Covering energy demands of Africa with radiative cooling and solar collection using a single device

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Abstract

The Radiative Collector and Emitter (RCE) is a renewable technology which enables heating and cooling in a single device. It is an innovative concept which reduces the dependency on fossil fuels, and therefore diminishes the carbon footprint. Africa as a whole, presents a high demand of cooling, and covering these needs with renewable energy is possible thanks to Radiative Cooling (RC). Three simulations were performed in Africa (Agadez, Calvinia and Libreville) to determine the relation between cooling and Domestic Hot Water (DHW) demands compared with the renewable energy produced with the RCE. Results show an annual coverage of the cooling demand of 26.80% at Agadez and 8.72% at Libreville, while at Calvinia there are surpluses almost all the year. DHW is fully covered with solar collection The simulations also show that temperatures below the ambient may be achieved in cold storage tanks. Actually, these temperature differences are 5.56ºC, 3.36ºC and 4.50ºC at Agadez, Calvinia and Libreville, respectively.

Keywords: Radiative cooling, solar thermal collection, renewable energy, energy demand, Africa

1. Introduction

Residential and commercial buildings are responsible for the consumption of 40% of the energy of the world (Atmaca and Atmaca, 2022). Part of this energy is used to refrigerate by means of non-renewable energy sources and, thus greenhouse gases are emitted. If nothing is done, the situation may become cyclic, as shown in Fig. 1.

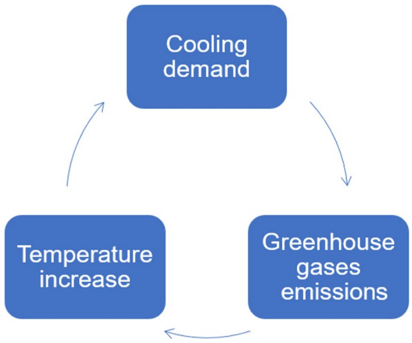

Fig. 1: Hypothetical situation derived from covering cooling demands with contaminant energy sources

An alternative presented is known as Radiative Collector and Emitter (RCE): the combination of radiative cooling and solar heating in a single device, producing heat during daytime and cold during nighttime. It is an innovative concept which helps to reduce the dependency on fossil fuels, and therefore reduces the carbon footprint.

The Radiative cooling (RC) is being studied as a passive cooling strategy which cools without any electricity input, having an important impact on global energy consumption (Raman et al., 2014). The aim is to radiate heat to outer space through the infrared atmospheric window between 8 and 13 µm wavelengths (Li et al., 2019), obtaining temperatures below the ambient.

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According to Vall et al. (2018) and Castell et al. (2020), the RCE (Fig. 2 and 3) has a similar shape to a flat plate solar thermal collector with two working modes: solar collection and radiative cooling. The water flowing through the device is heated during the day and chilled during the night. Different material characteristics are needed to operate under these different modes, and for this reason, it incorporates a movable cover. The collector is placed horizontally to maximize radiation to the sky. The solar collection cover lets solar radiation get to the collecting surface while mid and far infrared radiations are blocked. On the other hand, the radiative cooling cover lets emit thermal radiation into the atmosphere.

Fig. 2: RCE prototype with a movable cover. Extracted from Castell et al. (2020)

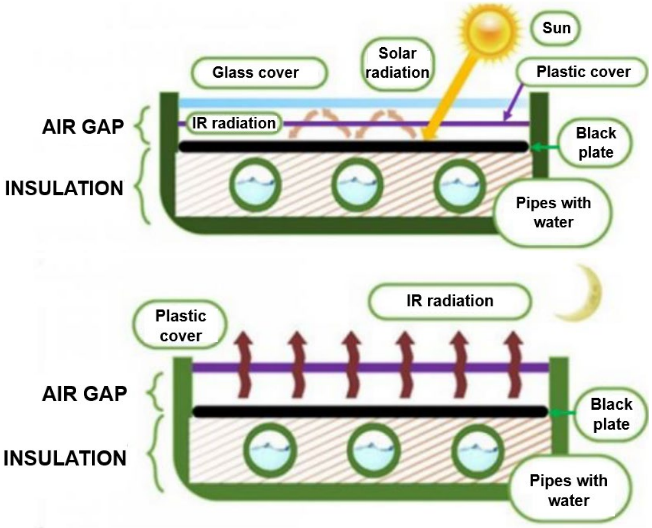

Fig. 3: RCE components for the heating mode (top) and cooling mode (bottom)

Fig. 4: Selected locations to obtain the energy demand and production

Regarding the maps created by Aili et al. (2021), high values of annual mean net cooling power are found in most parts of Africa. Considering the RC potential, three African regions can be distinguished: the Sahara Desert with the highest RC power potential, the tropical area remarkable for low values and the south of Africa with values in between.

This study presents an analysis related to the demands of cooling and domestic hot water (DHW) of three identical office buildings in Africa compared with the RCE's energy production. As it can be seen in Fig. 4, the offices are specifically located in Agadez (high RC power potential), Libreville (low RC power potential) and Calvinia (cooling potential in between).

2. Data acquisition and methodologies

Meteorological information was obtained from the Meteonorm database (Remund et al., 2019), corresponding to the radiation period from 1991 to 2010 and the temperature period from 2000 to 2009. DHW and cooling demands were obtained from the EnergyPlus simulation software, in which office buildings were taken from the USA Department of Energy, DOE ("Commercial prototype Building Models," n.d.) (Fig. 5). The same modifications were made as those implemented by Vall et al. (2018), that is to say, set point temperature schedules at 25/27ºC and natural ventilation through occupants controlled windows (7-22 h). The same building (Tab. 1) was used in the three locations in order to get comparable results, as the offices usually have the same comfort indoor conditions in all locations.

Tab. 1: Geometric parameters of the offices simulated

Wall area [m^2]	Window area [m^2]	Net conditioned area [m^2]	Roof area [m^2]
1,978.00	652.60	4,982.20	1,660.50

The Trnsys software was used to simulate the facility shown in Fig. 6 and to determine the production of energy. During the day, water from the hot tank was heated in the RCE, while during the night, water from the cold tank was refrigerated.

The results obtained (energy demand and production) were then analyzed using RStudio.

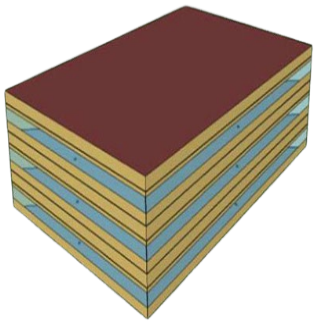

Fig. 5: Office building simulated in EnergyPlus

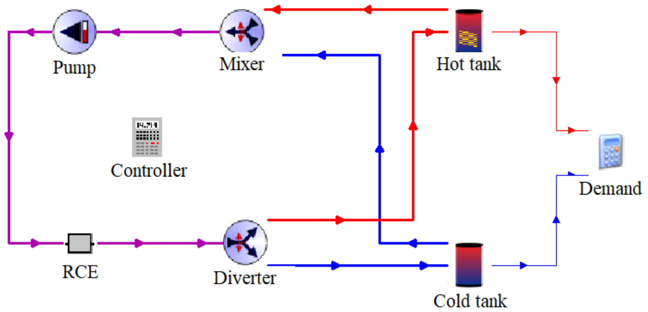

Fig. 6: Scheme of the facility simulated in Trnsys

The RCE device was presented as a Trnsys type, simulating the model developed and experimentally validated by Vall et al. (2020), in which parameters like the difference between the fluid temperature at the inlet and outlet of the RCE were calculated using energy balances between the device, the ambient air and the sky. The working mode (daytime solar collection or nighttime radiative cooling) was also considered.

Hot and cold tanks were used to store water obtained from heating and cooling modes, respectively, and to cover demands when needed. The demand was simulated in the following way: water from the hot and cold tanks was replaced by grid water at 20ºC during the night and during the day, respectively.

The controller type determined whether the RCE worked as a solar collector or as a radiative cooler, and modified both the pump flow rate (changing its speed) and the cover properties of the RCE (allowing the correct operation in each mode). The daily sunrise and sunset time were used to determine whether it was nighttime or daytime, and thus select the radiative cooling or solar collection mode, respectively.

The total roof surface in the analyzed building was 1,660.5 m^2. In this study, 1,330.0 m^2 (A_{RCE}), 80% of the total roof surface, was filled with RCEs in order to cover as much cooling demand as possible. A reasonable 20% of the roof was left for other uses. As the RCE's surface is 2 m^2, a total amount of 665 plates were required. The main technical characteristics of each RCE are presented in Tab. 2.

Tab. 2: Technical data of the RCE

Pipe diameter	**Pipe thickness**	**Insulation thickness**
8.00 mm	0.60 mm	30.00 mm
Cover solar absorptivity (heating mode)	**Cover solar transmissivity (heating mode)**	**Cover solar reflectivity (heating mode)**
0.05	0.90	0.05
Cover > 4 µm absorptivity (heating mode)	**Cover > 4 µm transmissivity (heating mode)**	**Cover > 4 µm reflectivity (heating mode)**
0.80	0.10	0.10
Cover solar absorptivity (cooling mode)	**Cover solar transmissivity (cooling mode)**	**Cover solar reflectivity (cooling mode)**
0.10	0.80	0.10
Cover > 4 µm absorptivity (cooling mode)	**Cover > 4 µm transmissivity (cooling mode)**	**Cover > 4 µm reflectivity (cooling mode)**
0.10	0.80	0.10
Radiator solar absorptivity	**Radiator solar transmissivity**	**Radiator solar reflectivity**
0.95	0.00	0.05
Radiator > 4 µm absorptivity	**Radiator > 4 µm transmissivity**	**Radiator > 4 µm reflectivity**
0.95	0.00	0.05

The tanks were dimensioned to store the heated and cooled water obtained during the daytime or nighttime hours, respectively, allowing their future use when required. The volume of the cold tank ($V_{cold\ tank}$) was determined using eq. 1 and the water flow rate for the cooling mode ($\dot{m}_{RC}$) was obtained using eq. 2.

$$V_{cold\ tank} = \frac{q_c \cdot A_{RCE} \cdot t_{RC}}{C_p \cdot \Delta T_{tank} \cdot \rho_w} \qquad [m^3] \qquad \text{(eq. 1)}$$

$$\dot{m}_{RC} = \frac{q_c \cdot A_{RCE}}{C_p \cdot \Delta T_{RCE}} \qquad [kg/s] \qquad \text{(eq. 2)}$$

where q_c is the expected RC power ($50\,Wm^{-2}$), t_{RC} is the time in which RC can be applied ($8\,h/day = 28{,}800\,s/day$), C_p is the water specific heat ($4{,}192\,J/(kg \cdot K)$), ΔT_{tank} is the temperature decrease of the water in the tank ($10\,K/day$), ρ_w is the water density ($1{,}000\,kg/m^3$) and ΔT_{RCE} is the temperature difference between the inlet and outlet of the RCE ($2\,K$). It should be noted that the mentioned values of q_c, ΔT_{tank} and ΔT_{RCE} are possible and reasonable according to the results from Castell et al. (2020).

On the other hand, the daytime facility was sized accomplishing the recommendations given by the Spanish public organization called IDAE (Institute for the Diversification and Saving of Energy) depending on the collecting surface (A_{RCE}): minimum volume of the hot tank of $75\,L/m^2$ and water flow rate of $40 - 60\,L/(h \cdot m^2)$.

To sum up, the dimensioning of the installation is shown in Tab. 3.

Tab. 3: Facility parameters in each working mode

Working mode	Water flow rate [kg/s]	Tank volume [m^3]
Solar collection (day)	22.17	99,750
Refrigeration (night)	7.93	45,687

As the water pump is a variable speed one, its flow rate is governed by the eq. 3.

$$\dot{m}_{RCE} = \gamma \cdot \dot{m}_{max} \qquad [kg/s] \qquad \text{(eq. 3)}$$

where $\dot{m}_{RCE}$ is the mass flow rate flowing through the RCE, $\dot{m}_{max}$ is the pump maximum speed (22.17 kg/s – solar heating mode) and γ is the coefficient in charge of modifying the pump speed ($\gamma = 0.36$ for the cooling mode).

In addition, the monthly energy values produced were calculated using eq. 4 and 5.

$$E_{RC,month} = \sum_{month}(P_{RC} \cdot \Delta t) \quad [kWh/(m^2 \cdot month)] \quad \text{(eq. 4)}$$

$$E_{SH,month} = \sum_{month}(P_{SH} \cdot \Delta t) \quad [kWh/(m^2 \cdot month)] \quad \text{(eq. 5)}$$

where P_{RC} is the radiative cooling power obtained in the RCE $[kW/m^2]$, P_{SH} is the solar heating power obtained in the RCE $[kW/m^2]$ and Δt is the period of time $[h]$ in which P_{RC} and P_{SH} are obtained.

3. Results and discussion

A comparison between the energy produced during daytime (solar heating mode) and nighttime (RC mode), for a year, is presented in Fig. 7, 8 and 9. It can be observed that solar collection increases during summer months, when solar radiation is higher. On the other hand, during the summer months, RC is lower in Niger and Calvinia, which is known as seasonal anomaly (Aili et al., 2021).

The three locations are far away from each other. In fact, Agadez is in the northern hemisphere and Calvinia is in the southern hemisphere, which means that seasons are reversed. As Libreville is near the equator, the climate is quite stable all over the year and the results prove that.

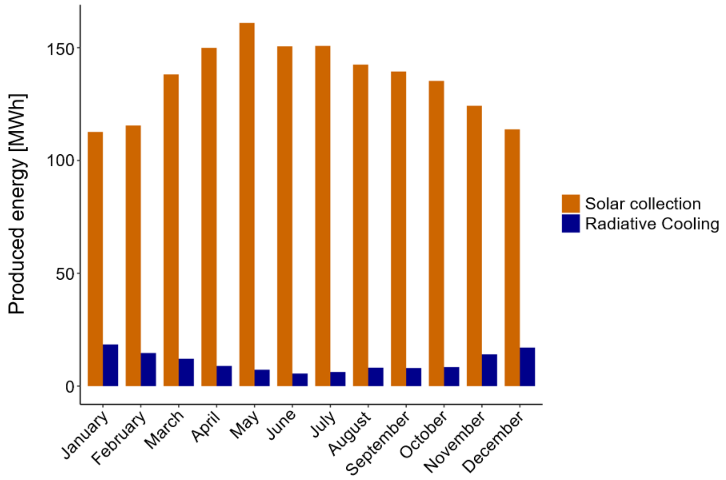

Fig. 7: Monthly energy production in an office building at Agadez (Niger)

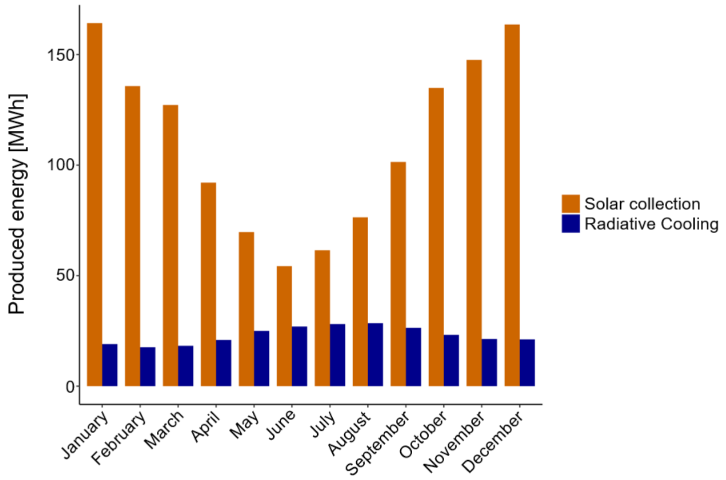

Fig. 8: Monthly energy production in an office building at Calvinia (South Africa)

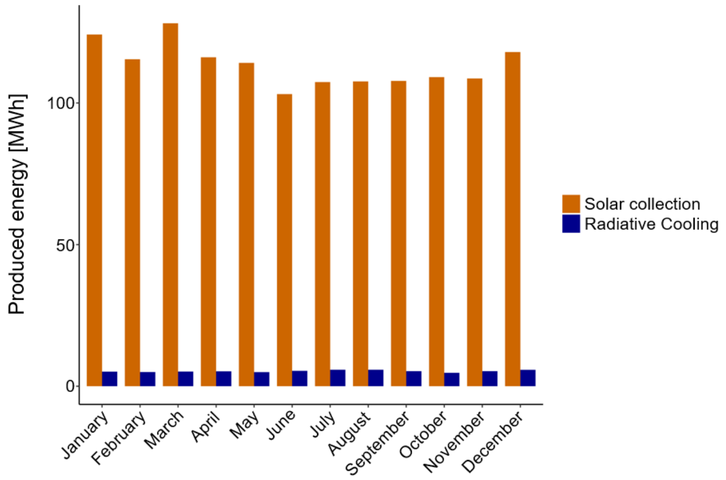

Fig. 9: Monthly energy production in an office building at Libreville (Gabon)

Fig. 10, 11 and 12 compare the cooling demand with the refrigeration energy production using radiative cooling, while Tab. 4 and 5 present the energy demand per square meter. The cooling demand at Agadez and Libreville is partially covered, while at Calvinia there are energy surpluses almost all the year (except January, February and March). Actually, Tab. 6 indicates that the mean annual cooling demand covered at Agadez and Libreville are 26.80% and 8.72%, respectively. In addition, the energy production at the capital of Gabon is quite stable, so the refrigeration covered is almost constant all the year (between 7.19% and 10.86%).

Tab. 4: Monthly DHW energy demand per square meter at each location [Wh/m²]

	January	February	March	April	May	June
Agadez	196.84	177.66	205.51	184.99	194.62	190.93
Calvinia	187.28	170.69	201.28	186.59	201.94	202.28
Libreville	196.07	177.45	205.52	185.06	194.76	190.78

	July	August	September	October	November	December
Agadez	182.32	198.57	182.85	191.16	189.87	191.68
Calvinia	194.80	210.20	189.84	192.87	186.50	184.22
Libreville	182.47	198.57	183.02	191.34	189.99	191.34

Tab. 5: Monthly cooling energy demand per square meter at each location [Wh/m²]

	January	February	March	April	May	June
Agadez	4,765.18	6,305.88	10,018.44	11,956.56	13,943.80	14,200.91
Calvinia	5,239.93	5,192.33	4,352.99	2,034.34	357.98	122.97
Libreville	12,716.65	12,355.99	14,268.66	13,124.59	13,903.82	12,120.44

	July	August	September	October	November	December
Agadez	14,592.36	14,962.17	12,875.00	11,720.39	8,453.95	5,820.12
Calvinia	176.26	102.77	406.39	1,813.79	2,647.50	4,172.68
Libreville	10,751,45	11,640.36	11,022.00	11,754.51	12,008.53	12,752.14

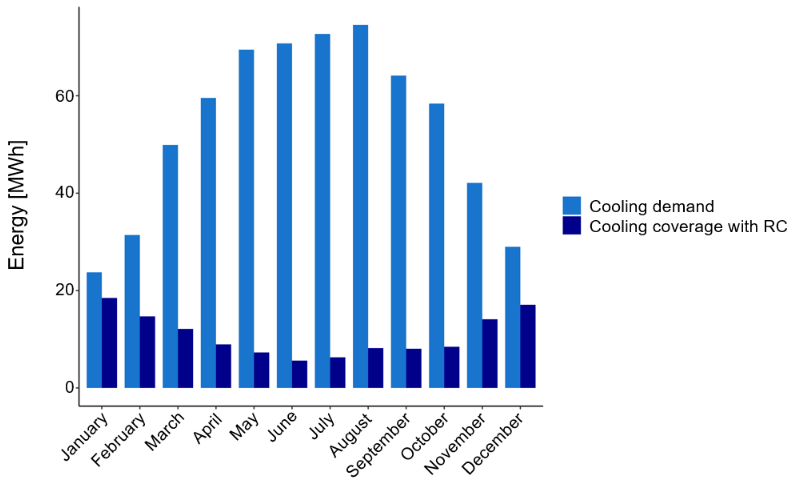

Fig. 10: Monthly refrigeration coverage in an office building at Agadez (Niger)

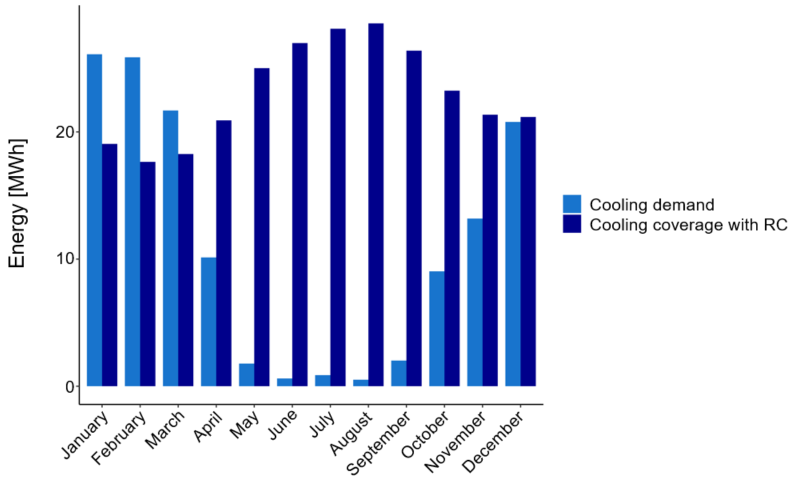

Fig. 11: Monthly refrigeration coverage in an office building at Calvinia (South Africa)

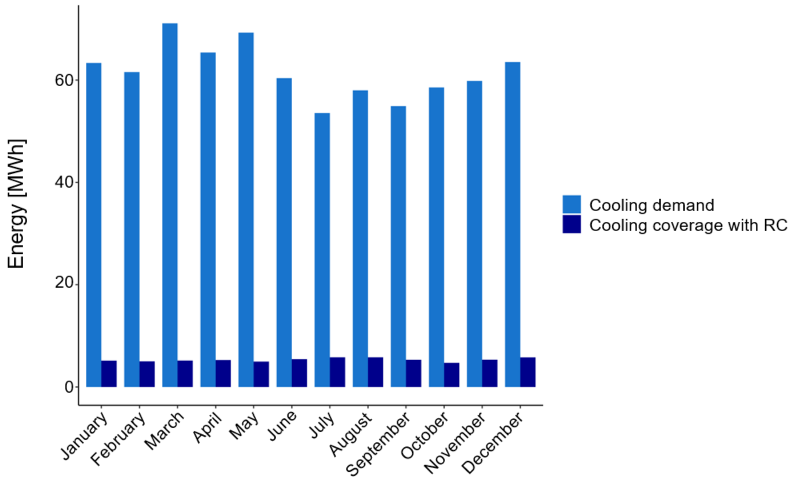

Fig. 12: Monthly refrigeration coverage in an office building at Libreville (Gabon)

Tab. 6: Percentages of cooling energy coverage ("surp." indicates that there are surpluses that specific month)

	January	February	March	April	May	June
Agadez	77.91	46.79	24.32	15.03	10.50	7.94
Calvinia	73.00	68.21	84.22	surp.	surp.	surp.
Libreville	8.16	8.16	7.28	8.09	7.19	9.03

	July	August	September	October	November	December
Agadez	8.66	10.99	12.56	14.50	33.50	58.95
Calvinia	surp.	surp.	surp.	surp.	surp.	surp.
Libreville	10.86	10.03	9.69	8.09	8.93	9.11

On the other hand, Fig. 13, 14 and 15 compare the DHW demand with the heating energy production using solar collection. A clear difference in the order of magnitude is observed between the heating and cooling energy production. It is important to highlight that office building demands count with lower DHW demands per square meter than other buildings typologies, such as hotels or residential buildings (Vall et al., 2018). As the facility was dimensioned to achieve the maximum cooling energy in an office building, there are many DHW surpluses in all the locations (additional energy accumulated after having covered all the DHW demand). Possible uses of these DHW surpluses include district heating in cold regions in Africa, industrial cleaning or water preheating in industries.

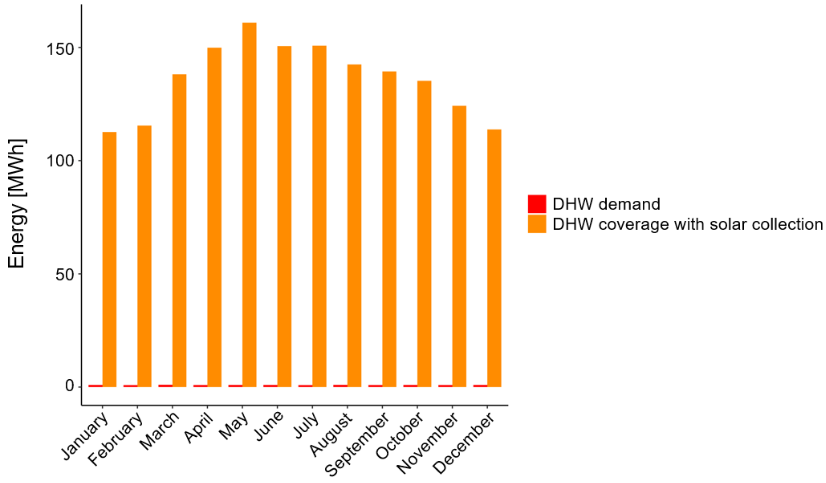

Fig. 13: Monthly DHW coverage in an office building at Agadez (Niger)

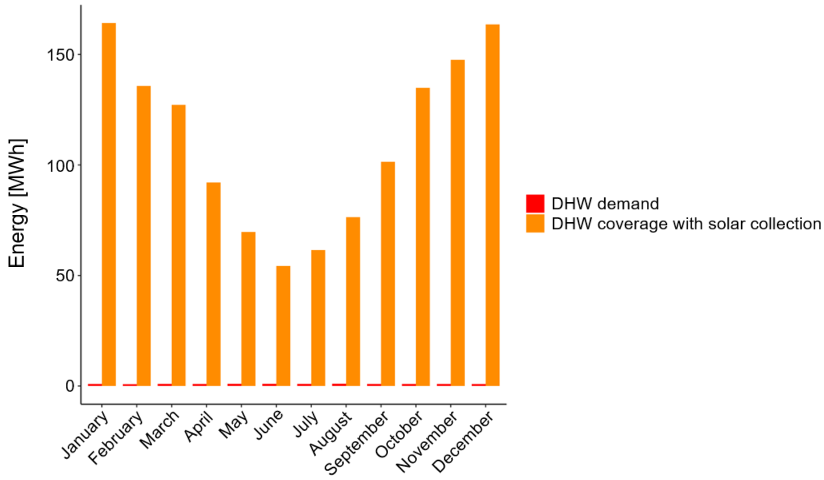

Fig. 14: Monthly DHW coverage in an office building at Calvinia (South Africa)

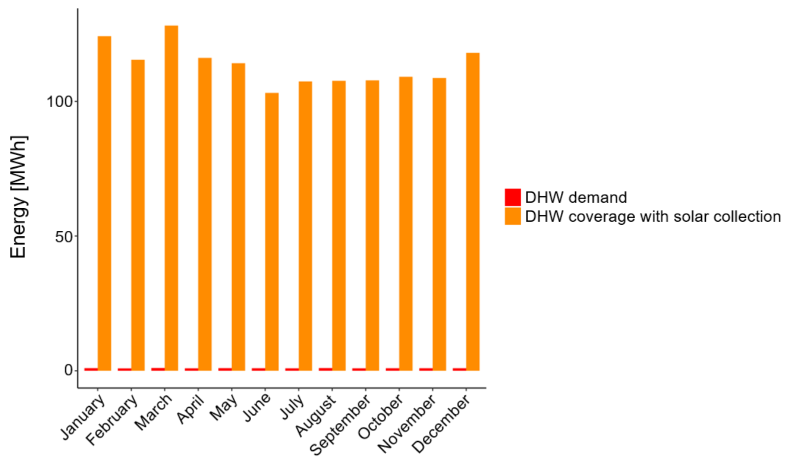

Fig. 15: Monthly DHW coverage in an office building at Libreville (Gabon)

Furthermore, Tab. 7 shows differences between the temperatures just before and after the Radiative Collector and Emitter. Higher changes of temperature are observed during daytime working mode (solar collection). Although the best performance is observed at Agadez when considering daytime mode, the best results are achieved at Calvinia for nighttime hours.

Tab. 7: Mean temperature changes between the inlet and outlet of the RCE

	Mean temperature reduction (nighttime)	Mean temperature increase (daytime)
Agadez	0.89 ºC	3.95 ºC
Calvinia	1.68 ºC	3.65 ºC
Libreville	0.41 ºC	2.90 ºC

Moreover, results extracted using RStudio show that sub-ambient temperatures may be achieved thanks to radiative cooling. As an average, the simulations indicate that during the night, temperatures of the cold tanks at Agadez, Calvinia and Libreville are 5.56ºC, 3.36ºC and 4.50ºC below the ambient, respectively.

Fig. 16 through 21 show the inlet and outlet temperatures of an RCE, the temporal profile of solar radiation, and the net power obtained per square meter of RCE (heating or cooling power). Negative values are used to represent cooling. For each location, data from the 10th to the 17th of January and July are presented. This allows the analysis of the RCE's performance under different weather conditions in each city.

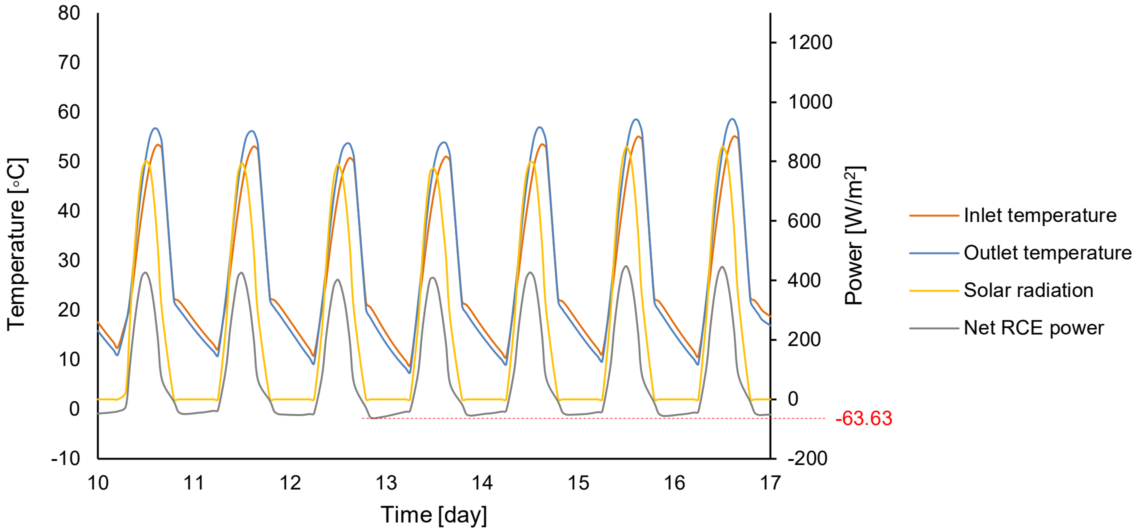

Fig. 16: Weekly RCE data from the 10th to the 17th of January at Agadez

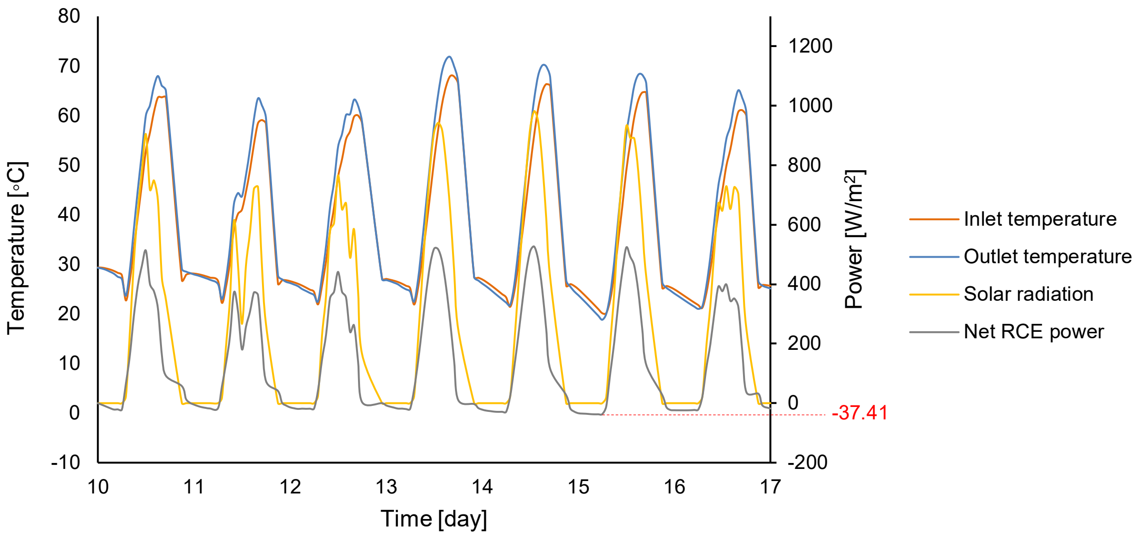

Fig. 17: Weekly RCE data from the 10th to the 17th of July at Agadez

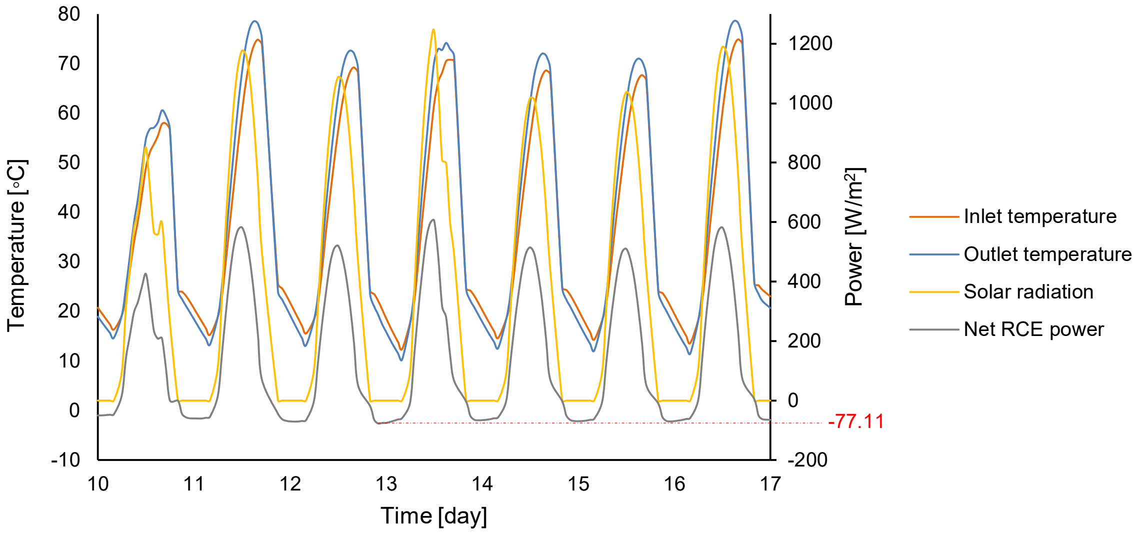

Fig. 18: Weekly RCE data from the 10th to the 17th of January at Calvinia

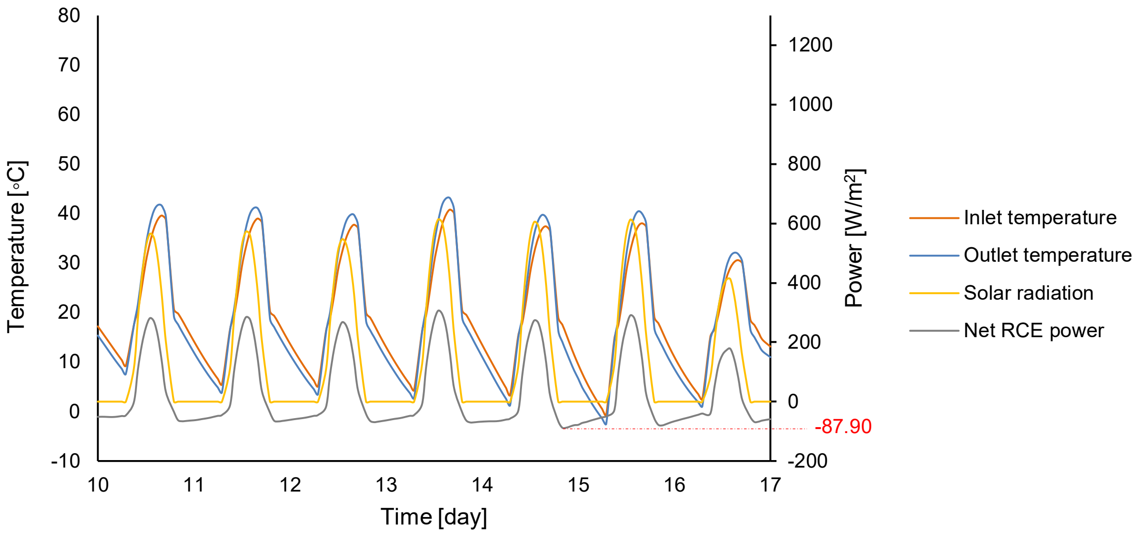

Fig. 19: Weekly RCE data from the 10th to the 17th of July at Calvinia

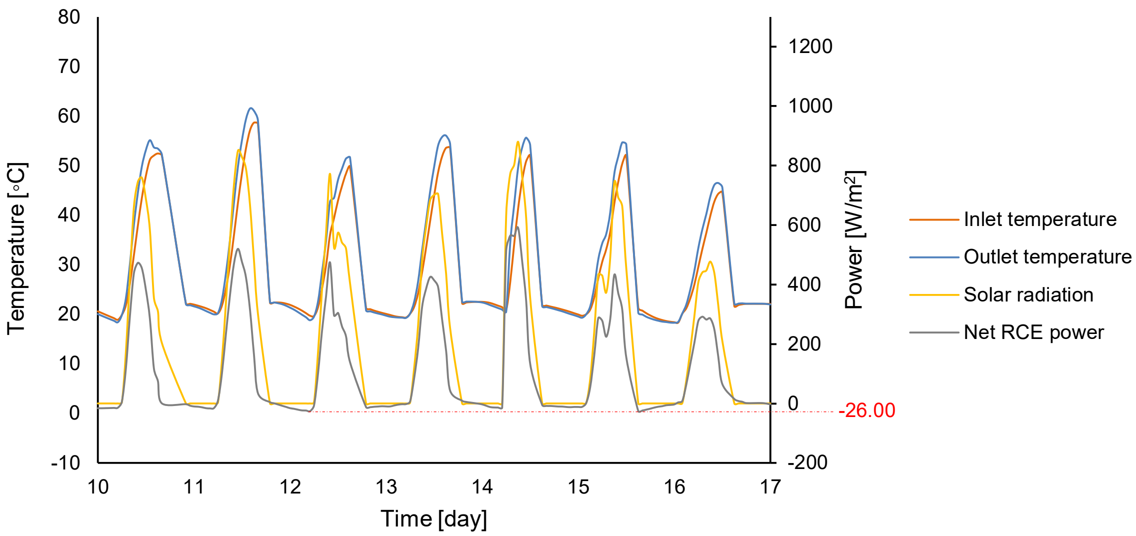

Fig. 20: Weekly RCE data from the 10th to the 17th of January at Libreville

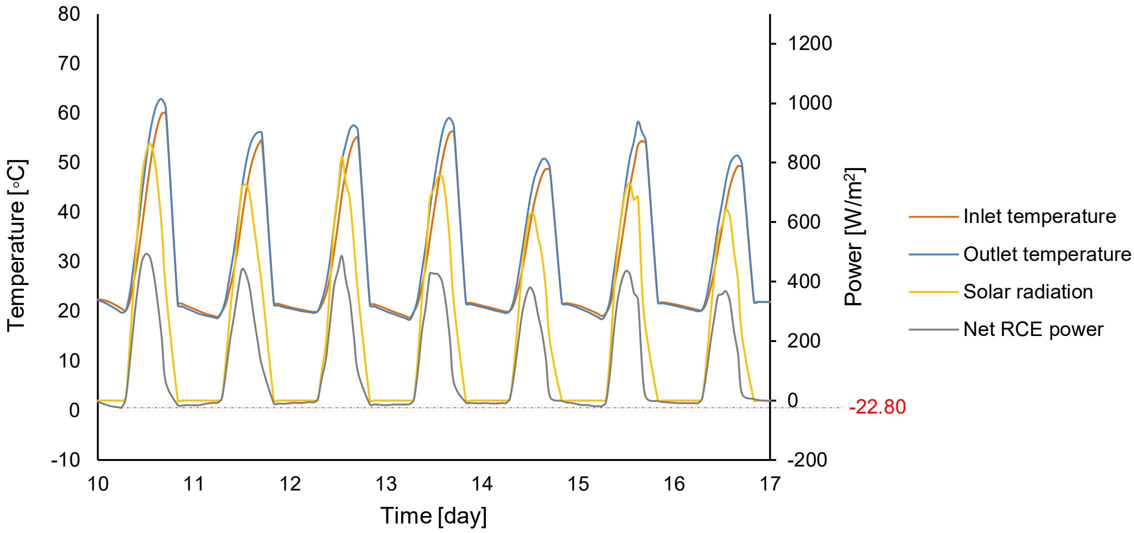

Fig. 20: Weekly RCE data from the 10th to the 17th of July at Libreville

It can be observed that when solar radiation is at its maximum, the net power is also at its highest. In the opposite case, when radiation is low or null, cooling power is maximized thanks to the RC. It can also be appreciated that the cooling power is of a different order of magnitude than the solar collection power, as mentioned before. The solar collection mode allows higher temperature changes compared to the Radiative Cooling mode, but the temperature reduction is enough to extract heat from the offices using close to ambient refrigeration systems, such as radiant floors or ceilings. The highest cooling potential results for these weeks are found in Calvinia.

4. Conclusions

As it was expected, the solar heating energy produced is higher than the energy obtained with RC. Mean annual values of heating energy production at Agadez, Calvinia and Libreville are 136.14 MWh/month, 110.73 MWh/month and 113.33 MWh/month, respectively; while the results of cooling energy production are 10.78 MWh/month, 23.06 MWh/month and 5.33 MWh/month, respectively.

While the cooling demand at Agadez and Libreville is partially covered (26.80% and 8.72%, respectively), at Calvinia there are surpluses almost all year. On the other hand, there are many Domestic Hot Water surpluses in all the locations. This extra energy could be used in nearby buildings or industries for other heating purposes such as building heating, commercial laundry or industrial pre-heating processes.

The seasonal anomaly described by Aili et al. (2021) has also been observed, especially in Agadez and Calvinia, where less RC power is obtained during the summer months.

The results also show that temperatures below the ambient may be achieved thanks to radiative cooling. In fact, mean annual temperature differences between the cold tanks and the ambient of 5.56ºC, 3.36ºC and 4.50ºC are observed at Agadez, Calvinia and Libreville, respectively.

5. Acknowledgments

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