# Publishable Summary for 21GRD03 PaRaMetriC
# Metrological framework for passive radiative cooling technologies

## Overview

Cooling systems account for nearly 20 % of electricity consumption and 10 % of greenhouse gas emissions, globally. With demand for cooling expected to grow tenfold by 2050, and the increasing frequency of extreme heat waves, improving the efficiency of cooling systems plays a critical role in addressing the global climate challenge. Passive Radiative Cooling (PRC) materials that can dissipate heat as infrared radiation have recently emerged. This project aims to develop a comprehensive metrological framework, including standardised performance indicators (i.e. figures of merit) and testing protocols, to enable the comparable evaluation of their cooling performance on-site and determination of the potential energy savings that could derive from the deployment of such technologies.

## Need

The annual cost of heat-related issues is estimated at about $2.4 trillion, with cooling systems costing an estimated $300 billion and producing 1 Gt of $CO_2$ per year. By 2050, the additional energy needs related to cooling are expected to surpass the total electricity use of China and India today, combined. This is often referred to as one of the most critical blind spots in today's energy debate, given that the rising demand for cooling will add an enormous strain on the electricity systems of many countries, driving up emissions and triggering a self-aggravating feedback loop.

PRC materials can dissipate heat through the infrared transparency window (8 µm – 13 µm) without using any electricity, using outer space as a cold and renewable thermal energy sink to reach sub-ambient temperatures even under direct sunlight owing to their tailored optical and infrared photonic properties.

Despite hundreds of promising PRC coatings and devices demonstrated in the literature in the past few years, reliable testing protocols to evaluate their cooling performance have not been established yet, which is a major obstacle hindering the further development and commercialisation of this new technology. Typical tests up to now are limited to measuring either a temperature drop or cooling power with a heater, using improvised testing rigs with inconsistent insulation and shielding properties, unspecified thermal loads and under different atmospheric conditions, altitudes, ambient temperatures, etc.

Defining standardised figures and testing protocols requires the development of a new conceptual framework and a highly multidisciplinary approach improving both the modelling and the characterisation of emissivity and reflectance properties of thin coatings over a broad wavelength range, the realisation of benchmark systems with known properties, the calibration of portable instruments for on-site monitoring, as well as models accounting for the impact of atmospheric and geoclimatic conditions on the expected cooling potential and the design of standardised testing apparatuses with known thermal loads and insulation.

## Objectives

The overall goal of this project is to establish a metrological framework for comparable performance assessments of passive radiative cooling technologies. The specific objectives of the project are:

1. To develop the conceptual framework for comparable performance assessments of passive radiative cooling technologies. This will include the preparation of candidate benchmark PRC materials and



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preliminary characterisation of their spectral responses, with a view to selecting a subset. Additionally, to define one or more figures of merit to assess the performance of PRC materials.

2. To develop and validate numerical models to correlate the cooling performance of PRC materials with the thermal and optical properties of their components, and thus to establish their specifications and associated tolerances. This will include carrying out the thermal infrared spectral modelling of the radiative exchanges between PRC materials, the atmosphere and space at different zenith angles for calculations of the net cooling power of the materials. Additionally, to evaluate the potential impact of PRC materials on energy savings and heat-island effect for urban environments in different climatic regions of Europe.
3. To develop accurate and traceable approaches for determining the thermophysical properties and thermal conductivity of PRC materials, and for converting measured radiometric quantities into a usable form for heat balance calculations. The reflectance and emittance will cover a broad spectral range (0.25 µm – 50 µm) encompassing the solar spectrum and the infrared transparency window of the atmosphere (8 µm – 13 µm). The target uncertainties will be below 3 % for emissivity and absorptivity, 5 % for the total hemispherical emissivity and below 10 % for the thermal conductivity.
4. To develop setups and protocols for on-site testing of PRC materials, with a target uncertainty below 10 % for the figures of merit.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (testing laboratories), standards developing organisations (CEN/TC 89) and end users in the commercial and residential sectors.

**Progress beyond the state of the art and results**

*Figures of merit tailored to passive radiative cooling materials and reproducible model systems*

To date, figures of merit to evaluate the cooling performance of a PRC coating are either based on intrinsic material properties, the temperature difference between the substrate and ambient air, or the cooling power of the radiator at ambient temperature. All these quantities are severely affected by ambient, atmospheric and geoclimatic conditions, failing to predict cooling performances under different solar irradiance or relative humidity levels, or to differentiate between broadband and selective emitters. Other parameters typically used for traditional cool-roof applications, such as the Solar Reflectance Index, suffer from similar shortcomings as they were designed for a different class of materials.

The project partners have identified a list of figures of merit that have been used in the literature up to date, along with the relevant environmental parameters that should be monitored. Technical reports on the types, applications and testing conditions of PRC materials have been shared and discussed with stakeholders and technical committees to identify the most relevant aspects. In the meantime, several candidate PRC materials have been directly fabricated by the project participants or collected from both academic and industrial stakeholders and collaborators. The available samples comprise several different types of PRC materials, ranging from paint-like formulations to porous polymer coatings, multi-layer films and mirror-like structures. Notably, preliminary tests performed with different types of materials at different partner institutes confirmed the observation of a net sub-ambient cooling action exerted during daytime hours, even without a convection shield. In the continuation of the project, particular attention will be paid to the reproducibility of the PRC materials, which is typically better for industrially manufactured products and/or PRC materials made of few components.

*Multi-scale modelling of PRC composite materials*

Modelling of PRC materials is a complex task involving several disciplines, numerical tools and length scales which span across several orders of magnitude in size, requiring research efforts beyond the reach of single institutes. Moreover, high-performing PRC materials are often hierarchical disordered materials, which is particularly challenging for numerical approaches often limited to 2D approximations.

Understanding the cooling performance of PRC materials requires modelling activities over multiple systems and scales. Numerical studies are being conducted in the project, concerning the optical response of multi-layered materials in the solar and thermal infrared wavelength range, or the thermal insulation required for the measurement test boxes. Heat balance models allow the simulation of the yearly energy needs for heating and cooling of typical buildings, as well as their thermal behaviour when cooled by a heat pump associated with a PRC emitter. On an even larger scale, models used up to date in the literature for quantifying the radiative exchanges between a PRC material, the Earth atmosphere and outer space have been reviewed. This led to the selection of a radiative transfer model which allows the calculation of radiative heat fluxes in spectrally resolved modes while taking into account the vertical distribution of atmospheric temperature and components (water vapour, ozone, etc.), improving over approaches relying only on ground-level environmental conditions.

*Optical and thermal characterisation of thin, composite materials*

Thermal characterisation of sub-mm composite coatings is particularly challenging for state-of-the-art methods used to measure thermal conductivity, such as the Guarded Hot Plate or Heat Flux Meter. More flexible, transient methods need to be examined and validated for this purpose. Similarly, routinely used methods to measure the emissivity of building materials rely on commercial instruments measuring directional emissivity values. However, heat balance calculations relevant to PRC materials require the total hemispherical emissivity, which must be either measured directly or extrapolated from directional measurements using validated methods. Similarly, the angular dependence of the emissivity of PRC devices needs to be evaluated to determine the best relative orientation between the radiating panels and the sky. The EMPIR project 16NRM06 EMIRIM, focused on the measurement of total hemispherical emissivity of the reflective foils used as the skin of thermal insulation products for buildings, demonstrated that the extrapolation of total hemispherical emissivity from near-normal emissivity is not well controlled in terms of uncertainty. Such uncertainty could be even less controlled for PRC materials due to their heavily “optically structured” coating.

Preliminary spectral characterisation of a few paint samples and PRC films has been conducted to evaluate their emissivity and selectivity in the infrared transparency window of the atmosphere (8 μm – 13 μm) using a reference technique based on direct blackbody comparison. Two PRC films in particular have been found to exhibit strong and selective emissivity within the atmospheric transparency window, and have been characterised from different observation angles to evaluate both their directional and hemispherical emissivity. Other promising materials will also be tested in the continuation of the project. At the same time, methods for the conversion of near normal emissivity into hemispherical emissivity have been revised, and will be applied to the measured data to verify their applicability to different types of PRC materials. In fact, PRC materials can be characterised by very different surface finish types, spanning from highly specular to diffuse white, which must be taken into account during spectral measurements. A set of identical metal substrates has been prepared, on top of which the first candidate materials will be applied and distributed among the participants for their further spectral characterisation.

*Testing protocols to assess the performance and energy savings deriving from PRC materials*

The cooling performance of PRC materials is typically measured using improvised testing rigs under shielding and thermal insulation conditions that are difficult to reproduce and not relevant for real applications, where realistic thermal loads and direct exposure to ambient conditions should be considered. Furthermore, testing of PRC materials should include intense heat conditions and monitoring campaigns spanning months rather than hours/days, which is rarely the case in the literature.

The design of the 4 planned experimental setups for the on-site measurement of the cooling performance of PRC materials has started, based on the output of numerical simulations on the thermal insulation required and the thermal mass. Information on methods, sensors and devices used to measure several parameters was collected among all participants through a survey, with a particular focus on the metrological characteristics of temperature sensors which is needed to accurately measure small temperature variations and correlate them with ambient conditions. This information is intended to ease the selection of sensors among the partners that will build the characterisation set-ups, and will serve as a metrological framework for the testing approaches, monitoring and evaluation of PRC materials. Additionally, two collaboration agreements have also already been signed with two European universities interested in improving their on-site characterisation with better insulation and more accurate sensors. The size of the small (< 0.01 $m^2$) and medium-scaled (between 0.25 $m^2$ and 0.5 $m^2$) set-ups has been defined, as well as their intended application for the cooling of either an air volume, or a water flux.

**Outcomes and impact**

The project partners have been engaging in a significant number of dissemination and communication activities aimed at scientific, metrological and industrial end-user communities since the beginning of the project. The project has been presented to several national standardisation technical committees and EURAMET Technical Committee for Thermometry, collecting their feedback. Project objectives and preliminary results have been presented at 5 national and international conferences aimed at the scientific/technical communities, as well as to organisations active in the field of refrigeration, air conditioning and heat pumps, which expressed a particular interest in alternative and more sustainable cooling technologies due to the increasingly stringent regulations and the need to increase the efficiency and reduce the operating costs of refrigeration appliances. Additionally, a pitch presentation on the project was given during the EIC Pathfinder Challenge: Clean and efficient cooling information day. Thanks to its broad visibility, the project is attracting the interest and support of several stakeholders and external collaborators, which resulted in the publication of two scientific publications addressing material science aspects of novel PRC materials. Additional dissemination and communication activities are targeted towards students, by holding seminars and offering master and PhD theses on the emerging topic of passive radiative cooling, and with the organisation of a Winter School on polymers, photonics and nanofabrication held in the first quarter of the project. Finally, the project is supporting the action of the external Cool White project aimed at improving the thermal comfort conditions inside schools and factories in Rwanda and South Africa, by testing and suggesting improvements on the locally available white paints. All project outputs and related events are promoted on the project website and posted on social media to further engage with additional stakeholders interested in the emerging field of PRC materials.

*Outcomes for industrial and other user communities*

This project will establish a shared framework for the performance assessment of passive radiative cooling technologies fostering the development of new energy-saving materials and providing a competitive advantage to EU companies in this emerging field. Companies in the building sector will be able to review their product portfolio in terms of the radiative cooling performance and to develop improved materials and coats based on well-defined figures of merit and standardised protocols for their evaluation. Similarly, industries in the HVAC sector will be able to quantify the expected performance boost and energy savings deriving from the synergic combination of active and passive cooling technologies. End users in both communities will further benefit from the guidelines developed within the project for the validation of emissivity measurements with portable instruments and from the identification of a benchmark material exhibiting near unity emissivity for the calibration of such devices. The consortium will continue to actively seek the engagement of stakeholders in industry, leveraging on the network of contacts of participants with trade and industrial associations, which will be targeted with dissemination activities.

*Outcomes for the metrology and scientific communities*

In the past few years, the scientific community has expressed the need to develop and define standardised testing conditions to assess the cooling performances of emerging PRC materials. Several critical points will be addressed within the scope of this project, including the need to account for different atmospheric conditions, different/extreme geoclimatic regions, and the lack of established figures of merit. By developing validated testing protocols and the expertise to evaluate PRC materials, the metrological community will be able to fulfil the needs of researchers in the scientific community seeking standardised testing and facilities to benchmark the performances of their proposed materials in an objective and reproducible way against well-characterised references.

*Outcomes for relevant standards*

The output of the project will contribute to the improvement of standardisation in the field of energy performance of building standards. The whole set of standards, starting from EN ISO 52000 “Energy performance of buildings - Overarching EPB assessment - Part 1: General framework and procedures” and those dealing with the performances of the building envelope developed under EC Mandate M/480 will be analysed and a list of possible adjustments, amendments, integrations will be proposed to the relevant standardisation bodies to foster the introduction of PRC technologies within the Energy Performance of Buildings Directive (EPBD) framework. Input to technical committees engaged in several fields such as the energy performance of buildings, thermal insulation, thermal performance and energy efficiency will also be provided, including CEN/WS 107 on “Mitigation of Urban Heat Island effects with cool materials”, developed by CEN under

AFNOR and ECRC leadership, whose CEN Workshop Agreement will be further analysed as a pre-normative document aiming at the integration based on the emerging PRC technologies. Efficient dissemination and uptake of the project's results will be ensured by the direct involvement of several consortium members in the relevant technical committees.

*Longer-term economic, social and environmental impacts*

Due to the energy intensive nature of cooling, which is responsible for 20 % of electricity consumption and 10 % greenhouse gas emissions globally, any technology optimising its efficiency will necessarily have long-term economic, social and environmental impacts.

Regarding social and health aspects, heat-related stress is known to affect human well-being and mortality with an associated risk that escalates rapidly with temperature. Especially in urban environments, increasing the albedo of buildings and roofs with PRC coatings can help curb the heat-island effect. The length, frequency and intensity of heat extremes is constantly increasing, causing tens of thousands of premature deaths in Europe each year, especially in vulnerable population groups. The emergence of space-cooling as a basic need could exacerbate energy poverty, especially for low-income households, while the inherently passive, all-day, electricity-free nature of sub-ambient radiative cooling offers opportunities for off-grid access to cooling power, thermo-electric generation and daytime solar water harvesting and purification.

On the environmental side, in addition to the benefits deriving from reduced freshwater and electricity consumption, this project also aims at tackling less explored but equally relevant aspects related to the introduction of new materials such as a life-cycle assessment of the different alternatives aimed at evaluating their sustainability and durability to weathering agents, which is especially relevant due to their inherently outdoor application.

### List of publications


1. Li, X., Ding, Z., Kong, L., Fan, X., Li, Y., Zhao, J., Pan, L., Wiersma, D.S., Pattelli, L. & Xu, H. (2023). Recent progress in organic-based radiative cooling materials: fabrication methods and thermal management properties. *Materials Advances* 4, 804-822. https://doi.org/10.1039/D2MA01000C

2. Li, X., Ding, Z., Lio, G. E., Zhao, J., Xu, H., Pattelli, L., Pan, L. & Li, Y. (2023). Strain-adjustable reflectivity of polyurethane nanofiber membrane for thermal management applications. *Chemical Engineering Journal*, 461, 142095. https://doi.org/10.48550/arXiv.2302.13043


This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

| Project start date and duration: | 1 October 2022, 36 Months | |
|---|---|---|
| Coordinator: Lorenzo Patelli, INRIM<br>Project website address: https://parametric.inrim.it/ | Tel: +39 055 457 2477 | E-mail: l.pattelli@inrim.it |
| Internal Beneficiaries:<br>1. INRIM, Italy<br>2. Aalto, Finland<br>3. CMI, Czechia<br>4. CSIC, Spain<br>5. DFM, Denmark<br>6. LNE, France<br>7. PTB, Germany<br>8. RISE, Sweden<br>9. TUBITAK, Türkiye | External Beneficiaries:<br>10. CNR, Italy<br>11. CP, Spain<br>12. CTI, Italy<br>13. FIW, Germany<br>14. NKUA, Greece<br>15. POLITO, Italy<br>16. ZAE Bayern, Germany (withdrawn from 31 December 2022)<br>17. CAE, Germany (joined from 1 January 2023) | Unfunded Beneficiaries:<br>18. ALMECO, Italy |