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Experimental Monitoring of an Air-to-Water Heat Pump Working with Low-GWP Refrigerant in a Zero Energy Building as Basis for AI Optimization

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Abstract: Heat pumps are widely recognized as the most cost-effective solution for decarbonizing the building sector. Their ability to provide both heating and cooling with a single system is especially relevant in today’s context of rising temperatures due to global warming. This work describes a new experimental setup and presents initial results on the performance of an air-to-water heat pump operating with the low-GWP refrigerant R454B in a pilot Zero Energy Building. The system has been equipped with research-grade instrumentation to monitor key parameters in both the refrigerant and hydraulic loops. This paper presents the monitoring system and a thermodynamic model of the building based on RC analogy, which will be compared to the experimental data. These experimental results and the thermodynamic model will serve as the basis for training an AI tool dedicated to the optimal energy management of complex renewable energy systems, from single buildings to energy communities.

Keywords: Zero Energy Building; Experimental monitoring; Heat pump; Thermodynamic models; AI optimization

1 Introduction

The new Energy Performance of Building Directive (EPBD IV), published in 2024, imposes the ambitious goal of decarbonising Europe’s building stock by 2050, through national plans for zero-emission renovation of the residential and non-residential building stock [1]. Among the possible ways to achieve this goal, the electrification of the built environment represents an important driver; in fact, electrification consists in replacing fossil-fueled technologies with devices powered by renewable energy sources, thus leading to a reduction in climate-changing emissions [2]. European directives [1, 3] emphasize the role of heat pump technology in integrating renewable energy for heating and cooling. In 2022, nearly 20 million heat pumps were installed across Europe—with France and Italy leading the adoption—yet gas boilers still dominate the market, accounting for about 84% of installations. This disparity poses a significant challenge to meet the sustainability targets established by the Paris Agreement [4–6].

The combination with renewable energy production systems such as photovoltaics, coupled with energy storage systems, is an effective solution to reduce building consumption, maximise self-consumption and minimise costs by taking advantage of any available incentives [7]. Moreover, these technologies find wide application in the context of Renewable Energy Communities (RECs) [8].

In response to the growing complexity of contemporary energy systems and the temporal mismatch between building energy demands and peak photovoltaic output, the implementation of dedicated control strategies is indispensable. Such strategies are pivotal for optimizing on-site energy utilization and, in turn, realizing both energy and cost savings. The integration of electrical and thermal storage technologies plays a key role in effective energy management, as these storage solutions enable decoupling of energy generation from consumption. In this framework, the Zero Energy Building laboratory (LAB-Zeb) at the Construction Technologies Institute of the National Research Council (ITC-CNR) in San Giuliano Milanese functions as a living laboratory for the evaluation of advanced building-sector innovations [9]. Equipped with photovoltaic arrays, solar thermal collectors, heat pumps, and battery systems, the facility has been instrumented—under the PNRR-funded RAISE project [10]—with a research-grade monitoring platform that records HVAC temperatures, heat fluxes, and the electrical consumption of all installed components.

Advanced control strategies should optimize the processes of energy production, storage and utilization. To achieve this, a reliable but fast forecast is required for all the main energy loads. For this reason, the thermodynamic models of building based on the electrical resistance-capacitance (RC) analogy can offer an interesting trade-off between accuracy and complexity [11, 12].

This paper describes in detail the new monitoring system installed in the LAB-Zeb and presents a new thermodynamic model of the building, based on the electrical RC model and validated against TRNSYS. The experimental data and the RC model will be the basis for training a control system adopting AI techniques to optimize the energy management of complex systems, from single buildings to energy communities.

2 Monitoring System

As aforementioned, the laboratory is located in San Giuliano Milanese (Milan, Northern Italy) [9]. It consists of a one floor building for office use of 45 m^2, divided in two heated and cooled rooms and one technical room, where the main HVAC appliances are installed. Within the project RAISE, the building has been refurbished to drastically reduced the energy demand: rockwool insulation layers were applied to every external envelope component (walls, roof and ground slab). Additionally, one wall was also equipped with a ventilated façade, and new high performance windows were installed. A layout of the building is shown in Figure 1.

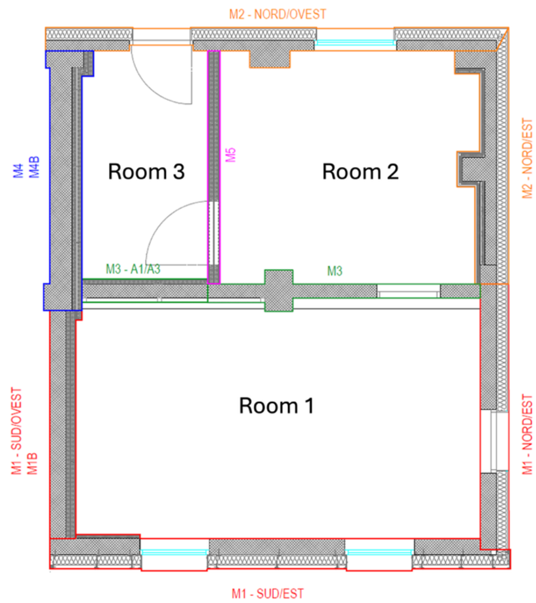

Figure 1. Building plant

Moreover, the whole HVAC system has been improved with the installation of an air-to-water heat pump serving the radiant floor and two fan coils, a new solar thermal collector for domestic hot water (DHW) production, and a photovoltaic system of 3 kW of peak production equipped with two electrical batteries of 5 kWh each. It is highlighting that the installed heat pump is based on the refrigerant R454B, which is low global warming mixture (GWP = 466) of R32 and R1234yf [13].

The main objective of RAISE is developing and testing an advanced control system based on AI techniques to optimize the energy consumption of the building under different scenarios, such as stand-alone photovoltaic production and prosumer within a Renewable Energy Community (REC). In particular, the AI control system will make decisions on whether to store energy in the batteries, directly use the PV production or the national grid for energy supply, based on model for weather, consumption and energy cost forecast. For these reasons, a sofisticated monitoring system was installed to measure all the main electrical loads of the building by means of several wattmeters. Since the heating and cooling of the building represents the highest electrical load, particular attention has been paid to monitoring the heat pump and whole hydronic system. A monitoring system consisting of research-level instruments has been installed to measure the most relevant quantity involved in the thermodynamic cycle, also within the refrigerant loop of the heat pump.

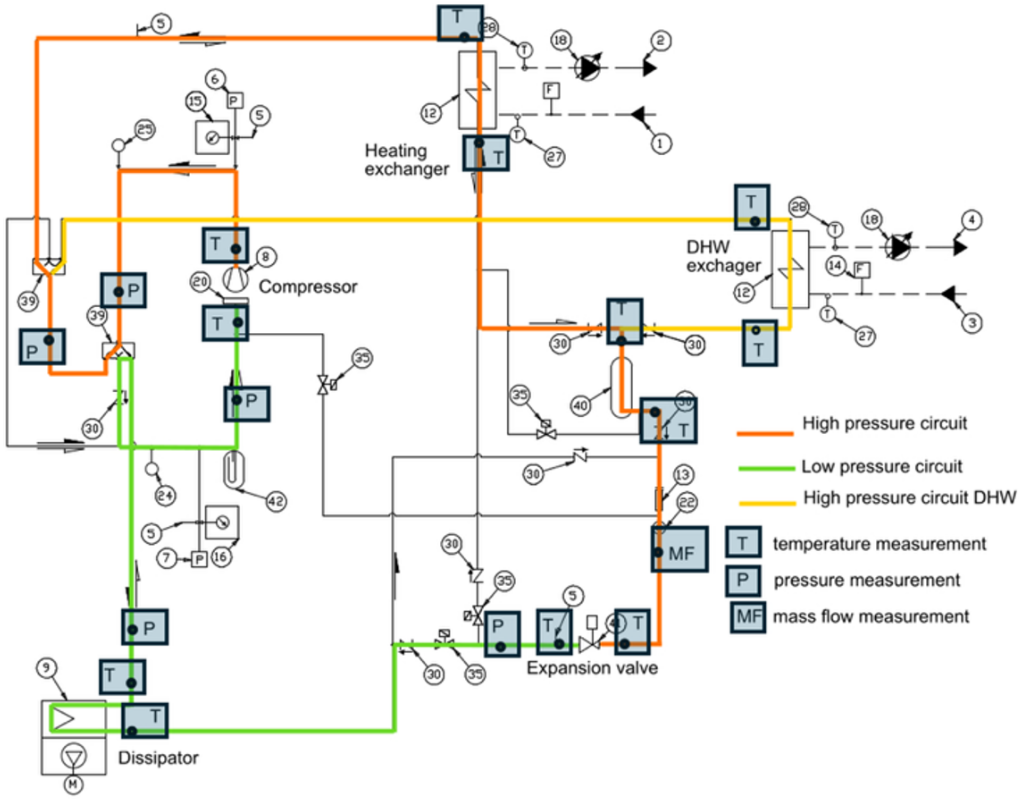

Figure 2. Monitoring system installed within the refrigerant loop from an extract of the refrigerating scheme

Figure 2 shows a simplified scheme of the refrigerant loop and the position of the sensors installed within. In particular, the monitoring system consists of:

• 11 standard platinum resistance thermometer PT100 Ω (4-wires, class AAA) with an accuracy of 0.1°C;

• 5 piezoresistive pressure transducers (Endress & Hauser Cerabar PMC). Such sensors work at pressure from 1 to 300 bar with an accuracy of 0.2% F.S.;

• A Coriolis flow meter (Endress & Hauser Cubemass C300) with an accuracy of 0.1% F.S.

Figure 3 displays the monitoring system installed within the hydronic loop, which consists of 14 temperature sensors, with the same kind of the refrigerant loop, and 7 electromagnetic flowmeters (IFM SM7020, accuracy of 0.8% F.S.) to measure the water flow rate in every part of the system. Table 1 reports a summary of the installed sensors.

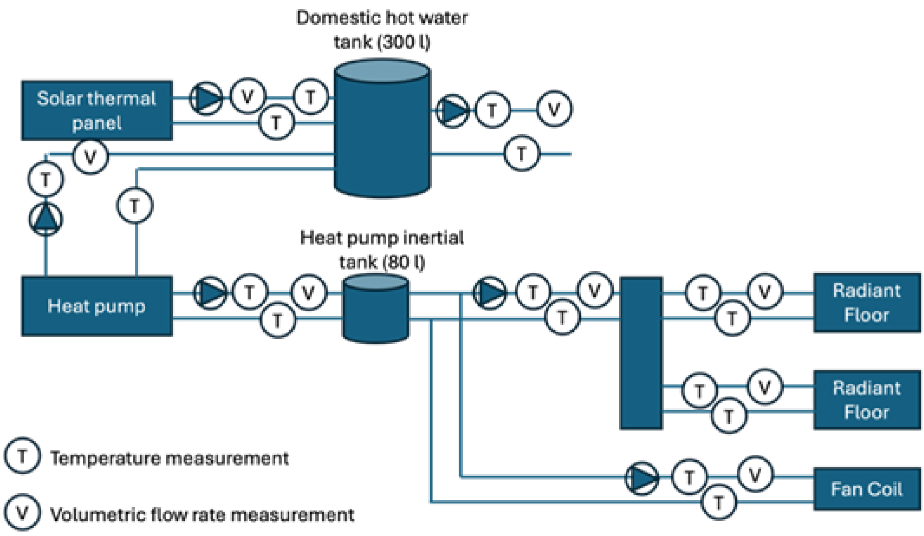

Figure 3. Monitoring system installed within the hydronic loop

Table 1. Details of the installed sensors

Quantity	Sensor	Accuracy
Temperature	PT100Ω (4-wires, class AAA)	0.1°C
Pressure	Piezoresistive pressure transducer	0.1% F.S.
Mass flow rate (refrigerant loop)	Coriolis flowmeter	0.1% F.S.
Volumetric flowrate (water loops)	Electromagnetic flowmeter	0.8% F.S.

At present, the control system is under development. However, in the next future, the monitoring system will start to collect valuable data.

3 Thermodynamic Model of the Building

3.1 Model Assumptions

A thermodynamic model based on the electrical RC analogy has been developed. RC models employ equivalent resistances and capacities to implement the phenomena of heat transfer and thermal inertia, respectively [11]. In the literature, a number of studies are dedicated to such models, and it is worth highlighting two important standards, VDI 6007 [14] and EN52016 [15], which describes two calculation procedures based on RC models. In general, RC models can be distinguished by the nomenclature mRnC, where m and n represent the number of resistances and capacities considered in model. However, such nomenclature may result confusing since it does not specify if the number of RC parameters refers to a single wall, a single thermal zone or the whole building [16].

Within the RC model developed in this work, every single wall (including floors and ceilings) have been modelled as 3R2C. Figure 4 shows the model scheme of the single wall. The three resistances are the internal and external surface resistances (R_{si} and R_{se}, respectively) and the equivalent resistance, R_{eq}, calculated as:

$$R_{eq} = \sum_i \frac{s_i}{\lambda_i} \tag{1}$$

where, s_i and λ_i are the thickness and the thermal conductivity, respectively, of the i-th layer consisting the wall.

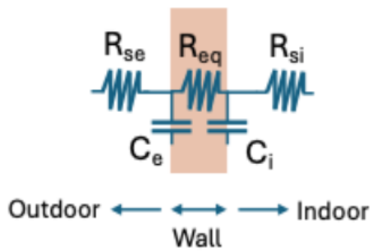

Figure 4. 3R2C model of the wall

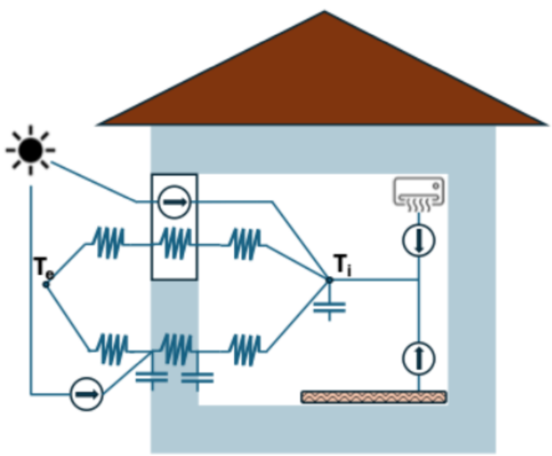

Figure 5. Simplified RC network

The internal and external capacities, C_i and C_e respectively, have been regressed based on the trends of the internal and external surface temperatures calculated with accurate, but computationally demanding, finite differences method (FDM). Figure 5 shows a simplified RC network explaining how the model is implemented.

Other assumptions of the model are given as follows:

• Every closed ambient is considered as thermal zone implemented through a single capacity, equal to the heat capacity of the room, referred as "air node".

• Windows are considered as single resistances, with no capacity.

• Solar gains are calculated through the Python package pvlib [17].

• Solar gains through the transparent elements of the envelope, infiltration from outdoor or from other source are considered as "heat generator" directly connected to the zone air node.

• Solar gains through opaque elements are considered by means of the "sol-air temperature" [18], equal to:

$$T_{\text{sol-air}} = T_{\text{ext}} + I_{\text{tot}} \cdot a \cdot R_{\text{se}} \tag{2}$$

where, T_{ext} is the outdoor temperature, I_{tot} represents the global irradiance on the tilted surface and a is the solar absorbance factor of such surface.

• Sensible internal heat gains are divided into convective and radiative gains. Convective gains are connected directly to the air zone; radiative gains are connected to internal surface node of every opaque element within the zone.

• Radiative heat transfer among walls and radiative heat gains are modelled with the "ScriptF" algorithm developed by Hotel [19], therefore by means of a view factor matrix and an equivalent radiant temperature for each zone.

Moreover, the model accounts for the humidity in the room by means of a dedicated vapour balance, which considers only the vapour content within the zone, the external air and, eventually, internal latent gains.

The model was developed by means of a dedicated code written in Python language and, therefore, open source.

4 Model Validation

Since the experimental data are not available yet, RC model was validated with the well-established software TRNSYS [20]. For this purpose, a hypothetical building has been implemented with both the models. Such building consists of single zone with a surface of 40 m^2 and a height of 3 m^2. The building envelope consists of a 20 cm of bricks and all the walls and roof are insulated with 10 cm of expanded polystyrene. The thermophysical properties of the wall layers are defined in Table 2.

Table 2. Thermophysical properties of the building layers

Material	**Density ($\mathrm{kg/m^{-3}}$)**	**Specific Heat ($\mathrm{J/kg^{-1}K^{-1}}$)**	**Thermal Conductivity ($\mathrm{W/m^{-1}K^{-1}}$)**
Bricks	2000	920	0.9
Expanded polystyrene	40	1500	0.035

A 2 m^2 low performing window was assumed on the South wall with the thermodynamic characteristics displayed in Table 3.

Table 3. Window properties

Glass Transmittance (U_g)	**Frame Transmittance (U_g)**	**Solar Transmission Factor (g-value)**	**Frame-to-Window Ratio**
5.69 $\mathrm{Wm^{-2}K^{-1}}$	2.27 $\mathrm{Wm^{-2}K^{-1}}$	0.823	0.15

The building was simulated for the first 60 days of year considering the climate condition set by the EnergyPlus weather file for the location of Venezia-Tessera (available at https://climate.onebuilding.org/). During such period of time, a fixed setpoint temperature of 20°C was assumed: at every time step, the room temperature was calculated based on the heating/cooling loads of the building, if the room temperature was lower than the setpoint, this was set equal to 20°C and the heating demand was calculated, otherwise the temperature was free to vary.

The same building was modelled with TRNSYS, considering the same boundary conditions. Figure 6 shows the comparison between the instantaneous heating demand calculated with TRNSYS with respect to the RC model. Within the simulated 60 days, the energy demand calculated with TRNSYS was equal to 1,255.7 kWh, while the same was equal to 1,306.0 kWh with the RC model, which corresponds to an overestimation of 4.0%. Considering the limitation already highlighted in the literature for the RC models, such result can be considered satisfying.

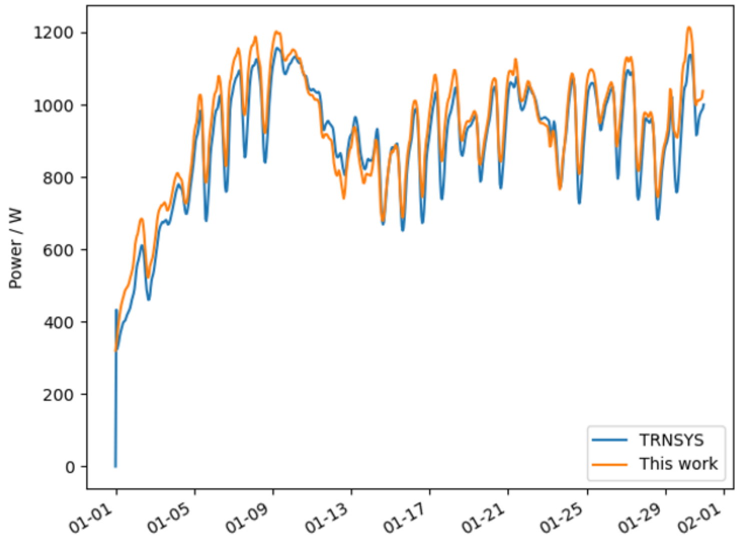

Figure 6. Comparison between the trends of heating demand calculated with TRNSYS and the RC model presented in this work

5 Results

The LAB-Zeb building has been simulated with the RC model. Since the laboratory is located in Milan (Italy), the weather file of Milan-Linate has been used (available at https://climate.onebuilding.org/). In this case, the office schedule of Table 4 was implemented for the setpoint temperature. Such schedule was applied to Room 1 and Room 2, while Room 3 was assumed unheated.

Table 4. Weekly schedule for the setpoint temperature

Weekdays		Weekends	
From 00:00 to 07:59	16°C		
From 08:00 to 18:00	20°C	From 00:00 to 23:59	0°C (no heating)
From 18:01 to 23:59	16°C		

The RC model allowed to evaluate the trends for the rooms temperature, as shown in Figure 7, as well as the trends for the heating demand of the building, displayed in Figure 8.

Finally, the annual heating demand resulted equal to 724.7 kWh and 492.2 kWh for Room 1 and Room 2, respectively.

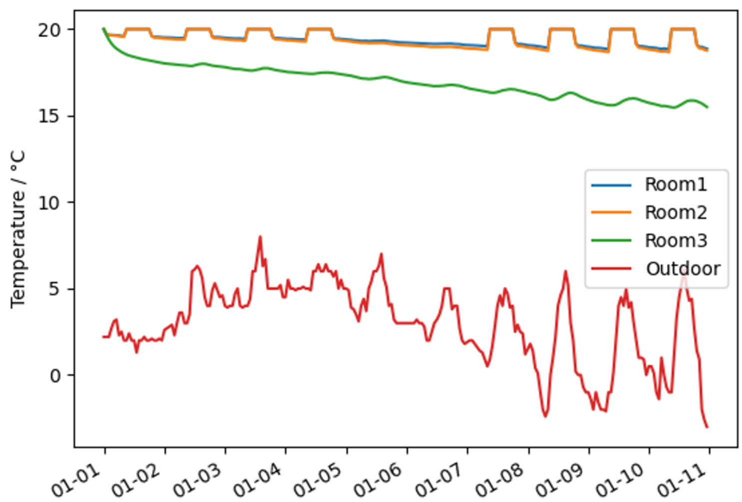

Figure 7. Trends for the room temperatures and the outdoor temperature

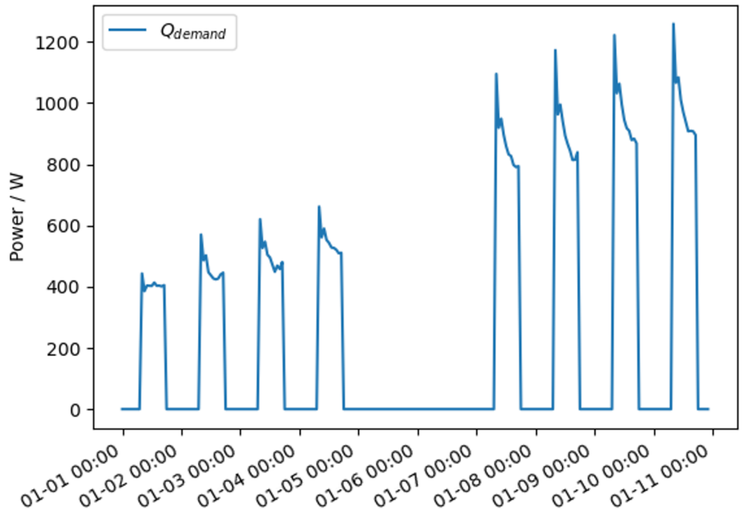

Figure 8. Trends for the overall heating power demand of the building

6 Conclusions

In this work, a comprehensive experimental monitoring platform and a fast, yet accurate, thermodynamic model of a Zero Energy Building (ZEB) laboratory have been presented. The monitoring system—comprising high-accuracy PT100 temperature probes, piezoresistive pressure transducers, Coriolis flow meters in the refrigerant loop, and electromagnetic flow meters in the hydronic loop—enables simultaneous tracking of the key parameters governing the heat pump cycle and the building's thermal behavior. These detailed measurements will form the foundation for data-driven AI algorithms aimed at optimizing the energy management of both single buildings and larger renewable energy communities.

The thermodynamic model, based on a resistance–capacitance (RC) network built with a 3R2C wall representation and an RC model for each thermal zone, was validated against TRNSYS simulations. Over a 60-day winter period under controlled setpoint conditions, the RC model predicted a heating energy demand of 1,306.0 kWh compared to 1,255.7 kWh from TRNSYS, corresponding to an overestimation of only 4.0%. This level of accuracy, combined with the significantly lower computational burden of the RC approach, confirms its suitability for real-time forecasting and control purposes. When applied to the LAB-Zeb, the model estimated annual demands of 724.7 kWh for Room 1 and 492.2 kWh for Room 2, demonstrating the model's capability for detailed, zone-level energy assessment.

Looking ahead, the integration of this experimental dataset with the validated RC model will enable the training of advanced AI controllers capable of making real-time decisions on energy production, storage, and consumption. By leveraging short-term forecasts of weather, occupancy, and electricity prices, the AI tool will optimize heat pump operation, photovoltaic self-consumption, and battery charging/discharging strategies. The next phase of this research will involve the deployment of the AI controller in the LAB-Zeb, continuous collection of operational data, and iterative refinement of both model parameters and control logic to achieve optimal performance under various scenarios, including stand-alone operation and participation in Renewable Energy Communities.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Acknowledgement

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Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Nomenclature

C	Thermal capacitity, JK^{-1}
I	Solar irradiance Wm^{-2}
R	Thermal resistance, m^2KW^{-1}
T	Temperature, K
U	Thermal transmittance, $Wm^{-2}K^{-1}$
a	Solar absorbance factor

Greek symbols

λ	Thermal conductivity, $Wm^{-1}K^{-1}$

Subscripts

f	Frame
g	Glass
se	External surface
si	Internal surface