Long-term energy performance of dew-point indirect evaporative cooler under the climate change world scenario

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ABSTRACT

The progressive increase in the global average outdoor air temperature has caused an increase in the cooling demand in buildings in recent years. Given this climate change scenario, there is a need to develop efficient air-cooling systems that improve the energy efficiency of traditional direct expansion units. In this sense, ventilative cooling technologies should be tested under the climate change world scenario.
In this research study, the main objective was to evaluate the seasonal energy behaviour of a Dew-point Indirect Evaporative Cooler (DIEC) for three different climatic zones under a hostile climate change scenario. An empirical model of a DIEC system was used to obtain Seasonal Energy Efficiency Ratio (SEER) values under different climatic conditions. This DIEC model and variable air flow control of DIEC were adjusted to perform several annual energy simulations in TRNSYS17 software. Three different climatic zones according to the ASHRAE climate classification were considered in this work: 1-Very hot, 2-Hot and 3-Warm. In addition, different weather scenarios were established using a specific tool for the development of meteorological data predictions, CCWorldWeatherGen.
Based on the results, the DIEC system showed high SEER values, between 2.5 and 6.3. The lowest SEER values, between 2.5 and 5.1, were obtained for Bangkok (Thailand) – climatic zone 1 with high outdoor air temperature values and high outdoor air humidity ratio values. However, the highest SEER values, between 5.9 and 6.3, were obtained for Brasilia (Brazil) – climatic zone 2 with low outdoor air humidity ratio values and high outdoor air temperature values. These results showed that the use of a Dew-point Indirect Evaporative Cooler could be interesting under the world climate change scenario, since its SEER value improved with increasing climatic severity.

KEYWORDS

Energy simulations, evaporative cooling technology, Seasonal Energy Efficiency Ratio, world changing climate.

1 INTRODUCTION

Climate change has several implications for both human health and the energy performance of buildings (Ciancio et al., 2020; Pörtner H-O, et al., 2022). Research papers have highlighted the significant contribution of buildings to global energy consumption and carbon emissions. The heating, ventilation and air-conditioning systems (HVAC) in buildings consume approximately 36% of the global final energy and are responsible for nearly 40% of total CO_2 emissions (Allouhi et al., 2015; Xu et al., 2023). One of the main effects of climate change is the increase in the average outdoor temperature around the world. This rise in temperature has direct implications for energy demand, particularly in the areas of refrigeration and global electricity consumption (Huang and Gurney, 2016). Therefore, ensuring comfortable indoor environments with low energy consumption in buildings is a major challenge.

The development and adoption of energy-efficient cooling technologies can help reduce the reliance on fossil fuels and minimize CO_2 emissions. According to several studies, indirect evaporative cooling technology offers an interesting solution for achieving thermal comfort while simultaneously reducing energy consumption and minimizing environmental impact (Romero-Lara et al., 2021; Yang et al., 2021). Energy Efficiency Ratio (EER) is a widely used index for evaluating the energy performance of indirect evaporative coolers (IEC). EER is defined as the ratio between cooling capacity and electrical-power consumption of an IEC. In a research work, a comparative study between a traditional air-cooling system based on vapor compression and two innovative air-cooling systems was carried out (Romero-Lara et al., 2021). The main finding was that a DIEC system demonstrated three to four times lower energy consumption than the traditional air-cooling system, which translates into a higher EER value. Another work studied the correlation between the EER value of a DIEC, from 10.6 to 19.7, and different climatic conditions (Duan et al., 2017): lower EER values for high values of outdoor air humidity ratio and higher EER values for high values of outdoor air temperature.

Given the rising cooling demand in buildings, the main objective of the present work was to assess the long-term energy performance of a dew-point IEC (DIEC) considering the effects of climate change. Energy simulations were performed in the TRNSYS17 software using the DIEC experimental model. The main analysis focused on the influence of the climatic conditions of different zones on the seasonal EER (SEER) for DIEC from 1995 to 2080.

2 METHODOLOGY

2.1 Empirical model of DIEC

In this study, an experimental model of DIEC was used to obtain its long-term energy performance in terms of Seasonal Energy Efficiency Ratio (SEER). In a recent work, the authors detailed the constructive and operational characteristics of this DIEC (Romero-Lara et al., 2022). The authors also provided an explanation of the experimental setup built to examine the energy performance of the DIEC under different operational conditions. The ranges of values of outdoor air temperature (T_{OA}), outdoor air humidity ratio (ω_{OA}), and volumetric air flow ($\dot{V}_{OA}$) were adjusted to obtain a complete empirical model of the DIEC. High values of the determination coefficient (R^2) were shown for the empirical models of cooling capacity ($\dot{Q}_{cooling}$), electrical-power consumption ($\dot{W}$), and EER: 0.9991, 0.9997 and 0.9973, respectively (Romero-Lara et al., 2022). These empirical models and a variable volumetric air flow control based on outdoor temperature, see Figure 1, were used to perform several energy simulations.

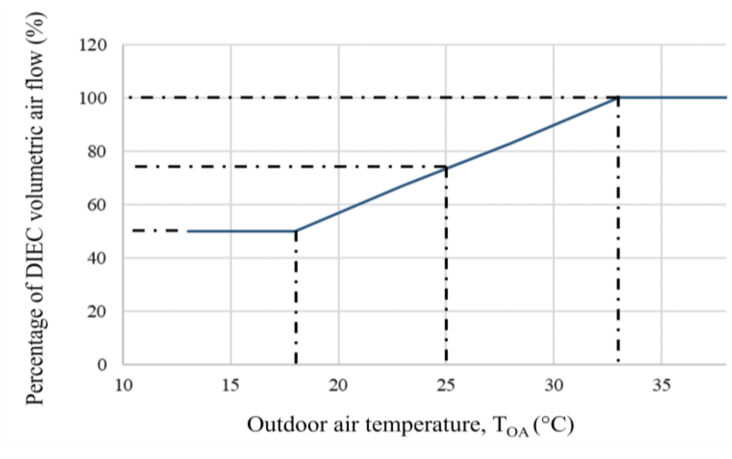


Figure 1: Variable air flow control of the studied DIEC.

2.2 Climatic zones classification

According to the ASHRAE climate classification, three different climatic zones were defined: climatic zone 1 for a very hot climate, climatic zone 2 for a hot climate, and climatic zone 3 for a warm climate (ASHRAE, 2007). This classification was made based on the thermal criteria of Cooling Degree Days (CDD), as indicated in Table 1. To ensure greater consistency in this work's analysis, two cities were selected from each climatic zone, see Table 1. In this way, a wider range of outdoor air conditions was covered.

Table 1: Classification of the climatic zones selected.

Zone number and name*	City	Country	Thermal criteria
1 – Very hot (humid)	Bangalore	India	5000 < CDD10°C
1 – Very hot (humid)	Bangkok	Thailand	5000 < CDD10°C
2 – Hot (dry)	Brasilia	Brazil	3500 < CDD10°C ≤ 5000
2 – Hot (dry)	Brisbane	Australia	3500 < CDD10°C ≤ 5000
3 – Warm (dry)	Valencia	Spain	2500 < CDD10°C < 3500
3 – Warm (dry)	Nairobi	Kenya	2500 < CDD10°C < 3500

*Humid = average ω_{OA} value > 11.0 g/kg. Dry = average ω_{OA} value < 11.0 g/kg. (Reference: year 1995)

Due to the selection of cities with different of T_{OA} and ω_{OA}, a more complete analysis can be performed to assess the impact of these climatic conditions on the SEER values of a DIEC.

2.3 Changing climate scenarios

Most scientific studies have used the *CCWorldWeatherGen* tool, which was developed at the University of Southampton, to generate and analyse new weather scenarios (Andrić, 2019). This tool has demonstrated to be highly valuable in simulating and modelling different climatic conditions, allowing researchers to explore and study the potential impacts of climate change on several environmental and economic factors (Ascione et al., 2022; Cruz et al., 2022; Thapa et al., 2023).

In this work, the *CCWorldWeatherGen* tool was investigated to create new weather scenarios: year 2020, year 2050, and year 2080. The reference scenario was the year 1995, since it is the year corresponding to the TRNSYS meteorological base. So, 24 cases were studied in this work, combinations of six cities in different climatic zones and four scenarios. As a summary, Table 2 provides the set of average outdoor air temperature ($T_{OA,avg}$) and average outdoor air humidity ratio ($\omega_{OA,avg}$) values for each city in each weather scenario. The cooling period considered in this study refers to the period when the T_{OA} value exceeded 18 °C.

Table 2: Climatic conditions in changing climate scenarios of the six selected zones.

	1995		2020		2050		2080	
Zone number and city	$T_{OA,avg}$ (°C)	$\omega_{OA,avg}$ (g/kg)	$T_{OA,avg}$ (°C)	$\omega_{OA,avg}$ (g/kg)	$T_{OA,avg}$ (°C)	$\omega_{OA,avg}$ (g/kg)	$T_{OA,avg}$ (°C)	$\omega_{OA,avg}$ (g/kg)
1 – Bangalore	26.0	11.8	27.1	10.4	27.9	10.6	29.5	10.9
1 – Bangkok	26.7	13.0	28.2	11.8	29.0	11.8	30.7	12.3
2 – Brasilia	24.7	10.9	26.3	10.5	27.2	10.5	28.7	10.6
2 – Brisbane	24.2	10.8	24.2	10.5	24.5	10.5	25.1	10.6
3 – Valencia	23.6	10.9	25.1	11.0	26.1	11.1	26.8	10.7
3 – Nairobi	23.1	10.9	23.4	10.6	24.1	11.1	25.3	11.8

It can be observed a progressive increase in the $T_{OA,avg}$ values for all climatic zones, see Table 2. Climatic zone 1 shown an approximate rise of outside temperature of 2.5°C, while climatic zones 2 and 3 exhibited increases of 1.8 °C and 1.7 °C, respectively, between 2020 and 2080. However, the $\omega_{OA,avg}$ values did not show any correlation. These $\omega_{OA,avg}$ values were between 10.4 and 13.0 g/kg for climatic zone 1, between 10.5 and 10.9 g/kg for climatic zone 2 and between 10.6 and 11.8 g/kg for climatic zone 3, see Table 2.

2.4 Energy performance index

In the present study, several energy simulations were performed using a DIEC empirical model and variable air flow control indicated in Figure 1. All SEER values were determined for the cooling period, using the TRNSYS17 software with a time step of 2.4 minutes for each climatic zone in each scenario (S.A. Klein, 2006).

The SEER values of DIEC were calculated according to the annual cooling energy, $Q_{cooling}$, and annual electrical energy consumption, W, of DIEC during the cooling period. For each of the 24 cases, Equations 1, 2 and 3 were used as follows.

$$\dot{Q}_{cooling} = \rho_{air} \cdot \dot{V}_{SA} \cdot (h_{OA} - h_{SA}) \tag{1}$$

$$\dot{W} = \dot{W}_{fan} + \dot{W}_{pump} \tag{2}$$

$$SEER = \frac{\sum \dot{Q}_{cooling}}{\sum \dot{W}} = \frac{Q_{cooling}}{W} \tag{3}$$

Where ρ_{air} is the density of air [kg/m^3], $\dot{V}_{SA}$ is the supply volumetric air flow [m^3/s], and h_{OA} and h_{SA} are the outdoor and supply air specific enthalpy [kJ/kg], respectively. $\dot{W}_{fan}$ and $\dot{W}_{pump}$ are the electrical-power consumption of the fan and pump of DIEC [kW].

3 RESULTS AND ANALYSIS

The long-term energy performance of a DIEC, in terms of SEER, was performed under the climate change world scenario. Different SEER values were obtained and analysed according to the different climatic conditions across four scenarios (year 1995, year 2020, year 2050, and year 2080) for six different cities, see Table 2.

3.1 Analysis of weather scenarios

The *CCWorldWeatherGen* tool was used to develop the prediction of weather conditions in year 2020, 2050 and 2080. These scenarios and the reference scenario, year 1995, were analysed for the two cities selected in each climatic zone, during their respective cooling periods.

Figure 2 illustrates the annual variation in T_{OA} from the year 1995 to 2080 for the city of Bangalore, India, serving as a representation of climatic zone 1. It is evident that the highest T_{OA} values, ranging from 30 °C to 40 °C, occurred during the period from early April to early July, see Figure 2. For each scenario – 1995, 2020, 2050, and 2080 – the $T_{OA,avg}$ values were recorded as 26.0 °C, 27.1 °C, 27.9 °C, and 29.5 °C, respectively, see Table 2. The most significant temperature difference of 1.6 °C was observed between the years 2050 and 2080. Therefore, it should be noted both the progressive increase in outdoor air temperatures within this climatic zone 1 and the accelerated rate of increase in T_{OA} in recent years.

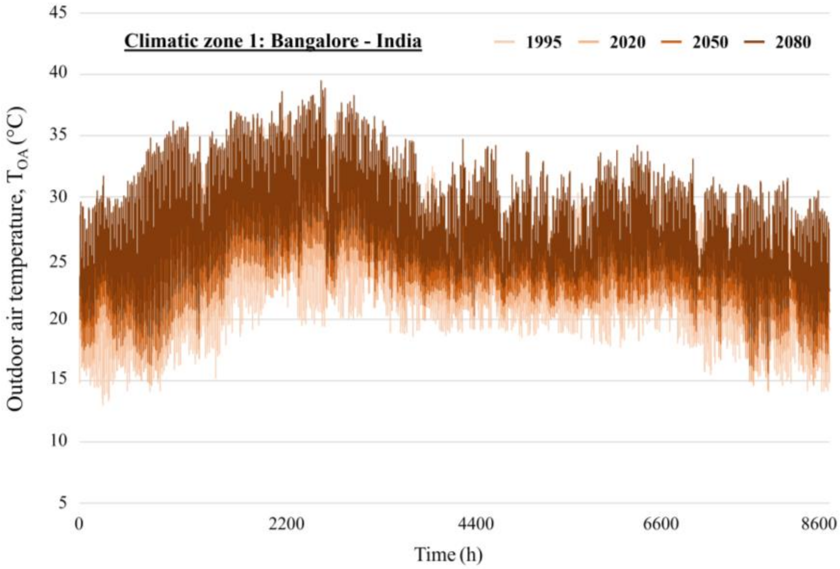


Figure 2: Hourly outdoor air temperature variation during the four weather scenarios for climatic zone 1.

According to the representation of climatic zone 2, Figure 3 displays the yearly fluctuations in outdoor air temperature for the city of Brasilia, in Brazil, from 1995 to 2080. It can be observed that high outdoor air temperature values were recorded, between 30 °C and 40 °C, throughout the year in Brasilia, see Figure 3. The $T_{OA,avg}$ values for the years 1995, 2020, 2050, and 2080 were recorded as 24.7 °C, 26.3 °C, 27.2 °C, and 28.7 °C, respectively, as shown in Table 2. The highest temperature differences were 1.6°C between the years 1995 and 2020, and 1.5 °C between the years 2050 and 2080. This indicated that the rate of T_{OA} increase in Brasilia (climatic zone 2) was relatively more stable compared to Bangalore (climatic zone 1).

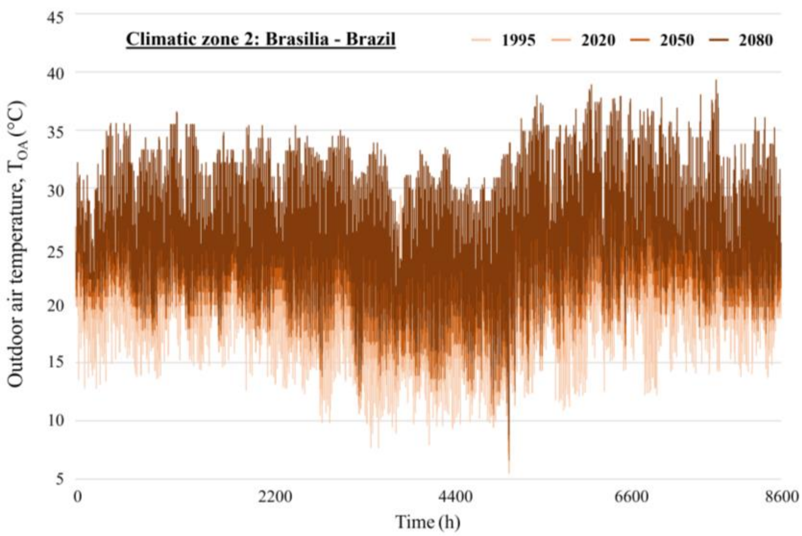


Figure 3: Hourly outdoor air temperature variation during the four weather scenarios for climatic zone 2.

Figure 4 exhibits the changes in outdoor air temperature from the year 1995 to 2080 for the city of Valencia, in Spain, serving as a representation of climatic zone 3. High T_{OA} values, ranging from 30 °C to 40 °C, were shown between the months of June (3624 hours) and October (6552 hours), see Figure 4. These months correspond to the summer season in Spain, characterized by more severe weather conditions each year. As depicted in Table 2, the average $T_{OA,avg}$ values for the years 1995, 2020, 2050, and 2080 were documented as 23.6 °C, 25.1 °C, 26.1 °C, and

26.8 °C, respectively. These findings indicate a progressive increase in outdoor temperature for climatic zone 3 as well as for climatic zones 1 and 2.

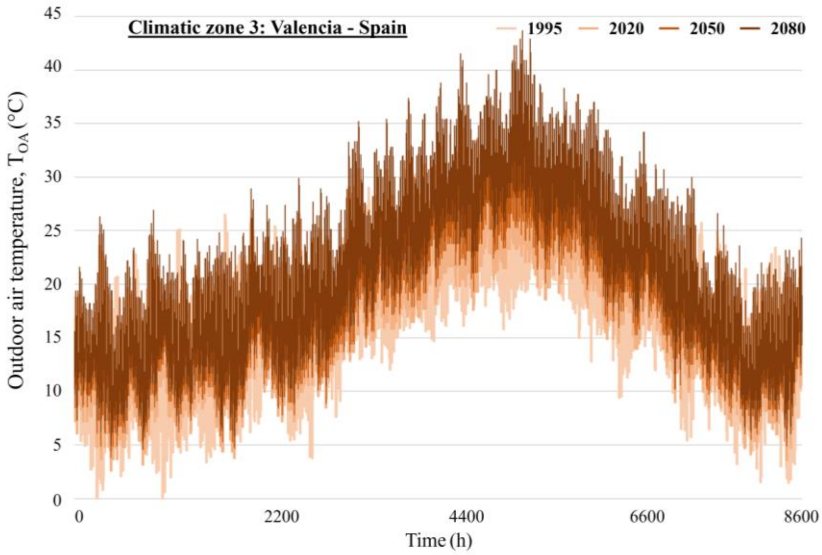


Figure 4: Hourly outdoor air temperature variation during the four weather scenarios for climatic zone 3.

3.2 Analysis of SEER for DIEC

The SEER values for the DIEC system were obtained under the changing climatic conditions of each selected city. The impact of the $T_{OA,avg}$ and $\omega_{OA,avg}$ values on SEER was grouped according to climatic zones: zone 1 in Figure 5, zone 2 in Figure 6 and zone 3 in Figure 7.
Despite belonging to the same climatic zone, Figure 5 shown contrasting variations in SEER between Bangalore and Bangkok. In both cases, there was a gradual increase in $T_{OA,avg}$. However, Bangkok experienced higher levels of $\omega_{OA,avg}$ than Bangalore. For climate zone 1, the highest SEER value recorded was 6.1, under a $\omega_{OA,avg}$ value of 10.4 g/kg (Bangalore 2020). Conversely, the lowest SEER value for climatic zone 1 was 2.5, with a $\omega_{OA,avg}$ value of 13 g/kg (Bangkok 1995). Thus, it is evident that outdoor air humidity had a significant role in influencing the energy efficiency of the DIEC.

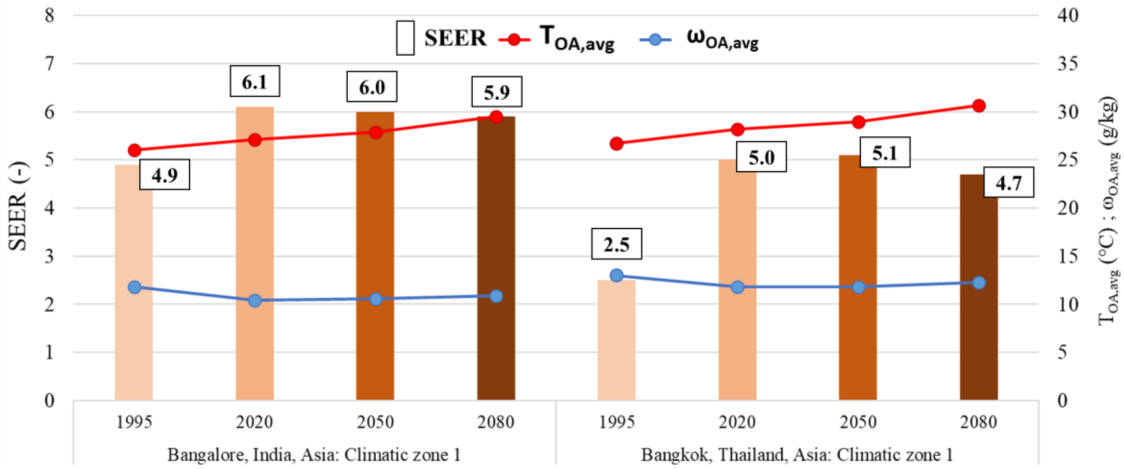


Figure 5: Impact of T_{OA} and ω_{OA} on the SEER values of DIEC for the climate change scenario in zone 1.

In the case of climatic zone 2, both the variations of $T_{OA,avg}$ and $\omega_{OA,avg}$ from 1995 to 2080 were similar for Brasilia and Brisbane, see Figure 6. The SEER variation for each city was similar in all four scenarios, due to the stability of the $\omega_{OA,avg}$ values. Therefore, the SEER value increased with the increase in T_{OA}. The SEER values were high for all cases of the climatic zone 2, in the range of 5.5 to 6.3, see Figure 6.

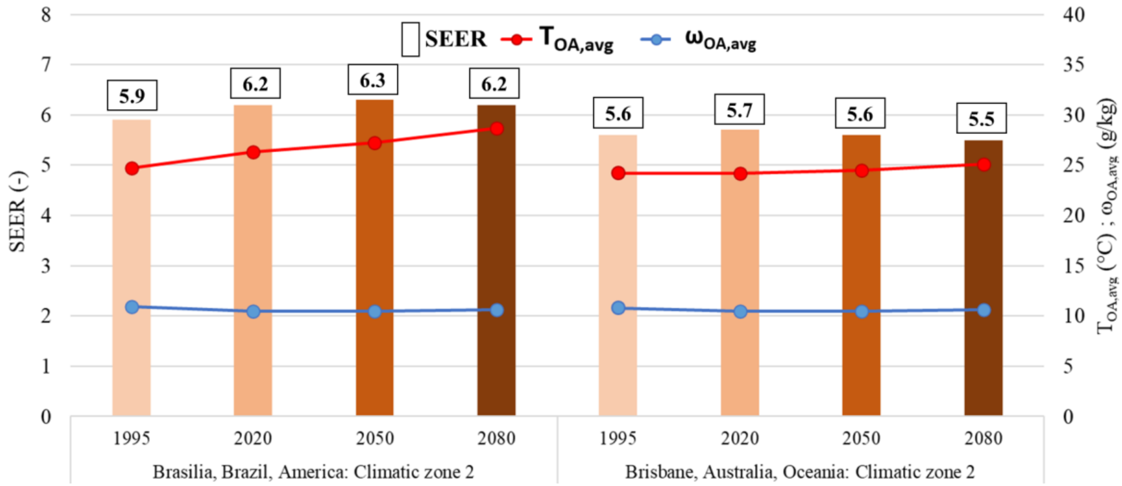


Figure 6: Impact of T_{OA} and ω_{OA} on the SEER values of DIEC for the climate change scenario in zone 2.

The SEER variation analysis carried out for climatic zone 3 confirmed the influence of T_{OA} and ω_{OA} on SEER. Research in the climate of Valencia indicated that the value of T_{OA} exhibited a progressive increase from 1995 to 2020. In contrast, the value of ω_{OA} remained constant or even decreased during that period, as shown in Figure 7. This combination of factors resulted in an overall increase in SEER of the four scenarios. However, the SEER results for Nairobi had lower SEER values in the years 2050 and 2080 due to increased outdoor humidity, see Figure 7.

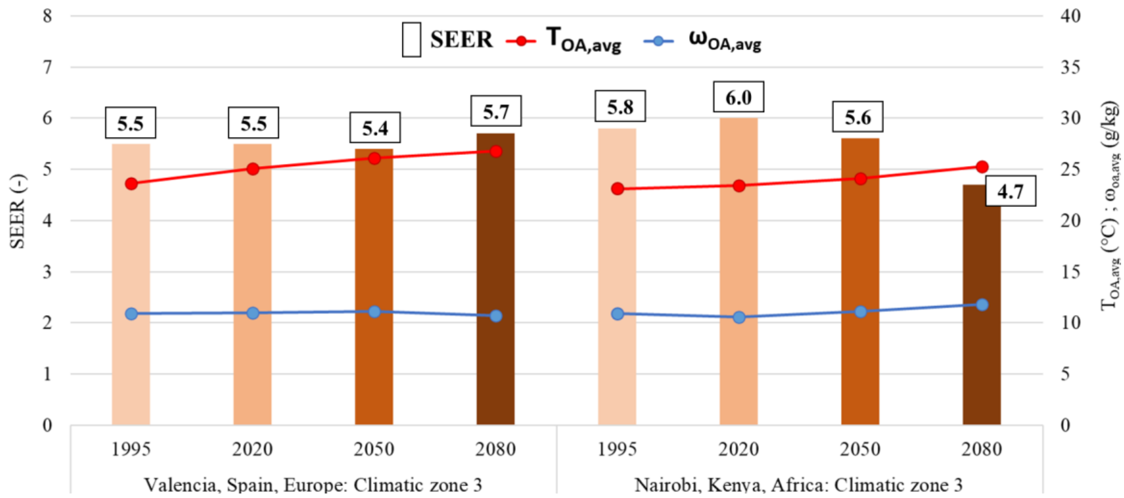
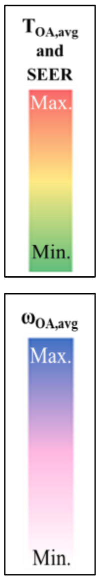


Figure 7: Impact of T_{OA} and ω_{OA} on the SEER values of DIEC for the climate change scenario in zone 3.

As a summary of the analysis carried out previously, Table 3 shown the values of $T_{OA,avg}$, $\omega_{OA,avg}$ and SEER in gradient format for the six cities and the four selected years. For the $T_{OA,avg}$ and SEER values, the green colour represented the lowest values, and the red colour represented the highest values, see Table 3. For the $\omega_{OA,avg}$ values, the white and blue colours represented the lowest and highest values, respectively. It can be observed that the lowest SEER values, between 2.5 and 5.1, were shown for Bangkok (climatic zone 1 with high $T_{OA,avg}$ values, but high $\omega_{OA,avg}$ values that penalize the SEER result of DIEC), see Table 3. However, the highest SEER values, between 5.9 and 6.3, were observed for Brasilia (climatic zone 2 with low outdoor air humidity). Brisbane and Valencia had similar SEER values due to similar $T_{OA,avg}$ and $\omega_{OA,avg}$ values, despite being different climatic zones, see Table 3.

Table 3: $T_{OA,avg}$, $\omega_{OA,avg}$ and SEER values of DIEC for the six selected cities and for scenarios.

City		Bangalore	Bangkok	Brasilia	Brisbane	Valencia	Nairobi
Climatic zone		1	1	2	2	3	3
$T_{OA,avg}$ (°C)	1995	26.0	26.7	24.7	24.2	23.6	23.1
	2020	27.1	28.2	26.3	24.2	25.1	23.4
	2050	27.9	29.0	27.2	24.5	26.1	24.1
	2080	29.5	**30.7**	28.7	25.1	26.8	25.3
$\omega_{OA,avg}$ (g/kg)	1995	11.8	**13.0**	10.9	10.8	10.9	10.9
	2020	10.4	11.8	10.5	10.5	11.0	10.6
	2050	10.6	11.8	10.5	10.5	11.1	11.1
	2080	10.9	12.3	10.6	10.6	10.7	11.8
SEER (-)	1995	4.9	2.5	5.9	5.6	5.5	5.8
	2020	6.1	5.0	6.2	5.7	5.5	6.0
	2050	6.0	5.1	**6.3**	5.6	5.4	5.6
	2080	5.9	4.7	6.2	5.5	5.7	4.7



4 CONCLUSIONS

Nowadays, there is the increasing concerns about adverse weather conditions due to climate change. There is a growing need to find sustainable solutions that rely on efficient air-cooling systems. In this study, the impact of the progressive rise in outdoor air temperature and the influence of outdoor air humidity on the SEER values of a DIEC was analysed.

The main findings obtained from the energy analysis of a DIEC for three different climatic zones during the years 1995, 2020, 2050, and 2080 were as follows:

- High SEER values for DIEC were obtained for all cities studied, between 4.7 and 6.3, except Bangkok due to its $\omega_{OA,avg}$ values.
- The lowest SEER value was 2.5, obtained in Bangkok in 1995, due to the high average outdoor air humidity value that year, 13 g/kg.
- The SEER value for DIEC increased considerably in Brasilia and Valencia when the outdoor air temperature increased.

Therefore, the DIEC showed a more efficient seasonal energy behaviour for hot-dry climatic conditions. Due to the continuous increase in outdoor temperature caused by climate change scenario, this DIEC technology could be an interesting solution in terms of energy efficiency.

5 ACKNOWLEDGEMENTS

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