INTEGRATING RADIATIVE COOLING AND CHILLED CEILINGS IN BUILDINGS: A SIMULATION STUDY FOR SUSTAINABLE COOLING

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Abstract

The Radiative Collector and Emitter (RCE) is a device that combines the functionalities of radiative cooling and solar heating to cool down or warm up water, respectively. This study present a first approximation of the integration of RCE systems with chilled ceilings to provide sustainable cooling solutions for buildings. The research focuses on a multifamily building in Lleida, Spain, and employs TRNSYS 18 for simulation during the summer months. The RCE system leverages the natural process of radiative cooling, emitting infrared radiation into space to dissipate heat and reduce temperatures with minimal electricity consumption. The combined system's performance was compared against a commercial air conditioner system, demonstrating energy savings for cooling demand of approximatively 140 kWh during the observed period, along with enhanced occupant comfort. The RCE system achieved a mean net radiative cooling power of 30.34 $W \cdot m^{-2}$ and an efficiency of 42.3%, reducing the storage tank temperature by an average of 3.29°C nightly. The chilled ceiling system operated autonomously 87.74% of the time, maintaining comfortable indoor temperatures.

Keywords: Radiative Cooling, Chilled Ceiling, Building Modelling, Numerical Simulation, TRNSYS

1. Introduction

Energy consumption in buildings is estimated to be 40% of final energy consumption in Europe, accounting for 36% of CO_2 emissions (Eurostat, 2019). The largest portion of this energy (80%) is utilized to meet the needs of space conditioning, which includes domestic hot water (DHW), cooling, and heating. Space cooling, in particular, is a major contributor to the rise in electricity consumption, with CO_2 emissions related to space cooling increasing by 2% annually. Worldwide projections show that by 2050, the energy demand for space cooling will have tripled, being necessary the installation of more air-conditioning units (IEA, 2019).

In the last decade, technologies based on the radiative cooling (RC) phenomenon have emerged as promising renewable solutions to address the growing energy needs related to cooling in buildings. RC is a natural process in which a surface emits infrared radiation into outer space, thereby dissipating heat and cooling down (Vilà et al., 2021). The peaks of radiation are in the wavelength range of 7 μm to 14 μm, which falls within the atmospheric window, the region of the electromagnetic spectrum where Earth's atmosphere is highly transparent. This transparency allows the radiation to escape into outer space, leading to a significant temperature reduction below ambient levels at the surface, with minimal or no electricity consumption (Chen et al., 2020).

The operation of radiative cooling, despite being opposite to solar heating, is entirely analogous and can be combined. Researchers at the University of Lleida have developed a device of 2 m^2, named Radiative Collector and Emitter (RCE) (Vall et al., 2020a), that combines both solar heating and radiative cooling functionalities to heat up water, during the day, or cool down water in contact with a radiative cooling surface, during the night. The RCE includes a grid of pipes through which water flows, such pipes are installed on a highly emissive/absorptive plate within the infrared spectrum. In solar collection mode, during the day, the RCE absorbs solar radiation to heat the water. In cooling mode, the plate emits infrared radiation towards the sky, cooling the water below ambient temperature.

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Despite the notable growth in radiative cooling research (Su et al., 2023), the integration of radiative cooling technologies with the built environment has not been thoroughly explored (Kousis and Pisello, 2023; Vilà et al., 2020). One explanation for this gap in the literature can be found in the limitation of nighttime radiative cooling devices, such as the RCE systems, which have a relatively low cooling density power, averaging only 50 W/m² (Vall et al., 2020b). This limitation results in that RCE achieves a temperature few degrees below the nocturnal ambient temperature, diminishing its power with the temperature reduction. For this reason, such devices cannot behave like conventional terminal units, like fan-coils, operating at 6-7 ºC. However, there is promising potential for these devices to be coupled with cooling technologies operating at higher temperatures, such as chilled ceilings, thereby broadening their applicability and enhancing their efficiency in the built environment.

Chilled ceilings are cooling systems designed to regulate the inside temperature of a space. These systems typically operate with a temperature difference close to 2 ºC between the water inlet and outlet (Jin et al., 2020), with an operating inlet temperature a few degrees above the dew point. Combining radiative cooling for cooling production with chilled ceilings for cooling delivery to buildings appears to be a practical option due to the similarity in operating temperature levels (Yuan et al., 2018). This study is a first approach to combine RCE with chilled ceilings. The paper specifically studies the radiative cooling functionality of the RCE, as it is the innovative solution and the one lacking result in literature, by simulating the thermal performance of an integrated systems (RCE + Chilled Ceiling) in a multifamily building in Lleida (Spain). The study seeks to assess the energy savings and thermal performance of these integrated systems, offering new insights into the applicability of radiative cooling technologies in the built environment, contributing to close the literature gap.

2. Methods

This section details the numerical simulations conducted to assess the energy-saving potential of integrating radiative cooling technology with building cooling systems. This study compares a reference case using a traditional air-to-water heat pump and chilled ceiling system with an improved case employing the Radiative Collector and Emitter (RCE) combined with chilled ceilings. The section includes descriptions of the multifamily building in Lleida, Spain, and the computational models used for both scenarios. Additionally, it outlines the mathematical model employed to simulate the radiative cooling performance of the RCE.

2.1. Conditions of Simulation

The transient behaviour of the systems was simulated using TRNSYS 18 for the warmest months in Lleida, Spain, spanning from May to September, both included. A timestep of 5 minutes was used in the simulations in TRNSYS.

Meteorological data for Lleida was sourced from Meteonorm's database (Remund et al., 2019), providing essential parameters such as solar radiation, ambient temperatures, humidity levels, and wind speeds, needed to simulate the behaviour of the RCE. Atmospheric radiation calculations (eq. 1) assumed the Walton correlation for sky emissivity (eq. 2), where T_{db} represents the dry bulb temperature in Kelvins, and N denotes the opaque sky cover in tenths.

$$R_{atm} = \varepsilon_{sky} \cdot \sigma \cdot T_{db}^4 \tag{1}$$

$$\varepsilon_{sky} = \left(0.787 + 0.764 \cdot \ln\left(\frac{T_{dp}}{273}\right) \cdot (1 + 0.0224 \cdot N - 0.0035 \cdot N^2 + 0.00028 \cdot N^3\right) \tag{2}$$

The net cooling power on the surface is defined as the difference between the radiation emitted by the surface (at the surface temperature of the RCE, T_s) and the incoming atmospheric infrared radiation absorbed by the surface (eq. 3).

$$R_{net} = \varepsilon_s \cdot \sigma \cdot T_s^4 - \alpha_s \cdot R_{atm} \tag{3}$$

2.2. Description of the Building

The building selected as a case study to analyse the performance of the Radiative Collector and Emitter (RCE) is a two-floor multifamily building located in Lleida, Spain. The thermophysical features of the building envelope are listed in **Table 1**, while **Fig 1** shows the occupancy profiles. The characteristics of the building, both in terms of geometry and materials, are selected based on the fact that 55% of buildings in Spain are older than 1980, with the average building age in Lleida being 33 years (Ministerio para la Transición Ecológica y el Reto Demográfico, n.d.). The selected values for the envelope fall between the first building normative in Spain (NBE-CT) (Presidencia del Gobierno, 1979) and the initial Technical Building Code (CTE) established in 2006 (Ministerio de Vivienda, 2006).

The building is divided into two floors, each representing an apartment and, therefore, a thermal zone in the developed system. In each apartment, the number of occupants is four (two adults and two children), each with different occupancy profiles. These profiles are crucial for determining when the cooling system should be activated to create comfortable indoor conditions and whether the heat gains are on or off.

Table 1: Features of the building envelope.

Building element	U (W/m^{2}K)	Thickness (m)	ρ_s (–)	ε (–)
Roof	0.509	0.373		
Façades	0.904	0.225	0.4	0.9
Ground floor	0.742	0.360		
Adjacent ceiling	0.904	0.225		
Windows glass	1.10	0.006/0.016/0.006	0.13	0.18

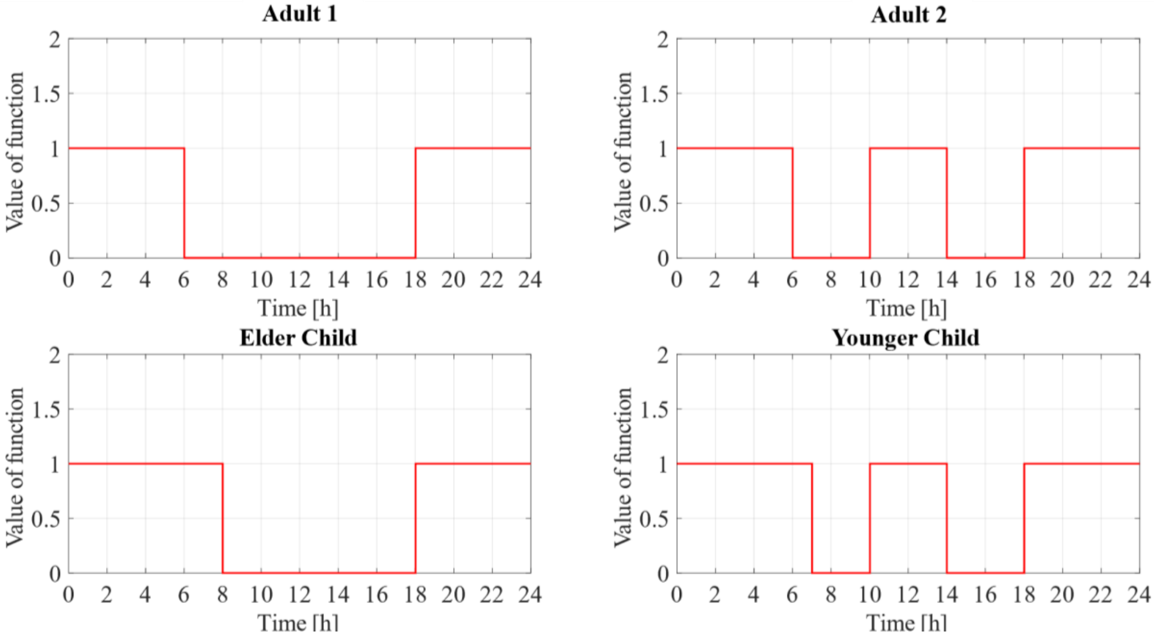

Fig 1: Occupation scheduling for the types of users of the multifamily building.

A set point temperature of 27ºC was established; any temperature exceeding this threshold was considered to induce discomfort. Consequently, if there was occupancy in the room, cooling systems were activated to restore comfort levels. The specific cooling systems utilized in the simulations are described in subsequent sections. However, a general control strategy was implemented, including a free cooling approach. This strategy leverages outdoor air to reduce indoor temperatures, reducing the needs of mechanical cooling when the outdoor air temperature was below the set point temperature. This free cooling strategy was scheduled to occur during specific hours: from 6:00 AM to 8:00 AM and from 4:00 PM to 10:00 PM.

2.3. Description of the Facility for the Improved Case (RCE + Chilled Ceiling)

This section describes the facility setup for the improved case, which integrates the Radiative Collector and Emitter (RCE) with chilled ceilings on the first floor of the building to enhance energy savings and cooling performance compared to the reference case.

The facility simulated in this study features a rooftop field of 45 Radiative Collector and Emitter (RCE) units covering 90% of the building's rooftop area, replacing the traditional air-to-water heat pump of the reference case (**Fig 2**). These units operate during nighttime hours to cool the water inside a 3.5 m³ storage tank. In this simulation, the tank is assumed to be adiabatic. The generation of cold occurs at night, while most of the cold is utilized during the day. Therefore, a storage tank was necessary to effectively manage and dispatch the cooling capacity as required.

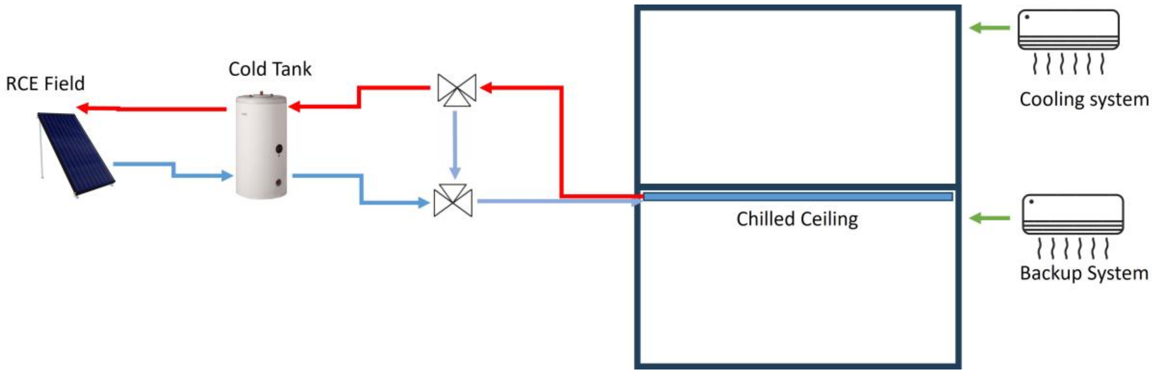

Fig 2. Schematic representation of the RCE + Chilled Ceiling facility.

During the daytime, the chilled ceiling system on the first floor operates with an inlet temperature range of 17-19 ºC, optimized to achieve indoor cooling. In the best scenario, the RCE field can cool down the tank to 12 ºC. The chilled ceiling has been modelled according to Uponor units, which are preassembled commercial panels of 1 m² (Uponor, n.d.). The geometric characteristics of the chilled ceiling are detailed in **Tab. 2**. To maximize the utilization of the cold stored generated by the RCE, the chilled ceiling system's inlet temperature is regulated to 18 ºC. This is achieved through a recirculation process where a portion of the water from the chilled ceiling's outlet is mixed with water from the storage tank. This mixing arrangement enhances thermal comfort while optimizing cooling discharge of the tank.

Table 2: Geometric and operational characteristics of the Chilled Ceiling on the first floor

Parameter	Description	Value	Unit
t_p	Pipe spacing	0.015	m
d_p	Pipe inside diameter	0.01	m
m_S	Specific normalized mass flow	0.5	$l·min^{-1}m^{-2}$
P_S	Specific normalized power	80	$W·m^{-2}$

In scenarios where additional cooling capacity is needed beyond what the chilled ceiling system can provide, typically when the storage tank temperature rises above 20 ºC due to increased cooling demand, the backup air conditioner system with a capacity of 4 kW on the first floor is activated to supplement cooling requirements. This backup system ensures continuous comfort conditions for occupants, seamlessly integrating with the overall cooling strategy. On the second floor, cooling is managed separately through a traditional air conditioner system, highlighting the contrast with the innovative integrated approach employed on the first floor.

2.3. Description of the Facility for the Reference case

Fig 3. shows the facility configuration used for the reference case, which includes a traditional air-to-water heat pump and chilled ceiling system. This setup serves as the baseline for comparison against the improved case incorporating the Radiative Collector and Emitter (RCE) combined with chilled ceilings. Similarly to the previous facility, this hydronic system developed to meet the cooling demand of the building is based on a 6 kW commercial air-to-water heat pump integrated with a 3.5 m³ water tank that stores the cooling energy.. To compare the cooling performance of the RCE and the heat pump, the same control strategy was used for both heat generation systems. The heat pump operates to provide cooling energy to the tank only during the night, the time window in which the RCE operates in cooling mode. This approach ensures that the comparison between the two systems is as similar as possible. Additionally, the heat pump operates only to decrease the temperature of the tank to 15°C. This control strategy reduces the consumption of the heat pump by operating with a small ΔT and therefore with a high Energy Efficiency Ratio (EER), allowing for a fair comparison of the systems under the same conditions.

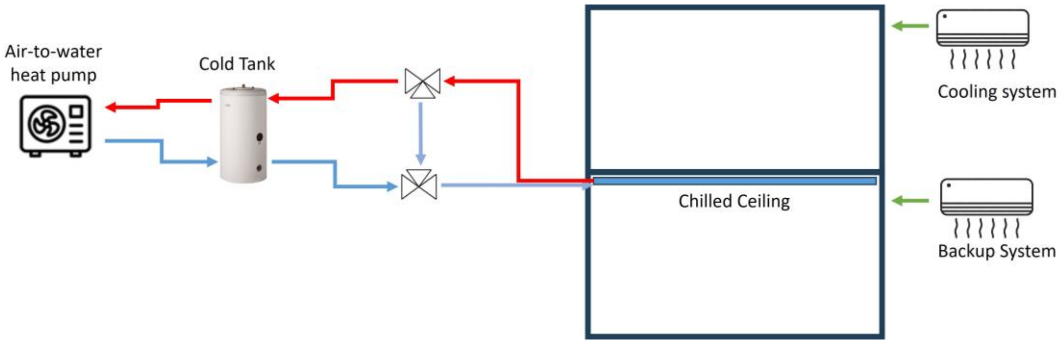

Fig 3: Schematic representation of the reference facility.

2.5. RCE Model

This research uses the numerical model of the RCE developed, and experimentally validated, by Vall et al. (Vall et al., 2020a). The implementation in TRNSYS v18 involved a comprehensive energy balance, designed considering the interactions between the RCE, ambient air, the sky, and the building. To develop a model not so heavy from the computational point of view, the RCE model was discretized into nodes using a one-dimensional electrical analogy (1D) approach. Two-dimensional effects were incorporated through detailed simulations using COMSOL Multiphysics. Radiative balance calculations were performed for four distinct wavelength ranges (0-4 µm, 4-7 µm, 7-14 µm, and >14 µm), with a specific emphasis on the infrared atmospheric window (7-14 µm). Solving energy balance equations, which are ordinary first-order differential equations, was achieved numerically using Euler's implicit method.

Tab.3: Parameters of the RCE.

Parameter	Description	Value	Unit
A_{RCE}	Useful surface	2	m^2
n_{pipe}	Nº parallel pipes	9	-
l_{pipe}	Pipe length	1.886	m
t_{pipe}	Distance between pipes	0.125	m
d_{pipe}	Pipe diameter	0.008	m
ε_{RCE}	Radiator emissivity	0.95	-
τ_{RCE}	Cover transmissivity	0.80	-
$\dot{m}_{RCE}$	Flowrate	4.5	$l \cdot min^{-1} m^{-2}$

3. Results and Discussion

3.1. Performance of the Radiative Collector and Emitter (RCE)

The simulations indicate that, on average, the RCE had the power to cool the storage tank by 3.29°C each night over the simulation period, with peak values equal to 7.82ºC. The daily temperature at the end of the night was 18ºC on average. During its operation, the chilled ceiling warmed the tank 2.98ºC. This indicates that RCE field was able to compensate the increasing of temperature derived from the chilled ceiling system. The average energy cooled by the RCE during the operational days was 12.38 kWh, cooling a total of 879 kWh in the simulated period.

The overall mean net radiative cooling power of the RCE was 30.34 W·m^{-2}, with peak values reaching up to 97.04 W/m². The average efficiency of the RCE, defined as the ratio between the cooling power in the pipes and the net radiative cooling power, was determined to be 42.3%, which is considered a good performance for this type of system. **Fig 4** shows the thermal evolution during three consecutive nights in July (from 10/07 at 00:00 to 13/07 at 23:55). During the day, a constant flow through the RCE has been simulated to maintain the emitter at a temperature below or close to the ambient. The energy stored in the tank is used in the chilled ceiling during the day, increasing its temperature above 23ºC. During the night, the RCE field is able to cool down the tank below 19 ºC. On the first and second nights, it was able to cool the water in the RCE 2 ºC below ambient temperature, and almost 2 ºC below ambient temperature in the tank in the second night. On the third night, it cooled it down only a few tenths of a degree below the ambient temperature. Powers up to 50 W·m^{-2} were reached.

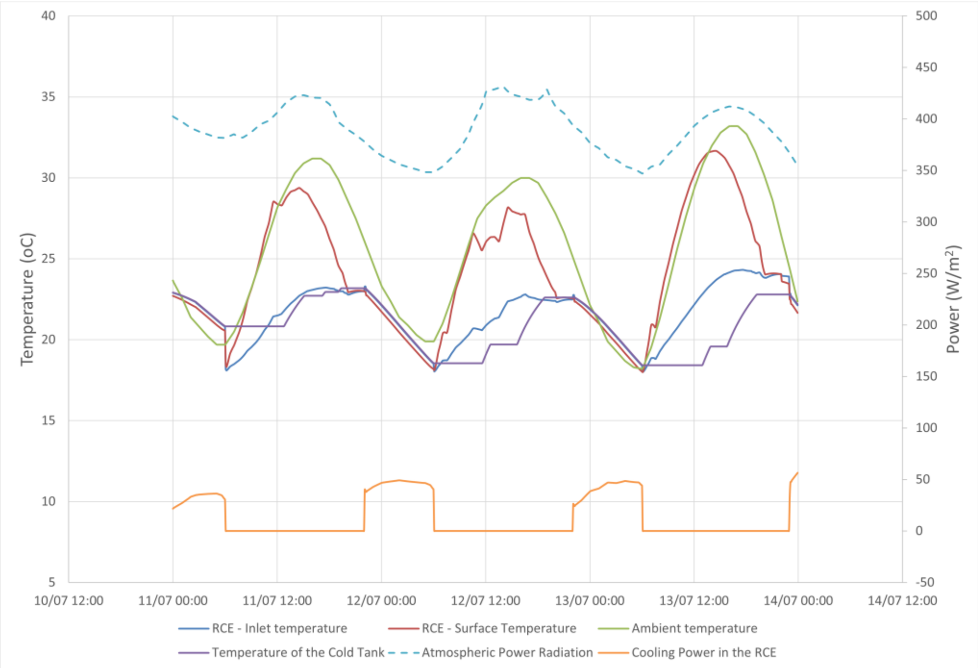

Fig 4. Thermal evolution of the RCE field between the days July 10th at noon and July 13th at 23:55.

Fig 5 shows the daily cooling energy produced by the RCE versus the energy absorbed by the chilled ceiling to cool down the first floor.

The RCE facility remained unused on many occasions. This suggests that in the unused nights, the RCE could have been used to renewably meet part of the second-floor demands. The figure also indicates that for 6 nights, the RCE system delivered negative cooling energy, warming the water instead of cooling it. These nights coincided with high atmospheric infrared radiation, highlighting the need for better optimization of the RCE control in future research.

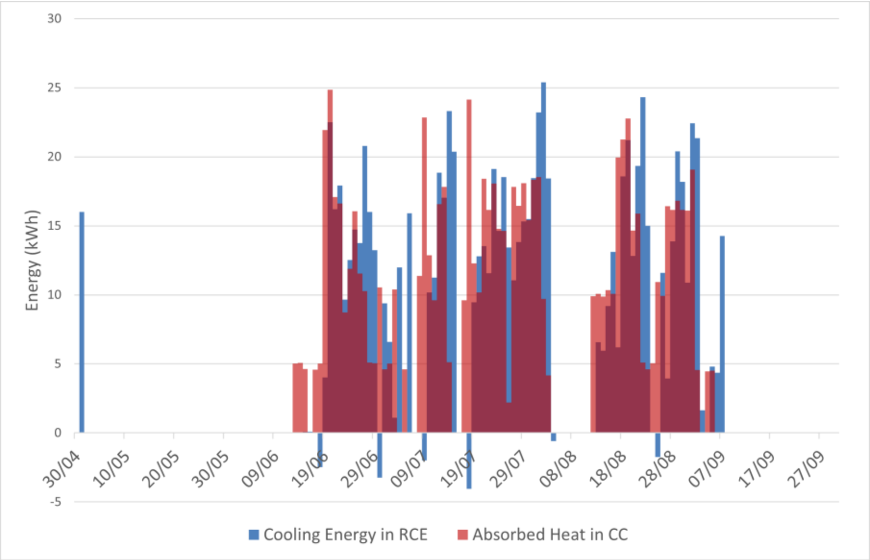

Fig 5. Visual comparison between the cooling energy produced in the RCE and the cooling energy consumed in the chilled ceiling.

3.2. Chilled Ceiling Performance

The chilled ceiling system was operational for 70 out of the 152 days simulated, working between 3 to 6.5 hours per day on average during half of the operational days. The total cooling energy load absorbed by the water in the chilled ceiling was on 859 kWh.

Fig 6 shows the cooling energy delivered by the chilled ceiling system and the backup system, air conditioner, over the simulation period. During its operational period, the chilled ceiling system functioned autonomously 87.74% of the time. The backup system was active for the remaining 12.26 % of the time. Notably, the backup system had to work for more than 50 % of the time on only three days (22/07, 23/07, and 24/07). The performance of the integrated system during the critical period from July 22 to July 25 is illustrated in **Fig 7** . The peak ambient temperature rises above 35 ºC, being the warmest days of the simulation. As a result, the temperature in the cold tank quickly rises above 23 ºC to compensate the warm days.

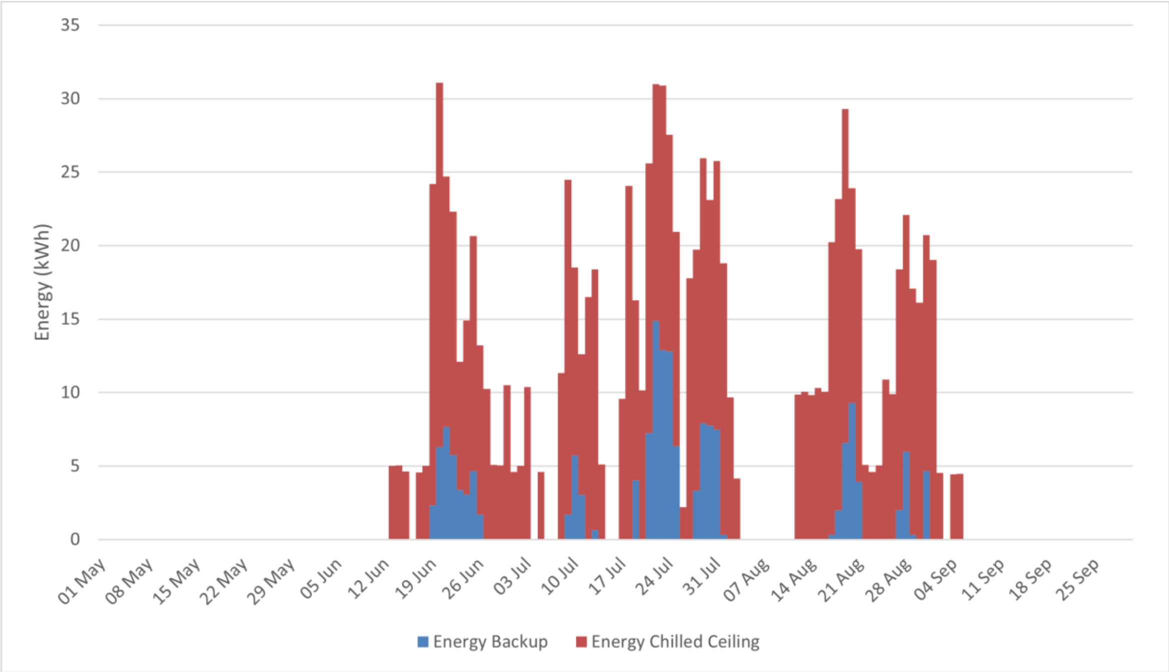

Fig 6. Difference between the energy contribution by the chilled ceiling and the backup system on the first floor.

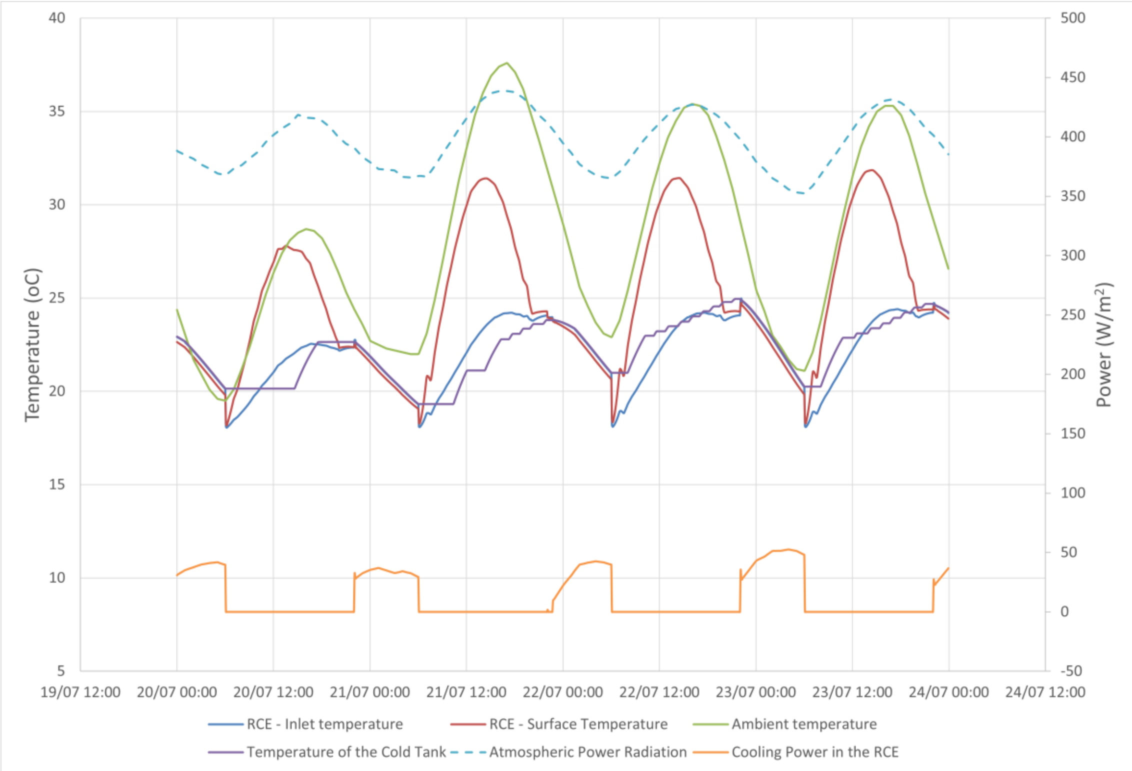

Fig 7. Performance of the RCE during the critical period from July 22nd to July 25th.

3.3. Comfort and Discomfort Analysis

Fig 8 and **Fig 9** show the room temperature (in blue) in the first and second floor, respectively; the green columns indicate when the cooling system (chilled ceiling or back up in the first floor) can be activated.

Comfort levels were analysed for the periods when the conditioning systems (free cooling, cooling system or backup) were designed to operate (represented by the green line in the graphics). Most of the time, the temperature of the floors is in the desired range. The first-floor experienced discomfort for only 0.8% of the time, with an average discomfort level of 0.21 °C and a maximum discomfort of 0.29 °C. In contrast, the second floor, which relied on a commercial air conditioner system, experienced discomfort for 5.76 % of the time, with an average discomfort level of 1.1 °C.

This discomfort observed on the second floor is specific to the sizing and control strategy used in this study. It is important to note that the use of a chilled ceiling with the RCE is not the sole determinant of comfort levels. However, these findings support the idea of utilizing underused cooling capacity from the RCE to partially meet the cooling needs on the second floor too, potentially reducing the occurrence of the discomfort observed.

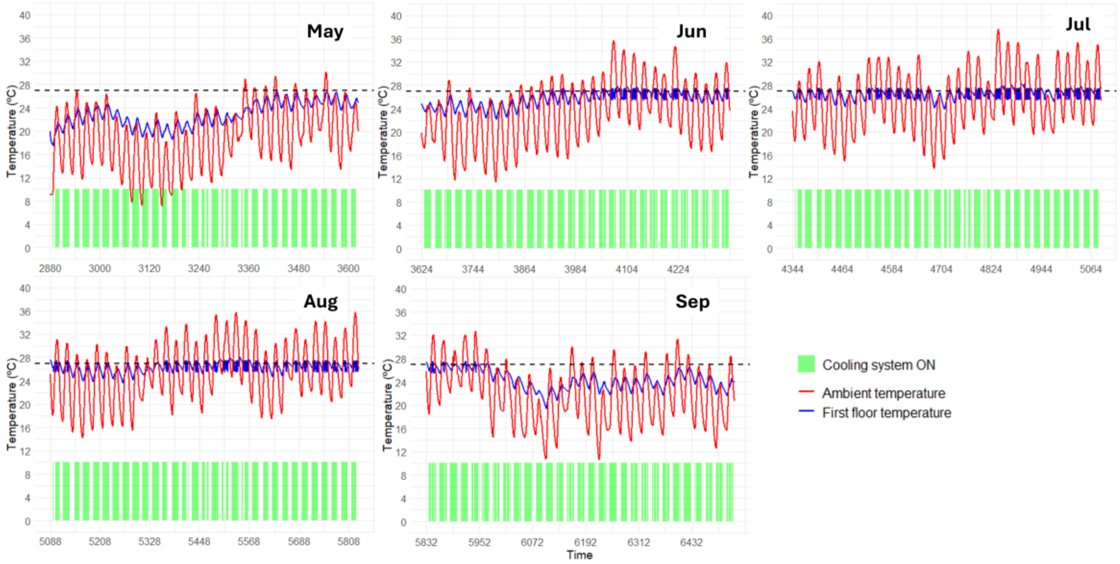

Fig 8. Thermal evolution in the first floor over the simulations months. The green line indicates when the cooling systems can operate.

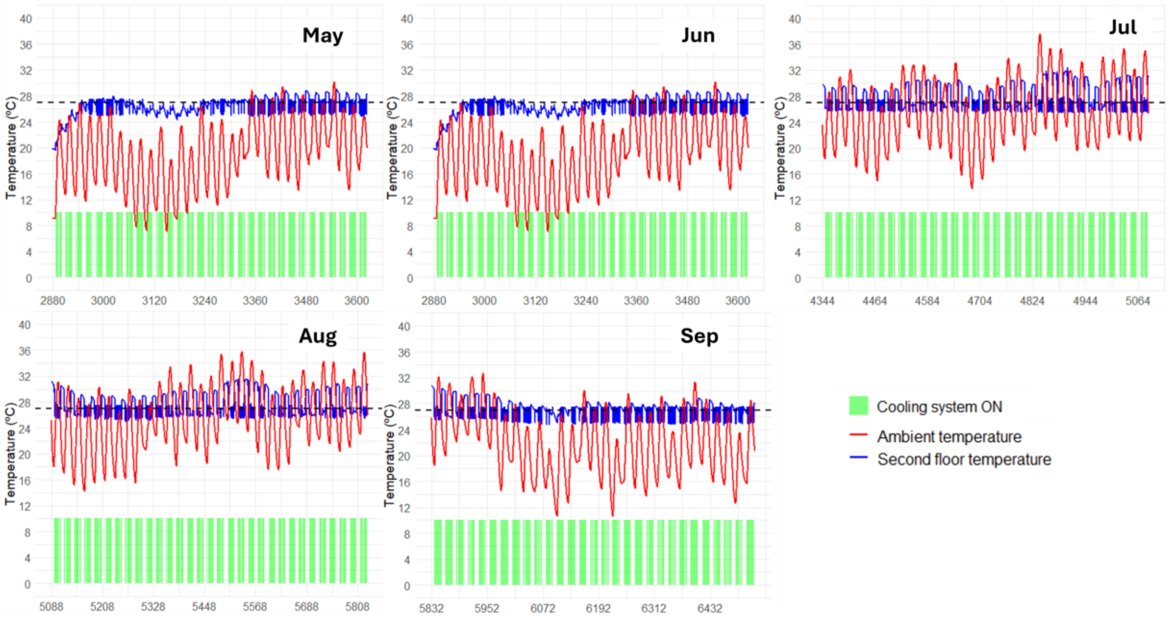

Fig 9. Thermal evolution in the second floor over the simulations months. The green line indicates when the cooling systems can operate.

3.4. Energy savings. Comparison with the reference case

The energy consumption of the reference system is due to the electricity needed by the heat pump to achieve the meet the cooling demands in the first floor. The distribution system is identical in both the reference and proposed cases, utilizing a hydronic system to supply cold to the user. **Fig 10** shows the electricity consumption of the heat pump over three consecutive days in July (from 10/07 at 00:00 to 13/07 at 23:55). The electricity consumption for heating is not considered since it is out of the scope of analysis for this study.

Regarding the electricity demand for cooling, shown in **Fig 10**, the electricity consumption is limited to a few hours, with the control strategy aiming to cool the water flow until the cold tank temperature drops to 15 °C.

In the RCE+CC case, the total electricity consumption is 1540 kWh, which accounts for the electricity consumption of both air conditioners (the backup system and the one on the second floor). The reference case shows a total electricity consumption of 1680 kWh, which includes the energy used by the air conditioners and the air-to-water heat pump. The total electricity savings in the improved system throughout the season is approximately 140 kWh due to the use of the RCE field.

It should be noted that this analysis does not include the electricity consumption of other hydronic components, such as the pumps that circulate water through the RCE field and the chilled ceiling. As a result, the actual energy savings achieved may differ to those reported in this study, as the additional electricity consumption from these hydronic components was not accounted for in the calculated savings.

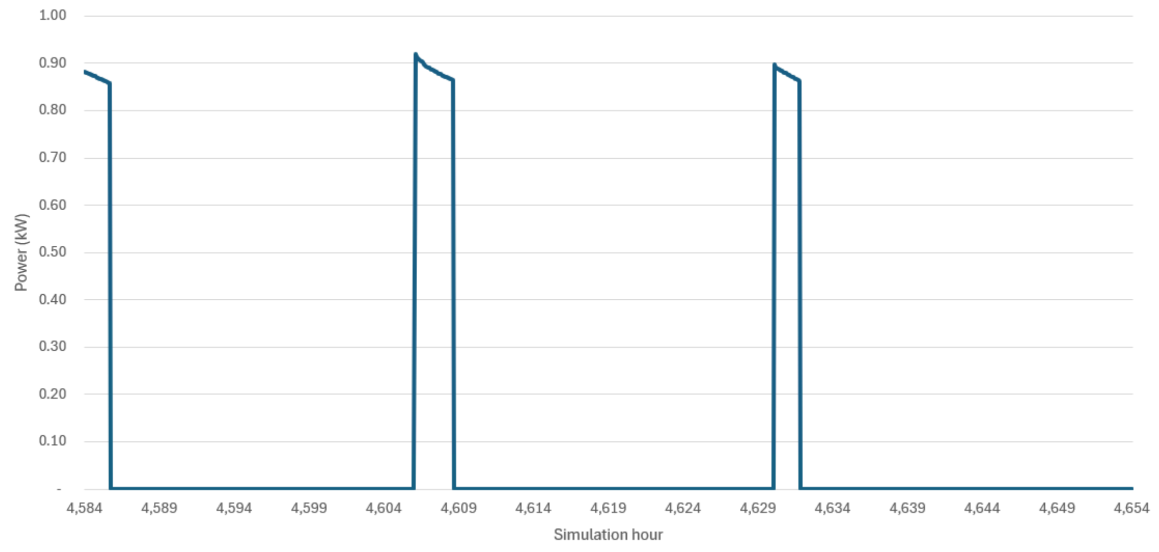

Fig 10. Electric energy consumption for cooling due to the heat pump between the days July 10th at noon and July 13th at 23:55.

4. Conclusions

This paper presented a first evaluation of the performance of an integrated Radiative Collector and Emitter system combined with chilled ceilings in cooling a multifamily building in Lleida, Spain. Using TRNSYS 18 for simulations over the summer months, key findings are as follows:

The RCE system's mean net radiative cooling power was 30.34 W·m^{-2} with an average efficiency of 42.3%. The chilled ceiling system operated efficiently and autonomously 87.74% of the time, rarely needing the backup system. The system demonstrated modest electricity savings for cooling demand of approximatively 140 kWh during the observed period compared to the reference case. In terms of indoor comfort, the first floor, using the integrated system, experienced minimal discomfort (0.8% of the time with an average discomfort of 0.21°C).

The RCE system reduced the storage tank temperature by an average of 3.29°C each night, with peak nights up to 7.82°C, while the chilled ceiling increased the tank temperature by 3°C during its operation

The findings from this study suggest that integrating radiative cooling technologies with chilled ceilings can lead to energy savings while maintaining occupant comfort in buildings. However, the RCE system still requires further improvement to achieve significant and consistent energy savings. The demonstrated performance highlights its potential for widespread application in sustainable building designs, but additional research is needed to refine the system's efficiency. Future studies should focus on optimizing the sizing and control strategies for these integrated systems and explore their performance across different climatic regions.

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