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Feasibility analysis of evaporative cooling technologies in various climate conditions: present and future potential

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Abstract

Due to global warming, air conditioning in indoor spaces is responsible for the growing energy demand in commercial and residential buildings all over the world. According to the International Energy Agency (IEA), cooling represents 20% of the total energy demand of buildings. Current active cooling technologies commonly used in air conditioning have a negative environmental impact caused both by increasing electrical energy demand and by refrigerant leakage characterised by high Global Warming Potential (GWP). Exploring alternative air-conditioning methods has become a significant area of interest to tackle the drawbacks associated with vapour-compression systems. This work aims to study the interest of evaporative cooling technologies in ten climatic zones and their potential evolution with global warming. The considered climatic zones are ranging from 0A to 6A according to the ASHRAE climate zone classification, 0A corresponding to Extremely Hot Humid and 6A to Cold Humid. The potential of evaporative cooling technologies is evaluated through a feasibility analysis. The performance of those techniques strongly depends on outdoor climate conditions, showing a better performance in dry climates. The evaporative cooling techniques studied in this work include direct evaporative cooling, indirect evaporative cooling, and variations of desiccant evaporative cooling technologies. For each operation mode, a theoretical performance limit can be determined, and the number of hours for which that limit cannot be reached using evaporative cooling techniques can be computed. It is shown that although active cooling systems dominate nowadays, there is a potential to use desiccant evaporative cooling systems in almost all climate zones worldwide.

1 Introduction

Evaporative cooling uses energy in the form of latent heat associated with water evaporation into the atmospheric air. Even though standard air-conditioning systems have the advantage of being able to supply an adequate cooling load in almost all climate conditions, evaporative cooling technologies (ECTs) can tackle some of their drawbacks. Their main advantage is that they do not require synthetic refrigerant which can contribute to global warming due to leakage in the atmosphere. Additionally, when evaporative cooling systems can provide adequate supply air conditions, their COP is higher than standard air-conditioning systems.

The usage of evaporative cooling can be extended by coupling with desiccant dehumidification. In desiccant evaporative cooling systems (DECS), components modify the air temperature and humidity content to reach desired supply conditions. The system is powered by thermal energy from a district heating network or waste heat, which reduces electricity consumption and potentially increases the demand for heat in summer. The major advantage of DECS over standard air-conditioning is the separate handling of sensible and latent loads [1]. There is no need to over-design the air-conditioning system to obtain the necessary latent cooling capacity by cooling the air below the dew point temperature, which leads to unavoidable reheating of the air until proper supply conditions.

DECS can be used in various applications, the most common one being air-conditioning of buildings for office and residential building applications [2]. Desiccant dehumidification used to be applied in industrial air conditioning and storage applications. More recently, it has also been used in commercial and institutional buildings to remove humidity loads brought by ventilation and to reduce the electricity consumption related to cooling [3]. Kashif et al. [4] studied the possibility of improving the thermal comfort of livestock by using DECS. Kamrani et al. [5] used DECS to control the temperature and humidity inside a greenhouse, reducing energy demand compared to a traditional greenhouse.

The operation of DECS strongly depends on inlet air conditions and the influence of climatic conditions on the system performance is a recurring topic in the literature. Ali et al. [6] and Zeoli et al. [7] evaluated the performance of several DECS configurations in various climatic zones regarding the energy demand to operate those systems and the provided cooling capacity. However, the system ability to provide adequate supply air conditions is rarely questioned.

This paper responds to the need to develop a general analysis which includes the possibility of using various devices based on water transfer depending on the prevailing weather conditions. The presented feasibility analysis offers a simple methodology to determine, for a given climate, if stand-alone evaporative cooling technologies are sufficient to ensure adequate supply air conditions, if they should be coupled with desiccant dehumidification, or if active cooling systems are mandatory to maintain a comfortable indoor environment. The feasibility analysis can be used as a preliminary tool to determine whether a climate is worth focusing on a particular system variant. It can be applied to evaluate system design in new sustainable buildings or support the implementation of ECTs in installations already equipped with active cooling systems to reduce electricity consumption.

2 Methodology

The evaporative cooling technologies can be combined into a generalized desiccant evaporative cooling system (DECS), described in Section 2.1. By modifying the operation mode of the DECS, the feasibility of diverse evaporative cooling techniques can be assessed. The air source of the DECS is outdoor air which should be conditioned before being supplied to the building. The meteorological data are thus of significant importance in the feasibility analysis and they are introduced in Section 2.2. The methodology of the feasibility analysis is finally described in Section 2.3.

The DECS is supposed to provide fresh air into a building. Nominal indoor conditions have been defined based on the WHO guidelines [8] which state that, during the cooling period, the indoor environment should be maintained around 24°C and 50% relative humidity to ensure acceptable thermal comfort. The corresponding indoor specific humidity ($w_{in,nom}$) is approximately 9 g/kg. The indoor conditions are given as a reference but are not used as a baseline for the feasibility analysis as they vary depending on the building type. Since the indoor environment should be maintained in a temperature range between 20-25°C, it has been assumed that the supply air temperature should be between 16 and 18°C to avoid local discomfort. Each device operation was evaluated separately to assess the feasibility of using open air-conditioning systems to cool buildings in various climate zones.

2.1 Technology description and theoretical performance

Various DECS configurations have been studied in the literature [9, 10]. It has been widely shown that the DECS configuration can impact the system energy performance and exergy destruction in components. As this work aims to evaluate the theoretical feasibility of DECS, a general configuration has been chosen. The system is an enhanced desiccant evaporative cooling system (DECS) as shown in Figure 1a. It consists of six main components: a dew point indirect evaporative cooler (D-IEC), a desiccant wheel (DW), a regenerator (Reg.), an indirect evaporative cooler (IEC), a coil (sensible heat exchanger), and a direct evaporative cooler (DEC). It is important to note that:

- If no water is supplied to the indirect evaporative cooler, it can also work as a sensible heat exchanger to recover heat from the indoor environment.
- The sensible coil is an air-water heat exchanger that can operate either as a cooling or heating coil depending on the season.

The evolution of the primary air conditions inside the system is shown in Figure 1b. It also illustrates the difference between the real and ideal air evolutions for each component, and the interaction between components to reach proper supply air conditions. Depending on the outdoor conditions, the system can operate in seven modes by (de)activating components. The operation modes are described below, along with the limitations of each mode. The performance limitations of each component have been established based on indicators extensively used in the literature [11]. Table 1 summarises the components that are required in each operation mode.

2.1.1 Heating

Heating the fresh outdoor air is necessary when the temperature falls below the minimum supply temperature. The air can be heated by recovering heat from the indoor environment in the IEC operating as a sensible heat exchanger. If necessary, the sensible coil can provide some extra heat.

2.1.2 Free chilling

A specific temperature range for the supply air has been established, the supply air temperature should be between 16 and 18°C which are referred to as the minimum and maximum supply temperatures respectively. If the outdoor temperature is between $T_{su,min}$ and $T_{su,max}$, all components can be turned off, and the system operates as a simple mechanical ventilation system.

2.1.3 Direct evaporative cooling

In the DEC, the outdoor air is cooled through direct water injection. The humidification process is considered adiabatic. Since the iso-enthalpy lines are almost parallel to the iso-wet bulb lines, it can be assumed that the minimum temperature that can be reached through direct humidification is the wet bulb temperature of the outdoor air, which leads to the definition of the wet bulb efficiency:

$$\varepsilon_{wb,DEC} = \frac{T_{DEC,in} - T_{DEC,out}}{T_{DEC,in} - T_{wb,DEC,in}} \quad (1)$$

The wet bulb efficiency definition allows to identify the outdoor conditions for which direct water injection enables reaching the desired supply temperature. DEC mode is applicable for all outdoor conditions that require a wet bulb efficiency lower than the maximum acceptable wet bulb efficiency, set to 85%, to reach the desired supply temperature.

However, solely considering the wet bulb efficiency as a limitation for the DEC operation may overlook the humidification of the supply air. In some cases, when the fresh air is humidified, its specific humidity can exceed the indoor specific humidity, resulting in building humidification. Hence, two zones can be

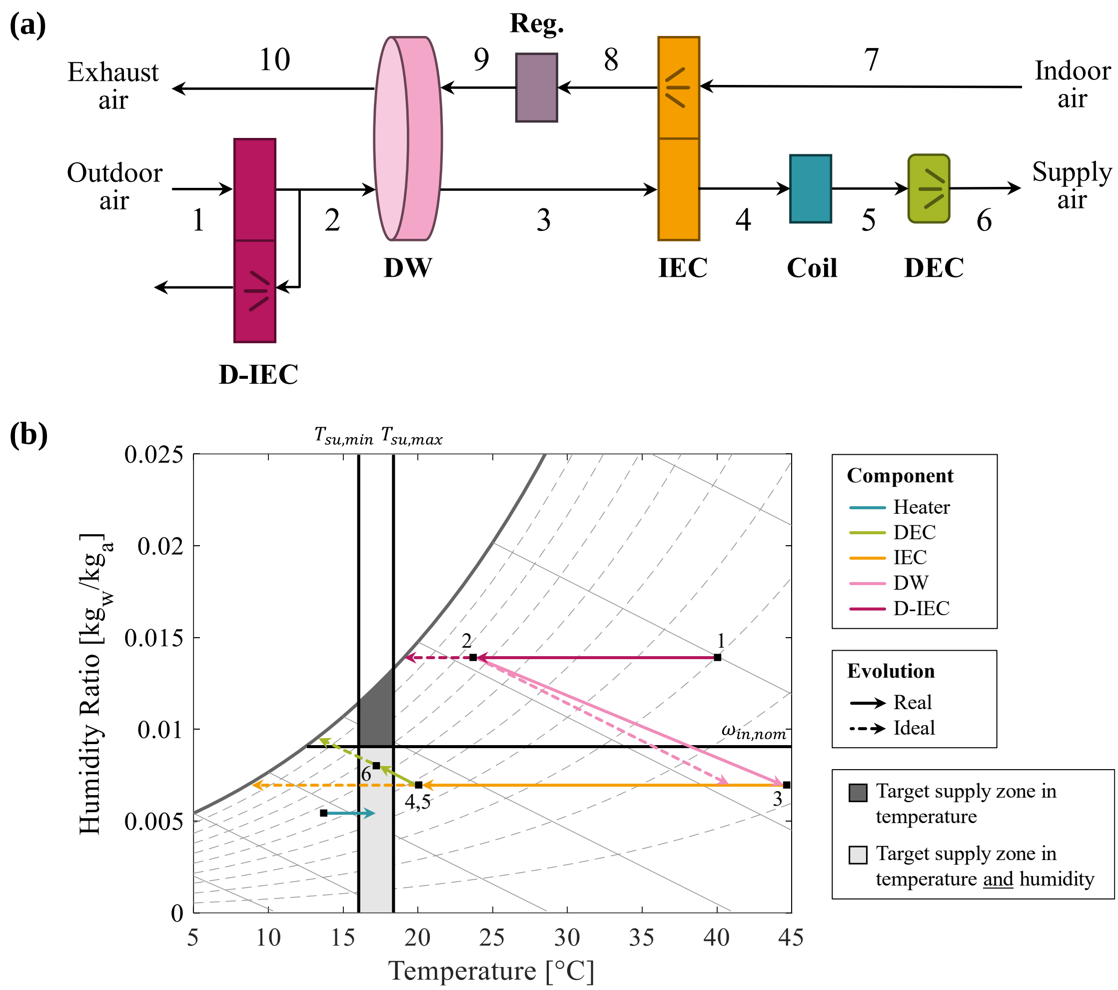

Figure 1: (a) General representation of a desiccant evaporative cooling system. (b) Comparison of real and ideal evolutions of the air conditions in each component of the DECS.

defined in the DEC operation mode: conditions where the desired supply temperature can be achieved without building humidification and those resulting in building humidification. To avoid supplying air at a specific humidity above the indoor specific humidity, the conditions of the outdoor air must be such that the wet bulb temperature of the outdoor air is below a maximum wet bulb temperature defined as:

$$T_{wb,DEC,max} = \mathrm{wetbulb}(T = T_{su}\ ;\ \omega = \omega_{in,nom}\ ;\ P = P_{atm}) \tag{2}$$

2.1.4 Indirect evaporative cooling

When the indirect evaporative cooler is activated, the fresh air is cooled down without being humidified. The lowest supply air temperature achievable through this sensible cooling process is the dew point temperature, leading to the definition of the dew point efficiency:

$$\varepsilon_{dp,IEC} = \frac{T_{IEC,in} - T_{IEC,out}}{T_{IEC,in} - T_{dp,IEC,in}} \tag{3}$$

The outdoor conditions suitable for achieving the target supply temperature through the indirect evaporative cooling process can be determined by applying the dew point efficiency definition. IEC mode is applicable for all outdoor conditions where the necessary dew point efficiency is lower than the maximum acceptable dew point efficiency, set at 85%, to achieve the desired supply temperature. It is also possible to define two zones in the IEC operation. If the outdoor specific humidity is above the nominal indoor specific humidity, the IEC process necessarily results in building humidification.

2.1.5 Desiccant evaporative cooling

If none of the above techniques is applicable, the fresh air can be dehumidified through a desiccant wheel (DW) before being cooled using evaporative cooling techniques [12]. In the DW, the moisture of the hot humid outdoor air is absorbed and stored in the DW matrix before being released into the secondary air stream during the regeneration process. Regenerating the DW requires heating the secondary air in a sensible heat exchanger known as the regenerator. As the air is heated during the dehumidification process, additional cooling is necessary to achieve the target supply temperature, which can be achieved through direct and/or indirect evaporative cooling.

In the ideal case, the dehumidification process in the DW can be considered isenthalpic. It is thus proposed to define an isenthalpic efficiency to account for the irreversibility generated during the dehumidification process. For a given dehumidification rate inside the DW, the isenthalpic efficiency can be defined as follows:

$$\varepsilon_h = \frac{T_{DW,out,h} - T_{DW,in}}{T_{DW,out} - T_{DW,in}} \tag{4}$$

With $T_{DW,out,h}$ the temperature at the outlet of the DW for an isenthalpic dehumidification. The application of this indicator to data available in the literature [13, 14] showed that an isenthalpic efficiency of 0.85 is suitable to represent the irreversibility of the dehumidification process.

As shown in Figure 1, the outlet of the desiccant wheel corresponds to the inlet of the indirect evaporative cooler. For the desiccant evaporative cooling mode to be feasible, the conditions at the outlet of the DW should thus be in the feasible zone of the IEC. In the DW, the air is dehumidified until the specific humidity is close to the indoor specific humidity. During the dehumidification process, the air is also heated. The maximum acceptable temperature of the hot dry air can be found at the intersection between the line of constant specific humidity $\omega_{in,nom}$ and the line of constant dew point efficiency of the IEC process. Once the maximum acceptable conditions at the outlet of the DW have been defined, it is possible to establish all the outdoor conditions that will fall in the feasible zone of the IEC using the isenthalpic efficiency definition.

In this case, it has been assumed that the desiccant material used in the DW is solid desiccant. Solid desiccant systems are considered a more established technology than liquid ones, and this study focuses on examining the feasibility of widely available technologies. The DW can be regenerated using low-temperature waste heat, solar thermal energy or thermal energy supplied by district heating networks with a temperature below 55°C.

2.1.6 Desiccant evaporative cooling with air pre-cooling

When the outdoor conditions become too hot and humid, the outdoor air can be pre-cooled before entering the DW [15]. The pre-cooling process occurs in a D-IEC, which operates based on the same principle as a standard IEC except that the secondary air source is the product fresh air that is partly recirculated. Compared to the system without precooling it allows obtaining a higher dehumidification ratio for the same regeneration temperature [16]. Therefore, the pre-cooling of the outdoor air before its dehumidification allows the extension of the operation zone of the desiccant evaporative cooling system. The performance of the D-IEC can be evaluated through the dew point efficiency, as for the IEC. The operation of the DECS with air pre-cooling is considered feasible if, after the pre-cooling process, the air conditions are such that the DECS process is in the previously established feasible zone of the DECS, considering that the D-IEC has a maximum dew point efficiency of 85%.

2.1.7 Active cooling

For some outdoor conditions, the temperature and specific humidity are such that it is impossible to reach the target supply temperature using a combination of desiccant and evaporative cooling technologies. An active cooling system is necessary to achieve proper supply conditions. The active cooling system can be integrated into the building in various ways:

- A sensible cooling coil can be integrated directly into the DECS on the primary air path. The cooling coil is fed with cold water produced through a refrigeration cycle and can be used to cool the air below the dew point temperature to further dehumidify the air.
- The active cooling system can also be independent of the ventilation system. A standard vapour-compression air-conditioning or a water chiller coupled with a water distribution system can be installed in the building to provide an adequate sensible load.

Due to the various existing implementations of active cooling systems, the active cooling mode has not been represented in Figure 1b.

Table 1: Operation mode summary. The components can be either mandatory: ✓ or facultative: (✓) in the considered operation mode.

	D-IEC	DW	Reg.	IEC	Sensible coil	DEC
1 – Heating				✓ (sensible)	✓ (heating)	
2 – Free chilling						
3 – DEC						✓
4 – IEC				✓		
5 – DECS		✓	✓	✓		(✓)
6 – DECS with pre-cooling	✓	✓	✓	✓		(✓)
7 – Active cooling	(✓)	(✓)	(✓)	(✓)	✓ (cooling)	(✓)

2.2 Outdoor conditions

Contrary to traditional vapour compressor systems which ensure adequate air cooling in every climatic condition, reducing electricity consumption using the natural ability of air to humidify requires the development of dedicated system variants for specific climatic conditions. The efficiency of air conditioning systems based on evaporative cooling strictly depends on outdoor air parameters such as temperature and humidity ratio hence why the feasibility of evaporative cooling techniques has been assessed in different climatic zones. Ten climatic zones have been selected to be studied in this work. Figure 2 illustrates the ten climatic zones and the corresponding cities. The climate types range from 0A to 6A, based on the ASHRAE climate zone classification [17]. 0A represents an extremely hot and humid climate, while 6A signifies a cold and humid climate.

Climate	Description	City
0A	Extremely Hot Humid	Singapore
0B	Extremely Hot Dry	Abu Dhabi
1A	Very Hot Humid	Guayaquil
2A	Hot Humid	Sao Paulo
3A	Warm Humid	Buenos Aires
3B	Warm Dry	Los Angeles
4A	Mixed Humid	Brussels
4C	Mixed Marine	Vancouver
5A	Cool Humid	Copenhagen
6A	Cold Humid	Montreal

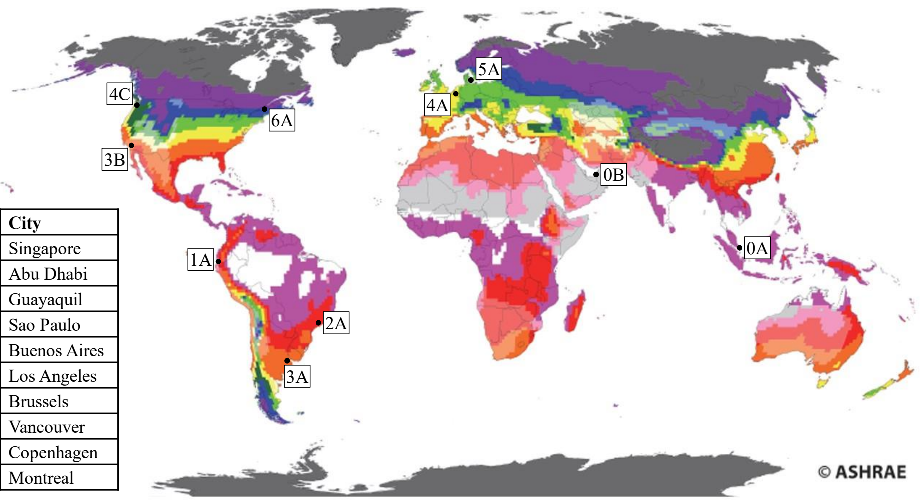

Figure 2: World climatic zones according to the ASHRAE classification.

Meteorological data for these climate zones have been generated and validated as part of IEA Annex 80 focusing on the resilience of cooling technologies [18]. The meteorological files include Typical Meteorological Year (TMY) data for the years 2001-2020 and projected TMYs for the years 2041-2060. The future meteorological data have been developed based on the RCP 8.5 global warming scenario outlined by the Intergovernmental Panel on Climate Change (IPCC). The RCP 8.5 scenario is considered the most severe, reflecting a "business as usual" approach where minimal efforts are made globally to address climate change. This scenario predicts a significant increase in greenhouse gas concentrations in the atmosphere, leading to an average increase of 8.5 W/m² in Earth's radiative forcing by 2100.

Typical ranges of the climatic conditions for all locations are summarised in Table 2 in Appendix A. It can be used by the designer to initially analyse a dedicated system for a given climate zone without the need to perform calculations using real data. However, it should be noted that depending on the geographical location, data may differ within a climatic zone.

2.3 Feasibility analysis

As described in Section 2.1, it is possible to define a theoretical limit for each operation mode of the DECS. Those limits can be drawn on a psychrometric chart and superimposed with the outdoor conditions of temperature and humidity for each hour of the year. For each considered technique, all the outdoor conditions beyond the associated limit can be considered as non-feasible for a stand-alone set of evaporative cooling techniques. An example of feasibility analysis is shown in Figure 3 for the city of Abu Dhabi (0B) which has a wide range of climatic conditions.

The indoor specific humidity is shown as an indication of the average expected indoor conditions inside a building. However, the indoor conditions were not considered as a criterion to assess the feasibility of the desiccant evaporative cooling techniques. This is because buildings have a wide range of indoor air conditions which depend on the purpose of the building. In public or residential buildings, the relative humidity should be between 40-60%, while in cotton spinning or weaving mills, high air humidity is crucial to correctly conduct the process. This is why for the DEC and IEC technologies, it has been indicated whether the cooling process is likely to result in a humidification of the building even though the techniques have been considered feasible in those zones.

The ultimate purpose of the feasibility analysis is to determine the number of hours during the year for which the studied technologies can be used. This cannot be concluded directly from the representation on the psychrometric chart but it can give the reader a clearer idea of the methodology of the feasibility analysis and the climate conditions of the considered zone. The percentage of operation time of each mode is shown in the next section.

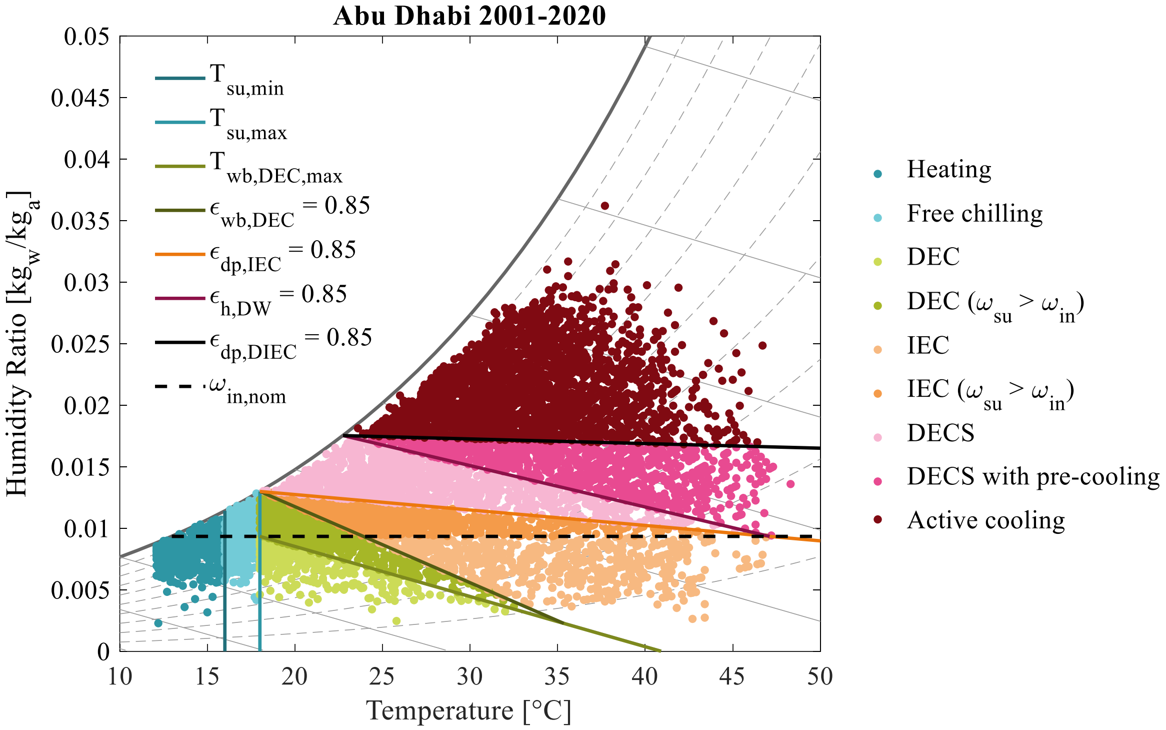

Figure 3: Example of feasibility analysis for climate zone 0B (Abu Dhabi).

3 Results and discussions

3.1 Potential assessment of evaporative cooling technologies

The results of the feasibility analysis are shown in Figure 4. The current and predicted percentage of hours in each operation mode is shown for each climate zone. The main findings are summarised below.

- The climatic zones that are most impacted by global warming are the hot regions (from 0A to 2A), with a significant increase in the zone in which active cooling or DECS with pre-cooling is necessary. In zone 1A in particular, the percentage of hours during which active cooling is necessary extends from 30% to 55%.
- An active cooling system is necessary in zones 0A and 0B. The climate conditions in zone 0A are such that desiccant evaporative cooling technologies can be only used 3% of the time. And this proportion is likely to be less than 1% by 2050.

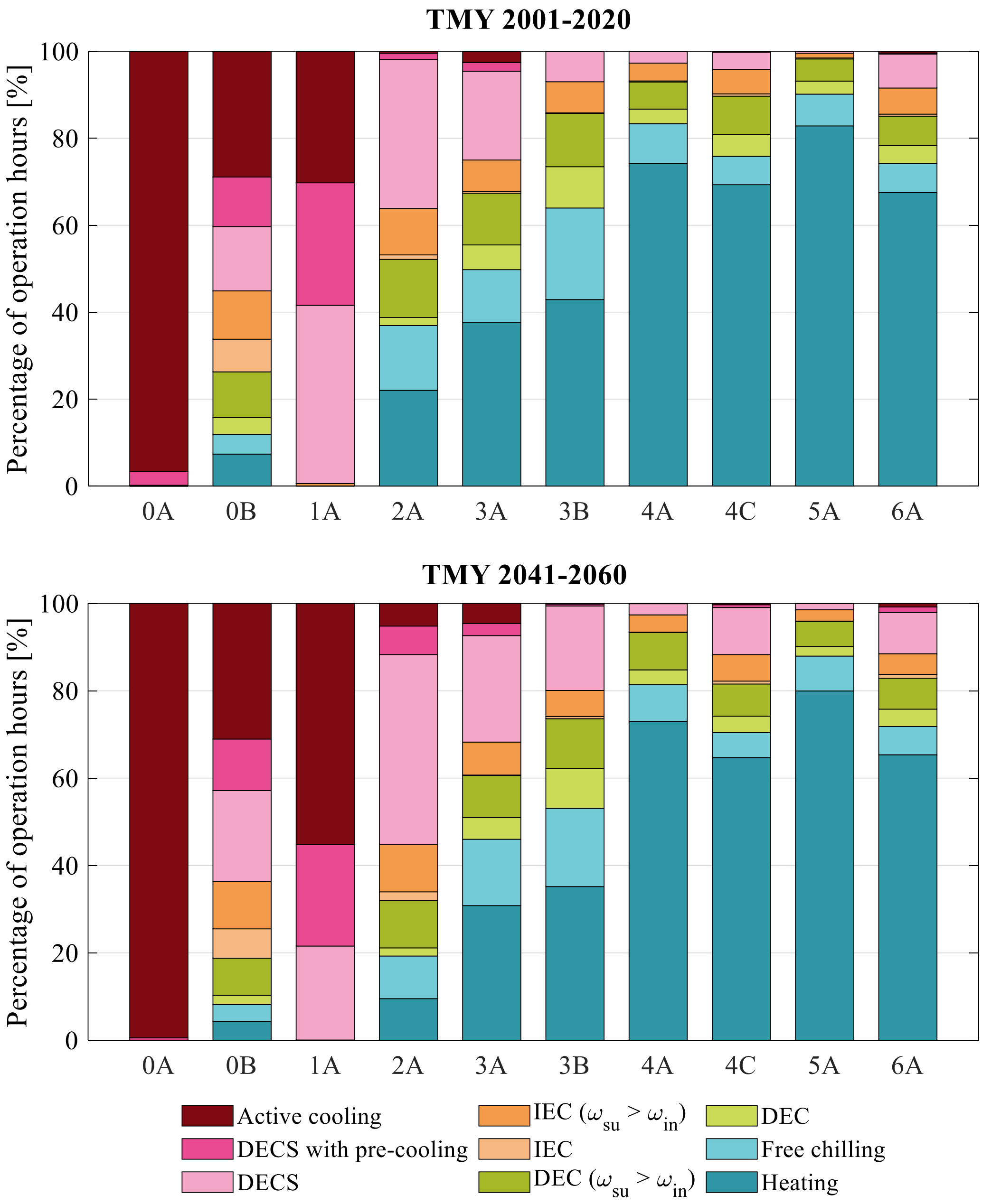

Figure 4: Percentage of hours of operation in each mode using feasibility analysis criteria.

- Climate zone 0B has the most diverse climate conditions and each evaporative cooling technique shows potential for more than 10% of the time. In such a climatic zone, the control strategy of the system is of primary importance to guarantee acceptable supply air conditions while decreasing the energy demand of the system. However, the DECS should be coupled with an extra active cooling system to guarantee good thermal comfort at all times.
- In currently heating-dominated climates, heating will remain the major demand of buildings in the future and evaporative cooling techniques will be sufficient to ensure supply temperature in an acceptable range at almost all times.
- In zone 4C, there will be an increase in the potential of DECS as they become necessary from 4 to 11.5% of the time.
- In the future, for climate zones 3A and 3B the combination of desiccant evaporative technologies will become necessary for 50 and 47% of the time respectively versus 48 and 36% nowadays. The rest is covered by free chilling and heat recovery.
- Indirect and direct evaporative cooling technologies show the most promising potential in dry climate zones (0B and 3B). However, those are also the zones in which water could be scarce.
- In heating-dominated climate zones (4A-6A), there is a potential for air cooling using evaporative cooling. While in practice this technology is not widely used, because active cooling is a more universal solution. DECS could be particularly interesting if the system can be coupled to an existing under-used DHN in summer to de-electrify the increasing cooling demand.

In summary, desiccant evaporative cooling technologies are feasible in most climatic zones around the world and they can be used to significantly reduce the electricity consumption related to cooling in buildings. The feasibility analysis can be used as a tool in the decision-making process of the design phase of an installation. For example, in climate zone 3B, it can be noted that a DECS operating in dehumidification mode would currently be interesting for 610 hours of operation (*i.e.* 7% of the time). There is also a significant potential for stand-alone evaporative cooling techniques, either direct or indirect. The main components that should be installed in a cooling system in this climatic zone are thus a desiccant wheel with its regenerator, indirect and direct evaporative coolers and a reheater. Those components together are supposed to ensure adequate control of the supply air conditions all year long. According to the results of the feasibility analysis, adding a D-IEC to pre-cool the outdoor air is not necessary. It would only result in additional head losses in the installation and increased energy demand. However, it should be underlined that the presented analysis considers a high efficiency for the DW and that for the detailed performance analysis, real component efficiencies and data should be used.

3.2 Discussions and Future Work

It is important to note that this work does not focus on a particular building and does not try to assess the performance of a real system. The aim is to show the range of outdoor conditions for which the coupling of desiccant and evaporative cooling systems can theoretically reach the desired supply conditions. However, using desiccant evaporative cooling technologies alone might be insufficient to maintain acceptable indoor comfort conditions, as it depends on the required air flow rate. Depending on the building, desiccant evaporative cooling technologies could be used independently or coupled with an existing active cooling system to reduce its electricity consumption.

It should also be noted that in this case, performance indicators have been assumed constant for all the considered outdoor conditions. In practice, the performance of components can vary depending on the operating conditions. The operation mode might differ from the theoretical predictions when considering a real system. Additionally, real system limits cannot be deduced from performance indicators only. Other constraints such as maximum water consumption or dehumidification rate should be considered.

The potential of desiccant evaporative cooling systems has been assessed for all hours of the year regardless of the date and hour. However, it would be possible to adapt the identified system limits to perform different feasibility analyses depending on the hour of the day or the period of the year. This could, for example, allow to state if some climates are adapted for night ventilation in summer to reduce the thermal loads during the day or if a DECS could increase the resilience of a building to a heat wave.

The methodology of the feasibility analysis can be applied to a real existing system to determine a control strategy for the system operation. The control strategy plays a major role in the system energy demand and in maintaining constant supply air conditions.

The feasibility analysis could be combined with land indicators that could help in the selection process of the technologies. For example, a water scarcity index or information about the electricity mix of the country could give complementary information on the feasibility or need for evaporative cooling technologies.

The solid desiccant system is considered for the dehumidification process because this paper addresses the feasibility of mature technologies. However, studies [19] show that liquid desiccant materials can be regenerated at lower temperatures. They are also characterised by lower heat requirements for the sorbent regeneration compared to the case of solid desiccant. It could extend the range of feasible conditions of the DECS more than adding a pre-cooler at the DW inlet. The comparison of those systems would be helpful for desiccant technology development. If the dehumidification induces a lower enthalpy decrease, the temperature increase will be of less importance and there will be more outlet conditions that will fall in the feasible zone of the evaporative cooling technologies.

4 Conclusion

The potential of desiccant evaporative cooling techniques has been assessed in ten climatic zones through a feasibility analysis. The desiccant evaporative cooling system (DECS) is a combination of components that can modify both the temperature and the humidity content of the air. The primary air source of the DECS is outdoor air that should be conditioned before being supplied indoors. The performance of evaporative cooling systems is thus strongly dependent on outdoor conditions. That is why, the feasibility analysis has been performed in ten climate zones, to account for the climate diversity worldwide. The considered climate zones range from 0A to 6A, according to the ASHRAE climate classification.

It has been shown that for very hot and humid climate zones (01 and 1A), the outdoor conditions are such that the desiccant evaporative cooling technologies can rarely supply air in a temperature range of 16-18°C. An active cooling system is necessary to maintain acceptable thermal comfort.

Climate zone 0B has the most diverse conditions and a DECS with controllable components would be suitable to operate in various modes and decrease the energy demand related to cooling. However, it should also be noted that in this climate, the use of evaporative cooling technologies could be jeopardized by water scarcity.

In heating-dominated climates, an increase in the potential of desiccant evaporative cooling technologies will be observed over the years. According to the results of the feasibility analysis, the desiccant evaporative cooling technologies are well suited to provide supply air temperatures in the range of 16-18°C. In real installations, active cooling dominates, while there is a theoretical potential to use alternative cooling technologies.

Acknowledgement

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Appendix A

Table 2 gives the typical ranges for the temperature and humidity conditions of the considered climate types.

Table 2: Climate description of the 10 considered climatic zones according to the simulation results of Annex 80 Weather Data task force [18].

	Present (2001-2020)		**Future (2041-2060)**	
	Temperature range [°C]	Specific humidity range [g/kg]	Temperature range [°C]	Specific humidity range [g/kg]
0A	22.1 – 34.5	14.2 – 22.9	22.5 – 35.4	15.2 – 26.0
0B	2.5 – 48.3	2.2 – 36.2	9.4 – 50.6	2.0 – 36.5
1A	18.3 – 36.9	6.3 – 27.7	21.2 – 38.7	10.4 – 24.7
2A	-8.1 – 35.2	1.6 – 20.5	4.1 – 37.7	3.3 – 21.5
3A	0 – 33.3	1.6 – 22.1	3.3 – 32.8	3.1 – 22.0
3B	3.9 – 36.6	0.4 – 15.7	5.2 – 34.3	1.1 – 18.2
4A	-9.3 – 32.5	1.4 – 18.3	-3.8 – 33.2	1.2 – 19.4
4C	-23.7 – 32.3	0.3 – 17.0	-23.7 – 34.1	0.2 – 19.2
5A	-9.6 – 28.3	1.4 – 14.2	-6.8 – 30.2	1.6 – 17.8
6A	-25.6 – 33.3	0.2 – 23.9	-26.1 – 35.0	0.3 – 21.9

Nomenclature

Abbreviations

DEC	Direct evaporative cooler
DECS	Desiccant evaporative cooling system
D-IEC	Dew point indirect evaporative cooler
DW	Desiccant wheel
ECT	Evaporative cooling technology
IEC	Indirect evaporative cooler
Reg.	Regenerator

Subscripts

dp	Dew point
in	Indoor/inlet
nom	Nominal
out	Outdoor/outlet
su	Supply
wb	Wet bulb

Symbols

ε	Efficiency	[-]
h	Enthalpy of humid air	[J/kg]
T	Temperature	[°C]
ω	Specific humidity	[kg/kg]

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