Domestic hot water and cooling demand coverage for nearly Zero Energy Buildings applying combined solar heating and radiative cooling

Albert Castell[1], Marta Delgado[1], Roger Vilà[1], Lídia Rincón[1] and Ingrid Martorell[1]

[1] Sustainable Energy, Machinery and Buildings (SEMB) Research Group, INSPIRES Research Centre, Universitat de Lleida, Pere de Cabrera s/n, 25001 Lleida (Spain)

Abstract

A new device capable to combine night radiative cooling and solar thermal collection (called Radiative Collector and Emitter, RCE) is analyzed to determine its potential to cover the Domestic Hot Water (DHW) and cooling demands for a single-family detached house following nearly Zero Energy Building (nZEB) standards. The energy demand of the considered house is determined by numerical simulations using EnergyPlus and compared to the energy (heat and cold) production of the RCE, determined by Trnsys simulations, in order to identify the potential for demand coverage. Results show best coverages can be achieved for climates Cwb and Csb, as well as BSh of the Köppen-Geiger climate classification, when considering the demand coverage, while the most promising climates are BSh, BSk, and BWh in terms of useful energy production. Further research is warranted to optimize the size of the system in order to identify more climates with significant potential, as well as study other building typologies with different demand profiles.

Keywords: Renewable Heating and Cooling, Radiative Cooling, Solar Thermal Collection, nearly Zero Energy Buildings, Demand Coverage, Polygeneration.

1. Introduction

Radiative cooling is a technology capable to produce cold through the dissipation of heat to the sky taking advantage of the infrared atmospheric window (7-14 µm) (Vall and Castell, 2017). The study of radiative cooling dates back to the 60s, although it has not reached the market, mainly due to its low power density (around 65W/m^2) (Berdahl et al., 1983; Ferrer Tevar et al., 2015; Landro et al., 1980). In the last years two new approaches have been studied in order to improve this technology. On the one hand, the use of selective surfaces with nanomaterials (Raman et al., 2014) allows the use of radiative cooling under sunlight conditions; on the other hand, the combination of night radiative cooling with daytime solar collection (the Radiative Collector and Emitter, RCE) (Hu et al., 2016; Vall et al., 2020) allows the production of two thermal products (heat and cold) with the same device. The RCE has a similar structure as that of a solar thermal collector, with a 2 m x 1 m x 80 mm aluminum frame, a metallic absorber painted black with 8 cooper pipes of 8 mm internal diameter and 0.6 mm thick, and 30 mm glass-wool back insulation. An adaptive cover consisting on a transparent 3 mm glass was used as cover for solar collection mode, and a 0.6 mm thick polyethylene (PE) film for radiative cooling was used (Fig. 1).Solar thermal collectors are a technology widely implemented in buildings in order to cover Domestic Hot Water (DHW) demands. However, cooling demands in buildings are commonly covered by non-renewable technologies. Vall et al., 2018 studied the potential energy savings achievable by integrating the RCE into different types of buildings in different climates, showing promising potential in several climates. However, the cooling demands are high compared to the production rates of the RCE, which limits the coverage of the cooling demands. The cold production of the RCE is one order of magnitude lower than the heat production, thus being especially suitable for applications with similar ratios of heat-to-cold demand.

Nearly Zero Energy Buildings (nZEB) are described as buildings that have very high energy performance. The low amount of energy that these buildings require comes mostly from renewable sources. The Energy Performance of Buildings Directive (European Parliament. Directive 2010/31/EU) requires all new buildings to be nearly zero-

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energy by the end of 2020. Therefore, it is expected that future trends in building energy demands will follow this tendency. Passive House is a well-known and internationally accepted standard for nZEB, which defines some strategies and key performance indicators to achieve nZEB specific goals.

In this paper the potential for integrating the above mentioned RCE technology in nZEB buildings (considering the heating and cooling demands limitation of Passive House) is studied. Cooling and DHW demand coverage are presented for different climates (Kottek et al., 2006).

2. Methodology

To evaluate the coverage of the cooling and DHW demands by the RCE under different climatic conditions, the energy production of the RCE and the energy demand of the buildings were determined by numerical simulation with Trnsys and EnergyPlus, respectively (see Fig. 2).

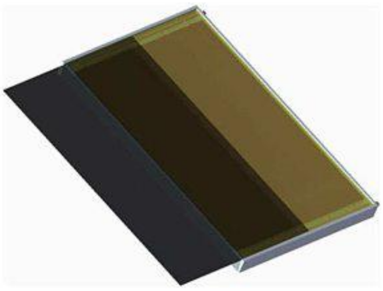

Fig. 1: 3-D sketch of the RCE device.

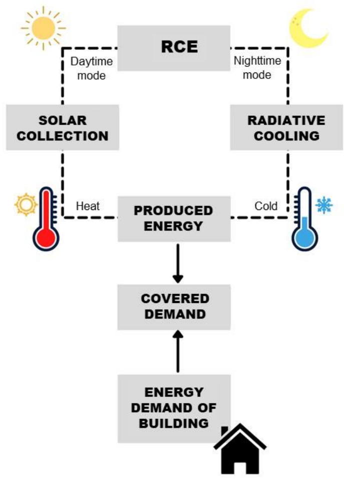

Fig. 2: Conceptual scheme of the energy production, demand and coverage calculation

2.1. World climates considered

Different cities representing different world climate zones, based on the Köppen-Geiger classification (Kottek et al., 2006), are analyzed in order to identify the most promising conditions for the RCE technology to cover the DHW and cooling demands. Tab. 1 presents the studied cities, their climate zone and coordinates. EnergyPlus weather files from the selected cities are used for both the simulation of the energy demands of the buildings and the energy production of the RCE system.

Tab. 1: Studied cities, climate zone and coordinates.

	Climatic zone	Latitude	Longitude
Cairo (Egypt)	BWh	30º N	31º E
Lleida (Spain)	BSh	41º N	0º E
Thessalonica (Greece)	BSk	40º N	22 ºE
Barcelona (Spain)	Csa	41 ºN	2º E
San Francisco (USA)	Csb	37ºN	122º W
Johannesburg (South Africa)	Cwb	26º S	28º E
Tokyo (Japan)	Cfa	35º N	139º E

	Climatic zone	Latitude	Longitude
London (United Kingdom)	Cfb	51º N	0º
Pyongyang (North Korea)	Dwa	39º N	125º E
Chicago (USA)	Dfa	41º N	87º W

2.2. Energy Demand

The Domestic Hot Water (DHW) and cooling demand for a single-family detached house (Fig. 3) is determined by numerical simulations carried out in EnergyPlus for different weather climates. The building considered was taken from the USA Department of Energy (DOE), which provides a set of prototype building models to be used in EnergyPlus. Full details of the buildings considered, in terms of envelope, schedules, internal loads, DHW consumption, etc., are presented in (U.S. Department of Energy). A summary of the envelope properties is presented in Tab. 2.

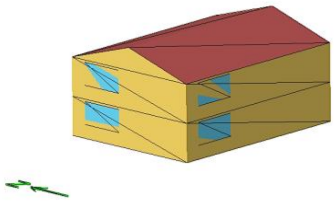

Fig. 3: Single-family detached house model. South and west view.

However, in order to reach nearly Zero Energy Building (nZEB) standards, some additional strategies, both active and passive, are implemented. The building model is considered to fulfill the nZEB standards if the energy demand for heating and for cooling is below 15 kW/m^2·year, the thermal transmittance of the external walls is below U_{max}= 0.15 W/m^2·K and the infiltrations are below 0.6 ACH, following the standards of Passive House (Passive House Institute, 2015). The strategies implemented are (Tab. 3): cooling set point temperature, increase of thermal insulation (using mineral wool with 0.034 w/m·K), triple glassed windows, fix and movable shadings for the windows, and summer night ventilation.

The different values used for each city are presented in Tab. 4 (U-values), Tab. 5 (fix solar protections), Tab. 6 (mobile solar protections), and Tab. 7 (night ventilation).

Tab. 2: Façade, floor, and roof composition of the building.

	Materials	Thickness [m]	Thermal conductivity [W/m·K]	Thermal resistance [m^2·K/W]	U-value [W/m^2·K]
FAÇADE	syn_stucco	0.003048	0.086500	0.035237	0.359
	sheating_consol_layer	0.012700	0.094018	0.135080	
	OSB_7/16in	0.011113	0.116300	0.095550	
	wall_consol_layer	0.139700	0.057165	2.443803	
	Drywall_1/2in	0.012700	0.160090	0.079330	
ROOF I	Asphalt_shingle	0.006340	0.081860	0.077448	5.358
	OSB_1/2in	0.012700	0.116300	0.109200	
ROOF II	cement_Stucco	0.019050	0.721000	0.026422	2.431
	Bldg_paper_felt	-	-	0.010567	

	Materials	Thickness [m]	Thermal conductivity [W/m·K]	Thermal resistance [m^2·K/W]	U-value [W/m^2·K]
	OSB_5/8in	0.015875	0.116300	0.136501	
	Air_4_in_vert	-	-	0.158499	
	Drywall_1/2in	0.012700	0.160090	0.079330	
FLOOR	floor_consol_layer	0.139700	0.049104	2.844988	0.291
	Plywood_3/4in	0.019050	0.115458	0.164995	
	Carpet_n_pad	0.025400	0.060131	0.422409	

Tab. 3: Additional strategies implemented in order to reach the nZEB standard.

	Single-family detached house
Wall area (m^2)	221.2
Window area (m^2)	33.2
Window-Wall Ratio [%]	15%
Net Conditioned Area (m^2)	223.1
Roof Area (m^2)	116.4
Additional passive and active strategies	
Cooling set point temperature (°C)	26
Reduction of the U-value	Included
Triple glassed windows	U= 0.76 W/m^2K
Infiltrations	Reduction of 40% of the infiltration area
Summer night ventilation	Included
Ventilation heat recovery	75%
Solar protection	Included

Tab. 4. Thermal transmittance of the envelope for each studied city.

	$U_{FAÇADES}$ [W/m^2·K]	U_{FLOOR}[W/m^2·K]	U_{ROOF} [W/m^2·K]
Cairo (Egypt)	0.1092	0.3690	0.08367
Lleida (Spain)	0.1237	0.1146	0.1277
Thessalonica (Greece)	0.1389	0.1275	0.1439
Barcelona (Spain)	0.1389	0.1275	0.1439
San Francisco (USA)	0.1389	0.1275	0.1439
Johannesburg (South Africa)	0.1389	0.1275	0.1439
Tokyo (Japan)	0.1389	0.1275	0.1439
London (United Kingdom)	0.1389	0.1275	0.1439
Pyongyang (North Korea)	0.1389	0.1275	0.1439

	$U_{FAÇADES}$ [W/m^2·K]	U_{FLOOR}[W/m^2·K]	U_{ROOF} [W/m^2·K]
Chicago (USA)	0.08611	0.08159	0.09541

Tab. 5. Depth of the fix solar protections for each orientation and for each studied city.

		Latitude	North [m]	South [m]	East [m]	West [m]
Cairo (Egypt)	Depth	30º N	0.2	0.9	1.9	1.9
	Width*		0	2	0	0
Lleida (Spain)		41º N	0.2	0.6	1.9	1.9
Thessalonica (Greece)		40º N	0.2	0.6	1.9	1.9
Barcelona (Spain)		41 ºN	0.2	0.6	1.9	1.9
San Francisco (USA)		37ºN	0.2	0.45	1.9	1.9
Johannesburg (South Africa)		26º S	0.6	0.2	1.9	1.9
Tokyo (Japan)		35º N	0.2	0.45	1.9	1.9
London (United Kingdom)		51º N	0.2	0.8	1	1
Pyongyang (North Korea)		39º N	0.2	0.6	1.9	1.9
Chicago (USA)		41º N	0,2	0.6	1.9	1.9

*Additional width of the fix solar protections respect to the window width.

Tab. 6. Schedule for mobile solar protections.

	Schedule	Covered window area [%]
Cairo (Egypt)	Always	90
Lleida (Spain)	From 1/06 to 31/08	70
Thessalonica (Greece)	From 1/06 to 31/08	70
Barcelona (Spain)	From 1/06 to 31/08	70
San Francisco (USA)	- Never -	
Johannesburg (South Africa)	From 21/09 to 30/04	85
Tokyo (Japan)	From 1/06 to 30/09	70
London (United Kingdom)	- Never -	
Pyongyang (North Korea)	From 1/06 to 30/09	70
Chicago (USA)	From 22/06 to 31/08	80

Tab. 7. Night ventilation conditions.

	Schedule	Period	Air changes per hour
Cairo (Egypt)	From 1/04 to 30/11	From 21 to 7	10 ACH
Lleida (Spain)	From 21/06 to 30/09	From 22 to 9	10 ACH
Thessalonica (Greece)	From 16/05 to 30/09	From 22 to 9	10 ACH
Barcelona (Spain)	From 21/06 to 30/09	From 22 to 9	10 ACH
San Francisco (USA)	From 21/06 to 30/09	From 22 to 9	10 ACH
Johannesburg (South Africa)	From 1/10 to 20/03	From 22 to 9	10 ACH
Tokyo (Japan)	From 1/06 to 31/10	From 20 to 7	10 ACH
London (United Kingdom)	From 21/06 to 30/09	From 22 to 9	10 ACH
Pyongyang (North Korea)	From 21/06 to 30/09	From 22 to 9	10 ACH
Chicago (USA)	From 22/06 to 31/08	From 22 to 9	10 ACH

To determine the DHW demand, the schedules considered in the model are used (with the exception for the showers, which are considered with no consumption during night). The consumers considered are presented in Tab. 8.

Tab. 8. Consumers considered for the Domestic Hot Water demand calculation.

Consumer	Capacity	Water consumption	Duration	Flow rate
Washing machine	7 kg	42 to 47 L	1h 30 min	28 to 31 L/h
Dishwasher	13 uses	6.5 to 7 L	3h (eco)	2.2 to 2.4 L/h

2.3. Energy production

The energy production of the RCE is determined by numerical simulation in Trnsys. A numerical model of the RCE developed by Vall et al., 2020 is used and integrated into a system with thermal energy storage for both heat and cold (Fig. 4). The numerical model discretizes the RCE in several nodes using one dimensional (1D) relations based on an electrical analogy. The heat balance equations are first order ordinary differential equations in time, which are solved using backward Euler method (or implicit Euler method), and the Gauss-Seidel iterative method. The model was experimentally validated for both solar heating and radiative cooling modes, showing a good accuracy (Vall et al., 2020).

The DHW and cooling demand obtained from the EnergyPlus simulations are introduced in the model in order to determine the demand coverage achieved with the RCE system. The RCE field considered has 10 m^2 (consisting of 5 RCE panels of 2 m^2 each) of surface and it is connected to a hot water tank of 0.6 m^3 and a cold water tank of 1 m^3.

The RCE operates under solar collection mode during daytime, and under radiative cooling mode during nighttime, with a flow rate of 576 kg/h.

Once both the demands and productions are calculated, the coverage achieved by the RCE system must be determined.

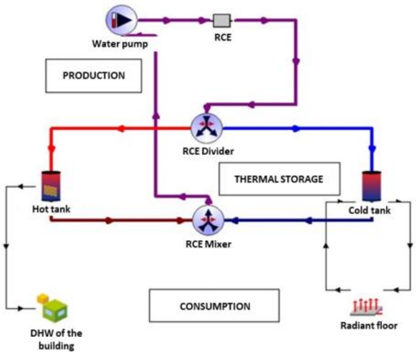

Fig. 4: Conceptual scheme of the RCE system and its link to the building demand.

2.4. Demand coverage

To determine the DHW demand coverage, the temperature of the DHW consumed is considered to be at 45ºC, while the fresh water refilling the tank is considered to be at 13ºC. The DHW demand coverage is determined as the ratio between the energy provided by the hot water tank to reach the DHW temperature level and flow rate required and the DHW demand determined by the EnergyPlus model.

To determine the cooling demand coverage, the energy provided by the cold water tank is calculated considering the temperature difference between the cold water and the building ambient temperature, and adjusting the flow rate to meet the demand from EnergyPlus simulations. Then, the cooling demand coverage is determined as the ratio between the energy provided by the cold water tank and the cooling demand determined by the EnergyPlus model.

3. Results

3.1. Energy demand for nZEB

Based on simulations on EnergyPlus, the cooling and heating demands for each city are presented in Tab. 9, reaching nZEB standards. Cooling demands are in the range 0.3-5 kWh/ m^2·year, with the exception of Cairo, that reaches a cooling demand of almost 13 kWh/m^2·year. On the other hand, heating demands are in the range of 0.3-5.5 kWh/ m^2·year, with the exceptions of London, Pyongyang, and Chicago, with heating demands of 7.5 kWh/ m^2·year, 13.5 kWh/ m^2·year, and 14.3 kWh/ m^2·year, respectively.

Tab. 9. Cooling and heating demand for each studied city.

	Cooling demand [kWh/m^2·year]	**Heating demand [kWh/m^2·year]**
Cairo (Egypt)	12.76	0.28
Lleida (Spain)	3.33	4.19
Thessalonica (Greece)	4.91	3.10
Barcelona (Spain)	2.30	1.38
San Francisco (USA)	0.28	0.16
Johannesburg (South Africa)	0.41	0.26
Tokyo (Japan)	3.18	5.51
London (United Kingdom)	0.34	7.49
Pyongyang (North Korea)	2.72	13.50
Chicago (USA)	4.13	14.28

3.2. Domestic hot water demand coverage

Tab. 10 presents the annual DHW demand and the annual DHW demand covered by the RCE. It can be seen that in every city, the annual DHW demand is very similar, around 3,200 kWh/year. On the other hand, the percentage of DHW demand covered by the RCE changes depending on the location and climate. As it can be seen in Fig. 5, the cities with a higher DHW demand coverage are Johannesburg and Cairo, with values around 90% and 86%, respectively. The cities with lowest coverage are London and Chicago, covering only 42% and 57% of the demand respectively. The other studied cities present coverages between 60-75%.

Tab. 10. Annual Domestic Hot Water demand and coverage by RCE.

	DHW demand [kWh/year]	DHW demand covered by RCE [kWh/year]	DHW demand covered by RCE [%]
Cairo (Egypt)	3,214	2,756	85.7
Lleida (Spain)	3,227	2,217	68.7
Thessalonica (Greece)	3,226	2,210	68.5
Barcelona (Spain)	3,223	2,179	67.6
San Francisco (USA)	3,218	2,422	75.3
Johannesburg (South Africa)	3,210	2,885	89.9
Tokyo (Japan)	3,229	2,139	66.2
London (United Kingdom)	3,236	1,368	42.3
Pyongyang (North Korea)	3,229	1,969	61.0
Chicago (USA)	3,230	1,851	57.3

3.3. Cooling demand coverage

Tab. 11 presents the annual cooling demand and the annual cooling demand covered by the RCE. It can be seen that, only in those cities with very low cooling demands it can be fully covered by the RCE system (10 m^2). However, again London is an exception, with a very low cooling demand (76 kWh/year) but with low coverage (41%) due to its low production.

As it can be seen in Fig. 5, the cities with higher cooling demand coverage are Johannesburg and San Francisco, covering all the cooling demand. The cities with lowest coverage are Cairo, Tokyo, and Pyongyang, covering only 8%, 12%, and 16% of the demand, respectively. Chicago, Thessalonica, and Barcelona present coverages around 23-24%, while London and Lleida reach values of 41% and 47%, respectively.

Tab. 11. Annual cooling demand and coverage by RCE.

	Cooling demand [kWh/year]	Cooling demand covered by RCE [kWh/year]	Cooling demand covered by RCE [%]
Cairo (Egypt)	2,817	223	7.9
Lleida (Spain)	736	348	47.3
Thessalonica (Greece)	1,084	248	22.9
Barcelona (Spain)	508	124	24.4
San Francisco (USA)	61	61	100.0

	Cooling demand [kWh/year]	Cooling demand covered by RCE [kWh/year]	Cooling demand covered by RCE [%]
Johannesburg (South Africa)	90	90	100.0
Tokyo (Japan)	701	84	12.0
London (United Kingdom)	76	31	40.8
Pyongyang (North Korea)	601	98	16.3
Chicago (USA)	911	208	22.8

It must be highlighted that the cooling demand is very weather dependent, and it can be very seasonal in some climates, while in other ones the cooling period can be longer. This significantly affects the cooling energy produced by the RCE that can be used. Locations where the cooling period is short may not use the energy produced by the RCE most of the year, not taking advantage of the full potential of the RCE. On the other hand, locations with longer cooling periods may use more energy produced by the RCE. Thus, locations with lower coverage values may present high production and use of cooling energy by the RCE. This is the case of Cairo, where the coverage percentage is the lowest (7.9%), while the energy production is the third one (223 kWh/year), after Lleida and Thessalonica. In these cases, although the coverage values are low, the energy savings can be significant.

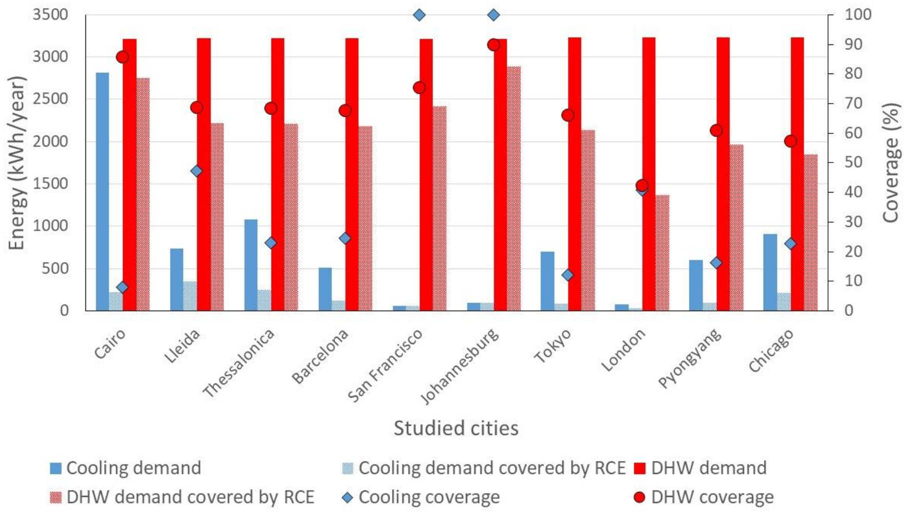

Fig. 5: Domestic Hot Water and cooling demand coverage for each studied city.

3.4. Climate effect

In order to determine the effect of the ambient humidity in the cooling demand covered by the RCE, a comparison between Lleida and Barcelona cities is presented. These cities are 130 km far away, thus presenting similar seasons and sunlight hours. However, significant differences are observed in terms of humidity during summer (Tab. 12).

Tab. 12. Ambient humidity for the cities of Lleida and Barcelona.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lleida (Spain)	74%	64%	57%	55%	51%	45%	45%	49%	57%	65%	71%	75%
Barcelona (Spain)	79%	76%	74%	75%	74%	72%	70%	72%	77%	80%	79%	79%

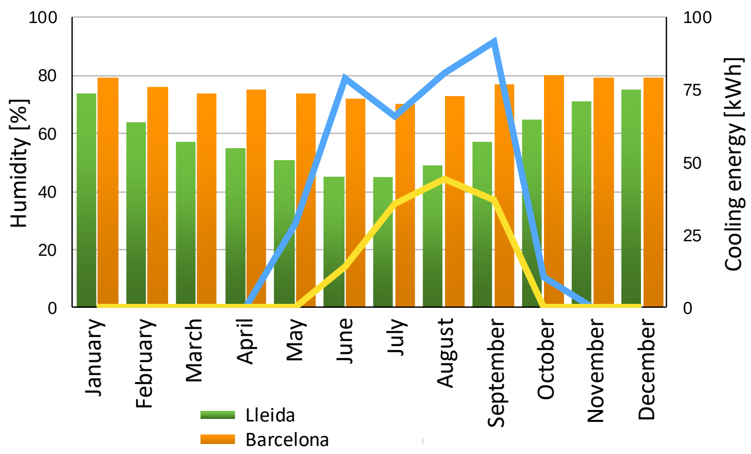

Fig. 6: Comparison of the cooling demand covered by the RCE and the ambient humidity between Lleida and Barcelona.

Fig. 6 shows that the cooling demand coverage during summer months in Lleida is significantly higher than that in Barcelona, although the cooling demand is lower in Barcelona. The higher humidity in Barcelona affects the dew point temperature, thus affecting the effective sky emissivity, which is critical for radiative cooling. This demonstrates the effect of the ambient humidity in the radiative cooling production. Therefore, climates with low humidity are preferred for radiative cooling implementation.

3.5. Suitable climates

In order to identify the most suitable climates for the RCE technology to be implemented in single-family detached houses, a minimum DHW coverage of 60% and a minimum cooling coverage of 40% are stablished. Based on these criteria, the most suitable cases are Johannesburg (DHW coverage of 89.9% and cooling coverage of 100%), San Francisco (DHW coverage of 75.3% and cooling coverage of 100%), and Lleida (DHW coverage of 68.7% and cooling coverage of 47.3%), representing climates Cwb, Csb, and BSh, respectively.

On the other hand, considering a criterion based on the energy production (minimum of 2,000 kWh/year of DHW and of 200 kWh/year of cooling), the most suitable cases are Lleida, Thessalonica, and Cairo, representing climates BSh, BSk, and BWh, respectively.

As it can be seen, only Lleida, representing climate BSh, fulfills both criteria.

These results are limited to the case of 10 m^2 of RCE. Higher RCE surfaces would lead to different results and could result in more climates with significant potential for the RCE implementation.

4. Conclusions

The potential of a novel renewable heating and cooling technology (RCE) to cover the Domestic Hot Water and cooling demands of a single-family detached house achieving nearly Zero Energy Building standards has been studied. The climates Cwb and Csb of the Köppen-Geiger climate classification are the ones showing more promising results in terms of demand coverage, followed by climate BSh. In terms of useful energy production, climates BSh, BSk, and BWh are the most promising ones.

In order to identify new opportunities and to determine the most suitable climates for the RCE implementation, other building typologies must be studied, especially those with different demand profiles.

Higher RCE surfaces could increase the energy production and coverage; thus, an optimization analysis of the RCE surface to be implemented for each city/climate is of high interest.

5. Acknowledgments

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