCM mortar and PV panel

During the cutting of samples from the test walls for gravimetric analysis, it became apparent that the bond between the PCM mortar and the PV panel was stronger than the bond between the layers of the PV panel itself. Two types of delamination were observed during removal of the PV panels.

The first type of delamination involved separation of the black coating from the back surface of the PV panel (Figure 28, left). In these areas, the black paint layer remained adhered to the adhesive mortar, detaching from the underlying PV backing. This mechanism was identified during dismantling of both the climate chamber test wall and the test wall exposed to real climate conditions.

The second delamination mechanism was more severe. An approximately 0.4 mm thick layer of the PV back-side polymer, together with the black coating, remained bonded to the adhesive mortar (Figure 28, right). This type of delamination was detected only on the external test wall during complete panel removal, 45 months after construction of the wall and two years after initial cut-outs had been made in the PV at the conclusion of the long-term experiment. Although the initial openings had been sealed with vapour barrier tape, which remained intact at the time of full removal, it is possible that the delamination was influenced by the earlier cutting of the PV panel.

The observed delamination behaviour indicates that the bond between the PV panel and the PCM mortar was generally strong. In certain areas, the adhesive bond to the PCM mortar exceeded the internal cohesive strength of the PV panel layers. Overall, the bonding strength between all the layers was satisfactory, and no evidence suggested any risk of panel detachment under natural conditions (e.g., wind load).

3.1.5 Corrosion of reinforcement mesh inside PCM mortar

The steel reinforcement mesh embedded within the PCM mortar was largely free from corrosion. Minor corrosion spots were observed near the diffusion channel regions, where small cavities or locally increased moisture exposure may have occurred (Figure 29). These isolated areas did not indicate widespread deterioration of the reinforcement, suggesting that the pH level within the PCM mortar remained sufficiently alkaline to prevent significant corrosion. In addition, even if some moisture ingress or local carbonation occurs, corrosion of the steel surface is expected to remain slow over the service life. It could be stated that PCM granules did not change the durability of the reinforcements and the reinforcement method described in the application guidelines (Appendix 5) is appropriate.



Figure 28. Delamination of the black back-side coating of the PV panel (left) and delamination occurring within the internal layers of the PV panel (right).



Figure 29. Destructive inspection of the reinforcement mesh embedded in the PCM mortar. Minor corrosion spots are visible to the left of the inspection opening.

3.1.6 Suggestions for design refinements in the future

Two years after the measurement period ended, the facade setups in the climate chamber and in the real environment were deconstructed. Opening the facades revealed some minor design shortcomings, and a list of recommended improvements for future TRL stages is provided in Appendix 7. These proposals concern technical detailing, such as the protection of electrical connectors and the geometry and material of the ribbons at the joint between the PV panels and the facade plaster. None of them would affect the overall hygrothermal performance of the facade system. However, they are important for ensuring the long-term durability of critical details.

3.1.7 Application guidelines for building PV-ETICS facades with PCM

The installation guidelines for the PV-ETICS facade system developed in this research are presented in Appendix 5. The guidelines provide a step-by-step description of the construction procedure required to reproduce the facade system that was designed, experimentally tested and numerically validated within the scope of this thesis.

The guidelines were developed based on the product development and experimental construction process described in this study, using the more advanced Design for Disassembly joints. The guidelines are presented in a clear, structured and practical format that can be readily understood by construction professionals. The aim was to translate the knowledge gained during the experimental work into concise installation steps while highlighting the critical detailing principles required to ensure the intended hygrothermal performance of the facade system.

It should be emphasised that the installation guidelines presented in Appendix 5 are based on an experimental facade solution developed within a research context and currently corresponding to TRL 5 (partial-scale prototype validation). As the system has not yet reached a fully mature development stage, further development, manufacturing optimisation, and large-scale testing are required. Prior to commercial application, the system manufacturer must therefore verify and further develop the installation procedures. Consequently, the current version of the guidelines should be considered research-based and advisory, rather than a fully validated commercial installation manual.

3.1.8 Answering the RQ1

It could be concluded that after the product development process, the physical construction of two test assemblies and the destructive opening of both, the method for designing and building a PV-ETICS facade system was developed. It was also proven that PV replacement was possible. How exactly to build the facade system wall and replacing the PV panels can be found in Appendices 5 and 6.

RQ1 - How to design and build durable PV ETICS?

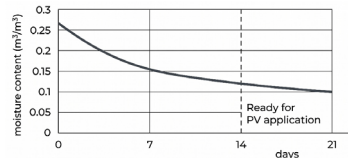
1. Cut diffusion channels inside PCM mortar (Pub. I & II)

- ✓ Enables efficient drying behind vapour tight PV.
- ✓ Enables leaked-in moisture to drip out.



2. Let PCM mortar to dry out before covering with PV (Pub. I)

- ✓ Drying out ~14 days is enough (20°C & 50%RH).
(Initial prediction by manufacturer was 35 days)



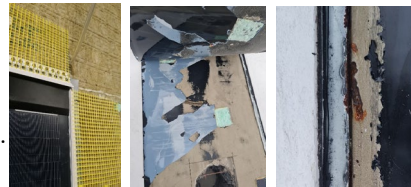
3. Accommodating PV connectors inside a PU foam-filled cavity

- ✓ Minimal thermal bridge, unpluggable.
- ! MC4 connectors corroded (Appendix 7).
- 💡 Sealing or creating air chamber for MC4?



4. Elastic joints between PV-PCM Section and Traditional ETICS designed for disassembly

- ✓ Steel ribbons behind PV and plaster profiles enabled safe PV removal.
- ! Corrosion of galvanized ribbons (Appendix 7).
Should use stainless steel.
- ! Cracks at ribbon edges after 3 years (Appendix 7).
Stainless steel ribbons should be narrower.



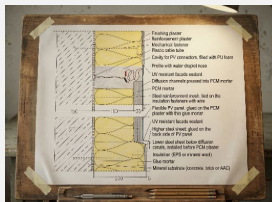
CONCLUSION:

Two large scale experimental test walls were successfully constructed. TRL 5 has been reached. Proposals for changes in some details of the design are proposed to fine-tune the system during upcoming TRL-s.



OUTPUTS:

1. Design drawings (Figure 8 to 10)



2. Application and PV replacement guidelines (Appendix 5 & 6)



3. TRL6 recommendations (Appendix 7)

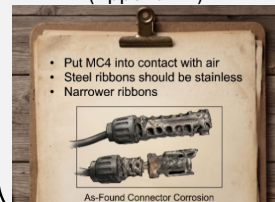


Figure 30. Graphical summary of the research conducted to answer RQ1. Visualisation creation in "Outputs" section was aided by Google Gemini 3.1 Pro.

3.2 Evaluation of methods for measuring moisture in PCM mortar [RQ2]

3.2.1 Over-hygroscopic moisture measurement strategy in PCM mortar

Initial hygrothermal modelling showed that porous cementitious material behind a vapour-tight PV panel on the external side of the wall would be in the overhygroscopic range for long periods of time. Unfortunately, measuring relative humidity becomes impractical once porous materials enter the over-hygroscopic range. Therefore, soil moisture sensors (SMS) were employed to measure volumetric moisture content in the PCM mortar. The SMS gives a voltage signal U (V) as an output that correlates with moisture content but is both material-dependent and temperature-dependent. Therefore, material-specific calibration for the PCM mortar was needed to be conducted at the early stages of the research to use SMS.

A dedicated calibration specimen was prepared from the novel PCM mortar mix, with the same ingredients that were used in the test walls built in later stages. The specimen was repeatedly soaked and dried, with its mass tracked gravimetrically while the embedded SMS voltage was logged. A conversion function $\psi(U)$ at 20 °C was derived for this mortar (Equation 1), enabling direct conversion of SMS output to volumetric moisture content.

Because SMS output is temperature-sensitive, a temperature-correction procedure was also established. The same calibrated specimen (at known MC) was sealed and held at a series of temperatures; linear correction relations were obtained for two different moisture contents (Figure 31).

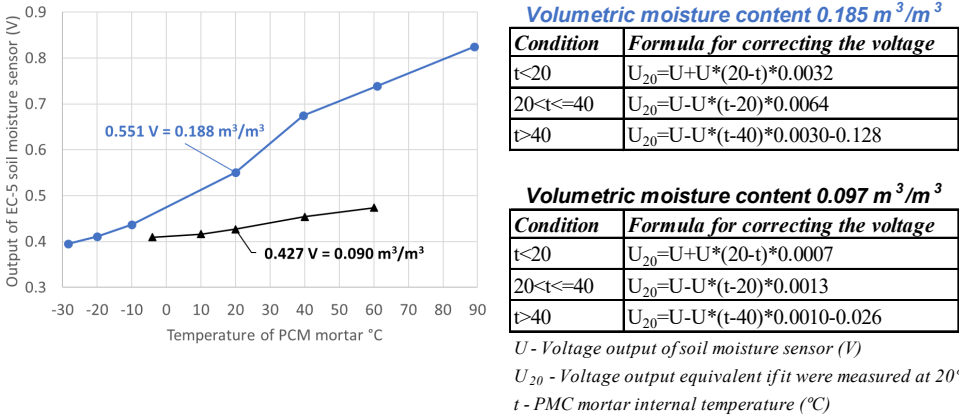


Figure 31. Temperature correction graphs for soil moisture sensors in PCM mortar and formulas for correcting the sensor output voltage. The black (triangular) line on the left graph represents the situation at the boundary between the hygroscopic and overhygroscopic range.

The phase-change interval (≈ 20 – 40 °C) produced a slight additional increase in readings. Therefore overall temperature correction formulas consisted of three linear functions (Figure 31).

After correction to U_{20} (voltage normalised to 20 °C), ψ could be computed with the PCM mortar specific calibration function:

$$\psi = 2.27U_{20}^3 - 5.346U_{20}^2 + 4.378U_{20} - 0.981 \quad (1)$$

where U_{20} is the voltage output of the soil moisture sensor (V) measured at 20 °C and ψ is volumetric moisture content of the PCM mortar around the sensor (m^3/m^3).

This approach provides corrected ψ for PCM mortar material at temperatures from -30 to 90 °C and was used throughout the research.

3.2.2 Validating SMS readings with gravimetric measurements after the long-term experiment

After the long-term monitoring period for the test wall concluded, final readings of SMS were further verified with gravimetric measurements. The results are shown in Figure 32 and it turned out that gravimetric measurements did confirm quite well the moisture contents of PCM mortar that were measured with SMS and calculated with Equation 1.

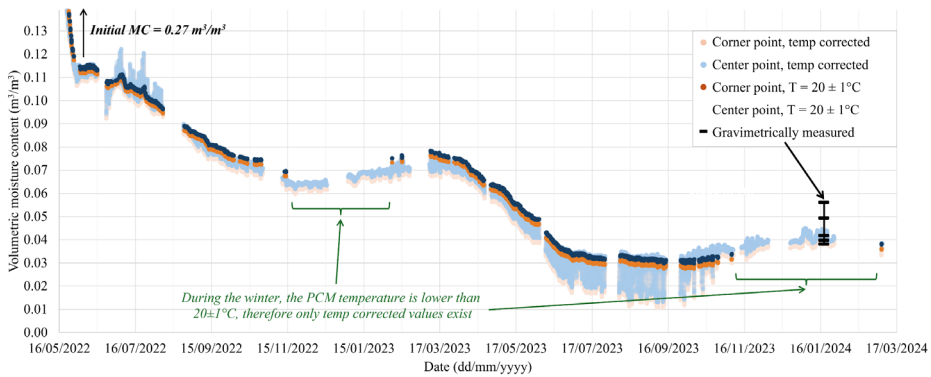


Figure 32. Volumetric moisture content measurement results from Pub. III during long term experiment.

During the analysis of the measured data in both the climate chamber and real wall experiment, it turned out that although temperature correction formulas helped, it was still more accurate to use 20 °C readings for defining the moisture content of PCM mortar. By and large, the 20 °C value was suitable for this facade application, as the south-facing PV facade increases its temperature over +20 °C relatively early in spring due to solar radiation, long before ambient temperature exceeds 20 °C. Therefore, getting exact moisture content measurement values at least twice a day was possible roughly from 1st of March until 15th of November.

From Figure 32, it is also noteworthy that the accuracy of temperature correction was significantly higher during the first year compared to the second year. That is because the temperature correction graphs were measured for just two moisture content levels, which were both on the higher side (Figure 31). During the second winter, the temperature correction formulas tended to underestimate the moisture content of the PCM mortar.

As the moisture content of thick PCM mortar behind PV panel is relatively stable throughout the winter, this accuracy could be considered to be enough for this application. However, if other thick porous materials were to be measured with SMS in the future at non-isothermal temperatures, more temperature correction formulas should be defined including also low MC.

It should be noted that the RH inside the PCM mortar entered the hygroscopic range only after the second spring after construction. Figure 33 compares the volumetric

moisture content of the PCM mortar measured using temperature-corrected SMS with the measurements obtained using a conventional temp-RH sensor SHT35. During approximately the first year of monitoring, the RH sensor readings remained at 100% RH and therefore provided no useful information about changes in moisture content.

This observation further justifies the use of SMS to measure the PCM mortar layer, as they were the only sensors in the setup able to monitor the hygrothermal performance of the wall during the initial phases.

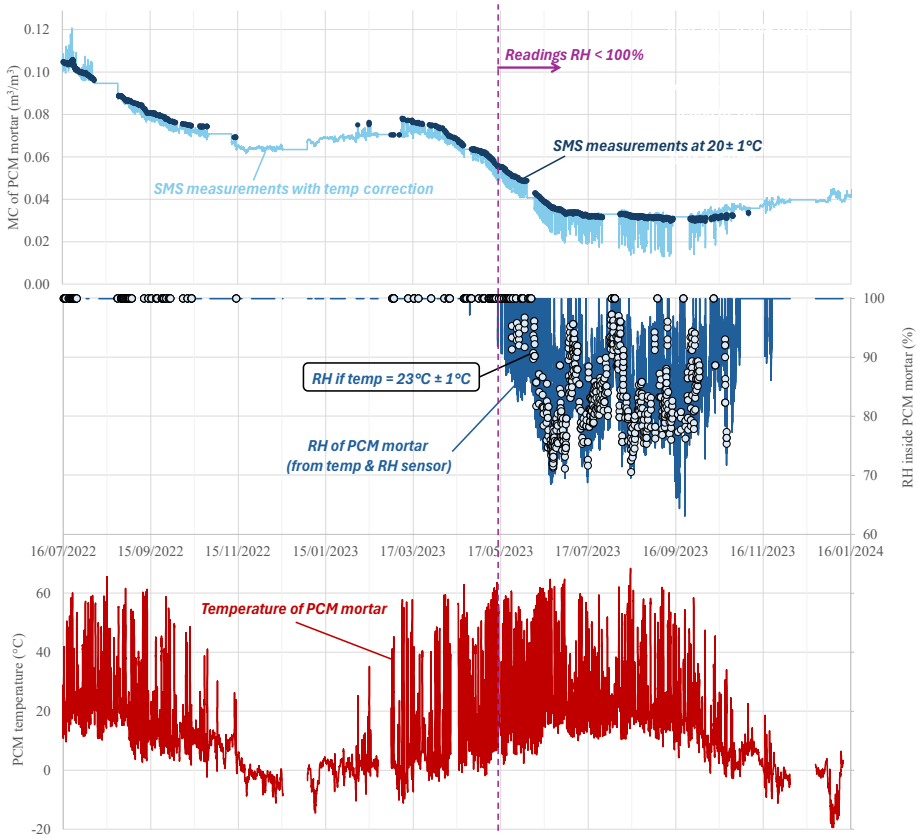


Figure 33. Volumetric moisture content (top), RH (middle) and temperature (bottom) of PCM mortar during long-term experiment. RH markers denote measurements at the temperature used to measure the sorption isotherm.

The RH sensor indicated a decrease below 100% RH at a slightly lower MC than expected based on the sorption isotherm of the PCM mortar (Figure 20). Gaps in the RH data correspond to periods when the sensor was removed from the material. Following prolonged exposure to 100% RH, the sensor was replaced in January 2023. At the end of the experiment, the replacement sensor showed a systematic positive error of 2.7%, averaged across measurements in calibration chambers containing saturated K_2SO_4 and $NaCl$ solutions (97.4% and 75.4% RH at 23 °C, respectively). All RH readings below 100% were corrected for this error.

3.2.3 Answering the RQ2

It could be concluded that the calibration process of EC-5 soil moisture sensors was successful and these sensors provided useful and reliable data for measuring moisture content of thick PCM mortar during all the experiments.

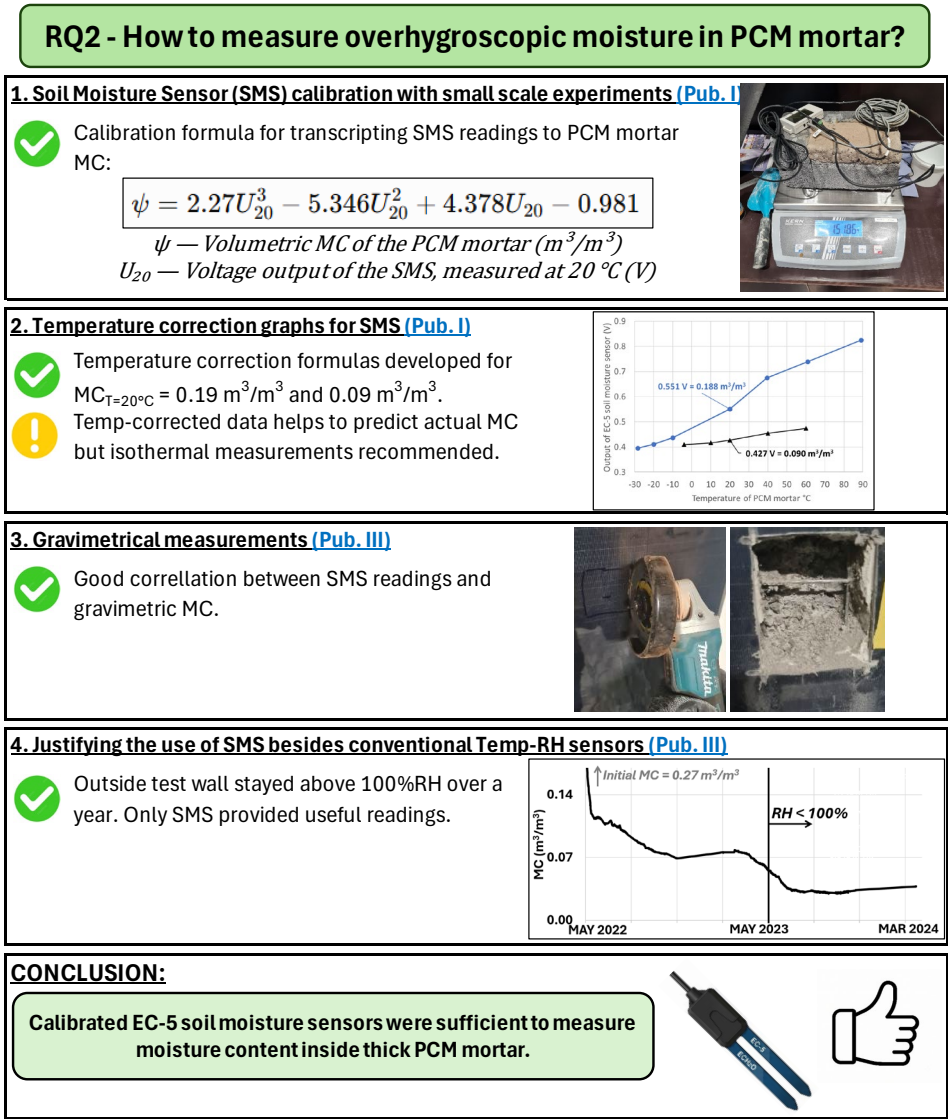


Figure 34. Graphical summary of the research conducted to answer RQ2.

3.3 Transferability of chamber-calibrated models to outdoor conditions [RQ3]

The overall modelling strategy in this research was based on the principle that a hygrothermal model calibrated under controlled laboratory conditions should be capable of predicting the behaviour of the facade system under real outdoor climate conditions.

Once the calibration phase was completed, the material parameters and model settings were no longer modified. Locally measured outdoor climate data from the real environment experiment location was used as input boundary conditions for the calibrated model. The hygrothermal performance of the facade system under real climate conditions was predicted using the calibrated model and compared with the measured results obtained from the outdoor test wall.

The underlying hypothesis of this approach was that, if the calibrated model can reliably reproduce the measured behaviour of the facade system under real outdoor conditions, climate chamber calibration could serve as a reliable basis for predicting long-term hygrothermal performance. In such a case, future development work of other facade systems could potentially omit medium-scale outdoor experiments, which are typically time-consuming due to their extended duration. Instead, facade concepts showing promising results after hygrothermal modelling with calibrated model could proceed directly to large-scale multi-storey building applications and validation studies.

3.3.1 Calibration procedure carried out during the climate chamber test

The calibration of the hygrothermal model was carried out using a series of experiments conducted in the climate chamber:

1. Initial drying experiment before PV installation

The drying behaviour of the PCM mortar was measured prior to the installation of the PV panels. These measurements were used to calibrate the **liquid water conductivity function (K_l) of the PCM mortar**.

2. Further drying process after installation of the PV panel

After the facade was covered with the vapour-tight PV layer, the drying process slowed significantly. These measurements were used to calibrate the **water vapour diffusion resistance (S_d) of the diffusion channels behind the PV panels**.

3. Initial solar absorption experiment with known radiation and wind conditions

Controlled solar radiation and varying air velocities were applied to the facade surface. These experiments were used to determine the **solar absorption coefficients (α) of the PV panel and the facade plaster surface** and to confirm **thermal conductivity (λ) and latent heat function $u(T)$ of PCM mortar**.

4. Water injection experiment

Water was injected directly into the PCM mortar layer to simulate moisture penetration through facade cracks. The time between water injection and the increase in SMS readings was compared with results from small-scale laboratory water uptake experiments and their corresponding model simulations to further verify the **K_l function of the PCM mortar**.

5. Repeated solar radiation cycles (500 W/m²)

Ten solar radiation cycles (500 W/m², minimal air movement) were applied to dry out the leaked-in water. These experiments provided **additional validation for the K_l , K_v and $u(T)$ functions of the PCM mortar**.

6. WDR and freeze-thaw cycles

The facade system was exposed to five 24h cycles consisting of 6h of WDR (+5 °C), 10h of -20 °C freezing, and 8 h of melting (+5 °C). This experiment was used to double-check the **KI and Kv functions of the facade plaster system**.

After completing the step-by-step calibration based on these six experiments, a calibrated two-dimensional hygrothermal model and material files for PCM mortar and facade plaster were established in Delphin 6. The final model was then used to reproduce experiments 1, 2, 3, 5 and 6, as well as small-scale laboratory water uptake and wet-cup experiments, to assess the reliability of the model.

More detailed descriptions of the climate chamber experiments and their measured and modelled results are presented in Publication II. The initial drying experiment and its modelling are presented in Publication I.

The final material properties, functions and boundary conditions used in the calibrated model are presented in Figure 19, Figure 20 and Figure 23.

3.3.2 Predicting hygrothermal performance of outdoor test wall with model calibrated in the climate chamber

After the model parameters had been fixed, following the calibration procedure described in the previous chapter and in Pub. II, the predictive capability of the hygrothermal model was evaluated using measurements from the real-environment experiment. The model used locally measured weather data as boundary conditions, and the results were compared with long-term sensor measurements obtained from the outdoor test wall as well as with gravimetric moisture measurements.

Modelling thermal behaviour of PV and PCM mortar

During the monitoring period, the highest measured temperature on the rear side of the PV panel reached 69 °C in mid-August. The calibrated model predicted a maximum temperature approximately 1 °C lower.

The PCM mortar layer reduced and delayed temperature peaks, demonstrating that the encapsulated PCM behaved as intended and as modelled. No evidence was found that the heat-storage capacity of the PCM mortar deteriorated during the monitoring period. The results confirmed that the PCM mortar continued to function as an effective passive thermal buffer behind the PV panels.

Besides the calibrated model representing the facade with the actually installed materials, an additional modelling scenario was analysed in which the PCM content of the mortar was set to zero. In this case, the 35 mm PCM mortar layer was replaced by a 35 mm layer of conventional cementitious mortar. The simulation showed that the predicted temperature peak would increase to approximately 72–73 °C instead of 69 °C (see Figure 4 of Pub. III), which is still below the durability limit of the PV panel (85 °C).

This indicates that, under Estonian climate conditions, the most expensive component of the PCM mortar—the PCM granules—could probably be omitted without exceeding the PV temperature limit. This is because a thick cementitious mortar layer already provides a noticeable thermal mass, with a specific heat capacity of $c = 800 \text{ J/(kg}\cdot\text{K)}$ and a density of $\rho = 1365 \text{ kg/m}^3$.

Modelling hygrothermal behaviour of PCM mortar

The long-term moisture behaviour of the PCM mortar in the outdoor test wall was evaluated by comparing the measured moisture content with the results predicted by the calibrated hygrothermal model. During the first summer after construction, the

moisture content gradually decreased as the built-in moisture dried out (Figure 35). During the following winter, the moisture content remained relatively stable, with only a slight increase.

The calibrated model predicted a slower drying process during the second summer compared with the measured results. From a practical perspective, this represents a conservative outcome, as the model overestimates the moisture content of the PCM mortar. However, when evaluating the quality of the model, the modelling accuracy during the second year was lower than expected.

This difference can be explained by the chosen modelling strategy, which required freezing the material parameters after calibration in the climate chamber. Because the climate chamber experiment had a limited duration, the PCM mortar in that setup did not reach the lower moisture levels later observed in the outdoor experiment. As a result, the model calibration was primarily based on higher moisture ranges, which explains the reduced prediction accuracy at lower moisture contents.

3.3.3 Extended hygrothermal modelling with condensation test years

After the measurement period described in Pub. III, the calibrated model was used to conduct extended hygrothermal simulations. In these simulations, seven consecutive years were modelled using the Estonian condensation test year, which represents severe climatic conditions for moisture accumulation analysis.

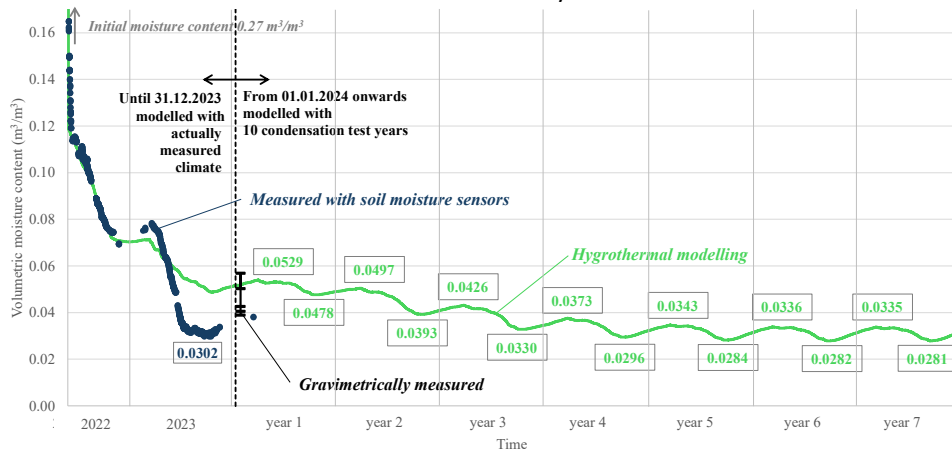


Figure 35. Comparison between modelled and measured PCM mortar MC during the 20-month outdoor experiment and long-term MC predicted by the calibrated model (Pub. III, Figure 8).

The long-term simulations indicate that, after the built-in construction moisture has dried out, the PCM mortar settles into a stable seasonal moisture cycle without progressive moisture accumulation. From approximately the fourth simulation year onwards, the predicted volumetric moisture content fluctuates within the range of 0.028–0.034 m³/m³, with higher values during winter and lower values during summer. This behaviour corresponds well with the seasonal pattern observed during the measurement period, where moisture content increased during winter and decreased during summer.

The stabilisation level around 0.03 m³/m³ is primarily determined by the sorption isotherm of the PCM mortar (Figure 20). However, the measurements indicated that the real facade reached this stable moisture level faster than was predicted by the model.

An important aspect of this analysis is that there was no water leakage behind the PV panels in the test facade nor in the hygrothermal model. In the climate chamber experiments, it was demonstrated that even when water leakage occurred, the liquid water was eventually able to exit the system through the diffusion channels, after which the PCM mortar dried out under solar radiation. Therefore, the conclusion that no long-term moisture accumulation occurs behind the PV panels can be considered valid only if diffusion channels are incorporated into the facade system, which is also defined as a mandatory design requirement for the PV-ETICS facade system.

3.3.4 Answering the RQ3

It could be concluded that the chosen approach to hygrothermal modelling where long-term outdoor experiment was not used for model calibration, proved to be sufficient. Saved resources would probably outweigh the reduction in accuracy in many cases and this approach could be recommended for other research projects with limited resources.

RQ3 - Was the climate-chamber calibrated hygrothermal model sufficient?

1. Initial dry-out of built in moisture (Pub. I)



Liquid water conductivity function (Kl) of the PCM mortar was calibrated.

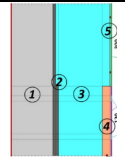
2. Additional drying after PV installation (Pub. II)



Water vapour diffusion resistance (Sd) of the diffusion channels was defined during 2 week drying experiment after PV application.



Solar absorption coefficients (α), thermal conductivity (λ) and latent heat function $u(T)$ were defined with preliminary solar radiation experiments.



3. Water injection experiment (Pub. II)



It was experimentally confirmed that in case of diffusion channels, leaked-in water would drip out.



Kl function was further verified.



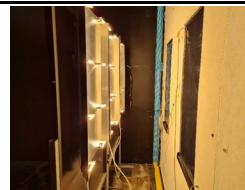
4. Repeated solar radiation cycles (Pub. II)



Test wall showed no damage after extended solar radiation experiment.



Additional validation of the Kl, Kv and $u(T)$ functions of the PCM mortar was conducted.



5. WDR and freeze-thaw cycles (Pub. II)



No leakage was detected through the joints.



Wet test wall showed no damage after rapid freezing after 10 cycles.



Kl and Kv functions of the facade plaster system were calibrated.



6. Using the hygrothermal model for predicting measured data of outdoor facade experiment (Pub. III)

Climate chamber stage resulted with calibrated model. All the parameters were freeze after that.



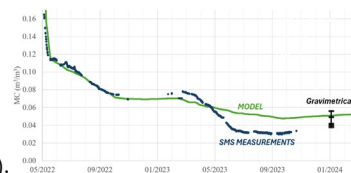
Temperature modelling was very accurate compared to the measured temperatures ($\pm 1^\circ\text{C}$).



Moisture behaviour was modelled accurately during the first year.



During second year model overestimated the MC of PCM mortar (low MC was not experienced in climate chamber).



CONCLUSION:

Strategy for using small scale experiments and series of climate chamber tests for model calibration proved to be sufficient and resource optimal. However, low MC conditions were not experienced in climate chamber and therefore modelled less accurately.



Figure 36. Graphical summary of the research conducted to answer RQ3.

3.4 Assessing PV-ETICS performance beyond conventional design rules [RQ4]

This chapter provides a consolidated evaluation of the hygrothermal performance of the PV-ETICS facade system. The assessment builds on the facade design principles identified in response to RQ1, the experimental methods and calibration procedures established to address RQ2, and the hygrothermal modelling approach validated in relation to RQ3.

3.4.1 Assessment of overheating risk of the PV panel

The thermal durability of the PV panels was evaluated with respect to their maximum allowable operating temperature, 85°C. The overheating risk was assessed using both the measured temperature data from the outdoor experiment and the calibrated hygrothermal model.

Results from both the climate chamber experiment and the outdoor test wall showed that the PV panel and PCM mortar were in strong thermal contact. The temperature measured on the rear side of the PV panel exceeded the temperature in the centre of the PCM layer by less than 1°C (Pub. III, Figure 4), indicating that the PCM temperature can be used as a reliable parameter when evaluating the overheating risk of the PV panel and that PCM could indeed effectively sink the heat from the PV panel.

During the monitoring period, the highest recorded temperature on the rear side of the PV panel reached 69°C, remaining well below the manufacturer's durability limit. To assess whether higher temperatures could occur during more extreme years, the measurement-period climate was compared with historical records from the Tallinn–Harku and Tõravere meteorological stations. The analysis showed that August represents the most critical period for south-facing facades in Estonia, when both solar radiation and ambient air temperature are relatively high. The days that produced the highest PCM and PV temperatures corresponded to the 95th–97th percentiles of historical daily solar radiation, while air temperatures were approximately at the 90th percentile. Based on this comparison, it can be concluded that the 85 °C limit is unlikely to be approached under Estonian climatic conditions.

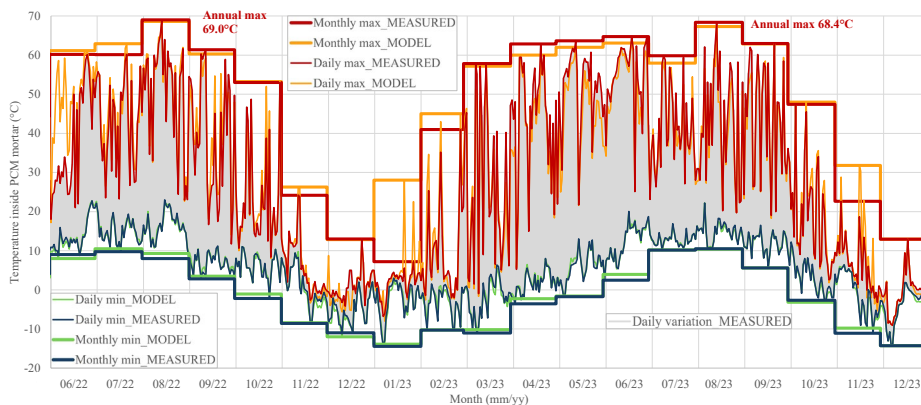


Figure 37. Comparison between measured and modelled daily temperature fluctuations and extreme values of PCM mortar at corresponding month. Shaded area stands for measured variation between the minimum and maximum temperature that occurred within 24 h period. (Pub. III, Figure 3)

One of the modelling scenarios involved a case where the PCM content was removed from the PCM mortar and only the cementitious mortar layer was modelled, peak PV

temperatures increased by only 3–4 °C during the most critical days (Pub. III, Figure 4). Previous numerical studies conducted before the current experimental programme showed that without any thermal mass behind the PV panel (i.e., PV applied directly onto insulation), the predicted peak PV temperatures would reach approximately 83 °C for the Tallinn climate and 91 °C for the Madrid climate (Talvik et al., 2021), which would be too close to or would exceed the performance limit. The presence of the thick mortar layer, however, already plays a significant role in reducing temperature peaks and would likely be sufficient even without PCM content for the Estonian climate.

The temperature distribution across the PV panel surface was relatively uniform for most of the observation period. Figure 38 presents a thermal image recorded on a winter afternoon, following a sunny morning. The lower and upper areas of the PV panel showed slightly elevated temperatures, which were clearly pronounced in the thermal image. Overall, the average surface temperature of the PV panel was approximately 14 °C higher than the ambient air temperature under these winter conditions. At the locations of the main temperature sensors, the measured PV surface temperature was in good agreement with the average temperature of the PV area. The maximum temperature was detected at the connector location (where there is no PCM mortar but PU foam in contact with PV), which was approximately 2 °C higher than the warmest zone in the lower part of the PV module. Lower temperatures were observed near the edges of the PV panel, which was expected.

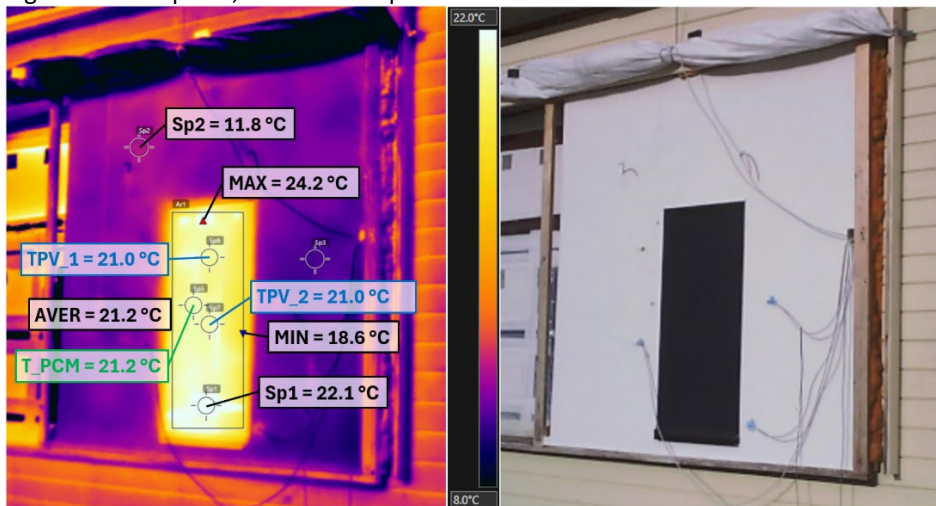


Figure 38. Thermal image of the outdoor test wall on a winter afternoon, following a sunny morning, taken on 13 February 2023 at 13:30. The ambient temperature at the time of the photograph was 7.1 °C. The sky was cloudy when the image was recorded but sunshine had been present throughout the morning. Photographed with FLIR E95. Measurement data of the sensors is presented in Pub. III.

3.4.2 Assessment of deformations of PV and facade plaster

The average measured thermal deformation coefficients of the facade plaster and the flexible PV panel are presented in Figure 39. The values obtained for the plaster layer applied on mineral wool are within the same range as those previously measured in laboratory-scale specimens. In earlier studies (Volkova et al., 2021), the temperature deformation coefficient for the same plaster system combination (C2 (Volkova et al.,

2021)) was measured $17.2 \times 10^{-6} \text{ m}/(\text{m}\cdot\text{K})$ on small-scale samples applied on mineral wool.

The flexible PV panel exhibited a slightly lower thermal expansion coefficient than the facade plaster. However, the temperature amplitudes experienced by the PV panel are higher due to its dark surface.

When the facade surface was warming up, the distance between reference tabs decreased, indicating that both the plaster and the PV panel expanded towards the joint. The magnitude of the measured joint deformation was modest, primarily due to the limited dimensions of the test wall. In the experimental setup, the plaster area adjacent to the PV panel was restricted in width before transitioning to another facade section separated by a deformation profile. In real facade applications, where the plaster area extends several metres between movement joints, thermally induced joint deformations are expected to be greater. Therefore, further investigations at higher TRL levels are required to validate the joint behaviour under full-scale conditions.

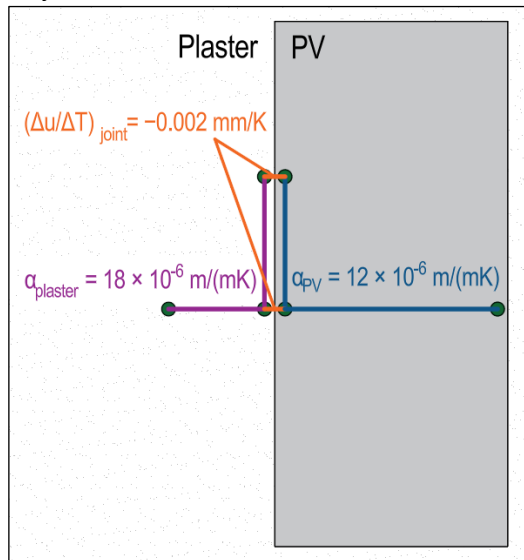


Figure 39. Measured thermal expansion coefficients of the facade plaster system on MW and the PV panel bonded to PCM mortar, together with the thermal joint displacement coefficient of the elastic joint. Measurements were carried out during the cycles shown in Pub. II, Figure 13 and Figure 14.

If the measured temperature deformation coefficients from the climate chamber test (Pub. II) are combined with the measured temperatures from the external test wall (Pub. III), the absolute maximum deformations of the facade system can be calculated. During the most critical days, the PV surface temperature approached 70°C , while the light-coloured facade plaster temperature was approximately 40°C (Pub. III, Figure 4). The measured thermal expansion coefficients were $\alpha_{pv} = 12 \times 10^{-6} \text{ m}/(\text{m}\cdot\text{K})$ and $\alpha_{plaster} = 18 \times 10^{-6} \text{ m}/(\text{m}\cdot\text{K})$. Assuming the lowest wall surface temperature to be -25°C , the total linear deformation would be 1.14 mm/m for PV ($\Delta T_{pv} = 95 \text{ K}$) and 1.17 mm/m for the light-coloured facade plaster ($\Delta T_{plaster} = 65 \text{ K}$), which are similar. This means that the deformations along the joint would also be comparable. However, the joint must still allow significant movements perpendicular to the joint axis.

3.4.3 Assessment of hygrothermal durability of PCM mortar

The long-term durability of the PCM mortar layer installed behind the vapour-tight PV panel was evaluated based on the combined results of the climate chamber experiments, the outdoor facade measurements, and hygrothermal modelling. The key durability indicators analysed were initial dry-out, freeze–thaw resistance, long-term moisture accumulation, and the ability of the facade system to manage potential water leakage.

Overall, the results indicate that the PCM mortar performed satisfactorily when installed behind the vapour-tight PV panel if diffusion channels were implemented. The moisture content of the PCM mortar stabilised at a sufficiently low moisture level, which was proven by both SMS measurements and gravimetric measurements. Moreover, long-term hygrothermal simulations did not predict any progressive moisture accumulation within the layer.

An important design element contributing to this behaviour was the presence of diffusion channels behind the PV panel. During the climate chamber experiment, sections with and without diffusion channels were measured side-by-side and the sections with channels showed much faster drying times during solar radiation cycles.

Moreover, any moisture entering the system was proven in the climate chamber, to be able to exit through these channels within a reasonably short time (Figure 26). Both the measurements and modelling results therefore confirm that the drainage/diffusion channel concept functions as intended and provides an additional level of moisture safety for the facade system.

No visually detectable freeze–thaw damage or structural deterioration of the PCM mortar was observed during the experimental period. The cycles used in the experiments were more severe than the freeze–thaw cycles defined in (EAD 040083-01-0404, 2024), which is used for testing ETICS systems on the market, despite there being fewer cycles in the experiment. Climate cycles did not cause noticeable damage to the system. This indicates that the moisture levels within the mortar remained below critical thresholds that could cause frost damage.

During the destructive opening of the test facade, a localised change in colour of the PCM mortar was observed near the diffusion channel areas (Figure 40, left). The discolouration was limited to the surface layer of the mortar adjacent to the channels and likely resulted from prolonged exposure to moisture. In some cases, it may also indicate minor wash-out of PCM components. The orange-coloured discolouration was limited only to the outer surface of the mortar in the vicinity of the diffusion channels. Inspection of the deeper layers showed that the PCM granules remained intact (Figure 40, right). No discolouration of the surrounding mortar was observed around the granules, indicating that the polyurethane (PU) encapsulation of the PCM particles remained stable and that no significant leakage or degradation occurred during the experimental period. No measurable reduction in the thermal performance or temperature-regulating efficiency of the PCM mortar was detected.



Figure 40. Discolouration of the PCM mortar (slightly orange surface to the left of the diffusion channel) (left). Structure of the PCM mortar after full removal of the PV panel (dark grey particles are PCM granules coated with PU, colour of the mortar is uniformly light grey both near the granules and further away) (right).

Overall, the combined experimental and modelling results demonstrate that the PCM mortar layer can maintain both thermal and hygrothermal durability when installed behind a vapour-tight PV panel, provided that diffusion/drainage channels are incorporated into the facade design.

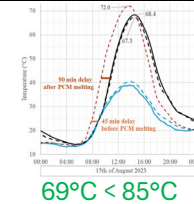
3.4.4 Answering the RQ4

Based on the entire experimental programme, hygrothermal modelling and destructive opening of the facade system, the PV-ETICS solution could be considered to perform well hygrothermally and should proceed to the next development stage (TRL 6).

RQ4 - How to evaluate hygrothermal performance of PV-ETICS?

1. Assessing the overheating risk of PV panel (Pub. III)

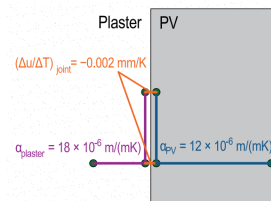
- ✓ Thick PCM mortar was able to keep the maximum PV temperature (69°C) well below the performance limit (85°C).
- ✓ Risk analysis with historical climate shows also that two measured summers was enough to reach this conclusion.
- ! Modelling shows that PCM is not even necessary for Estonian climate. Thick mortar alone is enough.



69°C < 85°C

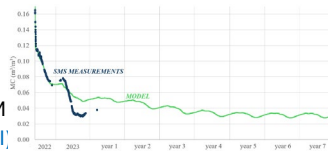
2. Assessment of Deformations and Joint Performance

- ✓ Total deformations are similar. 1.14 mm/m for PV ($\Delta T_{PV} = 95$ K) and 1.17 mm/m for plaster ($\Delta T_{plaster} = 65$ K).
- ✓ Measured joint movement was -0.002 mm/K and no cracking from the joint line was detected.
- ! Wall dimensions were too small for final conclusions. Larger building scale experiments needed in upcoming TRL-s.



3. Assessment of hygrothermal durability (Pub. II & Pub. III)

- ✓ No damage detected during stress tests in climate chamber. (Pub. II)
- ✓ Leaked in moisture was able to exit from the system via diffusion channels. (Pub. II)
- ✓ SMS and gravim. measurements showed that MC of the PCM mortar stabilised at a sufficiently low moisture level. (Pub. III)
- ✓ No moisture accumulation predicted by the model in long-term, using 7 continuous condensation test years. (Pub II)



4. Assessing possible PCM escape (Pub. III)

- ! After destructive opening, a localised change in colour of the PCM mortar surface was observed next to the diffusion channel.
- ✓ Comparing measured temperature data between 1st and 2nd summer showed no reduction in PCM potency to sink heat.
- ✓ Even if PCM does escape, the temperature peaks would be below service limit for Estonian climate.



PV-ETICS system with thick PCM mortar is hygrothermally safe to proceed for further development.



Figure 41. Graphical summary of the research conducted to answer RQ4.

3.5 Effects of dark facade surfaces and external PCM on indoor climate [RQ5]

To address the question, whether PV-ETICS system on a facade could lead to unacceptable overheating conditions inside the apartments, a building-level energy model was developed and calibrated using the measured thermal data from the experimental facade. The calibrated model was then applied to simulate a representative renovated apartment building and evaluate the contribution of PV-ETICS to indoor overheating.

During calibration, it was found that heat-flux modelling could be improved by using a temperature-corrected thermal conductivity value for the insulation material at elevated temperatures.

3.5.1 Evaluating overheating risk in typical post-World-War II-era apartment with PV-ETICS

After the energy model was calibrated, the simulation framework was applied to a representative post-war concrete apartment building. For the PV-ETICS case, 50% of the windowless end wall facade area was covered with the PV-PCM wall type, while the remaining surfaces were finished with light-coloured plaster.

The results showed that the additional overheating caused by PV-ETICS compared to light-coloured ETICS was relatively modest in well-insulated renovation scenarios. On average, the PV-ETICS system added between 3 and 10 °C·h above 27 °C for cases with a typical insulation thickness of 200 mm ($U_{WALL} = 0.12 \text{ W}/(\text{m}^2 \cdot \text{K})$). However, if the insulation thickness decreased, the number of additional degree-hours increased. Therefore, even for warmer climates, an insulation thickness of at least 100 mm could be recommended for PV-ETICS applications to mitigate indoor overheating.

Overall, the simulations showed that solar gains through windows dominate the overheating behaviour of the apartment. Parameters such as window-to-wall ratio, glazing g-value, and shading conditions have a significantly larger influence on indoor temperature than the additional heat flux caused by PV-ETICS. This means that the dark colour of the PV panel and the high thermal mass on the external side of the insulation should be taken into account in energy calculations; however, the resulting overheating effect can be compensated by other means.

3.5.2 Evaluating indoor overheating risk of dark facade plaster

Besides PV-ETICS, traditional ETICS with a dark surface was also analysed, as this is an issue that raises many questions in the practical construction sector. Numerous parametric simulations were used to generate graphs showing the increases in overheating degree-hours and cooling demand as the solar absorption coefficient of the facade plaster increases. It was shown that if a building has a dark ETICS facade, this must be considered in energy calculations, and the IDA ICE default value of $\alpha = 0.5$ is not sufficient, especially for thinner insulation layers. It was also shown that PV-ETICS increases indoor overheating less than dark-coloured traditional ETICS, mainly because the dark-coloured area of the facade is limited to 50%.

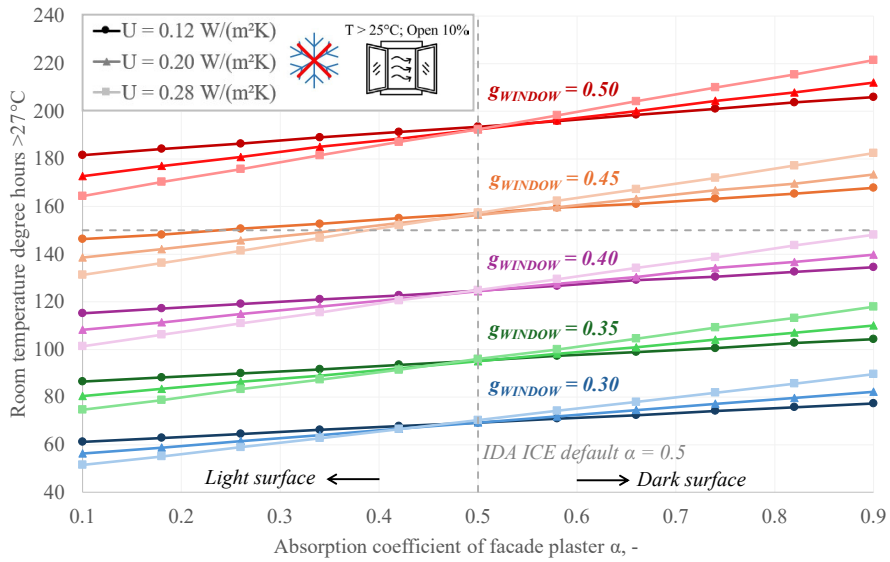


Figure 42. Overheating degree hours as a function of the facade plaster absorption coefficient (α). The thermal transmittance values correspond to a renovated apartment building with additional insulation thicknesses of 50 mm, 100 mm, and 200 mm. (Pub. IV, Figure 6)

3.5.3 Dynamics of indoor cooling demand

Analysis of the hourly cooling demand of the indoor climate revealed that the overall increase in cooling demand due to PV-ETICS is relatively small (in the case of 200 mm insulation), the cooling demand increases by an average of 36 kWh for 63 m² apartment over the whole summer compared to light ETICS.

Most of the increase in cooling demand occurs during the evening peak electricity consumption hours (Figure 43). For 200 mm insulation thickness, 44 % of the additional cooling demand occurs between 16:00 and 22:59 in the case of PV-ETICS, while for dark ETICS this share is 31 %. For 50 mm insulation, the corresponding percentages are 77 % for PV-ETICS and still 31 % for dark ETICS.

This indicates that although the total increase in cooling demand is modest, it mostly occurs during the hours when cooling is most expensive. This effect becomes more pronounced with lower insulation thicknesses. During the daytime, when the PV facade produces electricity, the thick PCM mortar acts as a heat sink. In the evening, when no electricity is generated by the facade, the heat flux reaches the indoor environment, which increases the already peaking (due to the west facing windows of the modelled apartment) cooling demand.

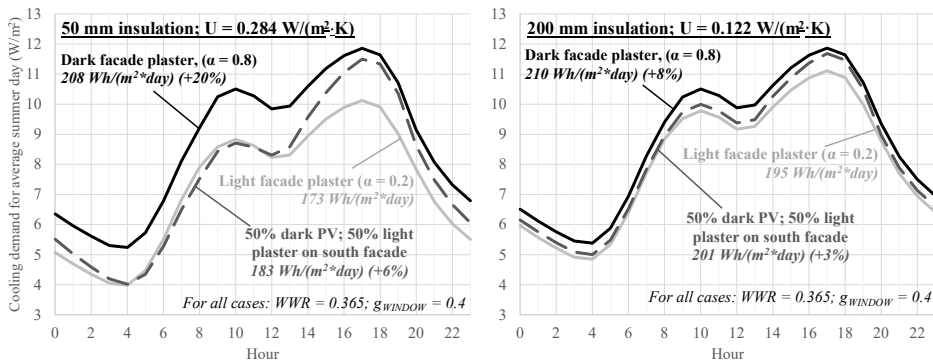


Figure 43. Dynamics of cooling demand during average summer day for case of 50mm EPS insulation (left) and 200 mm insulation (right). Averaged over all summer days, including cloudy and rainy ones.

3.5.4 Key takeaways from overheating analysis

The combined experimental and modelling results demonstrate that the dark PV-ETICS facade surface and external thermal mass do contribute to indoor overheating, but their overall impact is moderate in typical renovation scenarios. For buildings with sufficiently thick insulation layers, the additional overheating caused by PV-ETICS remains relatively small compared with the influence of solar gains through windows.

The results indicate that PV-ETICS systems can be implemented on residential facades in cold climates without causing significant indoor overheating, provided that the effect of the dark facade surface is properly accounted for in energy calculations. Using temperature-corrected thermal conductivity values (according to (ISO 10456, 2007) is recommended when assessing overheating in dark ETICS facades.

In practice, the overheating impact of PV-ETICS is generally smaller than that of dark ETICS, suggesting that the integration of PV modules does not represent a major thermal comfort risk when properly designed.

3.5.5 Answering the RQ5

Concluding the energy part of the research, the implementation of the PV-ETICS system could also be recommended for the renovation market. In the case of sufficient insulation, the additional heat load on the indoor environment caused by the dark surface and external thermal mass could be easily mitigated with low-g windows and/or external shading.

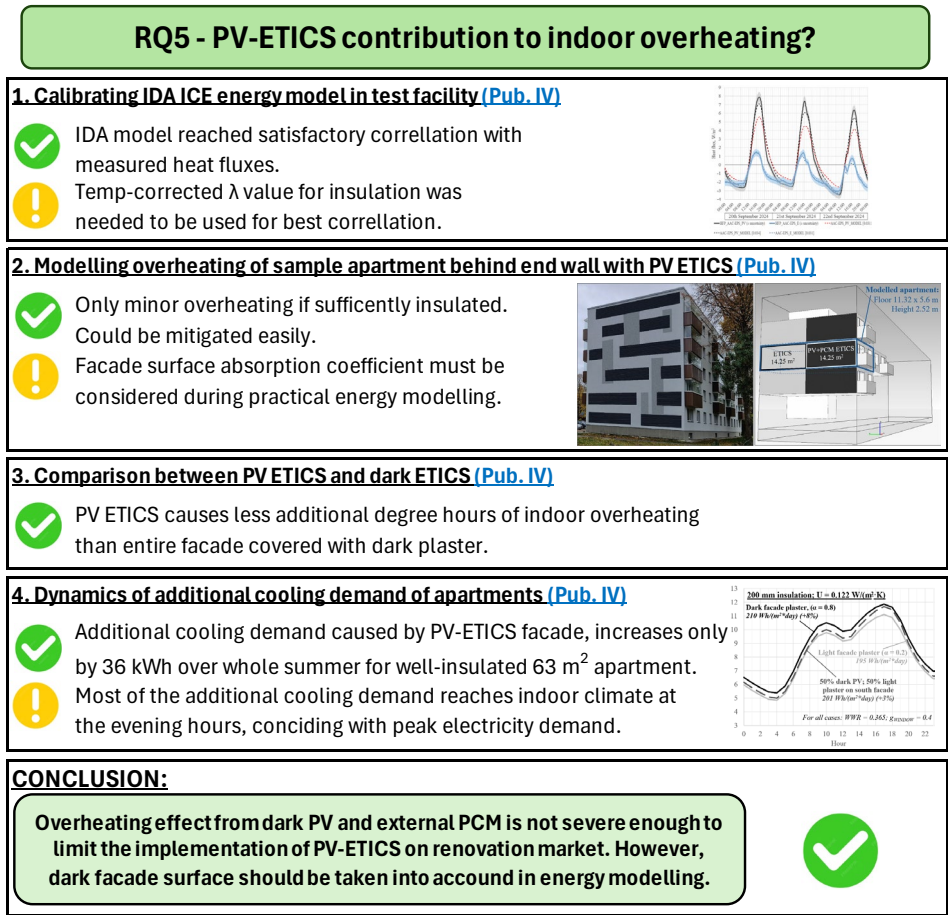


Figure 44. Graphical summary of the research conducted to answer RQ5.

4 Discussion

4.1 Technology readiness progression of PV-ETICS and future development [RQ1]

The starting point of this thesis was the initial functional concept of the facade system (TRL 2) (Ilomets et al., 2020). The study successfully followed the PV-ETICS development to TRL 3 through small-scale experiments (Pub. I), to TRL 4 through climate chamber experiments (Pub. II), and to TRL 5 through the long-term experiment on an external facade (Pub. III). The concept has been validated experimentally and through modelling, and its performance meets both hygrothermal and thermal requirements.

According to some criteria, it could be argued that the system is already close to TRL 6, as demonstration in a relevant environment was in principle carried out during the long-term outdoor experiment (Olechowski et al., 2020). The main limitation in declaring TRL 6 is that the test wall was still too small in its dimensions to fully assess deformation behaviour. For this purpose, a full facade surface of an apartment building, with at least three storeys and a width of at least 10 m, would be recommended to reach TRL 6. If the joints perform successfully under such conditions, TRL 6 could be declared.

It was also demonstrated that some of the design for disassembly (DfD) principles (Ostapska et al., 2024; Salama, 2017) were successfully applied to the PV-ETICS section, as the PV panel could indeed be removed and replaced without damaging the surrounding ETICS plaster (see Appendix 6). The solution could be improved even more if the PV panel was fixed mechanically with removable bolts instead of an adhesive bond.

The research demonstrates that further development of the PV-ETICS system beyond TRL 5 is justified. The main challenges for future development relate to scalability and industrialisation, including:

- possible implementation of prefabrication techniques;
- optimisation of installation processes;
- improved protection and corrosion resistance of electrical connections;
- minor redesign of the deformation joint using thinner stainless-steel ribbons;
- economic feasibility analysis of a mass-producible facade system;
- carbon footprint assessment.

Addressing these aspects would support the transition from a prototype system to a commercially viable facade solution. Given the promising results, the PV-ETICS system has strong potential for application in both renovation and new construction.

4.2 Reliability of SMS for measuring MC in PCM-containing materials [RQ2]

The use of soil moisture sensors (SMS) for measuring overhygroscopic moisture content was found to be strongly justified in the present study. Conventional temp-RH sensors are not suitable for monitoring high moisture ranges, and the long-term outdoor experiment showed that such sensors began to provide meaningful data for PV-ETICS only approximately one year after installation of the facade system. In contrast, the SMS enabled continuous monitoring from the beginning of the initial drying process until a stable long-term moisture regime was reached. The agreement between SMS readings and gravimetric measurements confirmed that the method provides sufficient accuracy for thick, porous materials such as PCM mortar, and that the effort invested in developing material-specific calibration curves was worth it.

The isothermal calibration curve obtained in this study was described by a cubic polynomial, consistent with the example calibration curves provided in the sensor manufacturer's datasheets (METER Group, 2026). Although cubic polynomials provide higher accuracy, the resulting relationship did not differ greatly from a linear simplification (difference between cubic polynomial and linear best fit was $R^2 = 0.94$), similar to those previously reported by (Karoglou et al., 2024) for various construction materials. The main calibration curve was established at 20°C, at which the PCM is in the solid state.

The nature of the experimental programme of this study was strongly non-isothermal. Most previous studies that have applied SMS in construction-related measurements have considered only isothermal conditions, while the need for temperature-correction functions has repeatedly been identified as an important topic for future research (Karoglou et al., 2024; Yu et al., 2021).

Temperature correction curves were established for two moisture levels and were found to differ between the solid and liquid states of the PCM. The correction was simplified into three temperature ranges: solid PCM (up to 20 °C), liquid PCM (above 40 °C), and the phase change region in between. The final temperature correction function was then constructed from these three linear functions. Addressing the phase change region in moisture measurements using SMS is a novel aspect of this work, as no comparable examples were found in the literature.

Although the temperature correction functions improved the accuracy of the sensor readings at different temperatures, the temp-corrected results were still less accurate than isothermal measurement results at 20°C. It was also noticed that the accuracy of temperature correction decreased over time. In retrospect, it would also have been beneficial to determine at least one additional temperature correction curve at lower moisture contents, as the stable long-term moisture content observed in the outdoor experiment was lower than that represented by the lowest calibration curve.

4.3 Justification of the climate-chamber-calibrated modelling approach [RQ3]

The modelling strategy adopted in this study was to calibrate the hygrothermal model under controlled climate chamber conditions and then use the calibrated model to predict the performance of the test wall under real outdoor exposure. The results showed that the calibrated model reproduced both the temperature and moisture

behaviour of the facade with reasonable accuracy, although some discrepancies remained at lower moisture levels.

The use of tailor-made climate cycles in the chamber was also justified, since the standard EAD cycles would not have provided the type of data required for model calibration.

In addition, the study highlighted the importance of determining material properties as accurately as possible, a requirement that has been repeatedly emphasised in the literature (Dang et al., 2023; Klößeiko & Kalamees, 2022).

4.4 Suitability of scientific methods for assessing PV-ETICS performance [RQ4]

The thesis aimed to identify scientific methods suitable for evaluating the hygrothermal performance of a facade system in which a vapour-tight PV panel is applied on top of a porous PCM mortar layer. In such a case, traditional envelope design logic and steady-state dew-point assessment are not sufficient. Previous studies on hygrothermal behaviour have shown that blind modelling alone is also not sufficient for new wall assemblies made of novel construction materials, and that calibration with measured data is essential for improving modelling accuracy. Therefore, the method used in this study, a combination of material-specific sensor calibration, climate chamber measurements, model calibration, outdoor validation, and destructive verification, was appropriate for demonstrating that a facade concept was indeed hygrothermally safe and durable. The final design (see Appendix 5) prevented overheating and moisture accumulation during the experiments even in the case of leaked-in water, and its durability was further assessed by long-term modelling.

The custom-made climate chamber experimental programme, including artificial solar radiation and direct water injection behind the PV panel, can also be considered appropriate for designing the facade system. The use of scientific methods was more suitable than relying only on the durability test described in (EAD 040083-01-0404, 2024), which is mainly intended for certification-oriented pass/fail testing of conventional ETICS and does not include the internal measurements, leakage scenarios, or radiative heating conditions needed for scientific understanding of the performance of a PV-ETICS facade and model calibration.

The methods used in this thesis can serve as a reference for the development of other complex building products and systems where a more thorough scientific approach is needed, rather than merely checking durability through accelerated climate chamber tests.

4.5 Extent of the PV-ETICS contribution to indoor overheating [RQ5]

The impact of PV-ETICS on indoor overheating was found to be moderate and manageable. In well-insulated buildings, the system increased overheating slightly compared with light-coloured facades, but less than dark ETICS facades did. This result is in line with the literature, which showed that windows generally remain the dominant source of overheating in highly insulated buildings (Simson, 2019; Thalfeldt, 2016), while additional heat gains through dark opaque facade surfaces become relevant mainly in the case of less insulated partitions.

Previous studies have also shown that the effect of dark facade and roof surfaces decreases linearly as insulation thickness increases (Yao & Yan, 2011), which is in good agreement with the present results.

At the same time, the PV-ETICS system differs from most earlier studies because of the PCM mortar layer behind the dark surface. The additional thermal mass delayed heat flow into the building and shifted part of the heat gain towards the evening hours. This effect should be considered in design, as the electricity demand peaks during the evening hours.

4.6 Limitations

4.6.1 Limitations of hygrothermal measurements

The use of SMS for measuring overhygroscopic MC introduces certain limitations. In reality, the temperature correction of SMS readings is a three-dimensional function. For calibration in this study, moisture variation from oven-dry to vacuum-saturated material was carried out only at 20 °C. Two additional temperature correction curves were defined at moisture contents that were expected to be most representative. A more detailed calibration covering a wider range of temperature & moisture conditions could have improved the accuracy of temperature correction.

However, the hygrothermal processes behind the vapour-tight PV layer were relatively slow, and for most of the seasons, it was possible to obtain measurements at 20 °C at least twice a day. During the winter, temperature correction made it possible to follow the moisture content, but overall trends remained sufficiently predictable even without it. Nevertheless, the three-dimensional nature of temperature-dependent calibration for SMS should be considered in future studies, especially in cases with less stable moisture regimes.

Temp-RH sensors also introduced some uncertainty. Although the sensors were calibrated before and after the experiments, a minor systematic deviation remained, which was corrected using linear offset correction. The temp-RH sensors inserted into the facade for shorter periods using insertion tubes behaved more reliably in terms of systematic errors and drift. However, there remains a risk that some leakage through the insertion tubes happened during the long-term experiment.

4.6.2 Limitations of other measurements

Unfortunately, possible PCM escape was not evaluated using methods other than temperature data analysis. Besides limitations in resources, there was a risk that as the distribution of PCM granules in the composite material was not uniform, there would be great differences between individual samples, which could be significantly higher than differences between new and aged samples.

However, comparing the PCM's capacity to absorb heat in the first and second summers showed no reduction in PCM potency. Moreover, towards the end of the experimental programme, it was observed that, in the Estonian climate, the thick mortar layer alone would be sufficient to keep PV temperatures below the performance limit, even without PCM content. Therefore, minor PCM loss would not significantly affect the system's performance.

The deformation behaviour of facade joints was assessed only on relatively small-scale test walls. Full-scale behaviour under real building conditions remains unverified; however, this is beyond the scope of a TRL 5 prototype.

During the real wall experiment, only a south-facing facade was studied. Other orientations, taller buildings, and higher wind exposure conditions should be investigated in future TRL levels.

4.6.3 Limitations of hygrothermal modelling

The hygrothermal model did not consider water leakage through facade defects. This is consistent with ETICS design principles, which assume a watertight facade, although numerous data show that the plaster layer is often not perfectly watertight. However, climate chamber experiments demonstrated that, in the case of leakage, water can drain and dry out through the diffusion/drainage channels. Since the system is designed to prevent water ingress and includes diffusion channels as a secondary safety mechanism, this simplification is considered acceptable. From the perspective of moisture safety, PV-ETICS may even perform better than traditional ETICS due to the presence of drainage channels.

Another limitation is the representation of a three-dimensional facade system using a two-dimensional model. This simplification was adopted to reduce computational complexity and improve efficiency, but it does not explicitly account for certain processes, such as enhanced moisture transport in corner regions. Nevertheless, the model was calibrated against experimental data from the test wall, which inherently reflect three-dimensional effects. This calibration supports the reliability of the modelling approach within the conditions investigated.

In addition, micro-convection within diffusion channels was not modelled explicitly but was instead represented through an equivalent vapour diffusion resistance (S_d) calibrated in the climate chamber.

4.6.4 Limitations of energy modelling

The energy modelling was based on a single building type and facade orientation. The analysed case, a south-facing, windowless end wall, represents a critical scenario and is in best agreement with the south-facing installation on the test facility. However, PV facades would be, considering the duck-curve, more effective at south-east and south-west orientations in terms of economic benefits.

The simulations relied on a standard Estonian TRY weather file and did not account for future climate scenarios. Additionally, occupant behaviour was simplified, particularly regarding window opening and internal heat gains. However, these assumptions were aligned with local regulations and typical energy calculation practices.

The analysis focused on the thermal impact of PV-ETICS and did not include a detailed assessment of electrical performance or the dynamic interaction between PV electricity production and building cooling demand. Furthermore, the model assumed normal system operation; scenarios such as PV malfunction, which can increase surface absorption and overheating risk, were not analysed in detail.

4.7 Future research

The thesis showed that PV-ETICS is a promising facade concept, while also identifying several scientific and practical questions that should be addressed in future research.

The usefulness of the calibrated EC-5 soil moisture sensors for measuring the overhygroscopic moisture content of thick, porous construction materials was proven through the study. The wider use of these sensors in building physics research is therefore encouraged, particularly in applications where conventional moisture measurement methods are difficult to apply. In future studies, these sensors could also be used for facade materials directly exposed to wind-driven rain, for example to analyse the hygrothermal behaviour of thick facade plaster systems and support their design against freeze–thaw deterioration. If SMS are used under non-isothermal conditions, they should first be calibrated at different temperatures and across a wider range of moisture contents.

Regarding hygrothermal modelling, micro-convection was neglected in the present work, as this provides conservative results. Further research could focus more specifically on analysing and modelling micro-convection in narrow channels that are open only at one end and have one side covered by a dark surface exposed to direct solar radiation. The real-life measurement data collected in this thesis could provide valuable input for developing and validating such models.

Moreover, the deformation behaviour of this facade system should be investigated more thoroughly in future studies using larger facade surfaces. The measurements presented in this thesis were conducted on a climate-chamber test wall measuring 3.3×3.6 m. Future research should examine the deformation behaviour of the facade system on full-scale apartment-building walls.

Beyond hygrothermal and thermal performance, future studies should address topics that remained outside the scope of this thesis, including electrical performance optimisation, fire safety, life-cycle assessment, and economic feasibility. The architectural concept, including the geometry of the PV layout, should be revisited to develop a more visually appealing design solution instead of relying only on rectangular PV panels applied in a straight line.

From a product-development perspective, further development of the PV-ETICS facade system beyond TRL 5 should be carried out in close cooperation with private-sector partners. Research should support the transition of PV-ETICS from an experimentally validated prototype towards industrial and market implementation. This includes the optimisation of details related to prefabrication, installation logistics and improved design-for-disassembly solutions.

5 Conclusions

The novel facade system developed and studied in this thesis performed well both in the extreme environment of the climate chamber and on the south-facing facade of the test building in a cold climate. Hygrothermal modelling results were broadly in line with the measurements and showed no signs of moisture accumulation in the years following the end of the real-scale facade experiment.

Hygrothermal measurements and simulations confirmed that the **thick PCM mortar, applied according to application instructions (Appendix 5), successfully prevented PV panel overheating [RQ1]**. The maximum recorded PV panel temperature was 69 °C during both summers (in August), which is significantly below the critical performance threshold of 85 °C. Ambient temperature and solar radiation data from the experiment were compared with historical climate data and showed that the PV-ETICS system retains a sufficient performance buffer, including some margin for future climate conditions. It also appeared that in the Estonian climate, a similar mortar without any PCM content already has sufficient thermal mass to mitigate the overheating of the PV. However, it has been shown in the literature that for central and southern European climates the PCM is necessary.

Regarding moisture accumulation behind the vapour-tight PV panel, both experimental and simulation results indicated that in the absence of facade cracks, the **moisture content in the PCM mortar did not increase due to internal moisture loads if the system was constructed according to instructions in Appendix 5 [RQ1]**. Moisture was able to dry out via diffusion channels and around the PV panel section. Even leaked-in water, injected into the PCM mortar layer, was able to exit the system via the channels.

These conclusions could not have been reached using conventional engineering methods for hygrothermal design, such as the steady-state dew-point method or even with dynamic simulations, without measuring any properties of a novel construction material and without any experiments. Therefore, **the more advanced methodology described in this thesis was both appropriate and necessary [RQ4]**.

Calibrated soil moisture sensors proved to be a reliable method for measuring high moisture content in the porous mortar with PCM content [RQ2]. The sensor-based measurements corresponded reasonably well with gravimetric measurements taken after two years of exposure. However, it was also observed that the most accurate sensor readings were obtained when the PCM temperature was close to +20 °C, which corresponds to the calibration conditions. While temperature correction functions for a novel material containing PCM, were applied to account for deviations, the accuracy of measurements still decreased during winter months when the PCM temperature was much lower. In these periods, hygrothermal modelling was useful in adjusting and interpreting the measured data more reliably.

Overall, a **relatively satisfactory correlation was achieved between the measured and modelled PCM moisture content in the outdoor experiment (RQ3)** by using a strategy in which small, relatively short-duration climate chamber experiments were employed for model calibration, and the same model was then used to predict the material moisture contents during the longer outdoor experiment. This demonstrates that similar calibration techniques could be applied to other applications in the future. Based on these positive examples, it may be possible to encourage researchers to perform model calibration based on shorter climate chamber experiments rather than

relying on lengthy and resource-intensive research programmes for calculation model calibration.

A small limitation of the PV-ETICS system is the increased heat flux from the external PCM layer towards the interior on summer evenings. However, energy modelling of an apartment building with a south-facing PV-ETICS facade showed that the **increase in overheating degree-hours and cooling demand remained within acceptable limits [RQ5]**. In practical energy simulations, it should be taken into account that the dark facade surface does contribute to overheating; however, the effect can be effectively mitigated by selecting lower g-value glazing or applying external shading.

Overall, the facade system reached TRLs 3, 4, and 5 at different stages of the thesis, and its future development is promising. Industrial-scale implementation should be considered.

Answers to the hypotheses proposed in the introduction are presented in Figure 45.

Answers to the hypothesis		
HYPOTHESIS 1 <u>Peak PV temp < 85 °C and no moisture accumulation</u>	TRUE	 Max temp during outdoor experiment 69 °C, leaving a sufficient safety margin. (Pub. III)  No moisture accumulation occurred with diffusion channels if built according to Appendix 5. (Pub. II & Pub. III)
HYPOTHESIS 2 <u>Calibrated soil moisture sensors are suitable and accurate enough</u>	TRUE	 Non-isothermal calibration conducted, including the phase-change range. (Pub. I)  Sensor readings matched gravimetric results after destructive opening. (Pub. III)
HYPOTHESIS 3 <u>A climate-chamber-calibrated HAM model can predict outdoor behaviour</u>	TRUE	 Measured and modelled PCM moisture content agreed satisfactorily during outdoor experiment. (Pub. III)  Measurements stabilised faster than the model, as low-humidity was not reached in climate chamber. (Pub. III)
HYPOTHESIS 4 <u>Simple engineering methods are insufficient for PV-ETICS hygrothermal assessment</u>	TRUE	 Dew-point and uncalibrated dynamic simulations are insufficient; experimentally calibrated HAM model worked. (Pub. II & Pub. III)  The EAD durability test was insufficient for PV-ETICS because it excludes radiative heating, water leakage, and freezing while wet. (Pub. II)
HYPOTHESIS 5 <u>Dark PV-ETICS contributes to indoor overheating and should be considered in energy calculations</u>	TRUE	 PV-ETICS increased overheating and cooling demand less than dark ETICS relative to light facades. (Pub. IV)  The increase was minor in well-insulated facades, but should still be included in energy modelling. (Pub. IV)
FUTURE WORK:		
The PV-ETICS system with thick PCM mortar could proceed for further development towards TRL 6+		

Figure 45. Graphical summary of the hypotheses formulated in the introduction and the corresponding conclusions.

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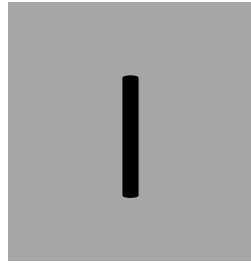
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Appendix 1



Publication I

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Construction process and measuring initial dryout of PCM mortar in Energy Activated ETICS Façade

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ABSTRACT

For both newly built and renovated nearly zero energy buildings, installing photo-voltaic (PV) panels on building façades vertically is a growing trend. To develop reasonably priced and aesthetically satisfying energy activated façades, adding flexible PV (FPV) panels to traditional external thermal insulation composite system ETICS façades is under consideration. To prevent the FPV from overheating, phase change material (PCM) granules, encapsulated in the thick layer of mortar, were installed behind the FPV. As FPV is vapor tight, it is necessary to allow the moisture to dry out behind the FPV and to prevent frost damage of the moist PCM mortar.

A full scale test wall was built in a climate chamber with three versions of energy activated ETICS sections with traditional ETICS separating them. Also, a PCM mortar composite was investigated in small-scale experiments to calibrate the soil moisture sensors used for measuring moisture content in the overhygroscopic range. Measured results from the climate chamber were compared with hygrothermal model calculation results.

The function for calibrating the soil moisture sensors to measure moisture content in PCM mortar was defined, as well as formulas to eliminate the temperature error caused by specifics of the sensor. A double steel sheet joint solution was developed to make it possible for excess moisture to dry out behind the vapor-tight PV panel. It turned out that 12 days at room temperature was enough for 35 mm (1-3/8") thick mortar with PCM granules to dry out enough to cover it with a PV panel. Hygrothermal modelling showed a similar drying out process with several candidate materials.

INTRODUCTION

During times of geopolitical and economical instabilities, our world must move towards a green economy even faster and our dependency on fossil energy sources must be reduced drastically. Easy and economically justified integration of photovoltaic with building envelope can be a reasonable solution towards low and zero energy buildings.

Building-integrated photovoltaics (BIPV) is becoming more and more widespread on rooftops. But as the available area is often limited by the size of the roof, shading must be taken into account and therefore it is not always possible to reach near-zero energy levels. More solutions with PV panels integrated into façades are coming onto the market. But most of the solutions have an air gap behind the PV panels on the façade, which keeps the back side of the PV panels ventilated and makes it possible for excess moisture to dry out (Quesada et al., 2012).

According to technical requirements provided by many producers the exploitation temperature of PV panel should not exceed 85°C (185°F). In case of unventilated photovoltaic integrated with building facades this critical value can be exceeded due to the high solar absorptivity of PV. The concept of keeping the PV panels temperature under control by using phase change material (PCM) has been studied before (Ilomets et al., 2020). Previous calculations have shown that adding a thick layer of

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mortar mixed with PCM granules helps to avoid severe overheating of PV panels, thereby avoiding physical damage, ageing effects and efficiency drop in electricity output (Heim et al., 2021; Talvik et al., 2021).

Studies have shown that using PCM for keeping the PV panel temperatures below critical values, helps to both increase the electricity output of PV panels and to decrease the risk of PV panels deteriorating prematurely due to extremely high temperatures. Direct integration of flexible PV with wide range applied External Thermal Insulation Composite System (ETICS) can be a reasonable alternative for BIPV in a form of ventilated façade. On the other hand, the risk of overheating is higher due to the insulation layer being in direct contact with PV from inside. For this specific combination of PCM cooled PV and traditional ETICS wall (En-ActivETICS), thermal modelling has shown that passive cooling with a 30 mm (1-3/16") thick layer of PCM mortar decreased the peak temperatures of the PV panel from 83°C (181°F) to 71°C (160°F) and resulted in a 2.2% increase of electricity output in Tallinn, Estonia (Talvik et al., 2021).

Moreover, as assumed in En-ActivETICS (Heim et al., 2020), adding the vapor-tight PV panel to the outermost material layer of the wall causes significant hygrothermal risks behind the PV panel (Ilomets et al., 2020). As the PV panel is watertight and vapor tight, it creates a situation where moisture is not able to transfer through the wall system by diffusion. It could lead to moisture accumulation behind the PV panels, potentially allowing the thick layer of mortar to reach high levels of moisture content and thereby leading to physical deterioration of the material when freezing or corrosion of PV. Many traditional ETICS façades have problems with deterioration (Sulakatko, 2019). Adding PV panels to the façade makes the system more complicated and the probability of cracks appearing in the façade plaster (mainly on the border of two materials) and the risk of moisture deterioration rises. One option to reduce the risk of moisture accumulation is to let the excess moisture dry out with diffusion channels located behind the vapor tight PV panel and connected to the external environment via dedicated inlets.

Moreover, it is necessary to let the PCM mortar dry out enough before installing the PV panels to control the built-in moisture inside the wall. This study tries to define the necessary time needed for a thick layer of PCM mortar to dry out, before the PV panel could be applied to the wall.

METHODS

Tests in climatic chamber with experimental wall

A test wall was built in the climatic chamber of Tallinn University of Technology, Estonia. The climate chamber has two separately controlled environments (simulating indoor and outdoor environments), separated by the test wall. The test wall was built using traditional ETICS with three sections of energy activated ETICS inset into the main construction (Figure 1 and 2). Two thirds of the traditional ETICS were assembled using expanded polystyrene (EPS) insulation and one third using mineral wool (MW).

Measuring moisture content of materials in the overhygroscopic range with soil moisture sensors

As it is impractical and imprecise to measure the relative humidity of porous building materials when they reach the overhygroscopic range, soil moisture sensors were used side-by-side with temperature and humidity sensors to measure moisture content. Researchers (Klõšeiko et al., 2017) have found the soil moisture sensors could be useful in hygrothermal experiments with mineral construction materials if the layer thickness is enough. In this case, the PCM mortar layer was 35 mm (1-3/8") thick which allows the application of soil moisture sensors into the specimen. Used soil moisture sensors have a measuring range between 0 m³/m³ to 1 m³/m³ and an accuracy of ±0.02 m³/m³ for any porous mediums (METER Group, 2021). It has been stated (Varda, 2017) that calibrating by weighing the measured specimen is necessary for each specific material.

For calibrating the soil moisture sensor, the same PCM mortar was applied onto the EPS around a pre-attached sensor. As well as the soil moisture sensor, there were capsules inside the mortar to measure temperature and RH with conventional sensors. The specimen was regularly placed into a water-vapor tight case for stabilizing the moisture levels. During the 2-month period, drying out and soaking cycles were conducted with a small-scale test specimen.

The specimen was weighed regularly to find the connection function between sensor output voltage and measured moisture content inside the PCM mortar. The function for converting soil moisture sensor output into volumetric moisture content at a temperature of 20°C (68°F) for this specific PCM mortar is shown below (Formula 1):

$$\psi = 2.27U_{20}^3 - 5.346U_{20}^2 + 4.378U_{20} - 0.981 \quad (1)$$

Where U_{20} is the voltage output of the soil moisture sensor (V) measured at 20°C (68°F) and ψ is volumetric moisture content of the PCM mortar around the sensor (m^3/m^3). This function could be used for measuring moisture content in PCM mortar in the overhygroscopic range. In the hygroscopic range, humidity could be measured with conventional RH sensors.

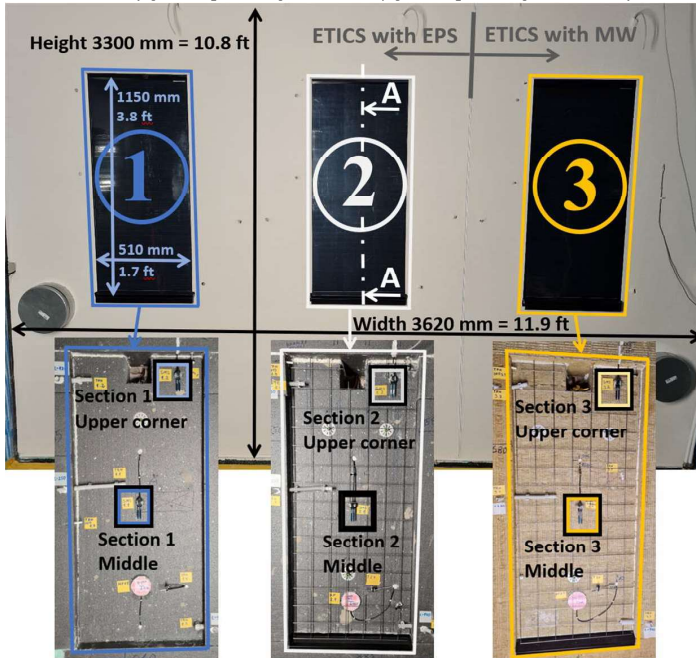


Figure 1 Overview of the test façade. Reference section 1, without diffusion channels; Reference section 2, PV panel on EPS with diffusion channels behind PV (2); Reference section 3, PCM mortar with diffusion channels on MW (3). Below are photos before the application of PCM mortar. Highlighted are the soil moisture sensors.

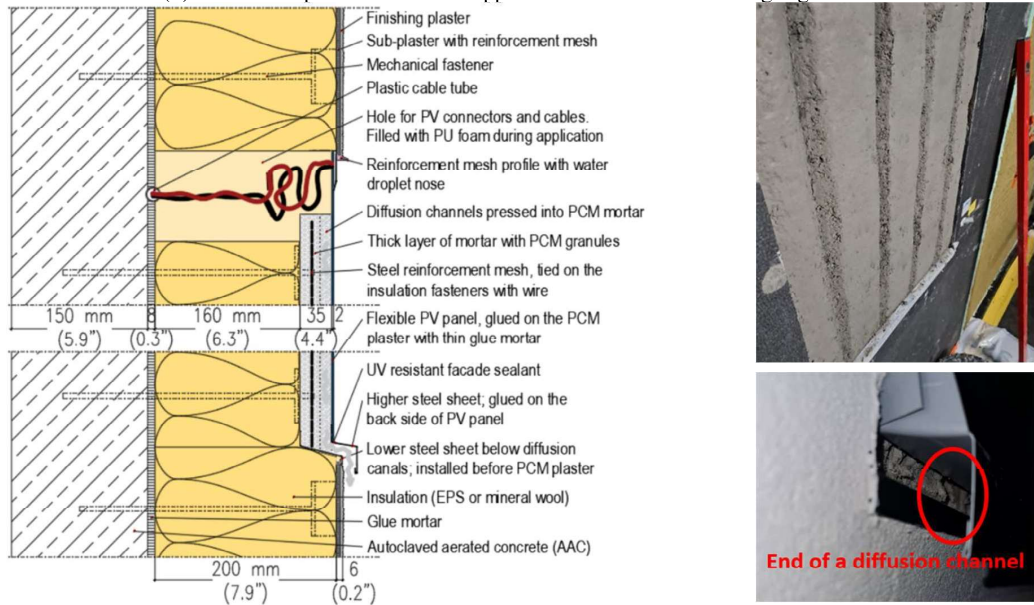


Figure 2 Cross section A-A (see Figure 1 section 2) of the test wall (left); diffusion channels pressed into fresh PCM mortar during application (right, above); air gap between steel sheets where diffusion channels reach to external environment (right, below)

It has been found that soil moisture sensors are sensitive to changes in temperature (Seyfried & Grant, 2007) (Fares et al., 2016). For applications in agriculture and forestry, the necessary corrections are in the reasonable limits, as soil temperatures are relatively stable during the vegetation period, compared to temperature fluctuations of a building façade. A study referencing 19 different soil types found that the temperature sensitivity depends significantly on the soil type (Seyfried & Grant, 2007). Therefore, it was decided to verify the corrections for this specific PCM mortar used in the test wall.

To compensate for the temperature dependency, the same test specimen with a known moisture content was sealed into a water-tight container and kept at different temperatures. Two experiments were conducted – the first with the specimen at a relatively low moisture content and the second at a higher moisture content (Figure 3). The results were different for different moisture contents, but the graphs were linear, as was expected based on other studies (Seyfried & Grant, 2007). The phase change area between 20°C (68°F) and 40°C (104°F) showed a slight additional increase in readings which could be explained by the phase change effect, but the amount of increase is in the margins of error. It is possible to adjust the sensor output for any temperature between -30°C (86°F) and 90°C (194°F) to voltage output at 20°C (68°F) with the formulas presented in Figure 3. After temperature correction, the U_{20} value could be used in the Formula 1 to calculate volumetric moisture content of PCM mortar.

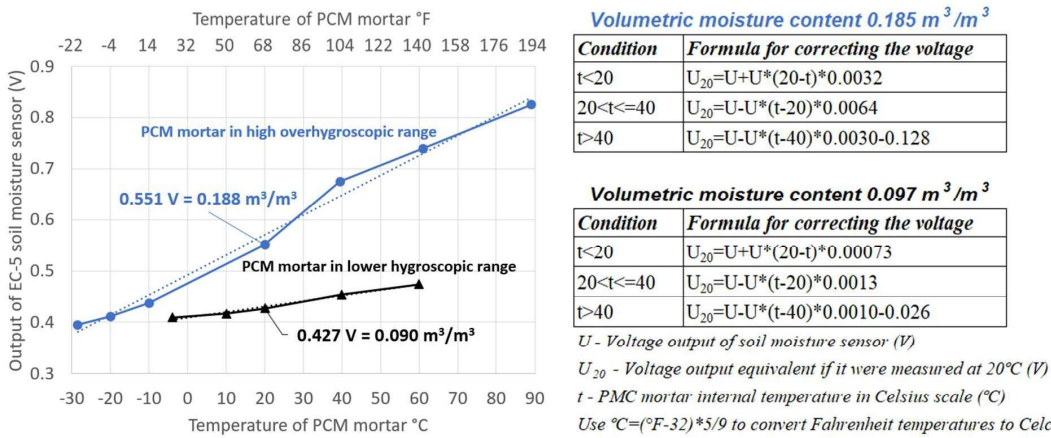


Figure 3 Temperature correction graphs for soil moisture sensors in PCM mortar (left) and formulas for correcting the sensor output voltage if the material temperature varies from 20°C (68°F) (right). The black (triangular) line on the left graph is just at the boundary between the hygroscopic and overhygroscopic range. The blue (dotted) line represents the moisture content three days after taking the soaked specimen out of the water.

As there are probably many different temperature dependency graphs between those two lines, this method for correcting the voltage results has some inaccuracies. During future experiments, more temperature dependency graphs could be researched to further increase the accuracy of temperature correction functions.

Hygrothermal modelling

Coupled heat, air, moisture, and matter transfer software Delphin 6 was used to model the hygrothermal performance of the wall. 1D model was used for calculations, as initial drying out process is not affected by the presence of diffusion channels. After 25 days, virtual PV panel was installed by adding boundary condition $S_d = 10\,000\text{m}$. Materials used in model besides PCM mortar were Autoclaved Aerated Concrete (database material no 1); Glue Mortar I (90); Polystyrene Foam Board – Expanded (186) and Lime Cement Mortar (143).

For hygrothermal modelling several small scale tests were conducted. Results from sorption curve measurements, wet cup experiment and water uptake tests were used to create a final material file. Measured material properties of PCM mortar were: bulk density $\rho = 1150\text{ kg/m}^3$; thermal conductivity $\lambda = 0.63\text{ W/m}^2\text{K}$; water uptake coefficient $A_w = 0.045\text{ kg/(m}^2\text{s}^{0.5})$; water vapor diffusion resistance factor $\mu = 154$ and effective saturation moisture content $0.28\text{ m}^3/\text{m}^3$.

To compare the new created material with other mineral, mostly cement based, mortars, 9 different materials from the library were chosen to compare newly developed PCM mortar material. For all the models, measured data from the climate chamber was added as boundary conditions and the PV panel was added into the model at the same time as it was installed on

the test wall. Initial moisture content of all the materials were taken equal to effective saturation moisture content.

BUILDING THE TEST WALL

Most of the test wall was built as a standard ETICS according to technical guidelines (ETAG 004, 2013) and data sheets of material producers. More effort was put into developing a new solution of a thick mortar layer with PCM granules and a new joint design to make it possible for the excess moisture to dry out behind the PV panel.

Reinforcement and anchoring of the thick PCM mortar

The PCM mortar consists of two main ingredients – a mixture of PCM granules with different melting temperatures and cement-based mortar. The mortar itself contains fibers and does not require any additional reinforcement, and could be applied as a thick layer of up to 30 mm (1 3/16"). However, as this mortar was transformed into a new composite material by adding the PCM granules, it was hard to apply the PCM mortar on a vertical surface without additional reinforcement mesh and there was a tendency for the mortar to fall down some minutes after the application. The problem was solved with 75x75x2,5 mm (3" x 3" x 0.1") steel reinforcement mesh which can be seen in Figure 1.

To avoid the PCM mortar separating from the wall during the service period, the reinforcement mesh was tied to the mechanical fixing of the ETICS system. Mechanical anchors are fixed on the structural layer of the wall system and thereby failure of the chemical bonding between the PCM mortar and insulation material does not result in a collapse of the PCM mortar and PV panel.

Pressing the diffusion channels into PCM mortar

One test wall section was constructed as a reference wall without any way for excess moisture to escape other than drying out on the sides of the PV panel through the façade plaster of ETICS. Two test wall sections were constructed with diffusion channels to make it possible for excess moisture to dry out behind the vapor tight PV panel by diffusion, micro-convection or dripping down by gravity.

There were 4 vertical diffusion channels for each section with PV panels (Figure 2). The channels were pressed into the PCM mortar right after application and were finished with an orthogonal masonry trowel. The results were triangular shaped diffusion channels with an average cross-sectional area of 400 mm² (0.62 in²). The spacing between diffusion channels was 120 mm (4.7").

Diffusion channels were open at the bottom. Below the PCM mortar there was a steel sheet installed with a 1:10 slope (Figure 2). If excess moisture condenses on the surface of the PV, it drips down on the steel sheet, which leads the water out from the wall system. The opening is covered with another steel sheet, fixed on the back side of the PV panel. The second steel sheet has a lengthened vertical part to protect the diffusion channels from wind-driven rain. All the diffusion channels were closed at the top. Therefore, only micro convection could occur in the channels, with no stack or convection effect as would be seen with a traditional air cavity. Creating similar rain-protected joints at the top of the PV would have resulted in the steel sheets leaning too far away from the main façade and potentially shading the very top photovoltaic cells of the PV, resulting in a significant efficiency loss of the whole PV panel.

RESULTS

Drying out process of the PCM mortar

According to the producer, a 35 mm (1-3/8") thick mortar layer would need 35 days to dry out but this is affected by boundary conditions. In the climate chamber experiment, different dry out times were used to cover the PCM mortar. For wall section 1 it was 25 days, for section 2, 17 days and for section 3 it was 12 days.

It can be seen from Figure 4 that in all three wall sections, the PCM mortar moisture level balanced after approximately 2 weeks. However, it could be stated that the PCM dried out slightly faster on the mineral wool (wall section 3) than it did on EPS (wall no. 1 and 2). The difference is small because during the drying out process, the PCM mortar was in contact with air up until the application of PV panels. As all wall sections had dried out relatively long time, there were no significant differences between the solutions with diffusion channels and those without, after installing the PV panels. There is a small amount of

increase just after the PV panels were installed, which is caused by the initial moisture content of the glue mortar used for fixing the PV panels.

It could be concluded from Figure 4 that a drying out time of 12 days was sufficient to allow covering the PCM mortar with a PV panel. There was some additional drying process on the test area on the mineral wool after covering, but it was not significant enough to conclude whether diffusion channels made it faster or not.

Boundary conditions in the climate chamber during the dry out period (Figure 5) were favorable. The temperature was mostly between 20°C (68°F) and 25°C (77°F) and RH between 30% and 60%. An increase in RH is noticeable on the days when new wall sections were covered with PCM mortar (days 1, 9 and 14).

To test out the temperature correction formulas developed with small scale experiments (Figure 3), the climate chamber temperature was dropped to 7°C (45°F) on day 29 (Figure 5). Initial data from soil moisture sensors showed a drop in readings, but after the temperature correction formula for lower moisture content was used, the change in PCM mortar temperature does not stand out in the graphed moisture content of PCM mortar (Figure 4).

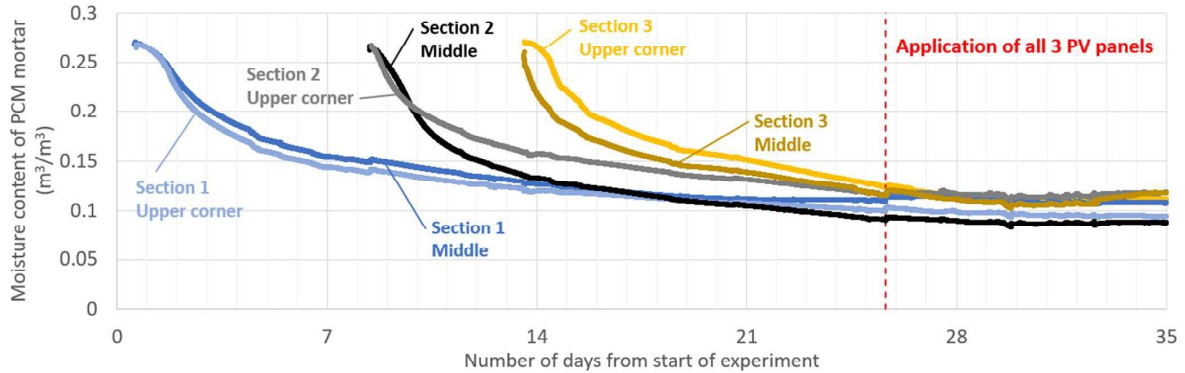


Figure 4 Initial drying out process of PCM mortar. Measured with calibrated soil moisture sensor.

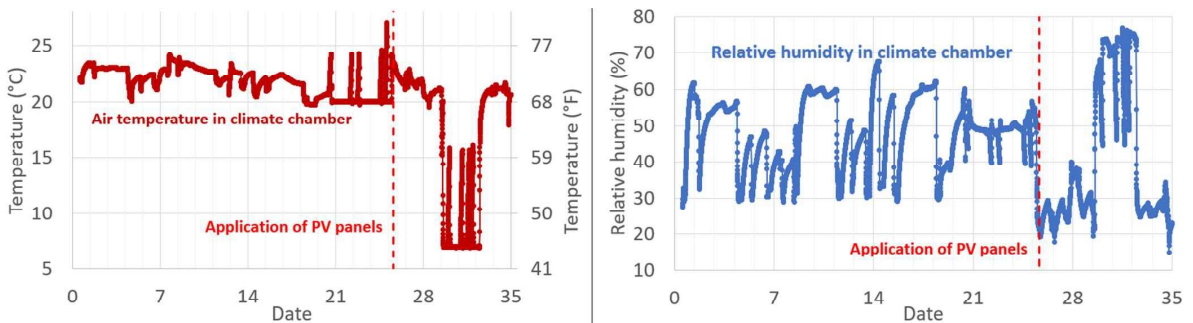


Figure 5 Boundary conditions during the PCM mortar drying out process. Air temperature (left) and relative humidity (right) inside the climate chamber during the measurement period.

Modelling the drying out process

Hygrothermal modelling was carried out with PCM mortar material file, which properties were measured during small scale experiments. To get an idea, whether measured material properties correlate with existing material files in the software, modelled results were compared with 9 mineral materials. All those modelled results were compared to measured data of wall section 1 – PCM mortar on EPS without diffusion channels (see Figure 6).

There is a correlation in moisture content between modelled and measured results. Only at the very beginning there is some difference, but as the material is expected to be at lower moisture content than 0.15 m³/m³, the difference is not very significant. Other plasters and cement based materials showed great differences in modelled results. Therefore, it could be stated that measuring exact hygrothermal properties of new building materials makes modelling results much more accurate than just picking materials from the database that seem to be similar from the first look.

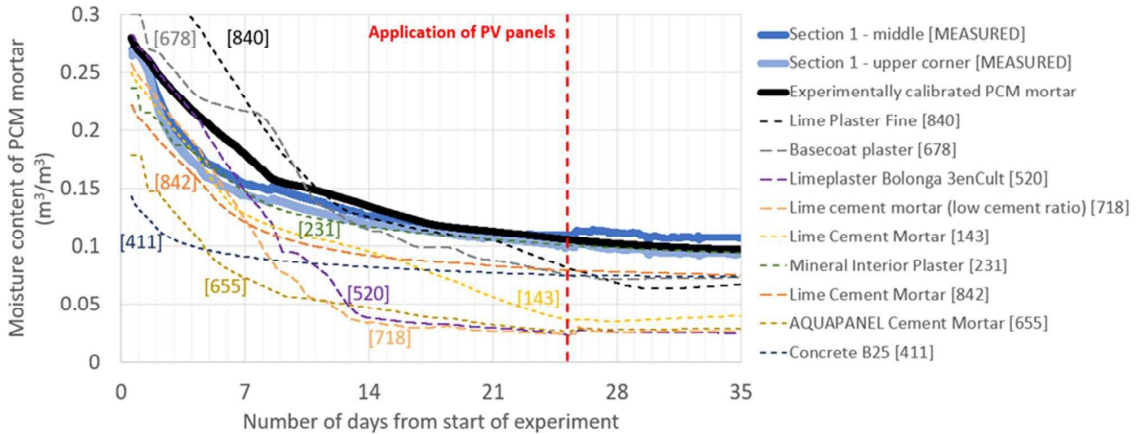


Figure 6 Drying out process modelled with experimentally calibrated material file (thick black line), compared with measured (blue lines) PCM mortar drying out on test wall section 1. Thin dashed lines are modelled results with different building materials with similar properties.

DISCUSSION

Using the soil moisture sensors

In general, using soil moisture sensors appeared to be appropriate for applications with high moisture content in the overhygroscopic range. Temperature correction formulas have been proven to work, but as there are more lines between the two measured formulas, then temperature dependency graphs for several different moisture contents should be studied in the future.

Voltage correction formulas presented in Figure 3 were calculated in three different temperature ranges because of the phase change effect, to get more exact results. However, it could be stated that the temperature dependency lines are linear all the way, as the differences are not tremendous.

Improving construction methods for the energy activated ETICS wall

The application process of the 35 mm (1-3/8") thick layer of mortar on the vertical surface was relatively time consuming and material intensive. It would not be the most economical way to build this wall on a real construction site. A future consideration would be to make the façade system partially prefabricated. PCM could be integrated with PV in form of a closed, thin-walled metal case for example.

A significant amount of time could have been saved by applying the PCM mortar if the PV panels were already covered with a rough-surfaced material layer to avoid the application of primer. Moreover, connection profiles for the application of the façade plaster system could have been pre-installed in the factory on the PV panels.

Drying out process of PCM mortar before covering with vapor tight PV panel

The time for covering the PCM mortar was selected according to material producer guidelines and common construction practices. So the available dry-out time for all the test areas was between 12 and 25 days which allowed enough dry-out time for all the sections, which means that the effects of covering the PCM before it is properly dried out are still unknown. During further experiments, it would be worthwhile to neglect the technically correct solutions and apply the PV panel onto wet mortar. Measurements could then be conducted after covering the PCM mortar at 3, 5 and 7 days at room temperature or 2 weeks under different external weather conditions.

CONCLUSIONS

During the study, a full-scale installation of energy activated ETICS façade was built in the climate chamber. Calibrated

soil moisture sensors were installed in the layer of mortar with PCM granules. The initial drying out process of thick PCM mortar was investigated.

It was possible to apply PCM mortar to a vertical surface after steel reinforcement mesh was installed. Diffusion channels were able to be pressed into the fresh mortar and a lower joint detail with two layers of steel sheet was developed and built successfully. Soil moisture sensors proved trustworthy for measuring high moisture content in the overhygroscopic range after temperature corrections were made.

For 35 mm (1-3/8") thick PCM mortar, 2 weeks proved to be enough drying out time before covering with a vapor tight PV panel. Under conditions close to an indoor climate, the drying out process was relatively fast. In the future, the drying out process at lower temperatures should be studied and there should be a shorter time between the application of PCM mortar and installing the PV panels.

Hygrothermal properties of PCM mortar should be further calibrated during various climate chamber tests to increase the correlation between the measured and modelled results. Comparing the drying out process of different database materials and PCM mortar material with measured hygrothermal properties, it was clear that exact hygrothermal functions make a huge difference in calculated results.

Many other experiments could be conducted with the test wall in the climate chamber – various frost resistance, wind driven rain and solar experiments are planned for carrying out in the future with the energy-activated ETICS façade set up.

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Appendix 2



Publication II

Talvik, M., Ilomets, S., Klõšeiko, P., Kalamees, T., Põldaru, M., & Heim, D. (2023). Hygrothermal performance of thick PCM mortar behind PV panels in energy-activated ETICS facades. *Buildings*, 13(6), Article 1572. <https://doi.org/10.3390/buildings13061572>

Article

Hygrothermal Performance of Thick PCM Mortar behind PV Panels in Energy-Activated ETICS Facades

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Abstract: The concept of integrating PV panels into traditional ETICS facades has been developing for several years. Problems concerning the options for passively controlling the temperatures of PV panels with PCM and directing excess moisture out of the wall via diffusion channels have been previously studied theoretically. During this study, real wall-scale experiments were conducted to test the thermal and hygrothermal performance of the wall system in an extreme climatic environment, as well as in a real outdoor environment in Tallinn, Estonia. Finally, a simulation model was calibrated according to the measured data. It was found that in case of test walls with diffusion channels, it was possible to keep the moisture content of PCM mortar under $0.11 \text{ m}^3/\text{m}^3$. Excess water drained out via channels leading to the external environment. Without diffusion channels, the moisture content rose as high as $0.18 \text{ m}^3/\text{m}^3$. Both the experiments and hygrothermal modelling showed that the high moisture content of PCM mortar, caused by water leakage, dropped to $0.08 \text{ m}^3/\text{m}^3$ over 10 solar cycles as moisture escaped via the diffusion channels. PCM mortar with a moisture content of $0.08 \text{ m}^3/\text{m}^3$ endured extreme rain and freeze-thaw cycles without visual damage, and PV panels retained their electrical production capabilities.

Keywords: ETICS; building-integrated PV (BIPV); PCM; En-ActivETICS; hygrothermal performance; hygrothermal modelling



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1. Introduction

Building-integrated photovoltaics (BIPV) are becoming increasingly widespread to reduce the CO₂ emissions of buildings, which account for 36% of emissions [1], and to produce green electricity locally. There is a large demand for visually appealing BIPV systems [2], but unfortunately, the majority of the BIPV systems still depend on fixed-tilt PV module systems [3].

For ventilated-façade-integrated photovoltaic (PV) panels, there are many solutions to choose from. Example procedures are available to clarify how to develop PV systems on ventilated facades [4]. The majority of BIPV facades are constructed as ventilated facade technologies using PV panels as a rain screen cladding system, which adds an additional protection layer against hygrothermal problems. There is some recent research on developing a system to apply PV panels onto existing and new ETICS (external thermal insulation composite system) facades, but there is still a ventilation gap planned between PV and ETICS [5].

The traditional ETICS concept consists of insulation material, glued directly to the structural layer with adhesive mortar and the plaster system, consisting of base coat and finishing plaster, which is applied directly to the insulation layer. This means that there is no air cavity, and the outer layer of the wall system has relatively high resistance to water vapour diffusion.

If PV panels were applied directly on thermal insulation, there could be some undesirable effects, e.g., overheating or moisture condensation. To address the aspect of

overheating, there has been some research about using latent heat storage of phase change materials (PCM) for temperature stabilisation of the PV panels, both passively [6] and actively [7]. There have also been studies conducted with double-skin facades with integrated PCM layers and PV glazing [8], but in this case there was an air chamber between the PV and PCM, with the possibility to open and close the ventilation gaps. Combination of PV and PCM has also shown potential in reducing overall energy consumption of buildings in cold climates [9]. Although PCM applications are a relatively new technology in the construction sector, there are some data from indoor applications stating that after a decade, PCM was still working as a passive heat sink, despite showing a significant decrease in the PCM capacity [10].

However, the PCM and PV solution has not been combined with traditional ETICS facade systems before. The application of diffusion gaps in the PCM layer to avoid moisture condensation and accumulation has not been studied in the past.

The concept of an En-ActivETICS facade integrates traditional ETICS facade technology with PV panels. There has been theoretical work conducted towards the development of the facade concept [11–13]. Measurements with real test walls regarding the electrical and thermal performance have also been conducted [14], as well as comparisons between different PV-ETICS integration solutions and free standing PV panels. However, the hygrothermal performance of this wall concept has not been studied by experimental methods before.

Earlier studies have proven that applying a thick layer of PCM mortar is effective in avoiding the overheating of PV panels [14]. However, applying a vapour-tight layer on the outermost side of the facade creates a situation in colder climates where moisture is not able to get out of the wall via diffusion in the same way it does in the case of traditional ETICS. This problem was identified and analysed numerically in [15]. A solution utilising diffusion gaps connected to the outside environment between a pair of steel sheets at the lower part of the PV has been proposed and developed [16]. However, the overall hygrothermal performance of this solution has not been studied before, except for the initial drying-out process of PCM mortar just after the application [16].

In the results of several empirical studies, it has been found that one common mechanism for ETICS facades to deteriorate prematurely is water leaks through the cracks [17–19]. During the lifespan of ETICS facades, micro-cracks tend to appear after several years. As water seeps into the micro-cracks, they become wider, leading to even more water penetrating the facade plaster, which starts the vicious cycle of degradation. Integrating a dark-coloured PV panel into the light-coloured facade significantly increases the theoretical risk of cracks appearing, due to the number of joint details between different materials. Unfortunately, ETICS systems are known to be not very robust, and minor defects could lead to deterioration [20]. Therefore, if more complexity is added to the ETICS system via the integration of PV, diffusion channels should be recommended as a countermeasure to increase the robustness of the system.

Therefore, it is necessary to thoroughly test this novel facade system, which takes into account the expectation that there will be cracks in the facade and that water will eventually leak into the wall. This is a new approach that has not yet been tried on a wall that combines PV panels, PCM mortar, and an ETICS facade. If a hygrothermally well-performing facade solution can be developed, then this novel En-activETICS facade could have a huge market potential to alleviate the energy crisis. There has been a great demand for BIPV for several years, and there are also many different BIPV solutions on the market, but there are many concerns among architects about the BIPV facade solutions available today, as they are difficult to blend in as a part of the architecture [21]. In contrast to ventilated BIPV solutions, En-ActivETICS would be on the same surface plane as facade plaster and would make it possible to create interesting patterns of PV and facade plaster areas.

It was found in [22] that despite ETICS facades being often preferred for building renovation as being a cost-optimal solution, they tend to have a higher carbon footprint

than pre-fabricated timber elements. If PV panels are integrated into otherwise affordable ETICS facades, they could offset some of the carbon footprint and become closer to also being CO₂e optimal. Therefore, there could be a large market potential for En-ActivETICS for both new and renovated buildings, but the hygrothermal performance of the novel wall concept must be thoroughly studied first.

The aim of the study was to test the constructability and study the hygrothermal performance of a novel facade system that combines PV panels, PCM mortar and ETICS.

2. Methods

To test the concept of hygrothermal performance, two real-scale test walls were built. One wall was built in a climate chamber to test the system in a controlled and critical environment. The test package consisted of water injection, solar radiation, wind-driven rain (WDR) and freezing tests. Another wall was built into the existing facade of a test building to be studied under real outdoor climate conditions. All measurements were compared with data from calculations in order to calibrate the model.

The cross-section of an En-ActivETICS element (Figure 1b) consists of a structural layer, 160 mm of insulation (EPS or mineral wool), 30 mm thick PCM mortar (cement-based mortar, mixed with PCM granules) and a 2 mm flexible PV (FPV) panel. Thin FPV was chosen because of its relatively light weight and its ability to be glued directly onto the surface of PCM mortar [11]. The 100 W FPV panel [23] used on the wall has monocrystalline silicon wafers in the functional layer, TPT (Tedlar Polyester Tedlar) as the back sheet and flexible transparent plastic as the outermost layer for weather protection. The FPV does not have any frame for structural integrity and therefore needs to be glued to the surface.

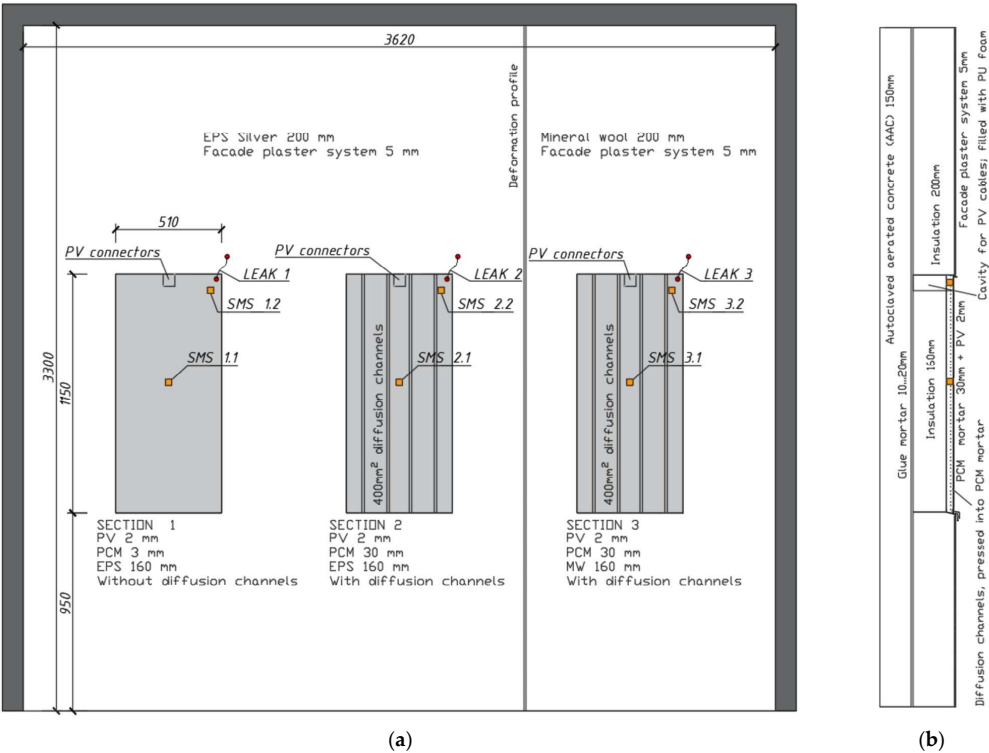


Figure 1. Layout (a) and cross section (b) of a test wall in the climate chamber. Locations of soil moisture sensors are marked as “SMS” and points where water leaked in are marked as “LEAK”.

Four diffusion channels for each panel were carved into the PCM mortar before hardening. Cable connectors were placed inside a cavity in the insulation layer, on the upper part of the PV and during installation, and the cavity was filled with PU foam. As waterproof MC4 connectors were used to make the connections, no special junction box was needed. The exact building process and detailing of the solution has been described before, in [16].

Between and all around the PV panels, a traditional ETICS with 200 mm of insulation was installed. The load-bearing structure was built from 150 mm of AAC (autoclaved aerated concrete) without internal plaster, to maximise the indoor moisture load corresponding to the worst-case scenario. The reasons for choosing AAC as the critical structural material are high levels of built-in moisture and relatively low water vapour diffusion resistance factor ($\mu = 7$).

2.1. Test Wall in Climate Chamber

The climate chamber can simulate both indoor and outdoor temperature ($-25\text{ }^{\circ}\text{C}$ to $+70\text{ }^{\circ}\text{C}$) and relative humidity (RH = 5 ... 98%). In the outdoor chamber, WDR was simulated with additional water sprinkler stands and short-wave thermal radiation was simulated with halogen stands.

A 3.6 m wide and 3.3 m high test wall was built in the climate chamber (Figure 2a) with three different sections: (1) Reference section with PCM mortar without diffusion channels; (2) PCM mortar on expanded polystyrene (EPS) with diffusion channels behind PV; and (3) PCM mortar on mineral wool (MW) insulation with diffusion channels behind PV (Figure 1). EPS and mineral wool areas were separated with PU foam and the facade plaster was separated with a deformation profile on top of the PU foam.



Figure 2. Climate chamber used for building the test wall (a) and the test wall inside the climate chamber (b).

2.2. Test Wall under Real Outdoor Climate Conditions

Besides the mock-up developed for investigations under a critical and controlled environment (climate chamber), it was decided to build another test wall to enable tests on the actual facade under real outdoor climate conditions in Tallinn, Estonia. Tallinn (59.44° N , 24.75° E) is located in a humid continental climate with warm to hot (and often humid) summers and freezing cold (Dfb according to the Köppen–Geiger climate classification system) [24]. The facade faces directly south (180° azimuth) and is located on the first storey, therefore not receiving the most extreme WDR loads (Figure 3). The wall itself was exactly the same as the one built in the climate chamber as section no. 2—PCM mortar

on EPS with diffusion channels (Figure 1a), in order for the results to be comparable. The analysed period of measurements was from June to August 2022.

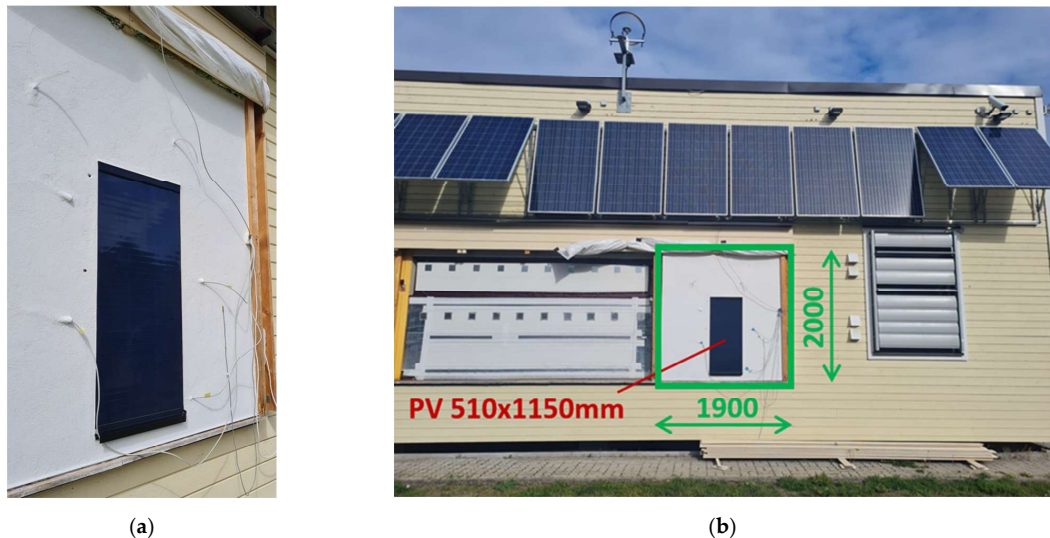


Figure 3. Test wall in Tallinn under real climate conditions (a) and overview of the test house (b). Pyranometer, used for measuring radiation, is visible above the roof line of test house.

2.3. Sensors Used for Measurement

Temperature, relative humidity (RH), volumetric moisture content and heat flux were measured inside the test walls (climate chamber and real facade) and on the surface. Solar radiation on the wall, wind velocity, outside air temperature and RH were also measured. Two or three alternative sensors were used to measure each parameter independently to optimise for data availability, cost efficiency and reliability of the measured data. To measure the temperature inside the walls, the following temperature sensors were used: Onset Hobo TMC15-HD with data logger UX120-006M and Littelfuse KS103J2 NTC thermistor with data logger Grant Squirrel SQ2020 1F8. RH and temperature were measured with an Onset Hobo UX100-023; a Rotronic Hygroclip HC2-C05 with A/D converter Siemens SM331 6ES7331 and a Sensirion SHT35 & tailor-made logger based on Arduino Mega.

Moreover, volumetric moisture content inside the PCM mortar was measured with EC-5 soil moisture sensors [25]. The sensors were calibrated specifically for measuring this PCM mortar, as the result of several small-scale experiments and formulas for calculating volumetric moisture content with temperature corrections [16].

2.4. Injecting Water into the Wall

As the climate chamber test is an accelerated version of real-life processes, real cracks were unlikely to develop during the test. Moreover, the overall facade plaster area was much smaller, and the construction process was carried out in a favourable environment. But it was still necessary to imitate water leakages through the cracks in the system as they tend to appear on real ETICS facades.

To imitate the critical leakages, water hoses were installed into the wall. It is most likely that the cracks on a real facade would appear on the corners, where PV panels and facade plaster are joined together. Therefore, the ends of the water hoses were installed to the upper corners, behind the PV panel and into the PCM mortar layer. Tubes were designed to make it possible to inject water into the wall using a common medical syringe (Figure 4b). PCM mortar moisture content was measured in the area immediately exposed

to the increased moisture content caused by the leakage (Figure 4a). Another sensor was further away. During the drying-out phase and WDR experiments, the injection tube ends were sealed with vapour-tight tape.

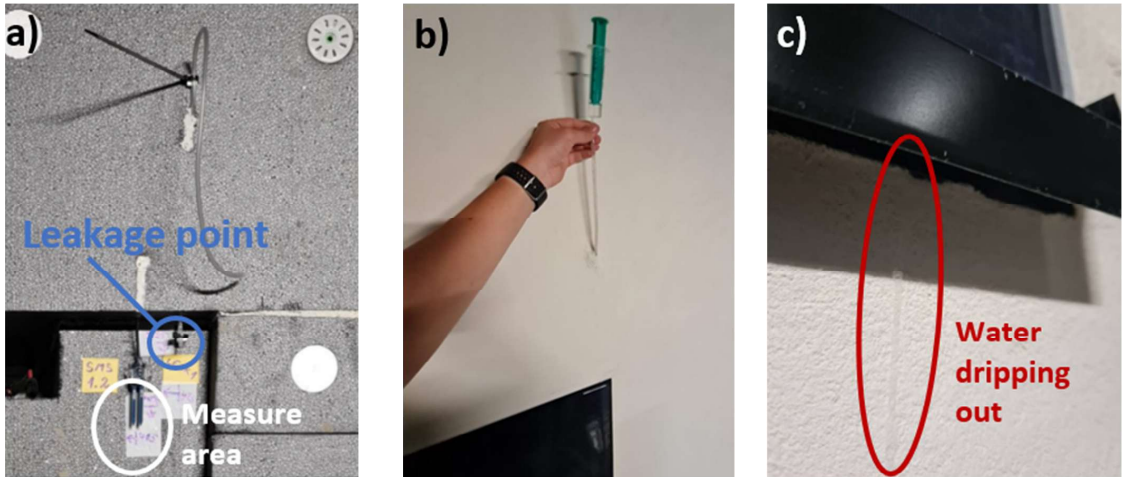


Figure 4. Water tubes for injecting water into the wall were installed before the application of PCM mortar (a); after finishing the facade system, water was injected behind the PV panel with a syringe (b); from sections with diffusion channels, water dripped out between bottom steel sheets (c).

The amount of water chosen to inject into the wall was chosen to be on the extreme side. It has been found out experimentally that through a 0.4×4 mm crack in the cement fibre board, it is possible for 18 mL/min of water to enter the wall when rain is forced into the wall with 150 Pa of air pressure difference and 12 mL/min in the case of no air pressure difference [26]. It takes into account the WDR entering directly into the crack, and also the water flowing down the surface of the facade and entering the crack on the way [26].

The water was injected into all three wall sections simultaneously, with quantities of 40 mL for one 5-min session. All three injection pipes were filled with 10 mL of water, as pipe volume was limited. After a minute, water was absorbed by the wall and the tube was filled again. One injection session consisted of 4 injections, 10 mL each, for each test wall section. 40 mL of water represents heavy rain for approximately 3 min through a typical 0.4×4 mm crack [26]. The next injection session was conducted after the moisture content sensor readings had been stabilised. The total amount of water injected into all of the wall sections was 220 mL over a period of 5 days.

2.5. Radiation Cycles with Solar Simulators

To simulate solar radiation in the climate chamber, three radiation modules were built, each containing eight tungsten halogen light bulbs, approximately 230 W each (see Figure 5). Halogen lights were fixed on the aluminium sheet to help to distribute the radiation more evenly on the wall surface and to remove excess heat from the bulbs. The distance to the wall was appropriately selected to achieve a radiation intensity of 500 W/m^2 , which corresponds to the peak solar radiation on a vertical surface during the summer in Estonia. The regularity of the radiation intensity was measured with a pyranometer at different points inside the illuminated area. In total, an area of 1.2 m height and 2.5 m width was illuminated with radiation of 500 W/m^2 with a deviation of less than 10%. For 3 modules, 24 halogen bulbs were used with a total nominal power of 5520 W.

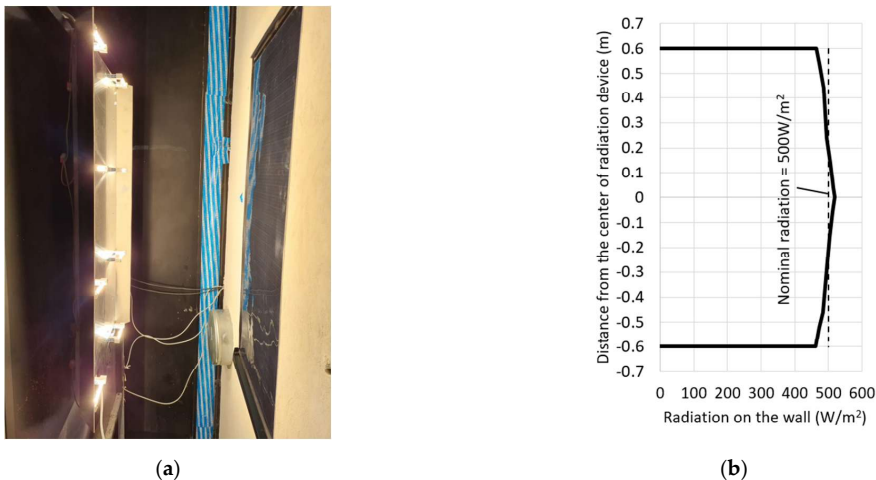


Figure 5. Solar radiation emulator, made of 8 Tungsten halogen lamps and an aluminum sheet (a). Three of these radiation stands were used, one for each wall section tested. Radiation intensity graph (b) for the radiation device at distance of 60 cm (right). Zipp Zonen CMP11 Pyranometer was used to calibrate the radiation devices.

Tungsten halogen bulbs were chosen as the radiation source because they give out high light intensity with relatively low cost and have near-sunlight spectral distribution [27]. Compared to sunlight, halogen radiation is a little weaker in the ultraviolet and stronger in the infrared range [28]. As the electrical output of PV panels was not the focus of the study, it can be stated that the thermal performances obtained under artificial and real environmental conditions were similar.

In total, 10 solar radiation cycles were performed to test the drying out of the leaked-in moisture. As an example, climate chamber temperature and RH for 2 of the cycles are shown in Figure 6. The temperature of the climate chamber was set to +20 °C, but the ventilator speed was limited to keep the air flow between the wall and the solar radiators within reasonable limits. There was stable vertical air flow at the wall of approximately 1.0 m/s.

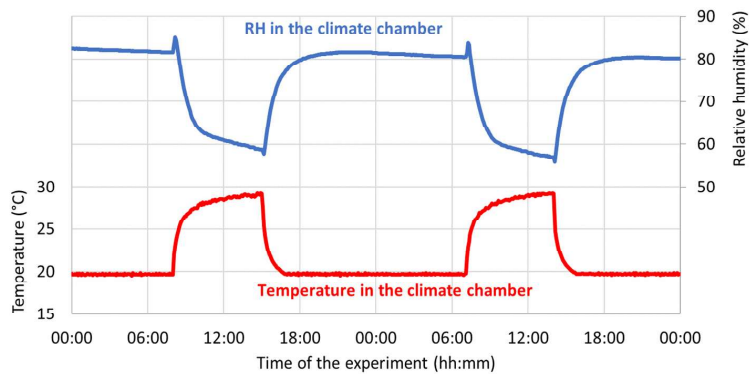


Figure 6. Temperature and RH inside the climate chamber during drying-out experiments. The increase in air temperature was due to the solar radiation simulators used to test the facade during 7 h cycles.

During the irradiation period, the air temperature close to the wall was measured at 29 °C, which simulates the air temperature on hot summer days in the Nordic climate. After approximately 7 h of stable radiation, the halogens were turned off and air in the chamber was mechanically cooled down to 20 °C, over approximately 1.5 h. Then it was kept stable during the following night for 17 h. Air flow was kept at the same level of 1.0 m/s during the whole experiment.

2.6. Wind-Driven Rain Experiment in Climate Chamber

For generating WDR load on the facade surface, water sprinkler stands were used. A method for calibrating exactly the same stands has been previously defined by Kotkas [29]. Three identical sprinkler stands were used, with 18 sprinklers in total. Each sprinkler was calibrated to spray water at 0.4 L/min. The distance between sprinklers and the wall was 55 cm and the amount of water reaching the wall was approximately 1.0 L/(min·m²).

The character of WDR-freeze cycles is described in Figure 7. The wall was sprinkled for 1 min and then there was a 9-min break for the water to absorb into the facade plaster. This cycle was repeated 36 times, resulting in 6 h of WDR. The external air temperature was stabilised at a level of 5 °C; however, as the tap water being used was warmer than 5 °C, it caused some temperature fluctuations in the climate chamber. During the experiment, the indoor climate was kept at +21 °C and 55% RH. External RH was not controlled, but rain cycles did raise it around 94% on average at +5 °C.

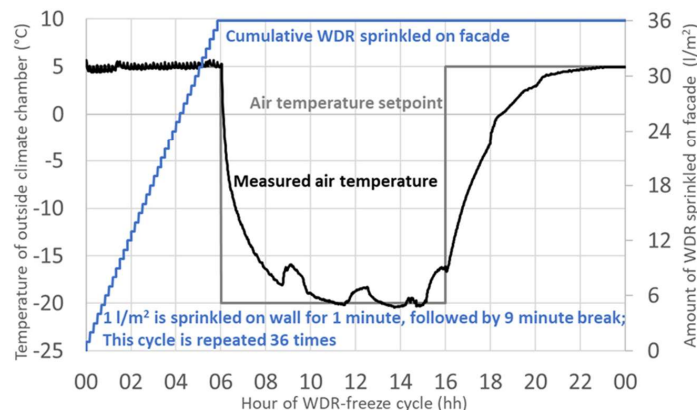


Figure 7. Characters of one WDR-freeze cycle. 6 h of WDR is followed by 10 h of extreme cold and 8 h of melting. This 24 h cycle was repeated 10 times.

After the 6 h rain period, a period of extreme cooling down to −20 °C followed (Figure 7). Cooling down the chamber was conducted as quickly as technically possible just after the sprinkler tubes were emptied. It resulted in a thin layer of ice emerging on the facade surface (Figure 8). After 10 h, the chamber was heated up to 5 °C. After 24 h, a rain period started again. This cycle was carried out 10 times.

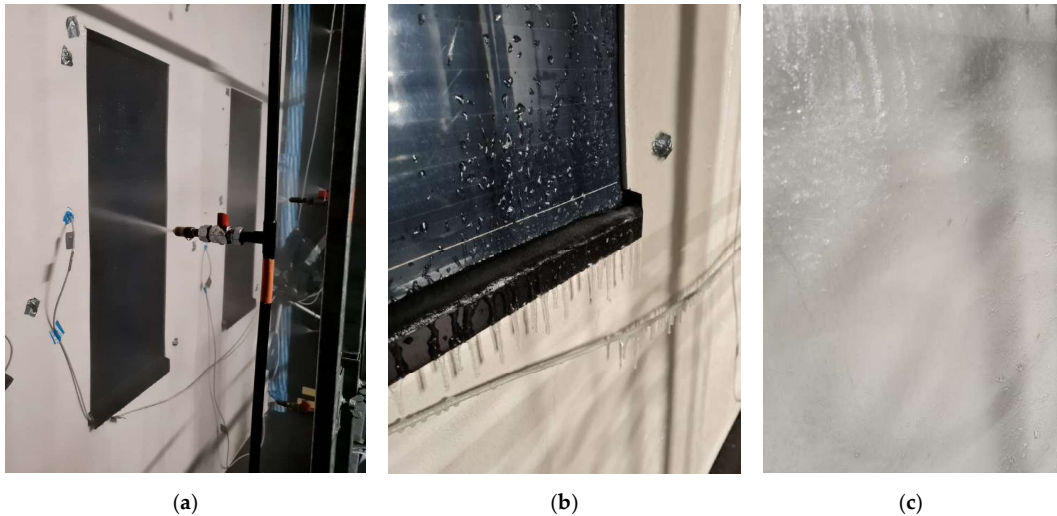


Figure 8. Sprinklers for imitating WDR in climate chamber (a). Frozen facade after rain period (b,c).

2.7. Hygrothermal Simulations

All the results from the climate chamber experiments and test building experiments were compared to results from hygrothermal modelling. Delphin 6 software was used to develop a model of an En-ActivETICS wall. Delphin 6 uses the finite volume method to simulate the heat and moisture flow inside construction materials. Mathematical equations used in hygrothermal simulations are given in detail in [30,31]. More information about Delphin 6 software and about numerical validation can be found in [32].

For modelling the WDR and freeze-thaw cycles, two different approaches were used: the ‘Kirchhoff potential for liquid flux calculation’ and the ‘equilibrium ice model’. The ‘equilibrium ice model’ takes into account the phase change effect of water, when the liquid water content inside the PCM mortar and facade plaster freezes. The ‘Kirchhoff potential for liquid flux calculation’ uses a function generated from the KI function to model the liquid water transport potential. Therefore, when a wet material freezes, calculations with Kirchhoff potential do not account for additional energy that is absorbed by the freezing of the water inside material pores, which leads to underestimation of the time needed for the freezing and melting processes. On the other hand, this effect is taken into account when the ‘equilibrium ice model’ is used to conduct calculations. Both calculation methods take into account the phase change effect of PCM itself, as this effect is written as a $u(T)$ function into the material file.

Material properties used in the modelling are given in Table 1. For autoclaved aerated concrete (AAC), adhesive mortar, EPS and mineral wool, materials from the Delphin database were used, with some minor changes according to local material manufacturers’ data sheets. The hygrothermal properties of the particular facade plaster system used in the experiment were previously measured at the Tallinn University of Technology [33]. Properties of the PCM composite mortar (made from PCM granules and cement filling) were measured both at Tallinn University of Technology and Lodz University of Technology [16].

Figure 9 shows a horizontal cross section of the 2D calculation model. The PV panel is modelled not as a material layer, but as a vapour-tight boundary condition. Diffusion channels behind the PV panel are modelled as 20 mm wide sections of boundary condition with equivalent vapour diffusion thickness $S_d = 0.5$ m, which considers the physical length of the channel as well as the micro-convection effect inside the channel.

Table 1. Material properties used in hygrothermal modelling.

	AAC	Adhesive Mortar	EPS Silver	Mineral Wool	PCM Mortar	Facade Plaster System	PV Panel
Absorption coefficient α , -	-	-	-	-	-	0.3	0.8
Bulk density ρ , kg/m ³	390	707	35	134	1150	1365	- ¹
Porosity θ , m ³ /m ³	0.87	0.733	0.935	0.92	0.5	0.42	-
Heat capacity c , J/(kg·K)	1081	945	1500	840	According to $u(T)$ function ²	1000	-
Thermal conductivity λ_{dry} , W/(m·K)	0.095	0.21	0.032	0.038	0.63	0.7	-
Water vapour diffusion resistance factor μ , -	7	25	30	1	154	100	-
Equivalent vapour diffusion thickness S_d , m	-	-	-	-	-	-	10,000
Water uptake coefficient $A_{w,}$ kg/(m ² ·s ^{0.5})	0.043	0.0376	1×10^{-5}	0	0.045	0.00345	-
Liquid water conductivity K_l , kg/(m·s·Pa)	6.026×10^{-10}	3.182×10^{-9}	0	0	4.1×10^{-11}	4.18×10^{-13}	-

¹ Most of the material properties of the PV panel are not defined, because the PV was modelled as a watertight boundary condition with high water vapour resistance. ² PCM heat capacity is described as a function for every temperature; however, outside the phase change region, the heat capacity for dry material is 1500 J/kgK. PCM mortar is a mixture of RT25HC (6% by mass; nominal melting temperature, 25 °C), RT28HC (6%; 28 °C), RT35HC (6%; 35 °C) [34], aluminium powder (24%) and cement based mortar (58%). More information about the thermal properties of the PCM mortar can be found in [14].

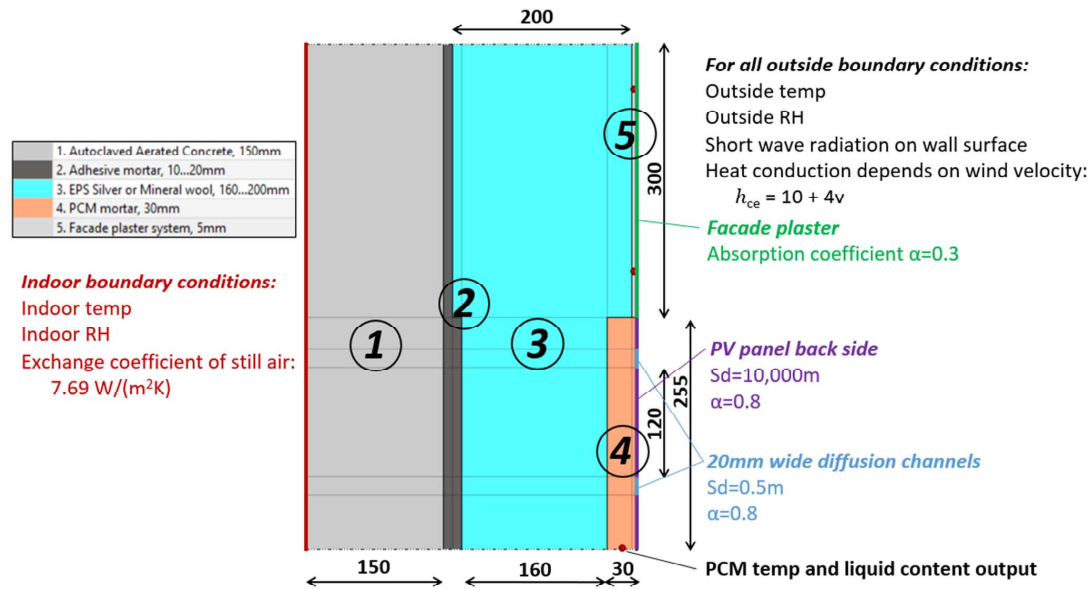


Figure 9. Two-dimensional calculation model in Delphin 6. Horizontal cross-section representing the wall section with diffusion channels. Numbers in the figure reference to the modelled materials, shown in the table left from the main figure. In case of calculation without the diffusion channels, corresponding boundary condition (blue) was replaced by PV panel boundary condition (purple).

Boundary conditions used for indoor and outdoor climates are also described in Figure 8. During all experiments, the indoor and outdoor temperature and RH were measured with sensors. Solar radiation was measured with a pyranometer (total radiation for wall surface in the case of the climate chamber and only diffuse radiation for the real facade, because the wall was behind scaffolding coverings). Before WDR experiments, the amount of water reaching the facade surface in one minute was measured according to guidelines by [29] and the data were used as a boundary condition in the calculation model.

Preliminary model validation, mainly concerning the PCM mortar moisture content, has been conducted previously and is described in detail in [16]. All the experiments described in the current study were simulated, using measured indoor and outdoor conditions as boundary condition inputs, to further validate the outputs of the calculation model.

3. Results

3.1. Impact of Diffusion Channels to Work as Drainage Channels

Despite injecting equal amounts of water into the PCM mortar layer for each wall section (Figure 4), it turned out to be impossible to increase the moisture content of PCM mortar above $0.11 \text{ m}^3/\text{m}^3$ in the example with diffusion channels (Figure 10). The reason for this was that, after the second injection, water was starting to drip out from the PCM mortar between two steel sheets that were installed below the PCM mortar (Figure 4c). The first drops of water were visible below the PV panels after approximately 40 mL of water had been injected in the EPS example and 60 mL in the mineral wool example.

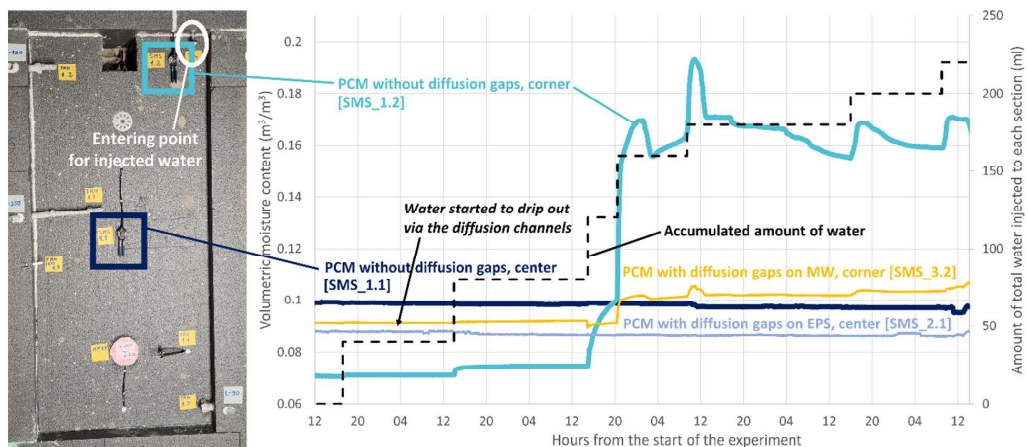


Figure 10. Moisture content of PCM mortar during water leakage simulation into the wall by injection.

In the case of the wall section without diffusion channels, all the water stayed inside the wall, and it was possible to increase the moisture content of the PCM mortar, short-term and locally, up to $0.195 \text{ m}^3/\text{m}^3$, but over the long term, it stabilised around the $0.16 \text{ m}^3/\text{m}^3$ level, as localised high moisture content spread around the leak source. However, even after 2 weeks, the moisture content registered by the soil moisture sensor in centre of the wall without diffusion channels did not change significantly, signifying that most of the 220 mL of water was absorbed locally into the PCM mortar and it takes time for the moisture levels to stabilise.

In the case of the two specimens with diffusion channels, most of the water injected into the wall found its way out via the channels. Therefore, they do act as a drainage channels as well. However, based on just two leakage tube locations, it cannot be stated that it is always 100% guaranteed that water will find its way to the diffusion channel after penetrating into the wall.

3.2. Drying out of PCM Mortar with Controlled Radiation Cycles in Climate Chamber

Twenty-four hours after the water injection experiment, a controlled solar radiation experiment (Figure 5) was started in the climate chamber.

It can be seen from Figure 11 that the drying out of moisture in PCM mortar without the diffusion channels was significantly slower. This is also backed up by the calculation model results. The worst-case scenario (without diffusion channels, and high initial moisture content from the water leakage) showed very small changes of dampness, and the high moisture level even short-circuited the soil moisture sensor used. Overall, the modelled results show that 10 cycles do not reduce the moisture level below $0.148 \text{ m}^3/\text{m}^3$.

Besides modelling the measured cases, one hypothetical and more extreme case was modelled and analysed. This simulated the possibility that larger quantities of water could be injected into the wall section with diffusion channels and that the water would not drain out of the wall through the diffusion channels. Results (Figure 11, dashed black line) show that diffusion channels help the excess moisture to dry out during the summer period faster than without diffusion channels.

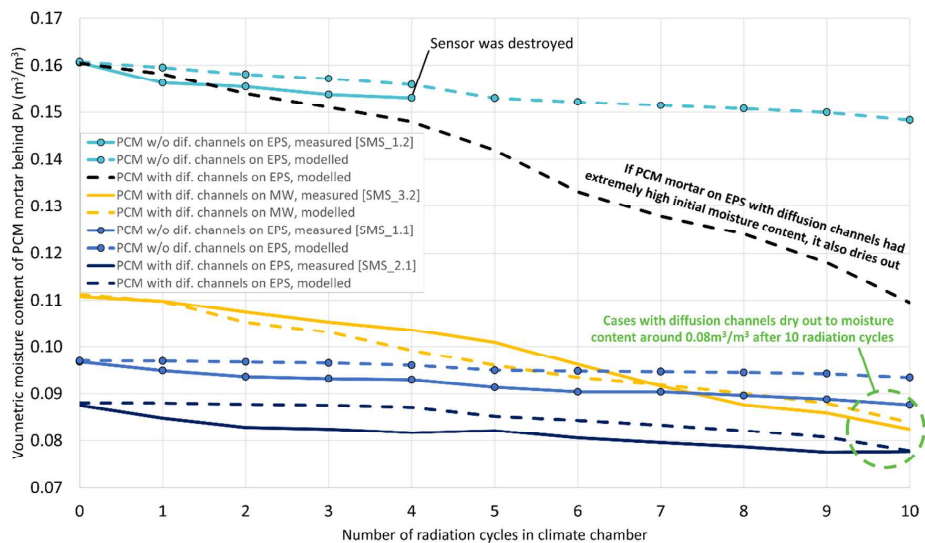


Figure 11. Drying out process of PCM mortar with solar radiation cycles in climate chamber. Measured moisture content is compared to modelled moisture contents of the PCM mortar with and without (*w/o*) diffusion channels behind vapour-tight PV panel.

Overall, diffusion channels with a cross section of 400 mm^2 spaced at every 130 mm do add additional moisture safety against water accumulation, and if a certain amount of water is still absorbed by the PCM mortar, it dries out much more easily during the summer period than without diffusion channels. Therefore, it can be assured that the moisture content will not build up over subsequent years.

Without diffusion channels, in cases where multiple PV panels are applied on the facade side-by-side, the situation becomes worse as the ratio between PV perimeter length and PV area becomes smaller. If diffusion channels are used, hygrothermal performance does not deteriorate if multiple PV panels are applied side-by-side as long as the height of the PV panel (and the height of the diffusion channel) does not change.

3.3. Initial Moisture Content and Drying out of PCM Mortar on Test Building Facade

Besides the climate chamber test, one test wall was built on the southern facade of the test facility and tested under real outdoor climate conditions (see Figure 3). AAC masonry

was built in late April and insulation was applied within early May 2022. PCM mortar was applied in the middle of May and the facade was left to dry out under white scaffolding coverings, protected from direct sunlight and rain. Two weeks of drying out time has been proven to be enough, according to previous research [16]. During the dry-out period, the real walls tended to dry out faster than model predicts (Figure 12). This could be related to some inaccuracies in the liquid water conductivity function of the novel PCM mortar material. However, in the hygroscopic region, which is more relevant during the service life for the facade, the modelling accuracy is higher. After the dry-out period, a PV panel was glued to the PCM mortar, and facade plaster was applied to the rest of the test facade.

It can be seen from Figure 12 that despite the warm and sunny summer months of June and July, after covering the PCM mortar with the PV panel, the volumetric moisture content decreases slowly for one month. It can be seen that the drying process of PCM mortar, after covering with PV, is faster in the immediate region of the diffusion channel (corner point), than between two channels (middle point).

There is an unexpected increase in moisture content after application of the PV panel on the corner sensor (solid light blue line in Figure 12), which is significantly higher than the modelled moisture content representing the same measuring spot (dashed blue line). This could be explained by the non-homogeneous moisture load from the PV panel glue and by the micro-convection processes inside the diffusion channels. As there was warm weather after the application of the PV panel, moisture from glue mortar could have been travelling upwards via the diffusion channel with warm air. Because of its complexity, micro-convection inside the diffusion channels was not modelled.

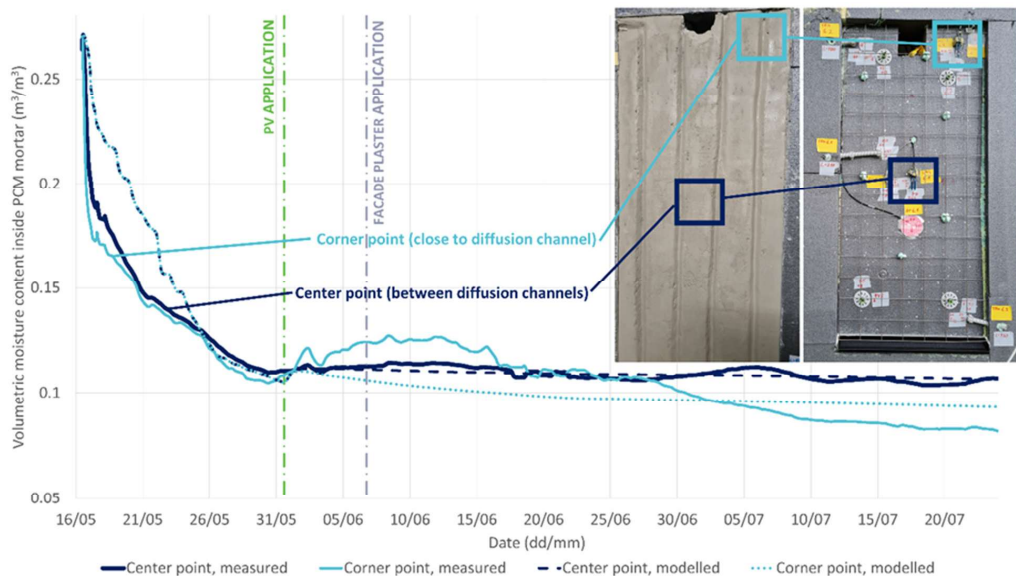


Figure 12. Drying out of PCM mortar under real conditions on southern facade in Tallinn, Estonia during summer. Locations of soil moisture sensors are highlighted on the photos before and after application of PCM mortar with diffusion channels. Comparison with calculation model results is shown with dashed lines.

3.4. Solar Radiation Experiment in Climate Chamber and Test Building

Solar radiation cycles in the case of the real wall were imitated in the climate chamber, but in a more controlled manner. In the climate chamber, there was constant irradiation for 7 h. Therefore, it made the hygrothermal performance of the wall easier to model. Overall, the temperatures of the PV panel, PCM mortar and facade plaster in the climate chamber

and under real conditions during some warmer days were relatively similar (Figure 13). However, because of the controlled environment, the examples in the climate chamber are much more stable and give a higher correlation when compared to modelled results. It should be noted that peak temperatures are dependent on wind velocity—in the climate chamber this was a constant 1.0 m/s, but under real-world conditions, it varied.

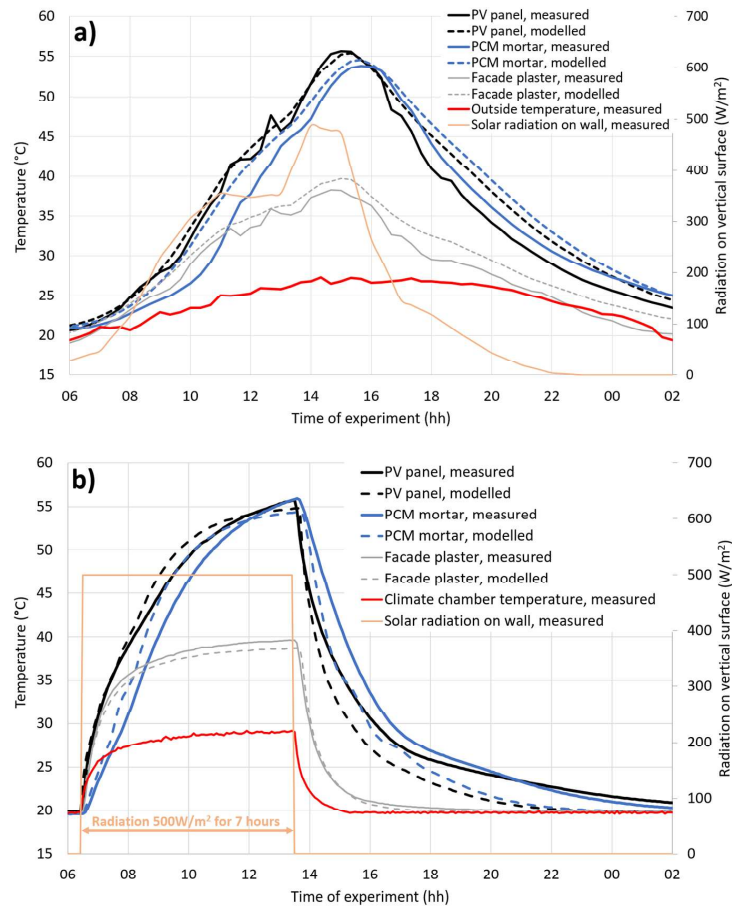


Figure 13. Temperature dynamics of energy activated facade, measured under real conditions on 30 June 2022 (a) and in climate chamber under simulated conditions (b).

There are noticeable differences between the modelled and measured temperatures in Figure 13. Although the maximum values are similar, there are differences in the heating up and cooling down speeds, especially under real climate conditions, which had much more unstable outside boundary conditions. However, if the results from the climate chamber are compared with those from the calculation model, it is visible that the real PCM mortar is heating up and cooling down slower than the modelled material. This could be most likely because of some inaccuracies of modelling heat capacity of relatively wet PCM mortar, but also because of some inhomogeneity in the mixture of PCM granules and mortar. Some differences could also be due to limitation of the Delphin model, being able to only use one average latent heat ($u(T)$) function for both the solidifying and melting processes, despite these processes being slightly different in the case of real material.

Differences in the facade plaster system temperatures are less significant, and, in the case of real wall, they are probably caused by some inaccuracies in modelling the wind effect and calculating the heat conduction of the surface. Differences in PV temperatures are probably a combination of differences in PCM mortar temperatures and inaccurate boundary conditions.

However, considering the prolonged nature of hygrothermal processes behind PV panels, the moisture content outputs are not so dependent on short-term inaccuracies of thermal modelling. Having a calculation model slightly underestimating the PCM effect could compensate the potential PCM capacity decrease over time [10].

3.5. Extreme Wind-Driven Rain and Freeze-Thaw Cycles in Climate Chamber

As expected, the temperature of the facade plaster changed much faster during cooling cycles than the temperature of the PCM mortar (Figure 14). It appeared that, during freezing cycles, there was a difference whether the ‘Kirchhoff potential for liquid flux calculation’ or the ‘equilibrium ice model’ was used in Delphin. The ice model does take into account the phase change effect when liquid water content inside the PCM mortar and facade plaster freezes. Using the ice model gives better correlation with measured results in the case of PCM mortar. However, as there is very little liquid water inside facade plaster, plaster temperatures are more accurate with the Kirchhoff model.

It should be noted that the difference between measured facade plaster temperatures and modelled ones during the WDR phase is caused by the fact that the tap water used in the experiment was slightly warmer than the air temperature (5 °C) in the chamber.

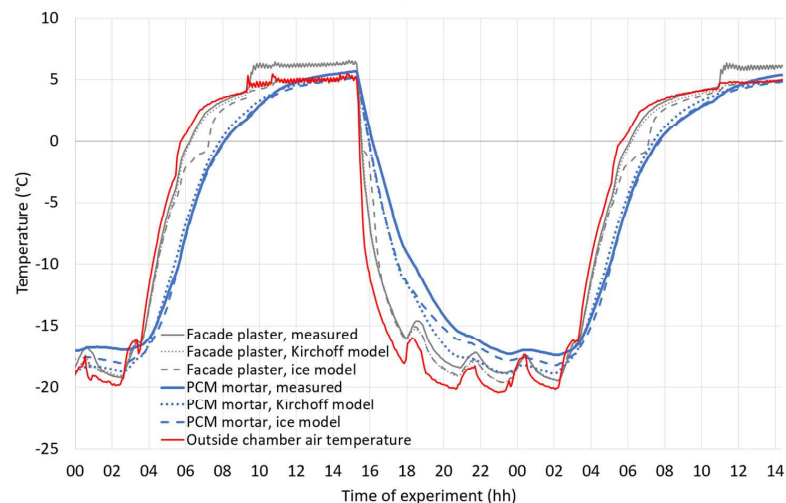


Figure 14. Facade plaster and PCM mortar temperatures measured in experiments and modelled with two different methods.

Besides temperature, the moisture content of the PCM mortar was measured with a soil moisture sensor during the WDR-freeze experiment. Overall, the moisture content of PCM mortar does not change significantly after 10 WDR-freezing cycles. At the beginning of the experiment, it was $0.078 \text{ m}^3/\text{m}^3$ for EPS and $0.075 \text{ m}^3/\text{m}^3$ for MW. After 10 cycles, volumetric moisture content was $0.076 \text{ m}^3/\text{m}^3$ for EPS and $0.080 \text{ m}^3/\text{m}^3$ for MW. Both test walls had diffusion channels.

Near-constant volumetric moisture content of PCM mortar during WDR-freeze cycles was also supported by modelled data. The main reason is that there were no cracks in the test facade and rainwater did not leak inside. Indoor excess moisture was not able

to increase the moisture content of the PCM mortar significantly because there were also diffusion channels that decreased the moisture content of the PCM mortar at the same time.

After the experiment, the facade was observed for cracks visually from a distance of 30 cm with light intensity of 13,000 lux perpendicular to the wall. No visible cracks appeared after 10 extreme WDR and freezing cycles. Also, none of the PV panels were damaged during the experiment and they were able to produce the same amount of electricity.

4. Discussion

Overall, the facade system survived the series of tests without showing any signs of deterioration. The method for measuring liquid moisture content with specifically calibrated soil moisture sensors proved to be appropriate. Although, only one sensor survived all the experiments in the harsh, humid environment, so the correlation with modelled results could have deviations.

High WDR loads did not increase the moisture content behind the PV panel. This signifies that in the case of a relatively small surface area of the wall, under correct application conditions, and with good workmanship, the probability of cracks appearing is relatively low. Without cracks, the energy-activated ETICS is watertight even under extreme WDR loads. There is much further work to be done to find out what would be the maximum size of the PV ETICS facade elements before cracks start to appear under different climate conditions.

Earlier studies [17–19] have proven that, sooner or later, cracks do appear and water penetrates the facade surface. Therefore, liquid water was injected directly into the wall to imitate leakages. It was the only way to significantly increase the PCM mortar's moisture content. This study showed that water injected into the wall with diffusion channels managed to escape through the double sheet steel joint below the PV panel. However, this might not be the case for every leakage location, as there were only two places where leaks were simulated. This is another topic where further studies are needed.

The study showed relatively good correlation between the experimental results and the calculated results from the Delphin 6 model. An accurate model makes it possible to conduct calculations for different climate conditions and with various loads and to therefore identify which climates are suitable for En-ActivETICS facades. Thorough hygrothermal calculations should be conducted in the future to assess the performance of the façade in other climates with the calculation model. More test facades should be built to different climate zones and to different buildings (for example, upper corners of the facades of high-rise buildings) to compare the calculated performance with actual performance. Critical climate zones for building the system could be selected via hygrothermal modelling.

Drainage channels with a cross section of 400 mm² spaced at every 130 mm are highly recommended for every climate, as the risk of cracks appearing near the joints is high. Regardless of location, craftsmanship errors and misapplication of construction technology can happen. If cracks have appeared, water leakage would increase the moisture content of PCM mortar behind the vapour-tight PV as it was simulated in the experiments. Results from drying-out experiments with solar radiation show that even if cracks do appear, the diffusion channels work as a secondary layer of protection.

Moreover, if diffusion channels are used, it makes it possible to apply multiple PV panels side-by-side, as excess moisture exits the wall through channels, not just through the surrounding facade plaster. This will make it possible to apply more PV panels on the facade and would lead to higher electricity production.

One limitation of the study was the relatively short time it took to perform the experiments. The extreme climate experiments were conducted during tens of climate cycles, but the results are not entirely extendable for the lifetime of the real facade system. The aging effect of the materials did not have an influence on the results because of the relatively short amount of time.

Despite the relative success of the experiments described in this study, the technology is still in development. Much more research should be conducted before manufacturing on the industrial scale can be started. Long-term hygrothermal studies should be conducted in real environments in different climate zones in the future. Possibilities to make the construction process of the wall system more effective via pre-fabrication should also be studied. Moreover, the economic aspects and carbon footprint of the system should be analyzed.

5. Conclusions

Creating a facade solution having a vapour-tight barrier as the outermost layer of the facade could result in high levels of moisture content inside the wall, especially if rainwater leaks inside the wall. This study proved that adding an extra layer of safety to the wall with diffusion channels helps the moisture to dry out much faster. Moreover, it was proven with water injection tests that diffusion channels also work as drainage channels. It is also significant that when vertical channels are used, applying PV panels side by side does not inhibit moisture performance as the PCM does not need to dry out only through the facade plaster. It makes the facade solution much more efficient, as there would be fewer PV-facade plaster joints to build on site for each PV panel installed. Overall, the diffusion channels are recommended to ensure the hygrothermal performance of the facade system.

This research resulted in a calibrated Delphin 6 model. Modelled results were calculated for each of the experiments to check the validation accuracy. A validated calculation model makes it possible to conduct long-term hygrothermal performance analyses for different climates in the future.

Overall, the En-ActivETICS facade system seems to be resistant to harsh wind-driven rain and freeze-thaw cycles. No cracks or physical deterioration appeared after 10 accelerated cycles. Facade plaster and PV panels were still fixed well on the thermal insulation and PCM mortar, and there was no immediate sign of frost damage. However, the overall durability still needs to be studied on the test wall under real climate conditions for several years. Before industrial application, several test facades with real building dimensions should also be tested in different climate zones.

It was found that in the case of test walls with diffusion channels, it was not possible experimentally to increase the moisture content of the PCM mortar higher than $0.11 \text{ m}^3/\text{m}^3$. Excess water drained out via the channels. Without diffusion channels, the moisture content in PCM mortar increased slightly because of the combined effects of indoor moisture load as well as injected water. Moisture content reached as high as $0.18 \text{ m}^3/\text{m}^3$. Both experiments and hygrothermal modelling showed that high moisture content (caused by water leakage) in walls with diffusion channels dried out to $0.08 \text{ m}^3/\text{m}^3$ in 10 days of high solar radiation, while it would take at least twice as much without the channels. Therefore, this facade system should be recommended to develop further only if diffusion channels are required.

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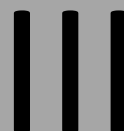
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Appendix 3

Publication III

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Abstract

This study assesses the hygrothermal performance of the Photovoltaic External Thermal Insulation Composite System (PV ETICS), using a thick layer of mortar with Phase Change Material (PCM) granules as a passive heat sink. The experimental scenario involved the wall system exposure to real outdoor climate conditions during a 20-month long measurement period. Measured data were compared with results from the hygrothermal modelling. The findings reveal that with carefully designed diffusion channels the PV ETICS demonstrated no accumulation of moisture behind the vapour-tight PV panel. Long term hygrothermal modelling for PCM mortar moisture content with a previously calibrated model predicted stable moisture content around $0.03 \text{ m}^3/\text{m}^3$, significantly lower than the moisture content during first 2 years. Relative humidity behind the PV panel falls into the hygroscopic range on the second spring after the construction. The annual maximum temperatures for PCM mortar during two summers were 69°C , occurring in mid-August. Risk analysis was conducted with historic climate data to understand, whether higher PCM temperatures could be reached in the same climate for different years. Overall, the wall system showed no signs of extensive moisture damage during the testing period, but slight discolouring of the PCM mortar was recorded. This study contributes valuable insights into the practical viability of PV ETICS with PCM mortar, reaffirming its potential for application on larger scale on real building facades.

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Keywords

External thermal insulation composite system, photovoltaic, phase change material, deterioration, moisture damage, hygrothermal measurement and modelling, soil-moisture sensors

Introduction

To mitigate global carbon emissions, there has been a significant surge in electricity production from renewable sources. The energy performance of buildings directive (EPBD (recast), 2021) requires that for future zero-emission buildings, their very low energy demand will be fully covered by energy from renewable sources that are generated on-site or nearby. According to estimates provided by (Defaix et al., 2012), building-integrated photovoltaic (BIPV) systems in 27 EU member states possess a technical potential of 951 GW and could produce 840 TWh of electricity. This amount equals 22% of the EU's total electricity consumption projected for 2030. The study finds that 20% of south-facing facade areas were suitable for BIPV installation. For example, in Germany, residential buildings accounted for 67% of the total facade surface potential, far outnumbering non-residential potential (Defaix et al., 2012).

More than 25% of the global energy demand (Nejat et al., 2015) and 28% of the final energy demand of households in the EU (European Commission, Eurostat, 2020) is attributed to residential buildings. For multi-storey apartment buildings, the available roof area might not be sufficient to accommodate an adequate amount of photovoltaic (PV) capacity, necessitating the wider use of facade systems. It has also been described by (Díez-Mediavilla et al., 2019), how the facade PV diversifies the locally generated solar energy mix by producing high outputs during different months and hours compared to rooftop PV.

Typical BIPV facade applications available on the market have a ventilated air cavity. The air gap behind the PV influences electricity generation efficiency and contributes positively to hygrothermal performance of the whole wall system. A study conducted in Hong Kong determined that the optimal thickness of the air gap for PV facades in terms of thermal performance is 6 cm and maximum PV temperatures exceeding 65°C for ventilated facade occur in October (Peng et al., 2013). Further decrease in peak PV temperatures would be possible to achieve with force ventilated PV facades. For example, in India, mathematical correlations were recently developed to calculate the overall energy performance for semi-transparent PV facades with ventilated air-cavities ranging from 5 to 25 cm (Preet et al., 2024). However, in colder climates, less complicated passive cooling solutions could be more reasonable.

Durability of ETICS facades

It is crucial to not only incorporate PV technology into the facades but also ensure adequate thermal insulation and hygrothermal performance. The thermal

transmittance of external walls for near-zero Energy Buildings (nZEB) varies between 5% and 50% of total energy loss depending on climate and member state regulation (Kalamees et al., 2016).

One widely used solution for facade insulation is the External Thermal Insulation Composite System (ETICS; Xu et al., 2023). In Europe, the market size for ETICS in 2017 was approximately 234 million m²/year (IPN, 2017). Compared to ventilated facades, ETICS is a more affordable option due to its reduced number of layers (IPN, 2017) and reduced mass. In comparison to a ventilated facade, the ETICS facade has a lower carbon footprint value in the material production and installation phase, although it increases significantly when system maintenance and lifespan are considered (Baptista et al., 2024; Kertsmik et al., 2023).

The lifespan of ETICS tends to be shorter than that of ventilated facades due to the higher risk of moisture-related damage. Unlike ventilated facades, ETICS relies solely on the facade plaster system for protection against climate loads. Inadequate workmanship can lead to various defects in each layer of the ETICS system, resulting in a loss of technical performance (Sulakatko et al., 2017). Using artificial neural networks, a study conducted in Portugal estimated the average service life of ETICS to be 21 years (Tavares et al., 2020). But climate loads and deterioration risk tend to be higher in cold climate. A thorough study in Estonia found that most defects, identified through visual inspections, tend to appear within 1–6 years and are mainly caused by high moisture and temperature loads, design flaws and application errors (Liisma et al., 2016).

PV temperature control with PCM

According to the definition, the ETICS system does not include a ventilation cavity. Therefore, it would be impractical to introduce a full ventilation cavity behind the PV panel. Consequently, an alternative solution must be employed to mitigate the overheating of the PV panels. One potential option to address this issue is the utilization of phase change materials (PCMs). In previous studies, using cement-based mortars containing encapsulated 11 wt% of PCM granules has led to energy savings of up to 33% for heating and 31% for cooling in hot-dry climates (Gbekou et al., 2024). By adding PCM to ETICS that contains BIPV we get an advanced building envelope solution – energy activated ETICS (En-ActivETICS; Heim et al., 2020) where the risk of surface overheating is lower (Heim et al., 2021).

For En-ActivETICS a PCM mortar was developed with pure PCM mass content of 20 wt%, consisting of a combination of three different PCM materials (RT25HC, RT28HC and RT35HC). These three PCMs were chosen based on comprehensive thermal modelling for various central and northern European climates and was considered the optimal combination (Heim et al., 2023b). The chosen approach involves the passive use of microencapsulated PCM granules mixed with cement-based mortar. This method eliminates the need to transfer the PCM from the facade to the indoor space, reducing the number of components that need to be moved and potentially minimizing the risk of leaks. Additionally, this approach

offers a cost-effective solution. By encapsulating PCM wax inside small granules and incorporating them into the mortar, the quantity of pure PCM required is reduced, also limiting the use of materials with significant environmental impacts such as aluminium cases for PCM. Furthermore, in addition to the latent heat of the PCM, the thermal mass of the cementitious mortar is utilized.

Previous theoretical studies on the PV-PCM facade system have utilized calculations to demonstrate that the facade with a 30mm PCM mortar mitigates extreme temperature peaks ≈ 10 K and results in a $\approx 2\%$ higher electricity production compared to the reference case without PCM (Talvik et al., 2021). Conversely, if PCM mortar were not employed behind the PV panel, temperatures would rise as high as 83°C in Tallinn and 91°C in Madrid (Talvik et al., 2021), in the latter case, surpassing the recommended operating temperature limit of 85°C (Hasan et al., 2015).

It is important to acknowledge that the temperature limit applies to the physical and material constraints of PV panels; thus, even PV panels that are not actively generating electricity should not exceed this threshold. To ensure a safety margin during experiments only with electricity-producing PV panels, the operating temperature threshold should be increased by a few degrees.

Experimental studies have previously been conducted in Poland on the same system under real climate conditions. These studies found that the maximum temperatures of the PV panels reached 63°C in August (Heim et al., 2023a). It was also revealed that without the PCM mortar behind the PV panels, the temperature would have been 74°C and with black-coloured facade plaster, the observed temperature reached 75°C . However, this PV-ETICS facade system has never been tested before in colder climates, and its hygrothermal behaviour has not been monitored.

Strategies to avoid moisture accumulation behind vapour tight PV

PV panel makes En-ActivETICS exterior surface vapour-tight (Ilomets et al., 2020), which can lead to moisture accumulation inside the thick PCM mortar layer and could result in moisture or frost damage and is not a suitable solution for cold climate areas. In this concept, there are two potential mechanisms to prevent excess moisture from diffusing into the facade and accumulating: either reducing the area covered by the PV panels to allow the moisture to dry out through the traditional facade plaster surface or creating an additional pathway for the moisture to be drained out. Previous research based on hygrothermal modelling also indicates that there is a risk of moisture accumulation in all five analysed locations if diffusion channels are not introduced (Heim et al., 2023b). Therefore, a solution without diffusion channels cannot be recommended for implementation. Taking this into consideration, this research focusses only on one cross section with diffusion channels.

Another critical factor in determining the durability of an ETICS facade is the potential for water leakage through cracks. ETICS systems are designed to function effectively only if there are no water leakages through the facade plaster

system. However, facade cracking is relatively common due to various imperfections during the application (Sulakatko et al., 2017), and water leakages tend to result in the widening of cracks and the acceleration of the deterioration process. In the case of En-ActivETICS, the cracks could also be caused by the different deformations between the facade plaster and the PV panel. Through larger cracks, water could spread inside the insulation layer between the rigid insulation boards and within the partial cavity between the insulation and structural layer. It is important to consider the lateral spreading of water inside the cavity and the surface texture of the materials on the boundaries of the cavity (Van Linden et al., 2022). Due to the complexity of the water spreading processes, the most efficient solution is to drain the water near the outermost layer of the facade installation.

The risks associated with water leakages and high initial moisture content becomes even more critical if the facade surface is partially covered with a vapour-tight PV panel instead of a facade plaster system, which has relatively low water vapour diffusion resistance. A cross-section without diffusion channels behind the PV panel has also been previously tested in a climate chamber and performed relatively well until water leakage was introduced (Talvik, Ilomets, et al., 2023). Therefore, the diffusion channels must be incorporated behind the PV panel. These channels have been tested in a climate chamber under extreme conditions and were found to be sufficient for accelerating the drying out process of the PCM mortar behind the PV panel, both on expanded polystyrene (EPS) and mineral wool (MW) insulations. Furthermore, any water that may leak inside the wall system can drip out through these channels.

The aims of this study were the following:

- (1) To determine the maximum temperatures of PV panels and PCM mortar in Estonia's cold climate (humid continental, warm summer), ensuring the durability limits of PV panels are not exceeded;
- (2) To demonstrate the absence of moisture accumulation in PCM mortar with diffusion channels through hygrothermal measurements and modelling;
- (3) To evaluate durability of the thick PCM mortar behind the PV panels after being exposed to cold climate conditions.

Methods

Test wall installation

Test wall installation, combining a traditional ETICS facade with a novel PV panel and PCM mortar section, was built as a southern facade of the Tallinn University of Technology test facility between May and June 2021. Installation is the same En-ActivETICS facade system, that had been previously tested in climate chamber for hygrothermal performance (Talvik, Ilomets, et al., 2023) and in the climate of Poland for thermal performance (Heim et al., 2023a). The facade system utilizes vertical diffusion channels embedded within PCM mortar to manage excess

moisture behind vapour-tight PV panels. A PCM mortar section behind the PV panel has four triangular diffusion channels with a cross-sectional area of 400 mm² and spaced 120 mm apart. These channels are open at the bottom, allowing condensate to drip onto a sloped steel sheet beneath the PCM mortar, which then directs the water out of the wall system. A second steel sheet, attached to the back of the PV panel, extends vertically to protect the diffusion channels from wind-driven rain. The channels are sealed at the top, thereby limiting airflow to micro-convection. PCM mortar is anchored on the structural layer, and steel wire mesh is used to reinforce the thick mortar. There was a 2-week period in May 2021 for the PCM mortar to dry out before the application of the PV panel. Afterwards, traditional facade plaster was applied on the EPS insulation around the PV panel. Additional information about the construction process and initial dry-out process of the facade system could be found in (Talvik et al., 2022).

To make it possible to replace the PV panels, a solution was developed with steel sheet ribbons glued on the back side of the PV panel. The starting profile of the facade plaster is fixed on the steel ribbon instead of the PV panel itself, which makes it possible to replace PV panels without the need to repair the facade plaster system. Deformation profiles were installed along the boundary between the PV panel and facade plaster to mitigate the deformations caused by the joining of materials with different surface temperatures.

The load-bearing layer of the test wall was made of 150 mm of autoclaved aerated concrete (AAC). All of the facade was insulated with EPS ($\lambda = 0.032 \text{ W/(m K)}$, $\mu = 30$), 160 mm for the PCM mortar and PV area and 200 mm for the traditional ETICS area (Figure 1). Inside the PCM mortar, the granules were chosen to be the combination of three different PCM waxes with nominal melting temperatures of 25°C, 28°C and 35°C.

Sensors inside the test wall

Inside the wall, different sensors were installed between the AAC structure and the insulation, inside the PCM mortar and behind the facade plaster to measure the temperature, relative humidity (RH), volumetric moisture content and heat flux inside the test walls (Figure 1). To measure the temperature within the PCM mortar and on boundary between the structural layer and the insulation, Onset Hobo TMC15-HD was used with data logger UX120-006M. To measure temperature just behind the PV panel, small Littelfuse KS103J2 NTC thermistors were used with the Grant Squirrel SQ2020 1F8 data logger. The RH and temperature inside the PCM mortar and behind the facade plaster were measured with a Sensirion SHT35 and custom-made logger based on Arduino Mega. These SHT35 sensors were installed 2 weeks after the construction was completed, to minimize the risk of very high initial moisture content damaging the sensors. To do that, measurement tubes were pre-installed into the wall during the construction process of the wall. This method also made it possible to replace the sensors during the measurement period if necessary. As the PV panel and PCM mortar temperatures were

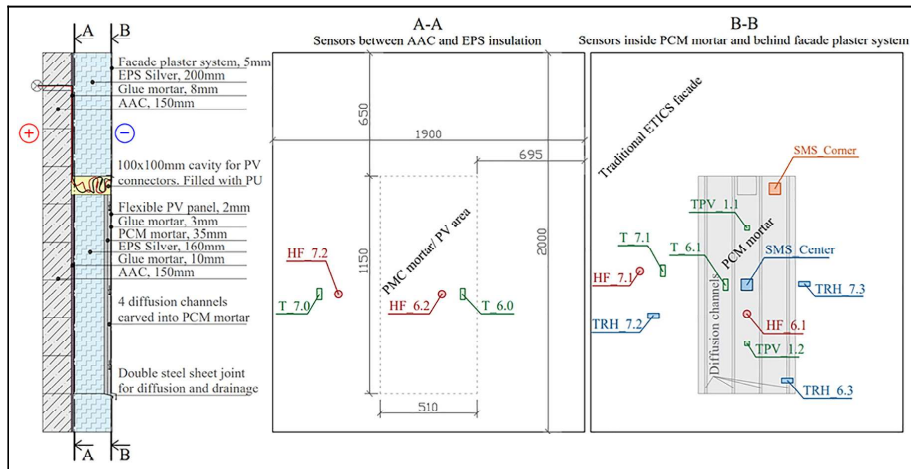


Figure 1. Cross section of the test wall and two sections with sensors.

HF: Heat flux sensor (Hukseflux HFP01); T: temperature sensor (Onset Hobo TMC15-HD); TRH:—Temperature and RH sensor (Sensirion SHT35); SMS: soil moisture sensor (EC-5); TPV: small temperature sensor (Littelfuse KS103J2 NTC thermistor) attached to back side of PV.

measured at similar locations with different sensors, there was always a backup sensor available in case one of the sensors was not logging due to technical errors.

To assess the crack resistance of the ETICS facade near PV panel area, temperature and relative humidity of the facade plaster was measured at 4 cm (TRH_7.3) and 25 cm (TRH_7.2) from the PV + PCM wall section (Figure 1).

Temperature and RH sensors were calibrated before and after the experiment. The largest drift after the 20-month experiment occurred with the sensor, installed inside the PCM mortar, resulting in an average of + 8% increase in RH readings. Sensors inside the facade plaster had less than a + 4% increase in readings after the experiment. In the following analysis, the errors are considered.

Volumetric moisture content inside the PCM mortar was measured with EC-5 soil moisture sensors. The sensors were calibrated to measure this specific PCM mortar. More about the calibration process and formulas for calculating volumetric moisture content and temperature corrections could be found in (Talvik et al., 2022).

The PV panel was producing electricity all the time, which represents the common conditions during the service life of the facade system. Electricity was converted to heat inside the test facility. However, it must be noted that the PV temperatures would have been higher if PV panels were not producing electricity, but moisture conditions would be less severe.

Measured outdoor boundary conditions

Outdoor boundary conditions (temperature, RH, wind speed, wind direction, rainfall, total and diffuse solar radiation on horizontal surface) were measured on the

roof of the test facility, 2.5 m above the test wall. All the measured outdoor conditions were compared to the data from the national weather station (Tallinn-Harku, 59.40°N, 24.60°E, elevation 34 m), located 8 km west from the test facility, to ensure that no measuring mistakes were occurring. As the pyranometer measuring diffuse radiation had a shading ring that needed to be corrected manually every 2 weeks, there were some short periods of time when diffuse radiation readings were equal to total radiation. These days were corrected in such a way that locally measured total radiation was used in combination with diffuse radiation values from Tartu, Tõravere weather station (58.27°N, 26.47°E, elevation 70 m; Figure 2).

Pre-analysis of the climate data

It is important to analyse the climate leading to high surface temperatures to predict PV temperatures for other climate zones without the need for detailed measurements or modelling. We compared climate data from the measurement period with historical climate data to determine if more extreme PCM temperatures could occur in the future. In Estonia (latitude 58.6°), the highest hourly solar radiation peaks on south-oriented vertical wall surfaces are in March and September. However, during the summer, the ambient air temperature and cumulative hours of solar radiation are higher, making August the worst month for PV facades. In August, air temperatures could be very high, there are relatively many hours of solar radiation and the solar angle is low enough to create solar radiation peaks of up to 800 W/m² on wall surface.

In Tallinn, the maximum solar angle in August at midday is between 48° on the 1st of August and 39° on the 31st of August (*TimeAndDate*, 2024). Therefore, during midday, there would be approximately the same amount of solar radiation on horizontal surfaces as there is on south-oriented facades. During this 1-month period, solar radiation on horizontal surfaces would be a relatively accurate parameter for comparing different climate data with measured data.

Table 1 shows a comparison of the measured data from the month of August with historical climate data from the nearest weather station in Tallinn, Harku and Tartu, Tõravere (located 160 km southeast of Harku and with the highest quality radiation data). The comparison shows that the days with extreme PCM temperatures were between the 95th and 97th percentile in terms of total solar radiation during the day. The average air temperature was also warm, but still around the 90th percentile, indicating that the daily average temperature is not the most critical factor leading to overheating of the facade surface. Only midday and afternoon temperatures between 12:00 and 15:00 showed that critical days were more on the extreme side than the daily averages, which was also the expected result.

It must be emphasized that maximum solar radiation and peak temperatures were not on the same day. Solar radiation on a horizontal surface tends to peak at the beginning of August. However, the solar angle is higher and affects the wall surface less towards the end of the month.

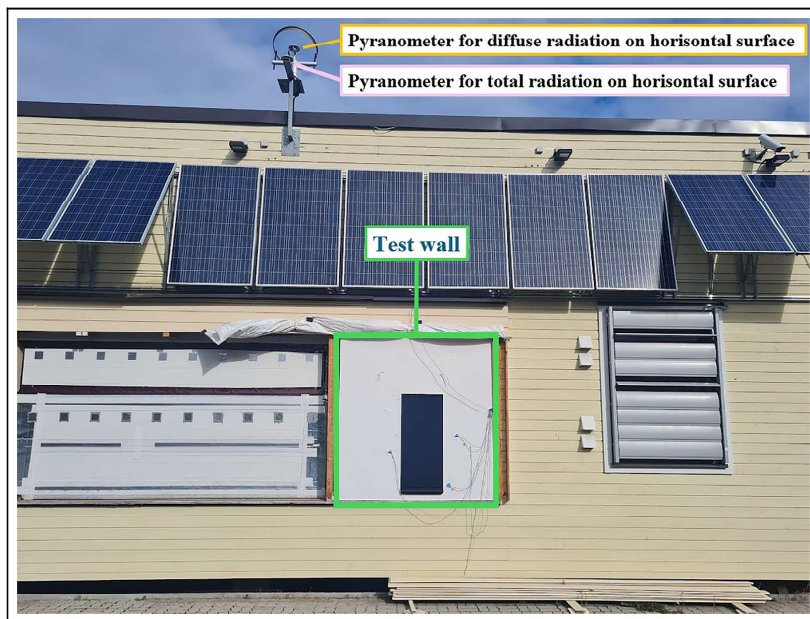


Figure 2. Location of the test wall on the south-facing facade and pyranometers on the roof of the test facility to measure direct and diffuse solar radiation separately.

Comparing the different long-term climate data sets, it turned out that there was no significant difference in the daily summarized solar radiation distribution curve between different climates. However, it appeared that both the daily average temperature and the 3-h average temperature after midday were significantly lower in the August months of 1970–2000 than they were in both locations measured in 2004–2023. This shows that although solar radiation (which depends mainly on cloud coverage) has remained relatively similar over the years, the air temperatures in August have become higher overall.

Indoor boundary conditions

Indoor climate conditions were measured inside the test building room with the experimental wall setup. The room was heated during winter, but not cooled during the summer. Heating setpoint was $+23^{\circ}\text{C}$. The average indoor temperature was 24.4°C . Lowest temperature during the experiment was 22.3°C . Highest short-term peak was 29.6°C . Air humidifier was regulated to 50% RH all year around. The average moisture excess during the heating season was 6.0 g/m^3 . During the summer RH was periodically higher than the setpoint, reaching up to 60% RH. To further increase moisture load into the wall via diffusion, the indoor surface of AAC was not finished. The unfinished wall surface also enables AAC to dry out

Table 1. Summarized daily radiation and average air temperatures of 24h and 3 h for two critical days with annual maximum PCM mortar measured temperatures.

Data set	Parameter	Summarized daily solar radiation on horizontal surface, W·h/m ²		Daily average air temperature, °C		Average air temperature between 12:00 and 15:00, °C	
		14.08.2022	15.08.2023	14.08.2022	15.08.2023	14.08.2022	15.08.2023
Measured data Harku 2004–2023	Measured value	6324	6441	20.8	19.9	26	24.6
	Percentile	96%	97%	91%	87%	95%	90%
	Max value	7185		26.0		31.8	
Tõravere 2004–2023	Percentile	95%	96%	89%	83%	90%	84%
	Max value	7058		26.5		32.8	
Tõravere 1970–2000	Percentile	95%	96%	95%	90%	97%	93%
	Max value	7278		23.5		30.6	

Comparison with long term climate measurement data of August, presented as percentile.

faster, but defining the exact time for the AAC wall to be unfinished would create another variable in equations.

Gravimetical measurement of PCM mortar moisture content

After the designated 20-month measurement period, physical samples were obtained from the wall in February 2024. To minimize moisture loss during the process, the samples were cut during a relatively cold period with temperatures below freezing point. During the cutting, the internal temperature of the PCM mortar was measured to be -5°C . This resulted in the majority of the humidity within the PCM mortar being in the form of ice at the time of cutting. The moisture content of the PCM mortar was determined through gravimetric measurement.

To ensure that the peak temperature of the PCM mortar in the wall was not exceeded, the drying process was conducted at an oven temperature of $+70^{\circ}\text{C}$. Drying continued until the change in mass readings between two consecutive measurements was less than 0.1%. The obtained results were then compared to those obtained from the soil moisture sensors. The presence of moisture in the form of ice also facilitated visual inspection of the moisture distribution within the wall.

Modelling hygrothermal performance of test wall

Hygrothermal modelling was carried out using Delphin 6 software (Grunewald, 1996; Nicolai, 2008). The model was calibrated using climate chamber experimental data (Talvik, Ilomets, et al., 2023). The aims of the modelling were to verify the modelled results by field measurements during the 20-month period and to model the hygrothermal performance in the future with more extreme outdoor climate conditions. The material properties used in the model, as well as the cross section of the calculation model and all the boundary conditions, are described in detail in (Talvik, Ilomets, et al., 2023).

Hygrothermal modelling with a test wall was conducted using the measured boundary conditions. The boundary conditions included the outdoor temperature, RH, direct and diffuse solar radiation, wind speed and direction and rainfall, as well as the indoor temperature and RH. Wind and rain data were combined to calculate the wind driven rain (WDR) load on the southern facade according to (EVS-EN ISO 15927-3, 2009). The initial moisture content of the PCM mortar was set to $0.27\text{ m}^3/\text{m}^3$. Initially, there was no PV in the calculation model until the date it was installed on site.

Additional modelling was carried out using the Estonian moisture reference year (MRY; Kalamees and Vinha, 2004). A 10-year period was used for this modelling, creating extremely harsh conditions for the system to operate in. These conditions are not likely to occur in real climate situations. The indoor climate had a moisture excess of $6\text{ g}/\text{m}^3$, which describe indoor humidity load with high occupancy (Ilomets et al., 2018). WDR data was applied to the facade surface without water leakage locations (unbroken facade).

Results

PCM temperatures during the whole measurement period

Both daily and monthly average extreme PCM internal temperatures are shown in Figure 3. The minimum PCM temperatures during the night are also visible to illustrate the daily fluctuation in different seasons. All the measured results are compared to the modelled ones.

In Figure 3, the measured daily fluctuation of PCM temperature is highlighted in grey – it demonstrates well the impact of solar radiation on the dark-coloured southern PV facade temperature. The highest daily temperature variation measured in March 2023 was 67°C, fluctuating between –9°C and 58°C. Overall, highest daily fluctuations tended to occur in March and April.

From Figure 3 it can also be seen that the critical period for high PV temperatures was longer than expected – temperatures above 57°C were reached from March to September, as solar radiation on the wall surface is highest in spring and early autumn in Estonia. In contrast to March and April, the ambient air temperature in summer months is higher, and also the number of hours with solar radiation is higher.

Figure 3 shows that, overall, the PCM mortar exterior layer temperature did not exceed 70°C during the two summers of the measuring period. The annual peaks occurred in mid-August for both years. The correlation between the measured and modelled results is relatively good, except for some days in November and late January. These discrepancies can be explained by the site location, as there are trees and neighbouring buildings at an intermediate distance from the test facility. Solar radiation was measured with pyranometers on the rooftop of the building, while the test wall was located 3 meters below (Figure 2). As a result, on a few days in November and January, when there was high direct solar radiation, the pyranometers were exposed to the direct radiation while the wall installation itself was not. In contrast, in December, when the solar angle is very low (about 8°), both the pyranometer and the wall are shaded by the trees, and only diffuse radiation creates the peak temperature values, which are accurately predicted by the model. Overall, these few days with shaded facade surface and exposed pyranometers did not create significant difference between measured and modelled hygrothermal performance of the facade.

Another period where the modelled results differ from the measured ones is at the beginning of the measurement period. This is because in early June 2022, the facade plaster and the sensors behind the plaster were being applied to the test wall, but sensors inside PCM were already measuring. During this period, scaffolding coverings were used to protect the facade. In hygrothermal modelling this period was modelled with just diffuse radiation on the wall surface.

Analysing the daily minimum temperatures, it could be seen that during the entire measurement period, the daily minimum temperature inside PCM mortar was never higher than 23°C. Since the PCM encapsulated inside the mortar was a combination of three different PCM materials, with the lowest having a nominal

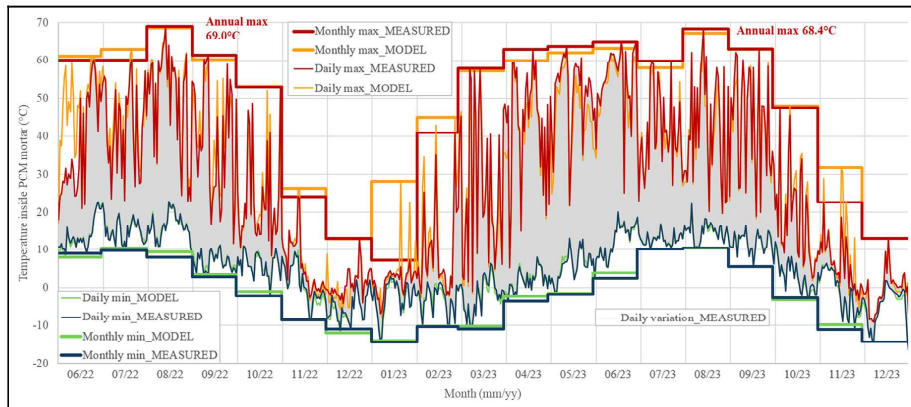


Figure 3. Comparison between measured and modelled daily temperature fluctuations and extreme values of PCM mortar at corresponding month. Shaded area stands for measured variation between the minimum and maximum temperature that occurred within 24 h period.

melting temperature of 25°C, it can be stated that the PCM probably managed to solidify during all the nights throughout the 20-month period. Therefore, the full potential of the PCM mortar was able to be utilized during the day.

Temperature dynamics inside the test wall and PCM mortar

The temperature dynamics inside the EnActivETICS wall are illustrated in Figure 4. Temperature measurements within the PCM mortar and on the rear surface of the PV panel demonstrate a close resemblance (with the maximum temperature on the back side of the PV panel being only 0.6°C higher than that in the middle of the PCM). It serves as evidence for a strong thermal connection between the PV panel and the PCM mortar. The Figure 4 also shows how the heated up outer layer of the facade affects the load bearing layer behind the insulation layer. Notably, there exists a 5.5-h delay between the temperature peaks observed within the PCM mortar and the region behind the insulation.

Figure 5 presents the comparison of measured and modelled temperatures. It could be seen that the model was able to predict measured temperatures better on days with undisturbed solar radiation (15th of August 2023) than on days with some cloud coverage (16th of August 2023). The black lines represent the PCM mortar centre layer temperatures, and the red dotted line represents the modelled situation with a PV panel applied directly on the EPS insulation, without any thermal mass behind the PV. The added thermal mass creates a significant delay in the temperature increase and lowers peak value. Since the PCM granules inside the mortar consist of PCM wax with nominal melting temperatures between 25°C and 35°C, this region increases the delay from 0.75 to 1.5 h, proving that the reduction

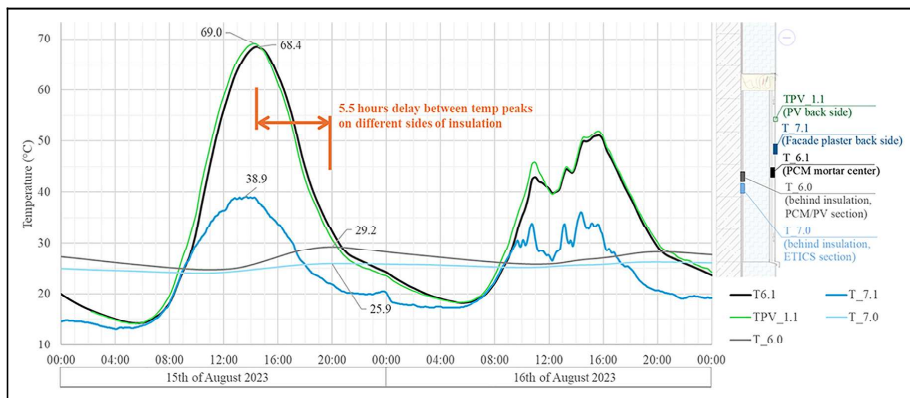


Figure 4. The measured temperature inside the EnActiveETICS wall during the day with the most extreme PCM temperatures of the measurement period and the following day with moderate cloud coverage. Cross section of the test wall with relevant sensor locations on the right.

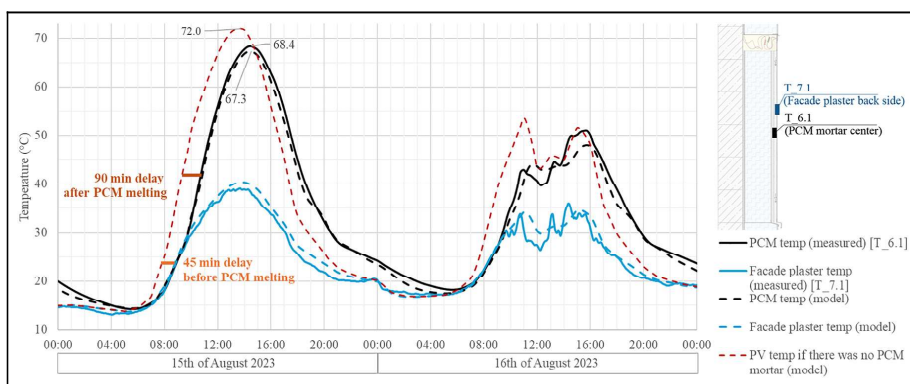


Figure 5. Comparison of measured and modelled temperature inside the En-ActivETICS, behind the light-coloured thin facade plaster, and in case without additional layer to buffer the excess heat. Cross section of the test wall with relevant sensor locations on the right.

in temperature increase speed is influenced by both the thermal mass of the thick mortar itself and the PCM granules inside.

On the 15th of August 2023, as depicted in Figure 5, the highest recorded PCM temperature during the measurement period was observed. When modelling without the PCM mortar, there was only a modest increase of 4.7°C on this particular day. However, when considering the entire measurement period under a hypothetical scenario without the thermal mass behind the PV panel, maximum PV temperatures reached up to 75°C on various days. In the absence of PCM mortar, with very small thermal mass, the PV panel can lose its heat energy faster during short wind events, compared to the case with PCM mortar.

Facade plaster temperatures and RH at close proximity from PV panel

Since thermal and hygric expansion are parameters that influence increased risk of crack occurrence, temperatures and relative humidity of the facade plaster was studied by measurement at 4 cm and 25 cm and modelled at 1 cm, 4 cm, 25 cm and 100 cm distance from the PV + PCM wall section. It appeared that there was no significant difference between the 100 cm and 25 cm distances, as they were both sufficiently far from the different material. Therefore, the graph for the 100 cm distance is not shown in the figures below, and the 25 cm distance represents the entire homogeneous facade plaster surface.

Sensor measurement data for the critical day with the highest PCM temperatures shows similar trend with the modelled temperatures of the facade plaster (Figure 6). Calculations show that on 15th of August, facade plaster had a temperature 7°C higher at 1 cm distance from the PCM area than it was on 4 cm and ≥ 25 cm distance from the PCM area.

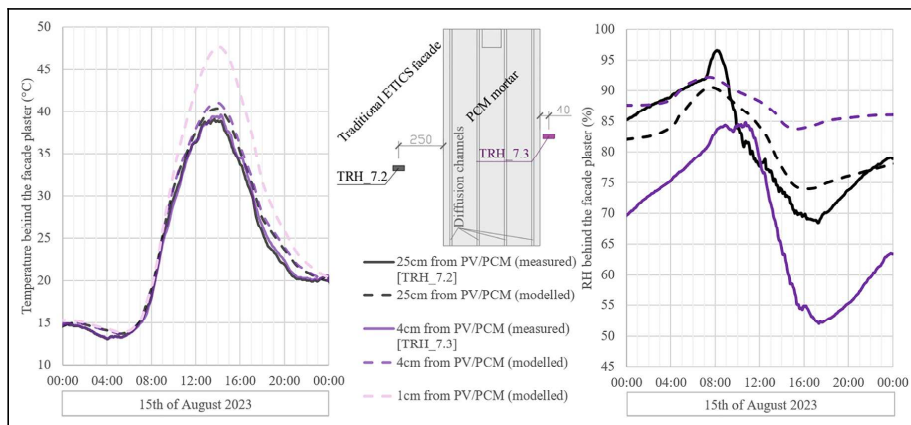


Figure 6. Temperature and relative humidity of facade plaster on different distance away from the PCM mortar and PV panel. Comparison between modelled and measured results during 24 h period.

When analysing the recorded data over 20 months, it was observed that the facade plaster temperatures increased by a few degrees during summer days, moving closer to the PV panel. The maximum difference in the modelled results between the facade plaster 1 cm away from the PV section and the rest of the facade surface was 19.2°C, while the difference between the location 4 cm away and the rest of the facade was only 1.4°C. The measured results showed a maximum difference of 4.5°C between the location 4 cm away and the rest of the facade. Overall, the temperature gradients were localized to the close perimeter of the PV panel.

An example of the RH dynamics of the facade plaster on August 15 is also shown in Figure 6. The modelled results indicate that the facade plaster should

have slightly higher RH, closer to the PCM mortar area, caused by the moisture from the PCM mortar drying out through the facade plaster. However, it should be noted that the measured results show the opposite – the sensor closer to the PCM mortar (TRH_7.3) displays lower RH readings than the one in the middle of the facade plaster area (TRH_7.2). This could be due to the diffusion channels speeding up the drying process in the real wall more than expected in the model without micro-convection, resulting in less moisture flow from the PCM mortar to the facade plaster. It could also be a measurement error caused by the exact positioning of the sensor, the varying thickness of the facade plaster layer above the sensor capsule or the fact that the application tube was longer for the sensor further away from the PV. Sensor error is ruled out as both sensors were calibrated before and after the experiment and showed similar readings.

Measured results from the two different locations of the facade plaster area show increased moisture inertia closer to the PCM mortar. It could be seen from Figure 6 that after the sunrise on 15th of August, in the middle of the plaster area, the RH decreases rapidly at the morning as facade plaster temperature increases. However, next to the PCM mortar with greater moisture inertia, the RH reaches a plateau at 8:00 and starts to decline only at 11:00. It can be observed that when the facade temperature starts to increase during the day, the RH of the facade plaster 25cm away from the PCM mortar decreases faster than in the point closer to the PCM mortar. During the night, moisture flow can be seen within the facade plaster layer.

If the modelled and measured RH in the facade plaster area further away from the PV panel section was analysed during the entire period. It appeared that the correlation between the two was mostly satisfactory. From October to March, the facade plaster sensors showed readings of 100% RH. The modelled results showed lower values, which is probably caused by inaccuracies in the material properties (especially at higher moisture contents) of the facade plaster and errors in measuring humidity close to the dew point with RH sensors. The main hygrothermal properties of this particular facade plaster were measured in the laboratory. However, it is much less accurate to define the moisture storage and transport parameters under high moisture conditions. Therefore, the calculation model rarely increased the RH of the facade plaster above 97.5%.

PCM mortar moisture content during measurement period

During the project, two soil moisture sensors were used to monitor the moisture content of thick PCM mortar. There were no significant differences between the two sensor readings after the initial dry-out process (Figure 7). This is probably because the diffusion channels equalized the moisture content all over the cross-section behind the vapour-tight PV panel.

It has been previously stated that soil moisture sensor readings are temperature-dependent. For this particular PCM material, temperature correction formulas were developed during the sensor calibration phase (Talvik et al., 2022). However,

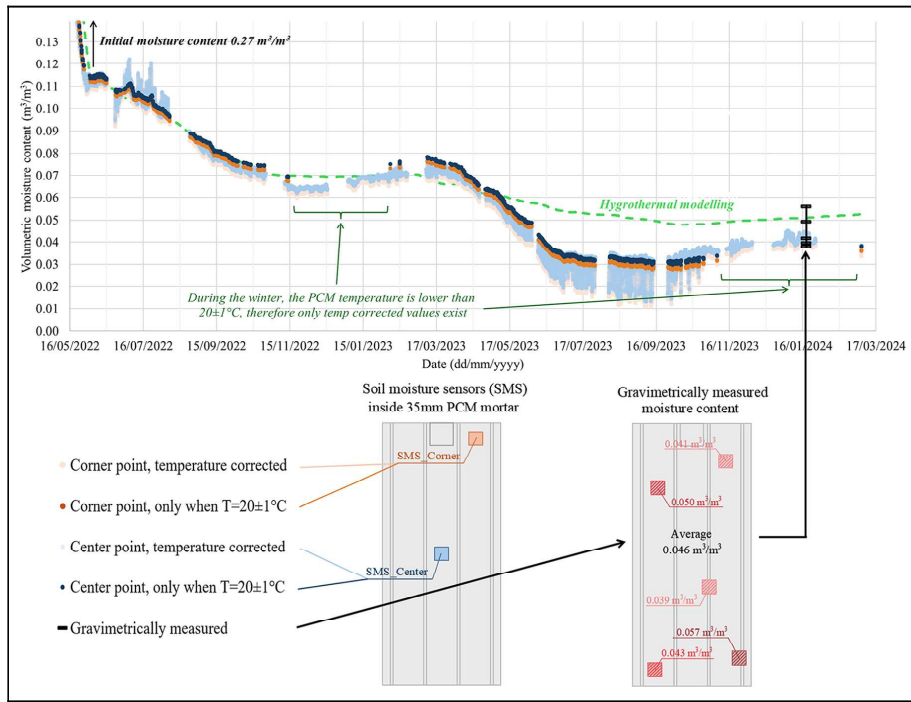


Figure 7. Moisture content of PCM mortar, measured with soil moisture sensors and comparison with modelled results. Lighter coloured points represent all the measured values, temperature corrected according to (Talvik et al., 2022). Darker coloured points represent timestamps when PCM is on the same temperature which the sensor calibration was conducted and are therefore more accurate. Black points represent the results of destructive gravimetric measurement on 18th of January 2024.

especially under low moisture conditions, these formulas underestimated the moisture content by up to $0.02 \text{ m}^3/\text{m}^3$ (Figure 7). Therefore, for more accurate results, only the sensor readings obtained around the sensor calibration temperature of $20^\circ\text{C} \pm 1^\circ\text{C}$ were filtered out. Most of the measurement days had at least two periods when the PCM temperature was in that range – in the morning and in the evening. However, during the winter months, there are longer periods when the PCM temperature never exceeds 19°C . Nevertheless, the temperature corrected graphs make it possible to predict the moisture content during the winter. In the data, there are also some gaps in both the temperature corrected and isothermic values, caused by temporary technical issues with the logging device.

At the end of the experimental period, moisture content of PCM mortar was also measured gravimetrically. The results are shown on the graph and in the drawings in Figure 7. In general, the gravimetrically measured moisture content is in the same range as the soil moisture sensor readings. However, two measurement points

showed slightly higher moisture content – in the lower right corner of the PV and in the middle left. As the gravimetrical measurement was carried out in January, to obtain the sample pieces while frozen, it could be that the lower right corner sample, situated just at the boundary with diffusion channel, had increased moisture content because of the increased moisture entering the wall system at the winter via the diffusion channel. There is some snow on the lower steel sheet after the snow blizzard events, which could temporarily increase the moisture content of the PCM mortar closer to the lower end of the diffusion channel.

If all the measured results are included, the average gravimetrically measured moisture content is $0.046 \text{ m}^3/\text{m}^3$ with a standard deviation of $0.0076 \text{ m}^3/\text{m}^3$. However, if the highest reading from the lower right corner is excluded from the data set, the average would be $0.043 \text{ m}^3/\text{m}^3$ with a standard deviation of $0.0050 \text{ m}^3/\text{m}^3$. Temperature-corrected moisture content from the soil moisture sensor was on the same day $0.041 \text{ m}^3/\text{m}^3$ on average. Hygrothermal modelling showed a moisture content of $0.052 \text{ m}^3/\text{m}^3$ on the same day.

Besides measuring the moisture content inside the PCM mortar, relative humidity was also measured inside the mortar (TRH_7.3 on Figure 1). The RH sensor inside the PCM mortar also showed a constant 100% RH during the first year of the measurement period.

A comparison of measured and modelled moisture content (Figure 7) showed that measurements had a faster decrease in moisture content during the second summer than the modelling predicts, however, the overall trends are similar to the measured results. The discrepancy between measured and calculated moisture contents could be explained by the increased moisture dry-out speed in the real wall compared to the conservative model, as the latter did not consider micro-diffusion inside the diffusion channels. Another aspect is that although the PCM mortar material properties were measured over a wide range of humidity conditions, the hygrothermal model was calibrated in the climate chamber test, which lasted a relatively short time and did not reach lower moisture contents.

Long term hygrothermal modelling of PCM mortar moisture content

Therefore, the same calculation model was used to make long-term calculations to evaluate the long-term durability of the system. Figure 8 shows measured and modelled PCM mortar moisture content dynamics during measurement period and following modelled results by using the Estonian moisture reference year for condensation. The moisture content of PCM mortar was relatively stable after the construction moisture was dried out. Moisture accumulation did not occur. From calculation year 4 onwards, the moisture level fluctuated between 0.028 and $0.034 \text{ m}^3/\text{m}^3$, being higher during the winter period and lower during the summer. This indicates that the initial moisture content dried out with two summers. Further modelling with condensation test years showed a slight decrease in moisture content during the next 4 years, after which a stable moisture regime was achieved.

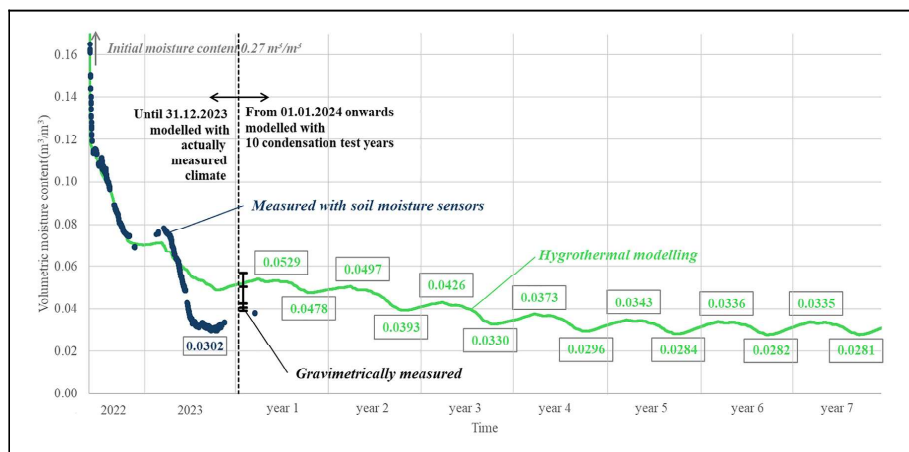


Figure 8. Long term prediction for PCM mortar moisture content dynamics. Modelling began with measured boundary conditions. After experimental programme, extreme climate conditions (temp, RH, solar radiation and WDR to surface) of moisture reference year of Estonia were applied.

The moisture content of PCM mortar increases every year from November to March and decreases from June to September – this phenomenon is also visible in the measured results. If the measured results from the second year were compared to the modelled results from year 6 onwards, it could be seen that the summer lows tend to have the same moisture content around $0.03 \text{ m}^3/\text{m}^3$. This means that the dry-out process during the second year was faster than predicted by the model.

There were no cracks in the facade plaster on the test wall. Also, the hygrothermal model does not consider water leakage from potential cracks. It has been shown in (Talvik, Ilomets, et al., 2023) that excess water from leakages would find its way out of the wall system via diffusion/drainage channels. Locally elevated moisture content of the PCM mortar, caused by possible leakages, was able to dry out relatively quickly with solar radiation through the diffusion channels. Therefore, modelled results without water leakage but with WDR applied on the facade plaster surface, a high indoor moisture load, built-in moisture of the structure and PCM mortar and extremely cold outdoor conditions for the condensation test year should predict the long-term durability relatively well.

Destructive opening of the test wall

A visual inspection was conducted to detect any possible defects inside the critical layers. It turned out that there were no visible ice crystals in the mortar structure, nor on the boundary between the PCM mortar and PV panel, or between the PCM mortar and insulation. If the PV panel was removed, in most places, the first layer

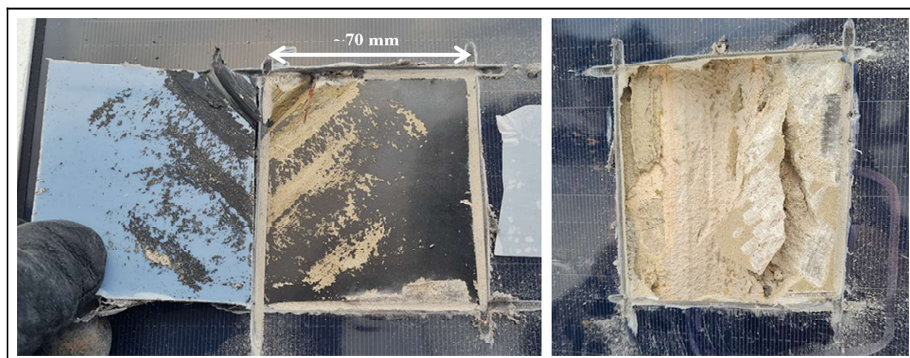


Figure 9. In places where there was full-surface bonding between PV panel and PCM mortar, delamination happened between the two coating layers of the PV panel product (left); slight colour change had occurred on the outer layer of the PCM mortar, on places without 100% bonding between PV and PCM mortar (right).

of coating remained on the glue mortar, indicating that all the installed layers were well-bonded (Figure 9, left).

There was visual evidence, however, that during the experimental period, there was elevated moisture content on the outer surface of the PCM mortar. In one specific location where there was no full-surface bonding between the PCM mortar and PV, the outer surface of the PCM mortar was discoloured from grey to light orange (Figure 9, right). This location was also near the diffusion channel. It could be due to the long-term presence of liquid water behind the PV panel, causing some pigments to travel to the surface. One possibility is that these pigments come from the PCM material that has penetrated the walls of the granules. Further studies are needed to determine the origins of this pigmentation and whether it has affected the latent heat properties of the PCM mortar.

Discussion

In some areas, there was visible discolouration on the outer side of the PCM mortar. This discolouration could be caused by the PCM wax, which is encapsulated into small granules, penetrating the walls of the granules and traveling to the outer layers of the PCM mortar along with moisture transport. The possibility of PCM wax escaping the system should be studied in the future, despite the current experiment showing no signs of PCM thermal capacity reduction during the 20-month period.

The factors that were not entirely ensured during this one-story-scale experiments that could increase the hygrothermal load were as follows:

- (1) The facade was facing south as traditional PV orientation and because of the test facility limitations for test wall orientations (only 0° and 180° orientations are available). South-west or south-east facing walls could be also worth studying the severity of PV overheating in future studies. WDR loads should also be considered in the critical orientation selection;
- (2) The location of the test facility is not on open terrain, therefore the wind speeds are not as extreme, resulting in less WDR;
- (3) The test wall had relatively small dimensions, so critical temperature and humidity deformations could not occur;
- (4) The 20-month test period is too short to evaluate the aging effect of the materials.

In this test wall, diffusion channels were carved into the thick PCM mortar behind the PV panel. The study showed that, the diffusion channels performed well also in field conditions and are needed for at least for two reasons. Firstly, the channels work as drainage channels if a significant amount of water leaks in. This has been proven previously in (Talvik, Ilomets, et al., 2023). Secondly, they facilitate faster drying during periods with higher solar radiation. The necessity of diffusion channels was proved also by long-term hygrothermal modelling, conducted with the MRY climate, where moisture accumulation did not occur.

The measured results reached a stable moisture content in the second autumn, while the modelling showed that this moisture level should be reached in the fifth autumn. Additionally, the measured drying out process was faster during the second year, compared to the model. This could be explained by the fact that micro convection is not considered in the calculation model. The cross-section of the real diffusion channel was approximately 400 mm², which should be enough to allow air circulation inside the channel, amplified due to significant daily temperature changes. On the other hand, the diffusion channel was modelled as a boundary condition with a constant equivalent vapour diffusion thickness of $S_d = 0.8$ m, which corresponds to 3/4 of the length of the whole diffusion channel. In the final model, no geometry was assigned to the diffusion channels, as micro convection is challenging to include in the Delphin models. Several variations of how to model the diffusion channels were tried out earlier, and it was concluded that it would be better to create a more conservative computational model. Overall, this hygrothermal calculation model could be used to evaluate the long-term performance of PV-ETICS facades in different climates.

One crucial key performance indicator for this ETICS facade system with integrated PV panels is the PV panel temperature. In case of overheating, the PV panels reduce in efficiency and could physically deteriorate. It is necessary to keep the PV temperatures under 85°C (Hasan et al., 2015) during the entire service life of the facade; therefore, PV should not be applied directly on the insulation layer. In this test wall, thick mortar with PCM granules was used as a heat sink. The PV backside temperature was approximately 0.6°C higher than the PCM mortar

temperature, indicating good thermal conductivity between the PV panels and the heat sink.

The long-term experiment also revealed that the period with high PV panel temperatures lasts from spring to autumn, and the most extreme temperatures in Estonia occur in August. Sensitivity analysis with historical data from 1970 to 2023 revealed that the climate in August 2022 and 2023 was on the critical side in terms of high temperatures and high solar radiation. However, there were more critical days in the historical dataset. The experimental period included two summers, and for both years, the maximum PCM temperature was 69°C. This correlates well with the first indicative calculation models carried out with Estonian MRY test year, showing peak temperatures for the solution with 30 mm of PCM mortar with different PCMs ranging from 67°C to 73°C (Talvik et al., 2021). The same study shows that if the same facade system were introduced in Madrid, the peak temperatures with 30 mm PCM mortar would be in the range between 79° and 82°C, which is just below the performance limit.

Experimental results from Lodz, Poland, previously measured the maximum temperatures of the PV panels to be 63°C (Heim et al., 2023a). Similarly, the peak results were measured in August. The study also revealed that without the PCM mortar behind the PV panels, the temperature would have been 74°C, and with black-coloured facade plaster, the temperature was measured at 75°C (Heim et al., 2023a).

The temperature measurements also show that having a dark surface on the facade with significant thermal mass causes the structural layer to warm up through 160 mm of EPS Silver insulation. It should be studied in the future how significantly the dark-coloured facade with significant thermal mass on the external side effects the heating and cooling demand of a building.

To investigate the hypothesis regarding whether the discolouration of PCM mortar is attributable to the escape of PCM from the wall system, a comparison of the temperature dynamics of PCM mortar in 2022 and 2023 was conducted. This analysis revealed no significant loss of thermal mass in proximity to the nominal melting temperatures. Nonetheless, this methodology lacks the precision necessary to draw definitive conclusions regarding the potential escape of small quantities of PCM wax from the system. In the preliminary phases of PCM mortar material development, the potential leakage of PCM through the PU coating was examined under high-temperature conditions, and the observed mass loss was deemed insignificant. However, the potential long-term escape of PCM, exacerbated by freeze-thaw cycles in conjunction with elevated temperatures, has yet to be studied. Future investigations should aim to produce a precise latent heat distribution graph in the laboratory for both the new material and the aged material retrieved from the test wall.

Another important aspect that was realized after the opening of the facade PV was that unless manufactured in the factory, the outer surface of the PCM mortar would not be perfectly flat. Therefore, the glue mortar applied between the PCM mortar and PV panel would most probably not have full surface bonding

everywhere. From a hygrothermal point of view, it would be better if the glue mortar grooves were orthogonal to the main diffusion channels, creating a network of diffusion where small glue-mortar channels lead to the main diffusion channels in the PCM mortar.

In the future, more resources should be allocated to increase the level of prefabrication of the PCM-mortar and PV panel cross section to increase the application efficiency on the construction site. But during this future development process, it must be kept in mind that the main principles of using the diffusion channels behind the PV panel, protecting these channels with double steel sheets and the possibility to replace the PV panel without damaging the facade plaster surface must be followed.

When designing an ETICS facade with integrated PV, it is important to consider that ETICS has a tendency to deteriorate prematurely if the initial moisture content of the structure is high and the construction process is too fast, preventing the layers from drying out sufficiently (Talvik et al., 2023). Therefore, it is necessary to take into account structural layers with high initial moisture contents, especially when a part of the facade is insulated with mineral wool.

Conclusions

Results from the 20-month experiment with a test wall under outdoor climate conditions of south-oriented facade in Estonia showed a decrease in moisture content in the critical layer of the PV-ETICS wall system inside the thick layer of PCM mortar behind the vapour tight PV panel. After the experiment, no cracks were identified, and the PV panel was still generating electricity. During the destructive opening of the facade to measure the moisture content of the PCM gravimetrically at the end of the experiment, no signs of physical deterioration inside the wall was identified. However, certain regions exhibited observable discolouration on the exterior surface of the PCM mortar.

Based on the experimental programme, following conclusions can be made:

1. Phase change material (PCM) mortar behind the PV panel managed to avoid extreme temperature peaks, during the test period. Maximum measured temperature of BIPV was + 69°C, that was lower than the performance limit of the thin PV system (+ 85°C);
2. Maximum PV panel temperatures for south oriented facade occurred in mid-August, when solar angle is already lower than at the solstice, but ambient air temperature is still high enough;
3. PCM was able to solidify during all the nights during the measurement periods, therefore full potential of the PCM could be used every day when there was high enough solar radiation. A combination of PCMs RT25HC, RT28HC and RT35HC proved to be efficient;

4. It took two summers for the wall system to dry out most of the built-in moisture from the thick PCM mortar;
5. Calibrated soil moisture sensors proved to be enough accurate method to evaluate moisture content of thick, porous material at high moisture levels, as the results coincide with gravimetrically measured results. Most accurate readings were obtained under isothermal conditions, although temperature correction was also possible to conduct relatively accurately;
6. Both measured and calculated results show that there would be no moisture accumulation behind the vapour-tight PV panel if diffusion channels are applied inside the PCM mortar;
7. Facade system and PV panels did not have any physical defects, cracks, delamination of layers etc at the end of the experimental programme. Therefore, large scale testing and long term implementation could be encouraged;
8. PCM mortar had some discolouring effects after the 20-month test period. Despite temperature dynamic graphs showing no smaller thermal mass in 2023 compared to 2022, latent heat properties of old PCM mortar from the wall should be measured in the future.

Overall, the En-ActivETICS facade system proved to be sufficiently performing and durable during the 2-year guarantee period. Moreover, hygrothermal modelling showed that there should be no significant moisture-related problems throughout the remaining service life of the facade system if diffusion channels are implemented as shown on Figure 1. After the experiment, the PV panel was still generating electricity. Therefore, PV-ETICS could be considered as a potential option for integrating on facade surfaces exposed to solar radiation in order to increase on-site green electricity production. This technology should be encouraged to implement in larger demonstration buildings in the future.

Declaration of conflicting interests

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Ethical considerations

Not applicable.

Consent to participate

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Consent for publication

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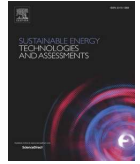
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Appendix 4

Publication IV

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Original article

Indoor Overheating Risks of PV-ETICS and Dark-coloured Facades: Experimental and Simulation-based Assessment

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ABSTRACT

Building-integrated photovoltaics (BIPV) are gaining attention for improving energy performance and on-site electricity generation. However, dark-coloured PV panels in facade applications may pose a risk of overheating, particularly when integrated into External Thermal Insulation Composite Systems (ETICS) without a ventilation cavity. This study investigates the impact of dark facade plasters and BIPV with external phase change materials (PCM) on indoor overheating in the cold climate of Estonia. A full-scale experimental test wall with PV-ETICS and light-coloured traditional ETICS was constructed and monitored for thermal behaviour. An IDA ICE simulation model was created and calibrated. Using this model, a typical concrete apartment building was analysed for overheating. The results showed that PV-ETICS systems only modestly increased overheating degree-hours — by 3–10 °C·h above 27 °C in the case of a 200 mm thermal insulation layer, while thinner insulations showed more significant overheating. While the overheating effect isn't severe enough to hinder the PV-PCM ETICS facade concept, it should be considered in indoor climate and energy modelling, especially for insulation levels ≤100 mm. Mitigation can be achieved by using lower g-value glazing or passive shading methods.

Introduction

Potential of Facade-integrated Photovoltaics (FIPV)

Building-integrated photovoltaic (BIPV) systems are increasingly popular in the renewable energy sector, supporting decentralized electricity production and increasing the energy performance of buildings. BIPV can reduce electricity transmission costs by generating power where it is consumed. However, conventional rooftop PV often struggles to match energy generation with demand profiles, as generation peaks during midday while residential consumption peaks in the morning and evening hours [1]. Rodrigues et al. [2] showed that the combined use of rooftop and facade PV installations can effectively address energy demand fluctuations, thereby improving grid stability and reducing reliance on non-renewable energy sources. Another challenge is that rooftop space is often limited, especially in taller buildings, where it must be shared between PV panels, technical equipment, rooftop terraces, etc. In such cases, additional surface area for PV installation can be obtained from the facades.

A promising approach to improving the alignment between energy

generation and demand is the integration of PV into southeastern and southwestern facades, where it can enhance energy yield during the early morning and late afternoon hours due to their vertical orientation, thereby addressing the temporal mismatch between generation and consumption [3]. Abuhussain found that by combining rooftop, facade, and semi-transparent PV, up to a 37 % reduction in building energy consumption was achieved compared to a conventional rooftop solar system with the same installed capacity [4]. Therefore, FIPV has significant potential for improving the energy performance of buildings. However, current facade-integrated PV solutions are predominantly ventilated systems, which facilitate PV temperature regulation but require specialized mounting structures on the facade, thereby increasing the wall's complexity and thickness.

Concept and Design of the PV-ETICS Facade System

The PV-ETICS facade system introduces an innovative solution by integrating PV panels directly into an External Thermal Insulation Composite System (ETICS). This approach offers a lightweight, cost-effective, and space-efficient alternative to conventional ventilated

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facade-integrated PV (FIPV) systems [5–7]. Eliminating the ventilation gap in PV panels can lead to overheating, reducing efficiency and lifespan. To address this, the PV-ETICS system uses phase change materials (PCMs) behind the panels to regulate temperature by absorbing heat and releasing it when cooler. Studies [8,9] show that PCMs can keep panel temperatures below the critical 85 °C limit and manage moisture-related risks through diffusion channels.

The PV-ETICS system has potential for application in the renovation of residential buildings, particularly given the widespread use of traditional ETICS in the regional renovation markets of Northern and Eastern Europe. However, in Estonia and neighbouring countries, cooling systems are generally not installed during apartment building renovation projects, which could make even a slight increase in internal heat gains from the dark-coloured facade a potential concern. Excessive heat accumulation on external layers could lead to indoor temperatures exceeding critical thresholds, highlighting the need for a thorough assessment of the thermal implications of PV-ETICS systems before their large-scale implementation in renovation projects.

Key factors influencing indoor overheating

Residential buildings face a high risk of overheating in current and future hot summers [10]. In Estonia, overheating has not been a significant problem in existing non-renovated apartment buildings [11], but it has been an issue in highly insulated residential [12] and non-residential buildings [13]. To avoid the health risks associated with overheating, the design and renovation of the building stock must change to accommodate future extreme and average climate conditions [14]. It is well established that windows are the primary contributors to indoor overheating, as they facilitate direct solar heat gain and significantly influence the thermal balance of indoor spaces. Comprehensive relationships between window area and parameters, cooling demand, and energy costs have been thoroughly examined in [15] in the context of office buildings, and in [16] for residential buildings.

Key factors influencing indoor climate comfort and overheating risk include the window-to-wall ratio (WWR) – the share of window area to the facade area (wall + windows; internal dimensions); shading and g-value of glazing, along with building geometry and orientation. Additionally, dark surfaces absorb more solar radiation, which increases the temperatures of external layers of wall and leads to heat transfer indoors, especially in the absence of ventilation cavities behind dark materials like in the PV-ETICS system [9]. Although thermal insulation offers considerable resistance to heat flow towards the indoor environment, very high surface temperatures and substantial thermal mass on the facade can still result in noticeable heat transfer into interior spaces.

Relationship between insulation thickness and overheating

It is generally known that overheating is a more severe issue in well-insulated buildings. A study simulating both historical and future climate conditions for 3,456 combinations of dwellings in the London area found that increased wall and floor insulation raises indoor temperatures [17]. Another study from cold climate regions in China showed that increasing wall insulation thickness (from 0 to 125 mm) exacerbated overheating by 6.9 % to 22.5 %, depending on the location [18]. In contrast to comparing insulated versus uninsulated buildings, a study in the Netherlands compared insulation levels of $U = 0.20 \text{ W/(m}^2\cdot\text{K)}$ and $U = 0.15 \text{ W/(m}^2\cdot\text{K)}$, confirming that greater insulation thickness increased the number of overheating hours [19]. However, in these studies, most of the external walls featured relatively light-coloured finishes and/or a ventilated air cavity.

The overheating effect caused by the dark facades without ventilation cavity is not sufficiently addressed in the existing literature. However, numerous studies have examined the surface temperatures of dark-coloured roofing materials and their impact on indoor temperatures in rooms situated beneath the roof [20,21]. It has been shown that the net

cooling demand reductions between dark roofs and cool roofs are significantly greater for poorly insulated roofs than for those with higher levels of insulation [22].

Contribution of PCM layers in external walls to overheating risk

Research on externally placed PCM in well-insulated walls is limited, but studies in warmer climates highlight its potential. Several studies have shown that external PCM can significantly reduce indoor discomfort and decrease cooling demand by up to 40 % [23,24]. Particularly in hot climates, it has been found that external PCM placement is more effective than internal for reducing cooling demands [25,26]. Zhu et al. [27] have demonstrated reduced overheating using PCM layers on both sides of a 75 mm insulation layer. However, all of these walls had less insulation than required in the cold climate renovation market [28].

Temperature-dependent thermal conductivity of insulation materials

In addition to insulation thickness, the thermal conductivity of the insulation material is also an important factor in determining the extent to which external PCM temperatures affect the indoor climate. It is important to note that the efficiency of thermal insulation materials does decrease at elevated temperatures. The thermal conductivity of the insulation materials is measured at an average temperature of 10 °C inside the insulation material [29]. With increased temperature, the thermal conductivity increases [30]. Typically, building energy modelling tools do not take this effect into account, thereby underestimating the heat flow through the insulation into the structural layer in the case of very high temperatures on the external side of the insulation.

Research problem, objectives, and research questions

Previous measurements of the PV-ETICS test wall [9] led to elevated interior surface temperatures in the evenings, raising concerns about its potential overheating effects. These findings prompted further investigation to quantify the extent to which the dark-coloured PV facade contributes to indoor overheating and to assess whether this effect poses a significant challenge to the widespread implementation of the PV-ETICS system.

The primary objective of this study is to evaluate whether the thermal impact of dark facade surfaces in the PV-ETICS system significantly contributes to indoor overheating. To achieve this, the research focuses on the following key questions:

- 1) To what extent does the dark facade surface of PV-ETICS contribute to indoor temperature rise?
- 2) In which cases should the facade system absorption coefficient be considered if overheating calculations are conducted during the design phase?
- 3) Is the PV-ETICS system suitable for retrofit applications in apartment buildings, or does it pose an excessive overheating risk or significantly increase cooling demand?

Methods

Measuring temperatures and heat fluxes inside the PV-ETICS test wall

The PV-ETICS test wall was installed on the southern wall of the test facility. The facade system had a 0.5 m² section covered with a PV-ETICS system with PCM, while the surrounding area (2.9 m²) was finished with light-coloured plaster (Fig. 1). Air temperatures were measured in all adjacent rooms and at three different locations and heights within the test room between September and November 2024 at 5-minute time steps (Fig. 1). The indoor temperature difference between two points (Ti_1 and Ti_3 in Fig. 1) in the test room was, on average, 0.08 °C and at most 0.43 °C, indicating a relatively uniform temperature in the room.

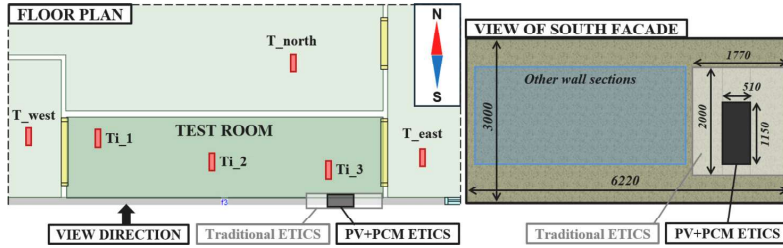


Fig. 1. Floor plan of a test building (left) and view of the south facade (right).

In the analysis, the average value of these three sensors was used.

Temperature (measured with Hobo Onset TMC15-HD sensors (measurement range: 40 °C to 100 °C, ± 0.15 °C)) and heat flux (using Hukseflux HFP01 heat flux plates (range -2000 to $+2000$ W/m², ± 3 %)) were measured inside the wall in both sections (Fig. 2).

It should be noted that in the PV-ETICS section, the thermal insulation layer was made thinner to accommodate the thick PCM mortar and to ensure that the final surface of the PV panel remained flush with the adjacent facade plaster. Consequently, the insulation thickness was reduced from 200 mm to 160 mm. More information on the design of the PV-ETICS cross-sections can be found in [8].

The PV-ETICS and light plaster ETICS sections were constructed adjacent to one another without additional thermal separation. However, the thermal sensors were placed in the central areas of each section to minimise the influence of edge effects (at a distance greater than 25 cm from the boundary, which exceeds the overall thickness of the ETICS system used).

Material properties

Thermal properties of materials were measured under controlled laboratory conditions at moisture levels corresponding to those present during the experiment. The material properties table has been included in the supplementary materials as Annex 1. The density was measured according to [31]. Thermal conductivity and latent heat for samples obtained from the wall were measured using the transient plane source (hot disc) method according to [32]. Thermal conductivity of carbon-enhanced EPS under varying boundary conditions at elevated temperatures was measured according to [33] with the TA Instruments Fox 200 heat flow meter. Properties of wood-cement chipboard were obtained from the literature [34–36]. The latent heat properties of the PCM mortar were defined based on prior calculations using granules with

Rubitherm PCM mixed with cement plaster [8]. The PCM mortar contained granules filled with RT25HC, RT28HC, and RT35HC in equal proportions, with a total PCM content of 12 wt% [5]. To consider the influence of temperature on the thermal conductivity of the EPS, it was additionally measured at elevated temperatures (Annex 2) up to 62.5 °C.

During the time of this experiment, the wall setup was already more than two years old. Therefore, the initial built-in moisture from the autoclaved aerated concrete (AAC) and mortar with PCM granules had dried out to long-term averages [9].

Indoor climate and energy modelling

IDA ICE simulation software was used for indoor climate and energy modelling. The model was calibrated based on measurement results from the south-facing facade in the test facility over two months. In the calculation model, the room with a test wall was modelled with all the partitions having the correct structures (Fig. 2), materials (Annex 1), and areas (Fig. 1), as well as climate conditions (air temperature, relative humidity, direct and diffuse radiation, wind speed, and wind direction). To calculate temperatures and heat fluxes at the interfaces between different materials, corresponding to the sensor locations on the actual wall, the wall structure was divided into additional layers. Corresponding output points were defined using the expert-level interface of IDA ICE.

After calibrating the test building model against measured data, a second model was developed to represent a real building featuring a similar facade system. This model was configured to reflect a typical post-World War II concrete apartment building, characterised by a large, windowless end wall. A representative example of such a building, located in Tallinn, Estonia [35,37], was selected due to its relevance to a significant portion of the local apartment building stock.

Preliminary modelling indicated that south-facing end wall facades

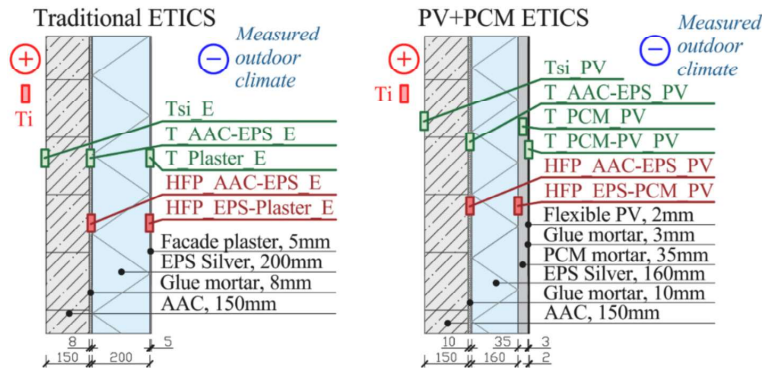


Fig. 2. Cross-sections of traditional ETICS finished with light-coloured plaster (left) and ETICS with PV and PCM mortar (right). Temperature sensor and heat flux plate locations are shown.

were the most critical in terms of overheating. Therefore, this orientation was chosen for modelling.

A single apartment, located on the third floor, was selected as the representative case for the analysis. While adjacent apartments and the staircase were included in the model, the rest of the building was omitted to optimize computational efficiency (Fig. 3, right). To streamline the simulation process and reduce computational complexity, the facade was simplified into two sections for each floor: one with a light-coloured plaster finish and the other with a dark-surfaced PV-ETICS system. Since the apartment was modelled as a single thermal zone, the results remained unchanged regardless of whether the facade was divided into two equal sections (Fig. 3, right) or into multiple smaller segments (Fig. 3, left), provided that the total area of the different facade sections remained constant.

Modelling scenarios for the sample building

Various external insulation solutions were added to the existing pre-renovation model, along with triple-glazed windows, which are widely adopted in Estonian renovation practices (Fig. 4). In the different modelling scenarios, windows with g-values ranging from 0.3 to 0.5 were used. In all cases, the thermal transmittance values were $U_g = 0.6 \text{ W/(m}^2\text{K)}$ for the glazing and $U_f = 1.2 \text{ W/(m}^2\text{K)}$ for the frame. The windows were modelled with a frame area of 10%.

The insulation thickness of external walls in ETICS sections varied between 50 mm and 300 mm (Fig. 4). The 40 mm difference between the insulation thicknesses was maintained between the traditional ETICS facade and 160 mm for insulation behind PCM mortar and PV. All the scenarios were named according to the insulation thicknesses of the traditional ETICS. In addition, the existing structure of the apartment building was defined according to [35] (Fig. 4).

Besides the light-coloured facade and 50% PV / 50% light plaster scenarios, in the third scenario all the walls were finished entirely with dark facade plaster.

For the overheating analysis, an apartment without a cooling system was studied. Window opening (10% of window area) was enabled in the model when the indoor temperature exceeded 25°C according to national regulations [38]. This setup reflects the common behaviour of occupants opening windows during summer to mitigate overheating through natural ventilation. The model also accounts for the presence of openable windows on opposite sides of the apartment.

For the assessment of cooling demand, a separate scenario was modelled with an “ideal cooler” applied in the model, maintaining a cooling setpoint of 25°C . In this model, windows were always closed.

Indoor climate was modelled according to EVS-EN 16798-1 [39] and national regulation [40]. Balanced mechanical ventilation had a constant airflow of $0.42 \text{ l/(s}\cdot\text{m}^2)$ representing typical design values for residential buildings. Internal heat gains included occupants, lighting,

and equipment. The occupancy rate was set to $0.035 \text{ occupants/m}^2$ [41], equivalent to approximately one person per 28 m^2 of floor area. Lighting and equipment loads were defined as 8 W/m^2 and 3 W/m^2 , respectively, based on standardised values in [41]. These gains followed typical daily and weekly usage schedules for residential use [38]. The outdoor climate was modelled using the Estonian TRY 1990–2020 climate file [42].

Results

Model calibration based on measurements

It was found that the modelled room temperatures corresponded quite well to the measured ones. The mean square error between measured and modelled room temperatures over the whole measurement period was 0.03°C and the maximum temperature difference was 0.36°C .

For a more detailed analysis of a test wall (Figs. 1 and 2), three days in September with high solar radiation were selected (Fig. 5, left). The measured temperature of the PCM layer reached up to 65.6°C , while the temperature behind the light-coloured facade plaster peaked at approximately 33°C . In both measured and modelled results, the temperature peaks in the PCM occurred approximately one to two hours after the facade plaster reached its maximum temperature. Due to the higher thermal mass and elevated temperatures of the PV-ETICS system, the evening cooldown period was significantly prolonged. While plaster temperatures in the traditional ETICS system approached outdoor ambient air levels around 18:00, the PV-ETICS section maintained elevated temperatures until approximately 02:00. The graphs also show a slowdown in the PCM temperature decline within the 35°C to 20°C range caused by the solidification process of the PCM granules embedded in the mortar.

In the case of the section with a light-coloured facade, the correlation between the heat flux of the IDA ICE model and the measured data was relatively good. It should be noted that, even on sunny days in September, the dominant direction of heat flux was from the interior to the exterior, indicating that, overall, the external wall finished with light-coloured ETICS is subject to net heat loss.

In the case of the PV-ETICS facade section, the afternoon heat flux through the insulation into the structural layer exceeded the heat flux from inside to outside during the night. It turned out that it was important to account for the temperature-corrected thermal conductivity of the carbon-enhanced EPS Silver to reach a satisfying correlation between measured and modelled results. When the declared thermal conductivity value measured under standard conditions ($t_{\text{mean}} = 10^\circ\text{C}$; $\lambda = 0.031 \text{ W/(m}\cdot\text{K)}$) was used, the IDA ICE model underestimated the heat flux into the structure (Fig. 5, right, red line). In contrast, using a temperature-corrected thermal conductivity value ($\lambda = 0.034 \text{ W/(m}\cdot\text{K)}$)



Fig. 3. Architectural sample of the PV-ETICS facade concept (left) and IDA ICE model. The black-surfaced PV panels cover 50% of the end wall facade surface.

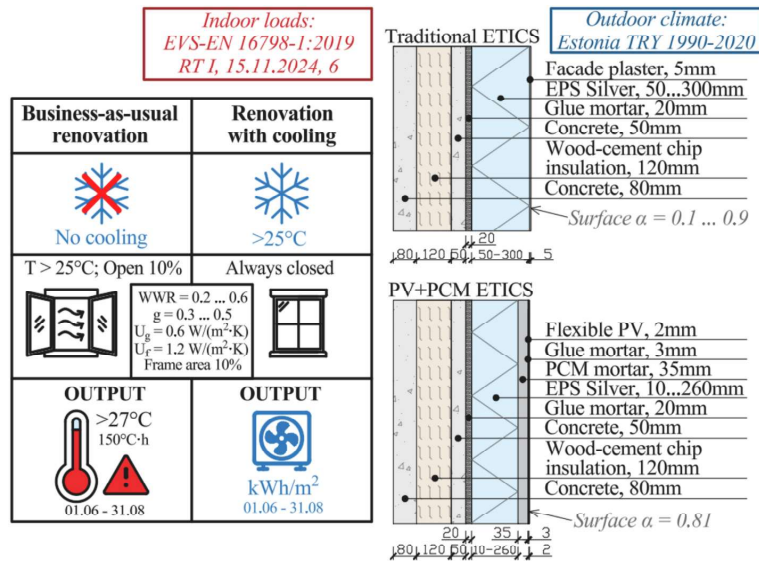


Fig. 4. Cross-sections and boundary conditions for energy modelling of the renovated apartment building.

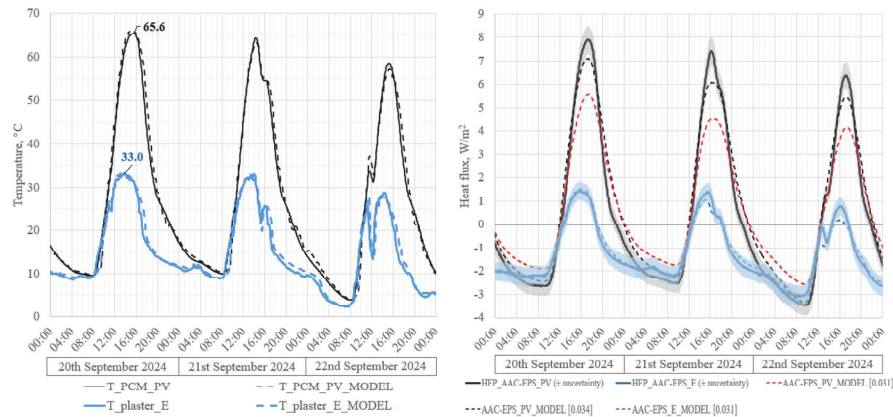


Fig. 5. Measured and modelled temperatures behind the light-coloured facade plaster and behind the dark PV panel inside the PCM mortar (left); measured and modelled heat fluxes through the EPS insulation layer into the structural layer of the test wall. Positive values correspond to heat flux from outside to inside (right).

resulted in significantly better agreement between measured and modelled heat fluxes (Fig. 5, right; black lines).

Another important aspect is the timing of when the heat flux peak values reach the structure and the indoor climate. Peak PCM temperatures were recorded at approximately 15:30 (Fig. 5, left), but peak heat fluxes on the backside of the insulation (HFP_AAC-EPS_E and HFP_AAC-EPS_PV in Fig. 2) were recorded at 17:15 (Fig. 5, right). It takes additional time for heat to transfer through the structural layer; in case of 150 mm AAC masonry (Fig. 2), the peak heat flux to the internal climate was modelled at 00:30, with positive heat flux towards the room lasting from 18:00 in the evening to 12:00 the next day.

It should be noted that both in the real wall and in the simulation model, the insulation thickness behind the PV panel differed from that of the traditional ETICS due to the design of the facade system (Fig. 2). While the thinner insulation does contribute to increased heat flux through the wall, the facade colour and PCM mortar temperature

remains a far more significant factor influencing the heat flux.

Overheating risk of renovated apartment buildings

The base case (“100 % light ETICS” in Table 1) assumed that the entire facade surface was finished with a light-coloured plaster, which is currently the most common finishing solution for these buildings. Other scenarios are compared with the base scenario in Table 1. In a scenario where the light plaster was replaced with PV-ETICS incorporating PCM (“50 % PV + PCM” in Table 1), results showed an increase of between 3 and 10 °C·h >27 °C, depending on the WWR and the g-value of the windows in the case of 200 mm thick insulation. For a typical case with a WWR = 0.4 and insulation thickness of 200 mm on the western and eastern facades, the increase ranged from 4 to 5 °C·h. These findings suggest that supplementing up to 50 % of the south-facing windowless facade area with PV-ETICS modules does not lead to significant

Table 1
Overheating degree hours >27 °C for three summer months for a renovated apartment building without a cooling system. Comparison between the base case finished with light-coloured facade plaster ($\alpha = 0.22$); a case where 50 % of the southern facade is finished with dark PV panels ($\alpha = 0.81$) on PCM mortar, and the rest of the facades have light plaster ($\alpha = 0.22$); and a case where all of the facades are finished with dark facade plaster ($\alpha = 0.80$). WWR = Window-to-wall ratio for the eastern and western facades; the south-facing facade had no windows; all shading elements were removed.

Insulation thickness (mm)		Overheating degree hours °C·h > 27°C											
		50	100	200	300	50	100	200	300	50	100	200	300
U (W/(m²·K))		0.28	0.20	0.12	0.09	0.28	0.20	0.12	0.09	0.28	0.20	0.12	0.09
WWR g-value		100% light ETICS				50% PV+PCM				100% dark ETICS			
0.2	0.3	24	31	38	41	39 ⁺¹⁵	40 ⁺⁹	43 ⁺⁹	45 ⁺⁴	73 ⁺⁴⁹	63 ⁺³³	57 ⁺¹⁹	55 ⁺¹⁴
	0.4	62	70	78	83	82 ⁺²⁰	82 ⁺¹²	85 ⁺⁷	88 ⁺⁵	127 ⁺⁶⁵	114 ⁺⁴⁴	106 ⁺²⁸	103 ⁺²¹
	0.5	113	125	139	146	141 ⁺²⁸	141 ⁺¹⁶	149 ⁺¹⁰	153 ⁺⁷	206 ⁺⁹³	189 ⁺⁶⁴	179 ⁺⁴⁰	175 ⁺²⁹
0.4	0.3	63	67	70	73	76 ⁺¹³	74 ⁺⁷	75 ⁺⁴	75 ⁺³	94 ⁺³¹	87 ⁺²¹	83 ⁺¹³	81 ⁺⁹
	0.4	120	124	130	132	135 ⁺¹⁵	133 ⁺⁹	134 ⁺⁴	135 ⁺³	157 ⁺³⁷	149 ⁺²⁵	145 ⁺¹⁵	143 ⁺¹¹
	0.5	189	195	203	205	206 ⁺¹⁷	205 ⁺¹⁰	207 ⁺⁵	209 ⁺⁴	233 ⁺⁴⁴	226 ⁺³¹	221 ⁺¹⁹	219 ⁺¹⁵
0.6	0.3	86	88	91	93	97 ⁺¹¹	94 ⁺⁶	94 ⁺³	95 ⁺²	108 ⁺²²	103 ⁺¹⁵	100 ⁺⁹	99 ⁺⁶
	0.4	153	156	160	161	164 ⁺¹¹	162 ⁺⁷	163 ⁺⁴	164 ⁺²	178 ⁺²⁵	173 ⁺¹⁷	170 ⁺¹⁰	169 ⁺⁸
	0.5	232	236	240	243	245 ⁺¹³	243 ⁺⁸	245 ⁺⁵	246 ⁺³	261 ⁺²⁹	255 ⁺²⁰	252 ⁺¹⁷	251 ⁺⁸

°C·h

+X

X - Increase in °Ch compared to light ETICS

overheating in the adjacent apartments for a typical renovation case in Estonia. However, when the additional insulation layer was only 100 mm thick, the contribution of the PV-ETICS facade to overheating began to increase. In cases with just 50 mm of added insulation, this effect becomes even more pronounced and must be considered during the design process.

Another scenario (“100 % dark ETICS” in Table 1) involved replacing the light-coloured plaster with a dark-coloured facade plaster. Results showed that in all cases, surface absorption coefficients should be considered when performing energy calculations for apartment buildings with dark-coloured ETICS facades. For example, with typical 200 mm insulation, the dark facade increased overheating between 9 and 40 °C·h, depending on the WWR and g-value.

Higher g-values lead to greater differences in overheating when the facade absorption coefficient is increased. This is due to higher solar gains through windows, which push indoor temperatures closer to the 27 °C threshold. Even a slight increase in heat flux from a darker facade can exceed this limit, amplifying the overheating risk in buildings with high g-value glazing. This should be considered in design process.

Among well-insulated facades (>200 mm insulation), one scenario (WWR = 0.2 and g = 0.5) crossed the critical overheating threshold of 150 °C·h over 27 °C after replacing light plaster with a dark alternative. These findings suggest that ETICS with dark surfaces should indeed be considered in energy performance calculations, even with thick insulation layers. Nevertheless, the associated overheating can be mitigated by selecting windows with lower g-values.

The significance of employing temperature-corrected thermal conductivity instead of the declared value was also evaluated. The differences observed when utilizing $\lambda = 0.034$ W/(m·K) for darker facade finishes instead of $\lambda = 0.031$ W/(m·K) yielded minimal increases in overheating degree hours, ranging from 0.2 to 0.7 °C·h. Consequently, in the context of typical energy calculations during the building design phase and even in most scientific applications, temperature correction of thermal conductivity values does not significantly influence the overall outcomes. Other parameters such as WWR, g-value, shading, orientation, facade colour, and insulation thickness have a much greater impact

on the results.

Impact of ETICS plaster surface absorption coefficient on overheating degree hours

For modelling overheating in dependence on the absorption coefficient of the facade (Fig. 6), no PV-ETICS was applied to the model; instead, the entire ETICS facade was finished with facade plaster featuring varying absorption coefficients and differing additional insulation thicknesses. The results show that, for traditional light-coloured facade, the number of degree hours above 27 °C increased with thicker insulation (Fig. 6). Thicker insulation decreases the thermal transmittance (U) of the wall, which traps internal and solar heat gains inside the building for longer periods.

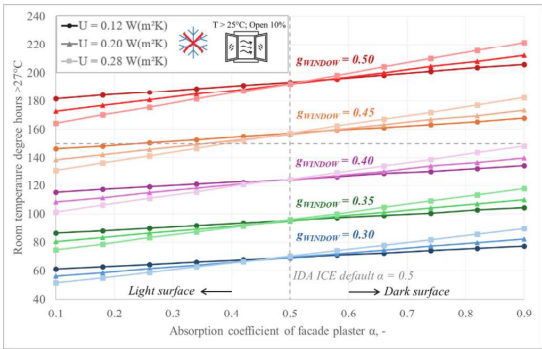


Fig. 6. Overheating degree hours as a function of the facade plaster absorption coefficient (α_s). Simulations are based on the original building geometry with balconies. $WWR_{EAST} = 0.38$ and $WWR_{WEST} = 0.35$. The thermal transmittance values correspond to a renovated apartment building with additional insulation thicknesses of 50 mm, 100 mm, and 200 mm.

However, the results show that in the case of dark ETICS facades, the situation is different. Thinner insulation on dark facades leads to more overheating compared to thicker insulation. While light-coloured plaster allows heat to flow from inside to outside, even in summer, dark facades reverse this flow, making thicker insulation more effective in reducing overheating.

With facade surface adsorption coefficient $\alpha = 0.5$ (the IDA ICE default value), the insulation thickness has a negligible impact on overheating degree hours. For light-coloured facades, using this default value instead of real α overestimates overheating, while for dark facades, it underestimates it. For example, in the case of an absorption coefficient $\alpha = 0.8$, using the default value instead of the actual absorption coefficient underestimates overheating by 6–9 °C·h with 200 mm of insulation and by 14–22 °C·h with 50 mm of insulation.

Impact of ETICS plaster surface absorption coefficient on cooling demand

Buildings with dark-coloured facades exhibited higher cooling demands compared to those with light-coloured facades (Fig. 7). The difference in cooling demand between dark and light facades decreases with increasing insulation thickness. Regardless of the surface absorption coefficient, cooling demand consistently increases with thicker insulation.

Choosing a dark-coloured facade plaster ($\alpha = 0.8$) instead of a light-coloured one ($\alpha = 0.2$) resulted in additional cooling demands over the summer of 1.5 kWh/m² for $U_{WALL} = 0.12$ W/(m²·K); 2.3 kWh/m² for $U_{WALL} = 0.20$ W/(m²·K) and 3.3 kWh/m² for $U_{WALL} = 0.28$ W/(m²·K). For a 63.4 m² apartment, this translates into an additional total cooling demand of 95 kWh, 146 kWh, and 209 kWh, respectively, throughout the entire cooling season.

Unlike the patterns observed in Fig. 6, where the convergence points of the linear trends occurred near the IDA ICE default value ($\alpha = 0.5$), the intersection point in this case shifts toward the dark facade side ($\alpha > 0.9$). This is because, in the previous scenario (Fig. 6), windows were assumed to open when indoor temperatures exceeded 25 °C, allowing passive cooling. In contrast, the simulation presented in Fig. 7 assumes windows remain closed, modelling a renovated building with a mechanical cooling system. This difference highlights an important phenomenon that should be considered when conducting energy modelling for overheating and cooling demand.

From the cooling demand calculations, it can be concluded that in cases with thinner insulation, the increased cooling demand of using dark facade plaster compared to light plaster is more pronounced.

Although facade colour has a smaller impact on cooling demand compared to WWR or the g-value of glazing, it should still be considered in design calculations for buildings with dark facades, particularly in

buildings with thinner insulation.

In addition to the total seasonal cooling demand, the daily timing of cooling loads is also relevant, particularly in relation to variable electricity pricing. The simulations showed that the greatest increase in cooling demand between sample building with light-coloured plaster, dark-coloured plaster and PV-PCM facades, was observed during the evening hours between 16:00 and 19:00. These hours coincide with peak electricity prices, meaning that even a small increase in cooling demand could be relatively expensive to offset using mechanical cooling.

Discussion

Overall, the results indicate that varying the WWR and the g-values of windows has a comparable effect on overheating and cooling demand, as reported in numerous previous studies [12,15,16]. The effect of the absorption coefficient (α) of the external boundary on cooling demand can be compared to findings from studies analysing roof surfaces of different colours.

For walls with only 50 mm of additional insulation ($U_{WALL} = 0.28$), it was found that switching from a light-coloured ($\alpha = 0.2$) to a dark-coloured facade plaster ($\alpha = 0.8$) results in a 17%–28% increase in annual cooling demand, depending on the g-value of the windows. This increase is consistent with findings reported by Synnefa et al. [22] who demonstrated a similar impact of surface absorption coefficient on cooling demand for roofs in warm climates with comparable insulation levels.

In cases with thicker insulation, the influence of facade colour is notably reduced. For example, with 200 mm of insulation, the increase in cooling demand due to switching from a light-coloured to a dark-coloured plaster surface is in the range of 7–11%.

If the ETICS facade is finished with light-coloured plaster, the study showed that thicker insulation leads to increased overheating. Several other researchers have previously reported the same phenomenon of increased overheating risk due to thicker insulation layers [18,19].

However, our results shows that if the ETICS facade is dark-coloured ($\alpha > 0.6$), the situation is reversed. Insulation protects the indoor environment from the heated facade surface (daily peak temperatures of PV-ETICS were measured over 65 °C), as the dominant heat flux is directed from the outside toward the inside. In this case, thinner insulation results in increased overheating compared to thicker insulation layers.

The reasoning behind these results was clearly observable in the physical experiment on the test house facade. Throughout the year with light-coloured facades, the dominant heat flux is from inside to outside. In contrast, for dark PV facades on sunny days, the dominant heat flux is from outside to inside. In both cases, thick insulation (i.e., lower thermal transmittance) reduces the heat flow through the internal boundary of the wall. Given the direction of heat transfer, this leads to increased overheating in the case of light facades and reduced overheating in the case of dark facades.

In comparison to a facade entirely covered with dark plaster, the PV-ETICS system produced a less severe overheating impact. This is primarily because the PV coverage is limited to 50 % of the facade area, and PV panels are only applied to the end wall.

The simulations showed that dark ETICS facades, and especially PV-ETICS facades due to their higher thermal mass, tend to increase cooling demand compared to light-coloured ETICS, particularly during the evening hours when peak electricity prices occur and PV panels are no longer generating electricity. However, this effect can be mitigated by using pre-cooling strategies to take advantage of surplus electricity generated earlier in the day or by incorporating battery storage into the PV system.

It should be noted that overheating of PV-ETICS facades can become more significant if the PV panels are disconnected from the grid and cease to generate electricity. In such cases, the surface absorption coefficient increases from $\alpha = 0.81$ to $\alpha = 0.93$, potentially raising

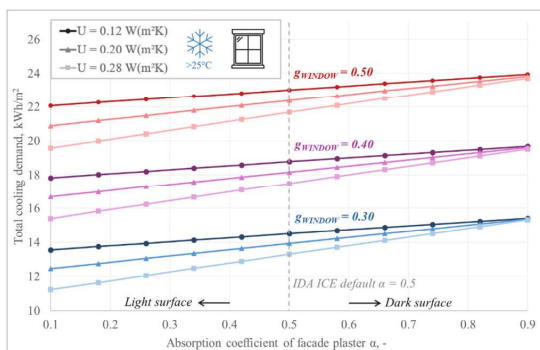


Fig. 7. Total cooling demand of the apartment as a function of the facade plaster absorption coefficient (α). Simulations are based on the original building geometry.

overheating degree hours by several degree-hours (see Fig. 6). This may occur due to PV system malfunctions or inverter shutdowns. Inverter faults are the most common failure in PV systems and can result in substantial losses in electricity output [43]. PV practitioners have reported that string inverters break down at a rate of 0.89% within their first two years of operation [44] and it is also reported that inverter reliability tends to decline with age, showing up to a 30% reduction in overall reliability over a 20-year period [45,46].

To avoid additional overheating of apartments adjacent to the PV-ETICS facades due to the inability of PV panels to generate electricity, it is important to detect system malfunctions as early as possible. Unfortunately, in apartment buildings, where PV-generated income is often channelled through the apartment building association and then redistributed among owners, malfunctioning inverters may go unnoticed for relatively long periods.

During model calibration, it was found that using a temperature-corrected thermal transmittance value for insulation yielded the best correlation between measured and simulated heat fluxes. However, applying this correction in real building simulations had minimal impact — less than 1 °C·h on overheating degree hours and under a 1.5% change in cooling demand. It should be noted that the temperature correction of thermal conductivity was applied by adjusting the material's constant λ -value, as this is the only practical approach for everyday energy modellers. In reality, the thermal conductivity of insulation increases during the day as the insulation material heats up, allowing more heat to flow inward. At night, when the heat flow is from inside to outside, the thermal conductivity of insulation decreases, providing greater resistance to heat loss. While a dynamic thermal conductivity model would likely result in slightly higher overheating, the difference is still expected to be marginal and not significant enough to warrant more detailed modelling in everyday engineering or in most scientific applications.

This study has certain limitations that should be considered when interpreting the results. The full-scale experiment and simulations were conducted on a single facade orientation. While this orientation was deliberately chosen for its critical solar exposure, it is not the most economically efficient direction for applying FIPV. Second, the analysis focused on a specific apartment within a particular building type. Although this building type is representative of many Soviet-era apartment buildings currently in need of renovation, its relatively large windowless wall surface may exacerbate overheating caused by heat flow through the ambient wall.

Third, the simulations relied solely on the Estonian TRY 1990–2020 weather file, which is required for national energy performance calculations. Analysing other locations or using future climate scenarios would provide broader insight into the long-term applicability and performance of PV-ETICS systems under varying climatic conditions, which could be explored in future research. Lastly, since the main focus was on the thermophysical effects of implementing PV-ETICS on renovated facades, the thermo-electrical performance of the PV system was not examined in detail. Future studies should consider integrated simulations that account for both energy production and cooling demand, enabling the optimization of PV sizing and pre-cooling strategies to maximize self-consumption and minimize peak-hour energy use.

In summary, the additional cooling demand and overheating degree hours associated with switching from light plaster to a PV-ETICS system are relatively modest in the case of thick insulation. This supports the potential of PV-ETICS as a viable solution for the renovation market, even for buildings without active cooling systems. The thermal impact is not severe enough to warrant excluding the system from design recommendations. However, dark facade surface should be taken into account when conducting energy modelling.

Conclusions

Based on the results, following conclusions could be made:

- 1) **IDA ICE can accurately replicate measured heat fluxes through ETICS with dark surface and external PCM.** Agreement between modelled and measured values improved further when temperature-corrected thermal conductivity was applied to the insulation layer.
- 2) **PV-ETICS facades only slightly increase the overheating risk in renovated apartment buildings.** The integration of PV-ETICS systems on 50 % of the southern facade area was found to modestly increase the overheating risk of a typical renovated apartment building in Estonia's climate without active cooling. On average, this system added between 3 to 10 °C·h above 27 °C for cases with a typical insulation thickness of 200 mm ($U_{WALL} = 0.12 \text{ W}/(\text{m}^2\cdot\text{K})$).
- 3) **Dark-coloured ETICS facades exacerbate indoor overheating.** Depending on window geometry and glazing g-values, an increase in the plaster's absorption coefficient from 0.2 to 0.8 resulted in an additional 9 to 40 °C·h above 27 °C for cases with an insulation thickness of 200 mm.
- 4) **Thicker insulation behind dark ETICS facades helps to reduce overheating.** Contrary to the common assumption that thicker insulation increases overheating, results indicate that in the case of dark-coloured facades, thinner insulation led to greater overheating than thicker insulation.
- 5) **PV-ETICS systems do not significantly increase summer cooling demand.** In apartment buildings with mechanical cooling and 200 mm insulation, PV-ETICS facade systems increased total cooling demand by an average of 20 kWh for the whole summer compared to light ETICS. However, 40 % of this additional cooling demand occurred in the evening hours when there was no more solar energy production from PV facades.
- 6) **Covering the entire facade with dark-coloured plaster increases cooling demand more significantly than the PV-ETICS solution.** Using dark facade plaster ($\alpha = 0.8$) instead of a light-coloured one ($\alpha = 0.2$) resulted in an additional total cooling demand of 95 kWh, whereas the PV-ETICS solution increased the cooling demand by 20 kWh.

The study demonstrates that while PV-ETICS and dark-coloured traditional ETICS increase the risk of indoor overheating, this effect is moderate in buildings with thick insulation and can be effectively mitigated during the building design process. The dark facade surface of ETICS must be considered in practical energy modelling, but it is not a limiting factor for the large-scale adoption of PV-ETICS in renovation projects. These findings help eliminate another barrier to the wider implementation of PV-ETICS, showing that renovated apartment buildings in cold climates can feasibly adopt PV-ETICS without causing severe overheating of the indoor environment.

CRediT authorship contribution statement

Martin Talvik: Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Simo Ilomets:** Writing – review & editing, Methodology, Conceptualization. **Targo Kalamees:** Writing – review & editing, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.seta.2025.104452>.

Data availability

Data will be made available on request.

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Supplementary data

Annex 1. Material properties for the external walls.

	Thermal conductivity λ , W/(m·K)	Density ρ , kg/m ³	Specific heat c , J/(kg·K)	Absorption coefficient α , -
Concrete	2	2300	880	-
Wood-cement chip board	0.07	350	1470	-
AAC	0.133	450	950	-
Adhesive Mortar	0.21	707	945	-
Carbon enhanced EPS	0.031 (see Annex 2)	14	1350	-
PCM Mortar	0.63	1200	According to u(T) function [5]	-
Facade Plaster System	0.7	1365	1000	0.30 (light) 0.80 (dark)
PV Panel	8	1160	1000	0.81

Annex 2. Measured average thermal conductivity of carbon enhanced EPS on various temperatures, comparison with theoretical values.

Average temperature of insulation, °C	Measured thermal conductivity, W/(m·K)	Calculated thermal conductivity [34], W/(m·K)
10.0	0.0307	0.0307 (base value)
30.0	0.0329	0.0326
62.5	0.0365	0.0359

Appendix 5 – PV ETICS application guidelines

These instructions guide you through the installation process of a long-lasting, elegant and sustainable PV-ETICS facade that will serve your building for many years.



APPLICATION REQUIREMENTS

Substrate

Only mineral structural layers are allowed. Remove any weak, flaking or chalking layers or coatings. The substrate must be clean and free of dust, ice, efflorescence, and any other substances that impair adhesion.

Check the initial moisture content of the substrate layer according to the facade plaster system manufacturer's requirements.

Climate conditions

Work only when air and substrate $> +5^{\circ}\text{C}$. Avoid strong wind, direct sun and rain. Protect the work area using scaffold sheeting/covers.

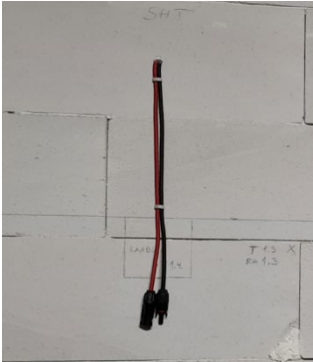
Keep conditions at least 3°C above dew point; low temperatures or high humidity extend curing.

Competency

PV system installation (cabling; connecting/removing PV panels; final inspection and documentation) must be carried out by a qualified electrician.

Application of PCM mortar and facade plaster should be carried out by trained ETICS facade contractors following all the facade system manufacturer's guidelines.

EXTENSION CABLES AND INSULATION



1. PV Cabling

Install DC cables for PV panels on the structural wall. Apply cables in strings. Use MC4 extensions; leave ~150 mm slack.



2. Insulation

Install ETICS insulation. Behind each PV use a thinner board (40 mm less than surrounding). Cut a 100×100 mm cable opening at top.



3. First steel sheet

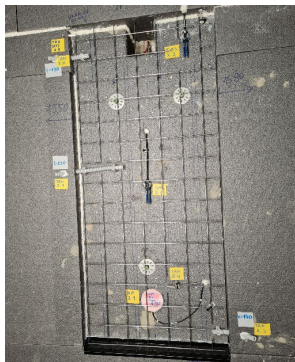
Cut the lower cavity edge to a 1:10 slope; set the lower steel sheet with PU glue foam. Tape and let cure.

REINFORCEMENTS



4. Grip tape

Apply 30 mm anti-slip tape to the first steel sheet to improve adhesion with PCM mortar.



5. ETICS anchors

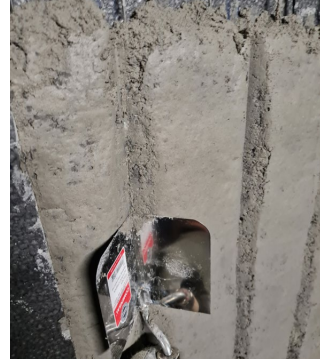
Install standard ETICS anchors. Per PV add ≥3 special anchors; leave them 15–20 mm proud; avoid damaging the cabling.



6. Fix reinforcements

Use 75 × 75 × 2.5 mm steel mesh as reinforcement, positioned 15–20 mm from insulation. Tie the mesh to the special anchors with wire.

APPLICATION OF PCM MORTAR



7. Mix ingredients

Mix a 25 kg bag of *Sto-Faserputz* with 7,5 l of water. Stir with a mechanical mixer >2 min. Wait about 5 min and add 16,5 kg of PCM granule mixture. Stir again >2 min.

8. Apply PCM mortar

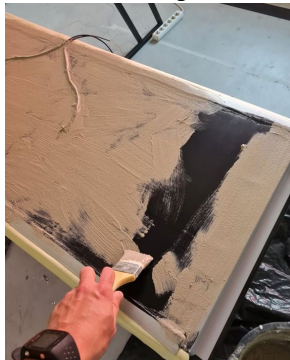
Fill insulation cavity with PCM mortar; keep a clear cable recess at the top (see step 14).

9. Cut channels

While workable, groove 15 mm deep diffusion channels into PCM mortar using an angled masonry trowel. 4 channels per PV panel.

PREPARATION AND APPLICATION OF PV PANELS

Proceed only after PCM mortar has dried ~14 days at 20 °C / 50 % RH. In colder and more humid conditions, drying time needs to be longer.



10. Fix steel on PV back

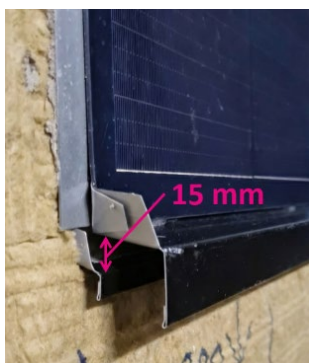
11. Primer on PV back

12. Apply glue to PV

Bond the second (drip) steel sheet to the lower edge of the PV and 20 mm steel ribbons to sides/top for plaster profiles. Use a single-component elastic polymer adhesive suitable for –30 °C ... +85 °C service.

Mix 20% cement (e.g., CEM I 32.5) into *StoPrep Contact* and stir. Brush the mixture evenly onto the PV back side and allow to set 24 h.

Apply *StoColl Mineral HP* glue mortar with a 6 mm notched trowel onto the primed PV back.



13. Press PV on wall

Attach PV to the PCM mortar, pressing from the bottom upward. Maintain 15 mm gap between two lower steel sheets.



14. Connect PV cables

Ease the top edge slightly, mate MC4 connectors until both click.

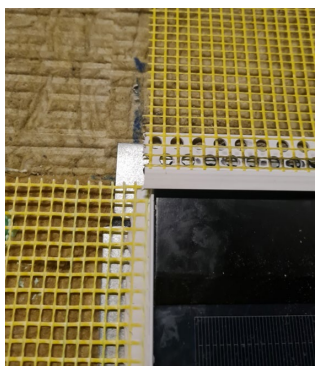


15. Fill cable cavity

Fill the 100×100 mm opening with low-expansion PU foam. Provide a small hole at the top to relieve pressure.

APPLICATION OF FACADE PLASTER SYSTEM

The PV-ETICS system has been tested only with an ETICS kit using *StoArmierungsputz* as the reinforcement plaster and *StoSilco MP* as the finishing plaster. Use with other ETICS is permissible only after written confirmation of compatibility from the facade plaster manufacturer.



16. Perimeter profiles

Fix elastic facade profiles to the steel ribbons around the PV. The upper drip nose



17. Plaster system

Apply reinforced facade plaster system according to manufacturer's



18. Perimeter sealant

Seal between PV and facade profiles with a

must overlap the vertical guidelines. Add 45° mesh weather-resistant elastic profile edge. patches at all PV corners. PU sealant.

Commissioning

Connect PV strings to inverters, perform all the necessary commissioning tests and inspections. Complete all handover documentation required by local standards and the grid operator.

Appendix 6 – PV panel replacement guidelines

Use these guidelines when a PV panel must be replaced while the facade plaster system remains intact.

All electrical work must be carried out by qualified personnel. Before starting the removal, switch off the inverter's AC supply and isolate the affected DC string.

REMOVING MALFUNCTIONAL PV



1. Cut edge sealant

With a sharp knife, cut the weather-resistant sealant between the PV panel and the facade profiles along both sides and the top edge.



2. Detach lower edge

Insert a thin chisel at the bottom edge and lever the PV panel away from the PCM mortar.



3. Pull PV at bottom

Work along the lower edge, pulling the panel outward by hand to break the bond to the PCM mortar.



4. Full removal of PV

From bottom-to-top, use a suction lifter to peel the panel away with steady force. Support the facade plaster profiles and the fixed steel ribbons.



5. Disconnect MC4

Open the cable recess, clear PU foam to expose the connectors and unclip the MC4 pair. Clear additional foam to free the leads.



6. Repair sub-surface

If the adhesive or PCM mortar is damaged, patch-repair with *Sto-Faserputz* and allow to cure. Do not fill diffusion channels behind adhesive.

Note: If the new PV panel cannot be installed immediately, fit a short MC4 jumper bridging the string leads. Leave the string isolated from the inverter until the replacement panel is installed and all tests are complete. Protect the exposed PCM mortar from precipitation.

ATTACHING NEW PV

- Prepare the new PV panel by following steps 10 and 11 of the Application Guidelines (Appendix 5). Do not add new steel ribbons at the edges, as these are already on the wall.
- Pre-test the panel electrically before installation. Connect the panel's MC4 connectors to the wall extension leads. Reconnect the inverter's DC and AC sides in the order specified by the inverter manufacturer. Check the system for any malfunctions. After testing, disconnect both AC and DC and remove the temporarily connected panel.
- Install the new PV panel in the same position as the original, following steps 12 to 15 of the Application Guidelines.

Note: As the old adhesive remains and the new adhesive adds 2-3 mm thickness, efficient perimeter seal geometry can still be achieved after the first replacement. If more than two replacements occur at the same location before end-of-life of the facade plaster, old adhesive must be removed from the substrate to restore initial thickness of PV-PCM cross-section.

Appendix 7 – Suggestions for design refinements in TRL 6

Two years after the measurement period ended, both test walls were deconstructed. The deconstruction revealed several technical details that should be refined in future product development to improve the durability of the system.

A7.1. PV connectors should not be inside PU insulation

After removal of the PV panels, significant embrittlement and cracking of the MC4 connector housings was observed, especially in the external test wall after approximately three years of service (Figure A7.1, left). Similar but less severe deterioration was also found in the climate chamber test wall after four years (Figure A7.1, right). In both cases, the connectors were no longer suitable for reuse.

The most likely cause was the location of the connectors inside the PU insulation, which may have led to elevated humidity, temperature fluctuations, and reduced heat dissipation during operation. These conditions can accelerate ageing of plastic components and may increase the risk of overheating.

Electrical connectors should not be placed directly inside PU insulation without additional protection. In future designs, one of the following solutions should be used:

- locate the connectors in an air-contact cavity, for example at the lower part of the PV panel to enable connection to the external environment through the gap between two steel sheets;
- use sealed protective enclosures designed for electrical components;
- select or design connector systems suitable for installation inside insulation.

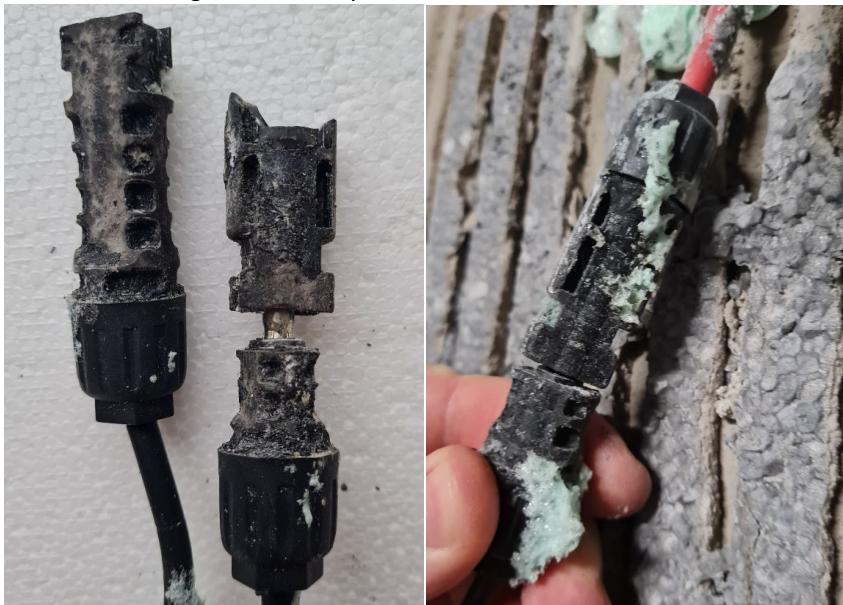


Figure A7.1. Condition of MC4 connectors after removal from the external facade after three years of service (left), and from the climate chamber test wall after nearly four years (right).

A7.2. Ribbon width should match the facade plaster profile in PV-plaster joints

In the test walls, zinc-coated 0.8 mm steel sheet ribbons were attached to the back side of the PV panel with elastic sealant. This avoided bonding the facade plaster profiles directly to the PV panel to create design-for-disassembly joints.

However, the steel ribbons used in the test walls were slightly wider than the starter profiles of the facade plaster system.

No cracking at the PV-plaster joint was observed during the climate chamber test or during the real-environment experiment up to the end of the two-year warranty period. However, a year after the long-term experiment had ended, cracks were observed near the upper corner of the PV panel (Figure A7.2), and local stress concentration at the ribbon edge may have contributed to their formation.

In future designs, the ribbon width should match the width of the plaster joint profile, especially the elastic double-sided adhesive tape, approximately 9 mm. This would reduce stress concentration in the plaster layer and minimise the risk of cracking at the joint edge.

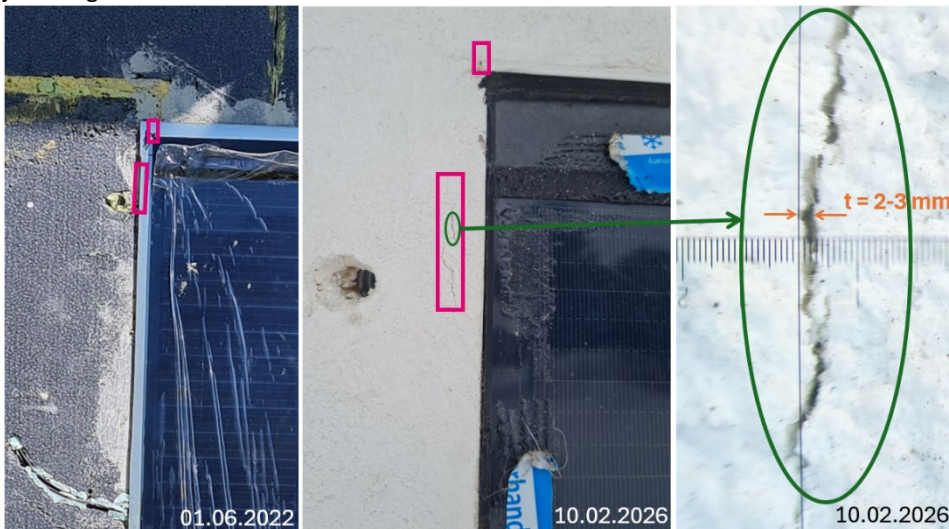


Figure A7.2. Cracks observed in the facade plaster near the PV-plaster joint. The larger crack was up to 3 mm wide at its widest point.

A7.3. Corrosion-resistant material should be used for the PV- plaster joint

Corrosion was observed on the zinc-coated steel sheet profiles at the joints between the PV panels and the facade plaster after the wall was opened (Figure A7.3). The corrosion was located beneath areas where small cracks had previously been observed at the boundary between the facade plaster and the PV panel. This indicates that wind-driven rain may have penetrated through the cracks. Other areas along the perimeter were free from corrosion.

In future designs, the joint component should be made from a corrosion-resistant material. Stainless steel is one suitable option, but the component does not necessarily have to be made of steel. Plastic or another durable, non-corroding material may also be used if it fulfils the mechanical and detailing requirements of the joint.



Figure A7.3. Signs of corrosion on the zinc-coated steel sheet ribbon after removal of the PV panel on 10.02.2026.

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