Covering energy demands of buildings with an Adaptive Radiative Collector and Emitter (AD-RCE)

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Abstract:

The building sector is one of the main consumers of energy, being the heating and cooling, as well as the Domestic Hot Water (DHW), the highest demands. The Radiative Collector and Emitter (RCE) is a renewable technology capable of providing both heating and cooling in a single device. This innovative technology reduces the dependency on fossil fuels, as well as diminishes the carbon footprint. An evolution of the RCE, the adaptive RCE (ad-RCE), which allows night-time radiative cooling and either daytime solar collection or daytime radiative cooling is presented for a single-family house in Johannesburg, South Africa. This new concept is capable to adapt its behaviour to the energy requirements, producing either heat or cold during daytime, as well as cold during night-time. Thus, the production of heat and cold adapts to the demands of the building. By means of numerical simulation, the relation between cooling and Domestic Hot Water (DHW) demands are compared with the renewable energy produced by the ad-RCE to determine the suitability of such technology to cover the energy demands of buildings by means of renewable energy. Results show that with a proper decision on the number of hours in solar collection mode and the rest for daytime or night-time radiative cooling, the ad-RCE field could yield to annual coverages of the cooling demand of 83% and of 100% for the DHW.

Keywords:

Radiative cooling, solar thermal collection, adaptive energy production, renewable energy, energy demand, single-family house.

1. Introduction

In the European Union, 40% of the final energy consumption and 36% of the CO_2 emissions are associated to the building sector [1]. The Eurostat [2] concludes that space heating represents 64.1% of the total consumption in buildings, Domestic Hot Water (DHW) 14.8%, and space cooling 0.4%. Although space cooling is a small fraction in the total energy consumption of households, [3] predicts that refrigeration demands will triple worldwide by 2050 if no action is taken. Today, the operating refrigeration systems account for 18.5% of the world's electricity consumption [4]. Most current cooling systems run on compression cooling cycles, consuming a lot of electricity, especially in the summer heat peaks. Typically, space heating and domestic hot water is produced by natural gas in households, whereas space cooling is all achieved by electricity consumption [5]. Both natural gas and non-renewable electricity production, contributes negatively to climate change and an alternative renewable production of these energy needs should be fostered.

The Radiative Collector and Emitter (RCE) is a renewable technology capable of providing both heating and cooling in a single device [6]–[8]. This innovative technology reduces the dependency on fossil fuels, as well as diminishes the carbon footprint. It combines in a single device the ability of solar collection during the day and radiative cooling (RC) during the night. Solar thermal collectors are a mature and commercially implemented technology to produce hot water from renewable energy. They rely on exposing an absorber to solar radiation to heat up a fluid circulating through different internal pipes [9]. On the other hand, radiative coolers are not mature yet. RC is the process by which a surface reduces its temperature by emitting thermal radiation (long wave) into the deep space, taking advantage of the transparency of the infrared atmospheric window at certain wavelengths (7-14 μm). The low effective temperature of the space makes it possible to cool down below ambient temperature [10]. Initially, RC was only possible at night, since the energy balance during the day resulted in gains due to solar radiation, but with the appearance of new materials it is also possible to

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cool a surface during the day by RC [11], [12]. Several papers have been published recently proposing different types of materials for daytime radiative cooling (DRC), such as nanoparticles, metamaterials, bio-inspired materials, photonic structures, and hierarchically porous polymers [15]. However, these new materials do not allow to take advantage of solar energy during the day.

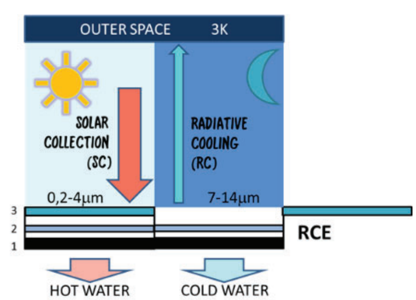
Vall et. al [6] showed how the RCE device could be integrated in several residential and commercial building types and in various cities located in different Köppen-Geiger climate classification regions over the world, covering most of the DHW usage. However, with the RCE surface sized for this DHW coverage, the covered fraction of the cooling demands was modest, being below 25% in 10 of the 15 climates studied. Besides, a not realistic 100 % efficiency for the radiative cooling mode was applied in this maximum cooling potential study, so even less cooling production and less coverage is expected for a real RCE prototype. The production of cooling could be increased mainly with two different strategies. On the one hand, the RCE efficiency should be substantially enhanced, as the achieved experimental values in a RCE prototype are only in the order of 25%, with peaks of 32%. This means that most of the cooling power generated in the RCE emitter is not used to cool down the circulating water but cools down the surrounding air and surfaces. On the other hand, the above mentioned daytime radiative cooling materials could be exploited, generating cold water also during the day. In summertime, when cooling is more necessary, DRC could reach a three-fold increase of the number of cooling hours.

An evolution of the RCE, the adaptive RCE (ad-RCE), which allows night-time radiative cooling and either daytime solar collection or daytime radiative cooling is presented in this study for one of the cities and one of the buildings used in [6]: a single-family house in Johannesburg (Africa). This new concept is capable to adapt its behaviour to the energy requirements, producing either heat or cold during daytime, as well as cold during night-time. Hence, this new equipment, which is still under development, avoids over-sizing the installation while maintaining high levels of energy coverage.

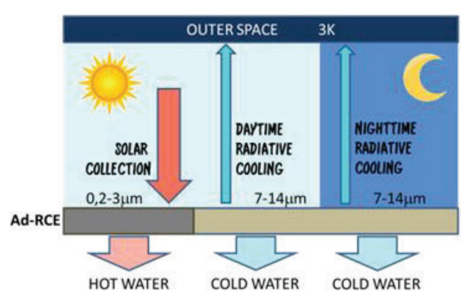
In this study, both the feasibility of the ad-RCE and the improvement it offers, compared to its predecessor, (RCE) is analysed. With this objective, this work presents a simple methodology to estimate the minimum operating hours of solar heating mode needed to cover DHW demands and for determining the hourly, daily and monthly production of heat and cold with the ad-RCE. As expected, the increase of cooling hours within a day thanks to daytime RC predicts a significant raise in annual cooling coverage, reducing the dependency on traditional CO_2 emitting cooling and heating systems.

2. Evolving the concept of RCE to ad-RCE

Figure 1 shows the conceptual differences between the original Radiative Collector and Emitter (RCE), which produces cold water during the night by radiative cooling and hot water during the day by solar thermal collection (Figure 1, a), and the evolution to the adaptive RCE (Figure 1, b) with a new design capable of producing both solar heating and radiative cooling at daytime, together with night-time radiative cooling. Thus, during the day the user can decide to apply it to heat up water or cool it down, adapting to variable energy demands of the building. The RCE concept has already been demonstrated experimentally with a prototype [7] and a model has been validated [8], whereas the ad-RCE is still under development. We aim to develop and validate a new ad-RCE model and to design, build and test a new ad-RCE prototype in the following 2 years.



(a)



(b)

Figure. 1. Conceptual differences between the RCE (a) and the ad-RCE (b), which includes DRC.

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3. Methodology

A simple steady state method was used to estimate the DHW and cooling production of the ad-RCE for a whole year in Johannesburg. The house energy demands were obtained from a whole-building energy simulation. Daily productions and demands were used to calculate the daily and monthly coverages of the ad-RCE.

3.1. Calculation of DHW and cooling building demands

Meteorological information for Johannesburg was obtained from the Meteonorm database [16], which corresponds with the radiation period 1991-2010 and the temperature period 2000-2009. The DHW and cooling demands for the simulated single-family house were obtained from the EnergyPlus building energy simulation software. The single-family house (Figure 2) is a template taken from the USA Department of Energy, DOE [17]. It consists of a two-floor, pitched gabled roof, detached house with a net conditioned area of 223.1 m^2. The original house model was modified to include additional active and passive strategies such as set point temperature schedules at 25ºC, summer night ventilation and overhangs. The same procedure as the presented in [6] was followed.

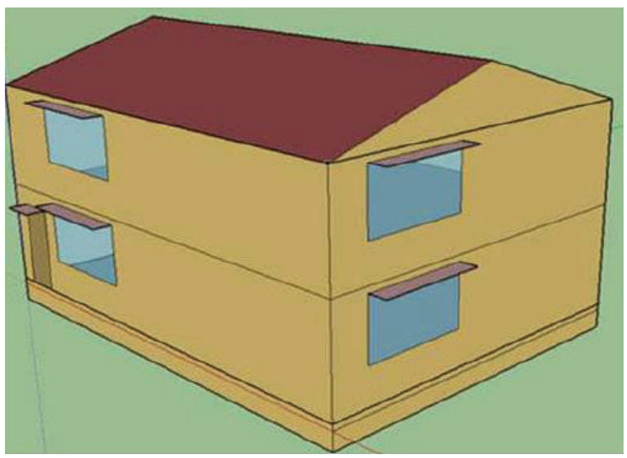

Figure. 2. Simulated single-family house in Johannesburg.

3.2. ad-RCE production

A very similar procedure to the one explained in [6] has been applied in this paper. A summary of the assumptions for the production of DHW and cooling, used both in [6] and in this work, is presented as follows:

- Steady state model.
- Conductive and convective losses are included in the ad-RCE efficiencies.
- Tilt angle for the ad-RCE is assumed horizontal, for maximum production of cooling.
- Wind-shield cover for solar collection mode with 100% transmittance in solar spectrum and 0% transmittance in the thermal spectrum is considered.

Contrary to the previous work, the daytime RC capability of the ad-RCE forces the wind-shield cover in DRC mode to have 100% reflectivity in solar spectrum and 100% transmittance in the thermal spectrum.

The DHW production thanks to solar collection was determined considering the hourly Global Horizontal Irradiance (GHI) given in the data file and the RCE efficiency in solar collection mode (Eq. 1). The solar collector efficiency is a common methodology and considers in a single parameter all the inefficiencies of the system (solar collector efficiency, losses due to inclination and shadows, etc.). The same annual average efficiency η_{sc} of 0.6 used in [6] was applied in this work for the solar collection calculations.

$$P_{solar,net}\left[\frac{W}{m^2}\right] = GHI \cdot \eta_{sc} \quad (1)$$

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The average thermal power calculated for each hour of the year is then converted into energy produced simply multiplying by the time step (1 hour). The integration of these values along a day will determine the daily DHW production and along a month, the monthly production. Eq. 2 presents the calculation of this monthly production:

$$E_{solar,month}\left[\frac{Wh}{m^2 \cdot month}\right] = \sum_{month} P_{solar,net} \cdot \Delta t \quad (2)$$

The assumed efficiency for cooling production by daytime and night-time RC in the ad-RCE is also 60%. The justification for this value is that it is expected that the achieved 32% efficiency in the first prototype could be improved with better design that reduces the heat gains by conduction and convection to the emitter. This RC efficiency η_{RC} is defined as the cooling power achieved by the circulating water and the maximum cooling power achieved on the surface of the radiative cooler. This maximum cooling power can be calculated as an energy balance on the radiative surface, as presented in Eq. 3 and in Figure 3:

$$Q_{net} = Q_s(T_s) - Q_{atm}(T_{atm}) - Q_{sun}(T_{sun}) - Q_{cond} - Q_{conv} \quad (3)$$

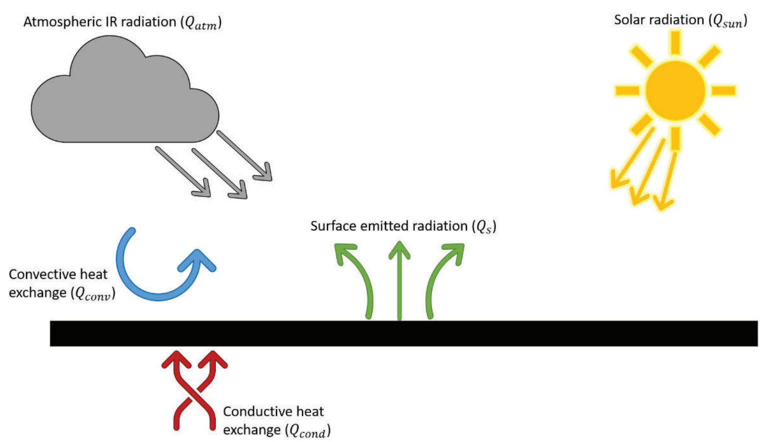

Figure. 3. Scheme of the thermal exchanges between the radiative surface (black) and its surroundings.

For this calculation, heat gains/losses by conduction Q_{cond} and convection Q_{conv}, are taken as 0. The infrared radiation coming down from the atmosphere Q_{atm} and the absorbed radiation from the Sun Q_{sun} are direct readings from the weather file, as the absorptivity of the surface is assumed equal to 1 in this study.
The amount of energy emitted from a surface with an average emissivity ε_s (in this study equal to 1) is given by Eq. 4.

$$Q_s = \varepsilon_s \sigma T^4 \quad (4)$$

Eq. 5 gives the useful cooling power given to the water, as the product of Q_{net} and the RC efficiency η_{RC}:

$$P_{RC,net}\left[\frac{W}{m^2}\right] = Q_{net} \cdot \eta_{RC} \quad (5)$$

The integration of the $P_{RC,net}$ values along a day will give us the daily cooling production and along a month, the monthly production. Eq. 6 presents the calculation of this monthly production:

$$E_{cool,month}\left[\frac{Wh}{m^2 \cdot month}\right] = \sum_{month} P_{RC,net} \cdot \Delta t \quad (6)$$

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The energy coverage is calculated as the ratio between the cooling or heating energy produced in a day divided by the daily demand. If this ratio is over 1 (or 100% in percentage), we take a coverage percentage of 100% for that day. When there is an excess of daily energy production, this excess is lost; it is not used in the following days. The monthly coverage is the average of the daily coverage. Note that this simplified approach, without considering energy storage tanks, is underestimating the potential maximum coverage. So, we are on the safe side of the coverage predictions. A correctly designed thermal energy storage system would slightly raise the coverage figures presented next in the results section.

All the meteorological data processing, all the above hourly calculations and the daily and monthly integrations are carried out with the Rstudio, version 1.3R.

3.2. ad-RCE sizing

A similar approach as the one proposed in [6] is followed in this work. Indivisible units of 2 m^2 are assumed for the ad-RCE and the number of ad-RCE installed on the roof should cover at least 75% of the DHW demands. In the case of Johannesburg, the RCE sizing resulted in 4 m^2 of surface area and 2 units of RCE, with 2 m^2 each [6]. Thus, in this study, 2 ad-RCEs of the same area used. However, an additional degree of freedom is available with the ad-RCE that was not present in the traditional RCE [6]. The number of solar collection hours during the day can be reduced while increasing the RC hours. Starting at 11.00 h, we have increased the number of hours of solar collection (and decreased the RC hours) until all the months had at least 80% DHW coverage with the ad-RCE. In this case study, running in solar heating mode from 11.00 h to 17.00 h is enough for the target DHW coverage for all the months, but May, June and July (winter months in Johannesburg), which need 12 h of solar heating instead of 6 h, from 7.00 to 19.00 h. The remaining 18 h (12 h for the latter three months) of the day are dedicated to RC, both in daytime and nighttime, increasing the cooling production with respect to pure night RC.

3. Results and discussion

Figure 4 shows the comparison of the DHW monthly demand with the ad-RCE monthly hot water energy production over one year in the selected single-family house in Johannesburg. As explained in the previous section, the DHW production is realized only during 6 hours with high insolation, in the middle of the day, from 11.00 h to 17.00 h (12 hours for May, June and July). The rest of the time the ad-RCE works in RC mode, producing cold water both at daytime and night-time thanks to the use of advanced daytime radiative cooling materials. The fine-tuned optical properties of these materials make them capable of reflecting barely all sunlight and emitting, almost as a black body, to the deep space. In most of the months, the monthly supplied DHW production surpasses the monthly demands, with the only exception of April, July and August, where the fraction of demand not supplied by the ad-RCE is small (in the range 1-10%). DHW demands are relatively constant in the house, ranging from 250 and 315 kWh/month. The expected increase in DHW demand in winter months due to the lower water grid temperatures is compensated by the above-mentioned increase in the number of hours in solar mode. Adding up the monthly demands and productions of DHW and making the ratio, the annual coverage reaches 108%. However, this coverage is an upper limit for the actual coverage as a non-realistic, large DHW tank, would be necessary to store all the excess heat that is not used in a particular day.

Regarding the cooling demand and supply, Figure 5 presents the cooling covered by the ad-RCE each month of the year. For months with modest, or almost inexistent cooling needs, the ad-RCE cooling generation clearly exceeds the demands. On the other hand, in the months with the highest cooling demands (January, February, March, November and December), the ad-RCEs cooling productions are well below the house cooling needs, being the monthly productions between 26 and 60% of the monthly demands. Adding up the monthly demands and productions of cooling and making the ratio, the annual coverage reaches 83%. The 37% yearly cooling coverage obtained in [6] for the same single-family house in Johannesburg with normal RCEs is clearly surpassed with the same surface of ad-RCEs. This is achieved due to the extra hours of DRC offered by the ad-RCE. However, more surface of ad-RCEs should be necessary if a higher percentage of RC fraction is targeted for the hot summer months.

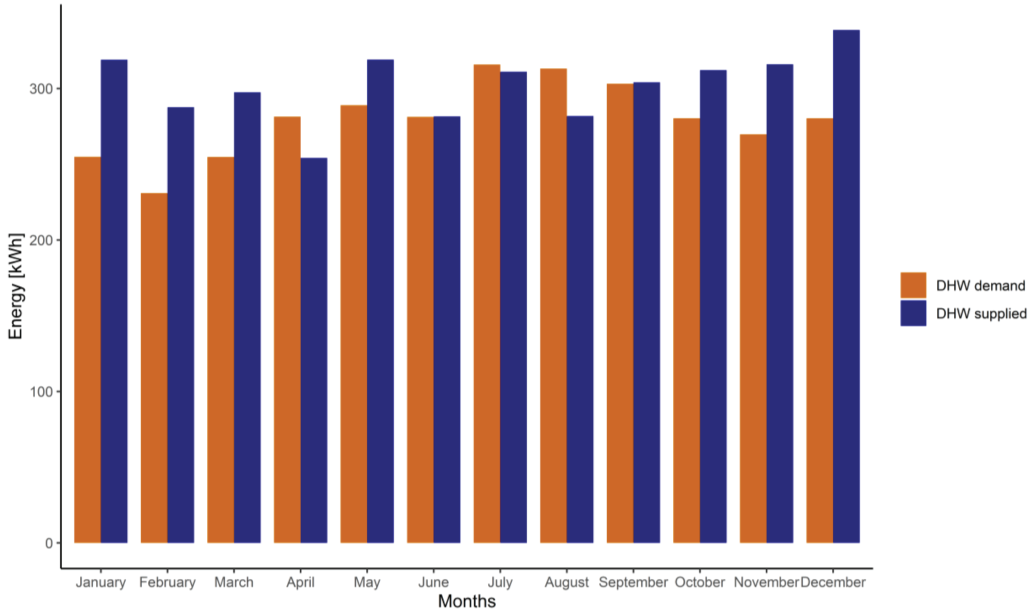

Figure. 4. Comparison of monthly DHW demand versus RCE DHW production.

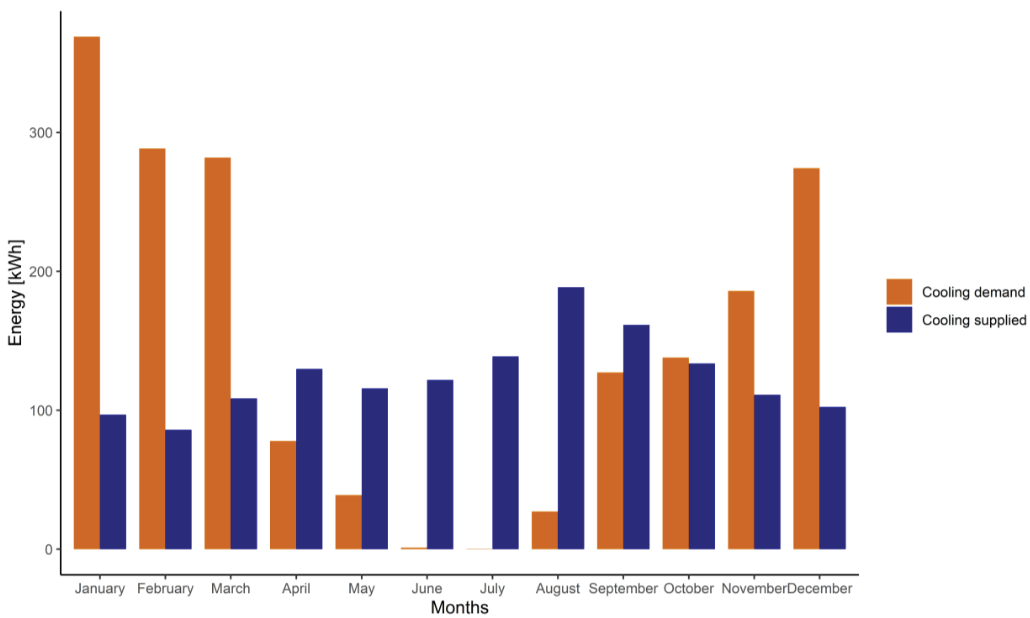

Figure. 5. Comparison of monthly cooling demand versus RCE cooling production.

It is important to note that these comparisons of Figure 4 and Figure 5 of annual demands over annual productions are overestimating the real coverage because we are assuming that any excess production of one day can be used in the following days of the month. Next, we will compare the monthly coverages as the average of the daily coverages, which is the lower end of the estimation, as the excess production of one day is not used in the following days of the month. In a real situation, with DHW and cooling storage tanks, the actual monthly coverage should be between these two extreme values.

The monthly energy coverage for both DHW and cooling is shown in Figure 6. These coverages are calculated as the average of the daily coverages. DHW coverages lie in the range 83-94%, meaning that, even in the sunny summer months, there may be some cloudy days when the DHW demand is not reached. As for the

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cooling, the coverages are above 90% in the central cold months (May, June, July and August) and it goes down to 32 % for February, the month with the lowest cooling coverage. Note that an easy strategy to increase the cooling coverage in summer months, without increasing the ad-RCE total surface, may be the reduction of the number of hours in solar collection mode, sacrificing in that way the DHW coverage. Nevertheless, it is out of the scope of this study the optimization of the number of operating hours per day to minimize the house operating costs and/or the environmental impacts of the consumed energy.

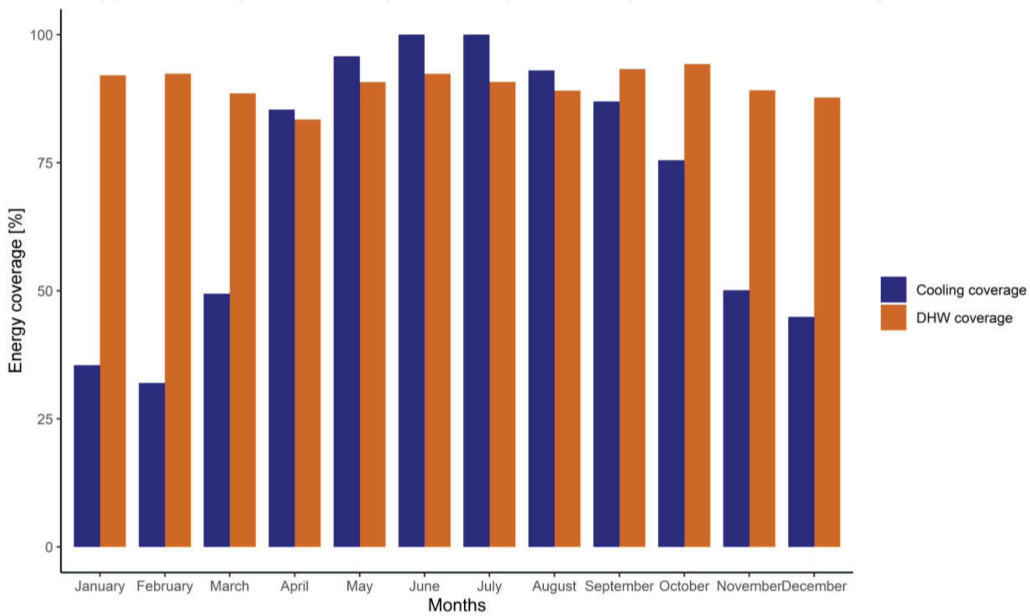

Figure. 6. DHW and cooling coverage of demands achieved by the ad-RCE.

Figure 7 illustrates the substantial increase in cooling coverage thanks to the substitution of normal RCEs by new ad-RCEs. In the hottest months of the year in Johannesburg, where the cooling is more needed, the growth in cooling production is in the range of 65-70%. This implies an increase in cooling coverage between 36 and 56%. These increases could even be higher for locations in the world where the difference of daily and night hours in summer are more pronounced than in Johannesburg.

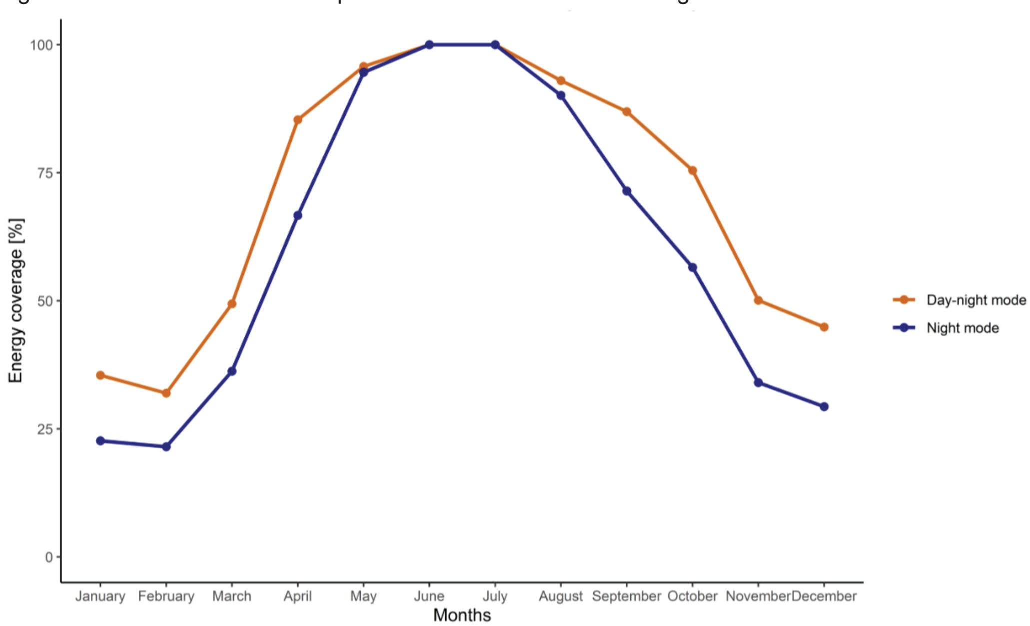

Figure. 7. Cooling coverage of ad-RCE with DRC and NRC, and normal RCE with only NRC.

4. Conclusions

In this study a new renewable energy device, the ad-RCE, is presented. The ad-RCE is an evolution of the Radiative Collector and Emitter (RCE), which is a single device able to produce cold water by radiative cooling at night and hot water by solar thermal collection at daytime. The ad-RCE is a new redesign of the RCE that enables the user to choose between daytime radiative cooling mode and solar collection mode, depending on the daily demands. The new ad-RCE is integrated in a house in Johannesburg, South Africa, to analyse the level of DHW and cooling monthly coverages for the house. Energy plus is used to calculate the DHW and cooling demands of the house and R studio is applied for the dynamic hourly simulation of the ad-RCE. The increased hours of radiative cooling in daytime enables a better match between the demand and production of cooling, increasing the annual production by 66%, while keeping the DHW coverage above 80%.

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Nomenclature

$\boldsymbol{A}$	Radiator/Absorber surface	(m^2)
$\boldsymbol{E_{solar,month}}$	Net monthly heating energy thanks to solar collection	(Wh/m^2/month)
$\boldsymbol{E_{cool,month}}$	Net monthly cooling energy thanks to RC	(Wh/m^2/month)
$\boldsymbol{Q_{atm}}$	Absorbed infrared radiation from atmosphere	(W/m^2)
$\boldsymbol{Q_{cond}}$	Conduction heat power	(W/m^2)
$\boldsymbol{Q_{conv}}$	Convective heat power	(W/m^2)
$\boldsymbol{Q_{net}}$	Net balance radiation power	(W/m^2)
$\boldsymbol{Q_s}$	Infrared radiation power emitted by a radiative surface	(W/m^2)
$\boldsymbol{Q_{sun}}$	Incident solar radiation power	(W/m^2)
$\boldsymbol{T_{atm}}$	Ambient and atmosphere temperature	(K)
$\boldsymbol{T_s}$	Surface temperature	(K)
$\boldsymbol{\sigma}$	Stefan-Boltzmann’s constant: $5.6704\cdot10^{-8}$	(W/m$^2\cdot$K^4)
$\boldsymbol{\varepsilon_s}$	Surface emissivity	(-)

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