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# Feasibility analysis of desiccant 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 buildings worldwide. Evaporative cooling technologies, potentially coupled with desiccant dehumidification, offer an environmentally friendly alternative to traditional air-conditioning methods. However, the performance of these techniques strongly depends on outdoor climate conditions. To deepen the knowledge of evaporative cooling technologies and assess their potential worldwide, the International Energy Agency has launched the Annex 85 project on indirect evaporative cooling. It is in this context that this work proposes a new approach allowing the building designers to decide on the relevance of desiccant evaporative cooling system configurations by obtaining the expected number of hours of operation of each component. The authors propose a generic system configuration and develop a systematic methodology based on a combination of performance indicators for each component. The resulting feasibility analysis methodology is applied to ten climate zones using current and projected meteorological data. Although active cooling systems dominate the market nowadays, it is demonstrated that there is a potential to use desiccant evaporative cooling systems in almost all climate zones, both now and in the future. Finally, general recommendations are provided regarding the implementation of desiccant evaporative cooling technologies worldwide.



*Keywords:* Evaporative cooling, Desiccant cooling, Alternative air conditioning, Feasibility analysis, Sustainable cooling, Global warming

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**Nomenclature**

| | | | |
|---|---|---|---|
| *Abbreviations* | | *Subscripts* | |
| DEC | Direct evaporative cooler | dp | Dew point |
| DECS | Desiccant evaporative cooling system | ex | Exhaust |
| D-IEC | Dew point indirect evaporative cooler | h | Isenthalpic |
| DW | Desiccant wheel | in | Indoor |
| ECT | Evaporative cooling technique | nom | Nominal |
| IEA | International Energy Agency | out | Outdoor |
| IEC | Indirect evaporative cooler | s | Secondary |
| Reg. | Regenerator | su | Supply |
| | | wb | Wet bulb |
| *Symbols* | | | |
| $\varepsilon$ | Effectiveness (-) | $T$ | Temperature (°C) |
| $h$ | Enthalpy of humid air (J/kg) | $\omega$ | Specific humidity (kg/kg) |

## 1. Introduction

### 1.1. Interest of desiccant evaporative cooling

Indoor air conditioning is of significant importance for people's health and thermal comfort [1, 2]. According to the International Energy Agency (IEA) [3], the growth in global demand for space cooling is one of the most critical yet often overlooked energy issues of our time. If not managed carefully, energy demand from air conditioners will more than triple by 2050. In this context, the IEA started the Annex 85 project in 2020 on indirect evaporative cooling technologies. Evaporative cooling technologies offer a less energy-consuming and more energy-efficient alternative to standard air-conditioning techniques. Evaporative cooling uses energy in the form of latent heat associated with water evaporation into the atmospheric air [4]. Contrary to standard air-conditioning systems, evaporative cooling technologies (ECTs) cannot supply an adequate cooling load in all climate conditions, but they can tackle some of their drawbacks. The main advantage of ECTs is that they do not require synthetic refrigerant which can contribute to global warming due to leakage in the atmosphere [5, 6]. Additionally, when evaporative cooling systems can provide adequate supply air conditions, their COP is higher than standard air-conditioning systems [7, 8].

The usage of evaporative cooling technologies is limited due to the inherent properties of humid air [9–11] but their operating range can be extended by coupling with desiccant dehumidification [12, 13]. In desiccant evaporative cooling systems (DECS), components modify the air temperature and humidity content to reach desired supply conditions. The major advantage of DECS over standard air-conditioning is the separate handling of sensible and latent loads [14–17]. DECS can be used in various applications, the most common one being ventilation and air-conditioning of office and residential buildings [18]. 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, and data centers to remove humidity loads brought by ventilation and to reduce the electricity consumption related to cooling [19, 20]. It has also been shown that DECS could be used in farms to increase the thermal comfort of livestock [21] as well as in greenhouses for temperature and humidity control, reducing energy demand compared to a traditional greenhouse [22].

Desiccant evaporative cooling systems (DECS) primarily depend on thermal energy in the form of heat to regenerate their materials, with potential heat sources including solar energy, industrial waste heat, or district heating network (DHN) [23, 24]. In many countries, DHNs are unused during the summer. DECS technologies can address the under-utilization of DHNs during warm seasons by re-purposing them for high cooling demand periods. This integration could reduce electricity consumption for cooling, support heat market expansion in summer, and promote the year-round utilization and transformation of district heating infrastructures [25, 26].

### 1.2. Objective of the paper

The operation of DECS strongly depends on inlet air conditions and the influence of climatic conditions on system performance is a recurring topic in the literature [31–34]. It has been found that the system's ability to provide

| Paper | Objective | Methodology | Considered components |
|---|---|---|---|
| El-Refaie & Kaseb [27] | Establish a systematic method to explore the possibility of using evaporative cooling in any particular situation and to determine the required airflow rate and the conditions that can be realized inside the conditioned space. | Use of performance factors to establish the limitations of various evaporative cooling system configurations based on the theoretical minimum supply temperature. | ✓ Sensible HEX<br>✓ DEC |
| Campaniço et al. [28–30] | Develop a performance indicator for ventilation-based passive cooling systems to assess building energy savings in the Iberian Peninsula without an actual building simulation. | Definition of an indicator called the *climatic cooling potential* based on the cooling load a passive system can bring inside a building. | ✓ DEC |
| Present study | Develop a systematic methodology to evaluate the possibility of using desiccant evaporative cooling in a given climate zone and determine the most suitable system configuration. | Combination of standardized performance indicators for each system component to determine the number of hours of operation of each mode. | ✓ DEC<br>✓ IEC<br>✓ D-IEC<br>✓ DW |

Table 1: Summary of existing feasibility analysis methodologies in the literature.

adequate air conditions is not always questioned while being of uttermost importance for proper building operation. This paper responds to the need to develop a general analysis to evaluate the possibility of using desiccant evaporative cooling technologies depending on the prevailing weather conditions. The need for a feasibility analysis methodology has already been addressed in the literature. El-Refaie & Kaseb [27] have established a systematic method to evaluate the possibility of using combinations of direct evaporative coolers and sensible heat exchangers in any given conditions. Campaniço et al. [28–30] developed a new indicator called the *climate cooling potential* to assess the energy savings generated by ventilation and direct evaporative cooling. As shown in Table 1, both studies are limited to direct evaporative cooling.

The paper's novelty is the integration of indirect evaporative cooling technologies and desiccant dehumidification in assessing evaporative cooling feasibility. The originality of the paper is twofold. Firstly, a generic component assembly including desiccant and evaporative cooling technologies is proposed and used as a basis for the potential evaluation of these technologies. A systematic methodology is developed based on a combination of performance indicators for each component, allowing to determine their number of hours of operation. Relevant performance indicators have been considered, keeping in mind that they can easily be assessed from component data sheets. Secondly, the paper investigates the evolution of the potential of DECS with global warming worldwide using projected meteorological data. Finally, the paper provides guidelines regarding the implementation of desiccant evaporative cooling technologies in the climate zones considered in this work.

The presented feasibility analysis offers a systematic 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 is intended to be used as a preliminary tool to determine whether a climate is worth focusing on a particular system variant. It can be applied to design new systems in buildings during the construction phase or to support the implementation of ECTs or DECS in installations already equipped with active cooling systems to reduce

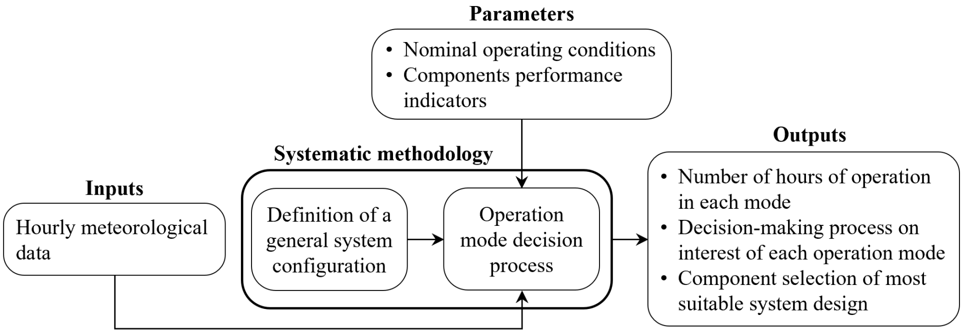



Figure 1: Definition of a systematic methodology for the feasibility analysis of desiccant evaporative cooling technologies.

electricity consumption.

## 2. Methodology

The feasibility analysis intends to determine whether, for given climate conditions, it is possible to consider desiccant evaporative cooling systems. The approach applied to develop the feasibility analysis is illustrated in Figure 1. Section 2.1 introduces the climatic conditions that were considered in this paper and treated as inputs for the feasibility analysis methodology. Section 2.2 focuses on the definition of the chosen generic DECS configuration. Section 2.3 develops the parameters required to perform a feasibility analysis. They are divided into two categories: parameters related to the nominal operation of the DECS and parameters related to the performance of components. Section2.4 shows how the feasibility analysis methodology can be implemented by gathering the notions discussed in the previous sections. Finally, Section 2.5 discusses the expected outputs of the feasibility analysis.

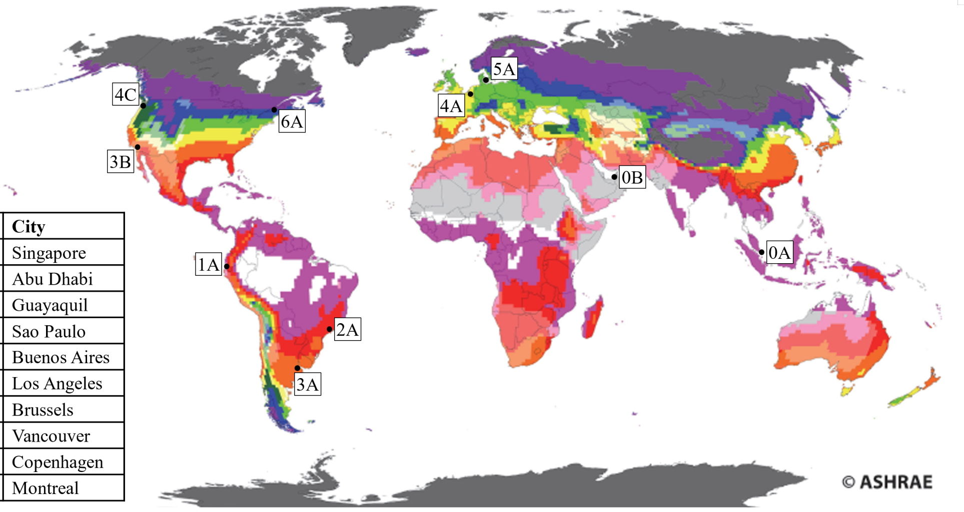
### *2.1. Inputs*

Contrary to traditional vapor-compression systems, the effectiveness of air conditioning systems based on evaporative cooling strictly depends on outdoor air parameters such as temperature and humidity ratio. Therefore, the feasibility of evaporative cooling techniques has been assessed in different climatic zones. The ten selected climatic zones and their corresponding cities are illustrated in Figure 2. The climate types range from 0A to 6A, according to the ASHRAE climate zone classification [35]. 0A represents an extremely hot and humid climate, while 6A signifies a cold and humid climate. Typical ranges of the climatic conditions for all locations are summarized in Appendix A.

Meteorological data for these climate zones have been generated and validated as part of IEA Annex 80 focusing on the resilience of cooling technologies [36]. 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.

### *2.2. Generic system description*

Various DECS configurations have been studied in the literature. It has been widely shown that the DECS configuration can impact the system energy performance and exergy destruction in components [37–39]. In this work, a generic system configuration has been chosen. The integrated elements were selected to promote the use of evaporative cooling technologies while maximizing the area covered on the psychrometric diagram. As shown in Figure 3a, the system is an enhanced desiccant evaporative cooling system consisting of six main components: a dew point indirect evaporative cooler (D-IEC), a desiccant wheel (DW), a regenerator (Reg.), an indirect evaporative cooler (IEC),




| 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.

a sensible air-water heat exchanger (coil), and a direct evaporative cooler (DEC). Those six components have been selected as key components of the generic system because they ensure improved system performance with minimal head losses in the installation. Table 2 develops why those components have been considered in the generic system configuration based on a literature review of papers studying the performance of various DECS configurations. In the chosen configuration, the air source of regeneration air is the air extracted from the indoor environment rather than outdoor air to prevent the need for a third fan in the air-handling unit. Moreover, it also reduces the dependency of the regeneration air conditions to the ambient air conditions, although it has been shown that it can have a positive impact on the system performance and reduce the energy required for the regeneration process [33, 34, 37, 40]. The evolution of the air conditions on the primary and secondary sides is shown in Figure 3b and the air-conditioning steps in the system are described below.

**1-2:** The hot air from the outdoor environment is pre-cooled in a dew point indirect evaporative cooler [42, 46]. In the D-IEC, the outdoor air is cooled sensibly in the dry channels. At the outlet of the D-IEC, part of the air is recirculated and used as secondary air in the wet channels, creating the cooling effect. The primary air leaves the D-IEC cooled but not humidified.

**2-3:** The air is then dehumidified in a desiccant wheel [47]. 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 (9-10). Regenerating the DW requires heating the secondary air (8-9) in a sensible heat exchanger known as the regenerator [48].

**3-4:** As the dehumidification process leads to a temperature increase of the primary air, it should further be cooled to reach adequate supply conditions. The first step of the cooling process occurs in an indirect evaporative cooler in which the primary air is cooled without being humidified. The evaporative cooling process takes place in the secondary channels in which the air source is air extracted from the indoor environment. The secondary air leaves the IEC heated and humidified (7-8). It is important to note that the IEC can also operate as a sensible heat exchanger if the water supply is turned off.

**4-5:** If necessary, the cooling coil can provide an additional cooling effect. The sensible coil is an air-water heat exchanger that can operate either as a cooling or heating coil depending on the season.

**5-6:** Finally, the primary air is cooled through direct water injection in the direct evaporative cooler before being

| Component | Role in the system | Advantage compared to similar components | Sources |
|---|---|---|---|
| DW | Dehumidification of the outdoor air to reach adequate supply air conditions and improve thermal comfort inside the building. | Compared to liquid desiccant technologies, desiccant wheels with solid desiccant are more mature and widespread technologies. | [31, 41] |
| D-IEC | Pre-cooling of the outdoor air before entering the DW to improve its performance. | Compared to other variations of IECs, the D-IEC shows higher COP, low pressure drop, high compactness, and low water consumption. | [32, 37, 42–46] |
| IEC | Sensible cooling of the process air. | Compared to a sensible HEX, IEC shows enhanced cooling capacity.<br>The IEC is a good replacement for the combination of a HEX and a DEC on the secondary airflow, showing lower pressure drop and increased performance.<br>Compared to other variations of IECs, the IEC shows low pressure drop, high compactness, and high cooling capacity. | [34, 37–40, 43, 45] |
| DEC | Final cooling of the process air before being supplied into the building. | Not including a DEC on the process side significantly reduces the system cooling capacity. | [40] |

Table 2: Summary of chosen components for the generic DECS configuration and description of their role in the system.

supplied to the building.

Since the system uses outdoor air as primary air, the system operation should vary depending on the outdoor air conditions as the air should be conditioned differently to reach adequate supply air conditions [34, 49]. In the case of the chosen DECS, the system can operate in seven modes by (de)activating components. The operation modes are presented in Table 3, which also summarizes the components needed for each operation mode.

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 several ways:

- A sensible cooling coil can be integrated directly into the DECS on the primary air path. The cooling coil is fed with chilled 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 vapor-compression air-conditioning or a water chiller coupled with a water distribution system and terminal units 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 3b.

### *2.3. Parameters*

#### *2.3.1. Nominal operating conditions*

The operation of the system components is influenced by several parameters referred to as *nominal operating conditions*. Those parameters are described below. It is explained how they can influence the system operation and

(a)

(b)

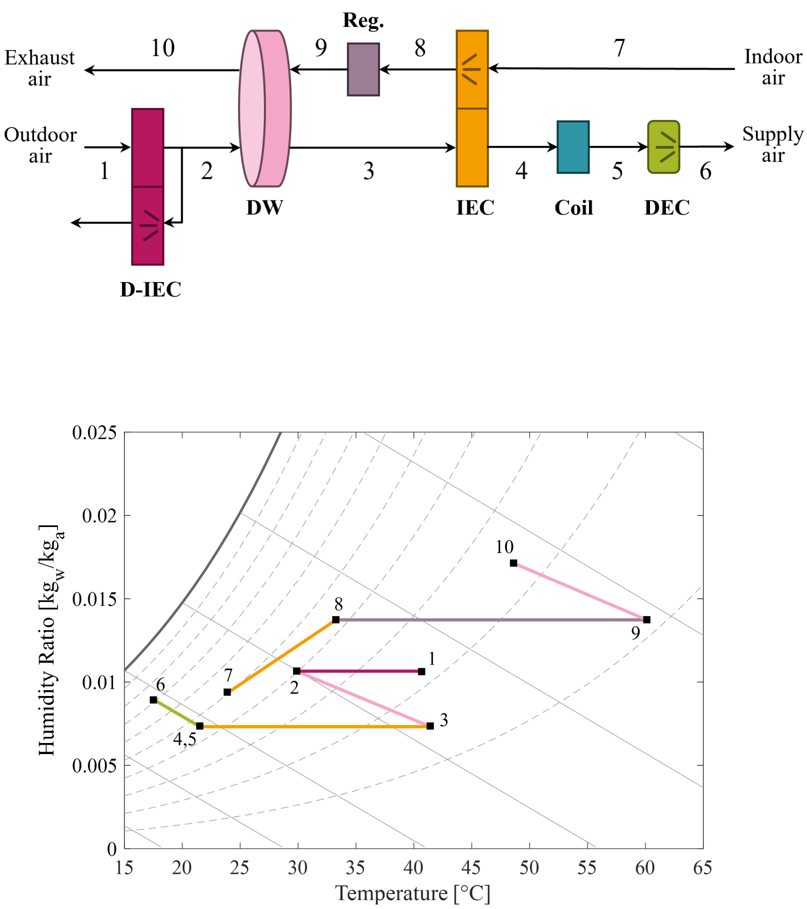



Figure 3: (a) Generic desiccant evaporative cooling system configuration. (b) Evolution of the air conditions in the DECS on the primary and secondary sides.

| | | Components | | | | | |
|---|---|---|---|---|---|---|---|
| | | D-IEC | DW | Reg. | IEC | Sensible coil | DEC |
| **Operation mode** | Heating | | | | ✓(sensible) | ✓(heating) | |
| | Ventilation | | | | | | |
| | DEC | | | | | | ✓ |
| | IEC | | | | ✓ | | ✓ |
| | DECS | | ✓ | ✓ | ✓ | | ✓ |
| | DECS with pre-cooling | ✓ | ✓ | ✓ | ✓ | | ✓ |
| | Active cooling | (✓) | (✓) | (✓) | (✓) | ✓(cooling) | (✓) |

Table 3: Operation mode summary. The components can be either mandatory: ✓or facultative: (✓) in the considered operation mode.

how their nominal value was chosen. The influence of the nominal operating conditions on the system operation is studied in Section 3.1.

**Nominal indoor conditions**

As the secondary air source of the system is air extracted from the indoor environment, the indoor temperature and humidity influence the operation of the system. According to the WHO guidelines [50], the indoor environment should be maintained between 22-26°C and around 50% relative humidity to ensure acceptable thermal comfort during the cooling period. The nominal indoor conditions have been set to 24°C and 50%, corresponding to an indoor specific humidity ($\omega_{in,nom}$) of approximately 9 g/kg.

**Supply air temperature range**
The goal of the DECS is to supply fresh air to the building to maintain the indoor environment in the desired temperature range. It has been assumed that the DECS should provide fresh air between 16 and 20°C to ensure indoor thermal comfort conditions while avoiding local discomfort due to draught [51].

**Regeneration temperature**
The regeneration temperature influences the air conditions at the primary outlet of the DW. The higher the regeneration temperature, the larger the dehumidification rate and the higher the outlet temperature. As a trade-off between dehumidification rate and temperature increase, the regeneration temperature has been set to 60°C. A low regeneration temperature also ensures integration with low-temperature sources such as solar energy or industrial waste heat.

### *2.3.2. Component performance*

The performance limitations of components have been established based on effectiveness indicators extensively used in the literature [52]. The definitions of the performance indicators are given using the nomenclature of Figure 4. For each component, it is important to distinguish the instantaneous effectiveness and the theoretical effectiveness. The instantaneous effectiveness can be computed based on a set of inlet conditions and desired outlet conditions. The theoretical effectiveness depends on the component characteristics and is the maximum value of effectiveness that the component can reach, under proper operating conditions. The instantaneous effectiveness value should be compared to the maximum value of the indicator to establish if the desired output conditions can be reached considering some given inlet conditions. The theoretical values of effectiveness considered in this work are given in Table 4 for all components. This section explains how the performance indicators of each component are defined and, if applicable, provides additional component-related considerations.

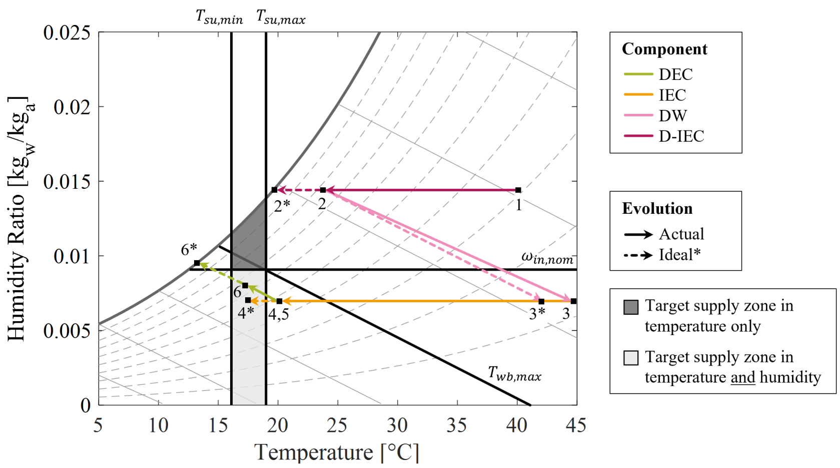



Figure 4: Comparison of ideal and actual air condition evolutions in each component and representation of the operating limits.

**Direct evaporative cooler (DEC)**
The humidification process is considered adiabatic [56]. 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 effectiveness*:

| Component | Operational parameters | Sources |
|---|---|---|
| DEC | $\varepsilon_{wb,DEC} = 0.85$ | [53–57] |
| IEC | $\varepsilon_{wb,s,IEC} = 0.75$ | [7, 58–62] |
| DW | $\varepsilon_{h,DW} = 0.85$ $T_{reg} = 60°C$ | [63, 64] |
| D-IEC | $\varepsilon_{dp,DIEC} = 0.85$ | [7, 62, 65–69] |

Table 4: Values of the operational parameters of all system components.

$$\varepsilon_{wb} = \frac{T_{DEC,su} - T_{DEC,ex}}{T_{DEC,su} - T_{wb,DEC,su}} = \frac{T_5 - T_6}{T_5 - T_6^*} < \varepsilon_{wb,DEC} \tag{1}$$

The wet bulb effectiveness definition can be used 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 effectiveness lower than the maximum theoretical wet bulb effectiveness of the DEC to reach the desired supply temperature.

However, solely considering the wet bulb effectiveness as a limitation for the DEC operation may overlook the humidification of the supply air. When the fresh air is humidified, its specific humidity can sometimes exceed the indoor specific humidity, resulting in building humidification. The outdoor conditions for which the desired supply temperature can be achieved without building humidification must be such that the wet bulb temperature of the outdoor air is below a maximum wet bulb temperature defined as:

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

**Indirect evaporative cooler (IEC)**
The IEC is an indirect evaporative cooler in which the secondary fluid is the air extracted from the building in the same conditions as the indoor environment. Since the indirect evaporative cooling process is sensible, in ideal conditions, the primary air can be cooled down to the wet bulb temperature of the secondary air. It is possible to adapt the definition of the wet bulb effectiveness to account for the actual minimum achievable temperature, which is the wet bulb temperature of the secondary fluid at the inlet. This indicator is thus referred to as the *secondary wet bulb effectiveness*:

$$\varepsilon_{wb,s} = \frac{T_{IEC,su} - T_{IEC,ex}}{T_{IEC,su} - T_{wb,in}} = \frac{T_3 - T_4}{T_3 - T_4^*} < \varepsilon_{wb,s,IEC} \tag{3}$$

State 4* represented in Figure 4 depends on the nominal indoor conditions of the studied building. They are developed in Section 2.3.1

**Desiccant wheel (DW)**
The authors proposed a new performance indicator to evaluate the performance of a DW with solid desiccant [70]. It is considered that in the ideal case, the dehumidification process in the DW can be considered isenthalpic. The proposed indicator is called the *isenthalpic effectiveness* and accounts for the irreversibility generated during the dehumidification process. The irreversibility of the dehumidification process and the resulting heat generation are caused by both the exothermic nature of the adsorption process and the residual sensible heat exchange on the process side because of the desiccant material regeneration, occurring at high temperatures. For a given dehumidification rate inside the DW, the isenthalpic effectiveness can be defined as follows:

$$\varepsilon_h = \frac{T_{DW,ex,h} - T_{DW,su}}{T_{DW,ex} - T_{DW,su}} = \frac{T_3^* - T_2}{T_3 - T_2} < \varepsilon_{h,DW} \tag{4}$$

With $T_{DW,ex,h}$ the temperature at the outlet of the DW for an isenthalpic dehumidification.

In the evaporative cooling process, the maximum humidification rate is determined by the inherent properties of humid air. However, with desiccant dehumidification, there is an additional limitation to consider, as the performance of the desiccant material is also constrained by its capacity to absorb moisture. Two methods can be considered to define the limitations of the DW:

- Definition of a maximum dehumidification rate for the DW.
- Definition of a maximum temperature at the DW outlet due to the pinch point between the primary and secondary sides.

In this study, we will consider that a pinch point between the primary and secondary sides restricts the operation of the DW. As a result, the temperature at the primary outlet of the DW is constrained by the regeneration temperature. The pinch point between the secondary DW inlet and the primary DW outlet has been assumed to be 10K, meaning that the maximum temperature that can be reached at the primary DW outlet is 50°C. Nevertheless, it is important to highlight that both limitations must be considered in an actual desiccant wheel.

**Dew point indirect evaporative cooler (D-IEC)**
The D-IEC is an indirect evaporative cooler in which part of the primary fluid is recirculated to be used as secondary fluid. Since the air is cooled down without being humidified, in the ideal case, the air can be cooled down to its dew point temperature. The *dew point effectiveness* can be defined as:

$$\varepsilon_{dp} = \frac{T_{DIEC,su} - T_{DIEC,ex}}{T_{DIEC,su} - T_{dp,DIEC,su}} = \frac{T_1 - T_2}{T_1 - T_2^*} < \varepsilon_{dp,DIEC} \quad (5)$$

### 2.4. Feasibility analysis

As introduced in Section 2.2, the system operation mode depends on the air conditions at the system inlet, i.e. the outdoor conditions. For each set of outdoor conditions (temperature and humidity), it is possible to define the operation mode of the system based on the control strategy proposed in Figure 5. The underlying principle of the feasibility analysis is to divide the psychrometric chart into operation zones for each operation mode. Each operation mode is limited by the latest component that has been activated in the system. The limits of operation of each mode are thus closely related to the performance indicators described in Section 2.3.2. For each component, it is possible to define the limit inlet conditions which will lead to the limit inlet conditions of the next component, considering a maximal component performance. 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 performed by assuming standard values of component performance is shown in Figure 6 for the city of Abu Dhabi which has a wide range of climatic conditions.

### 2.5. Outputs

Thanks to the feasibility analysis methodology developed in the previous section, it is possible to compute the number of hours of operation in each operation mode. A preliminary conclusion can then be drawn regarding the selection of the most suitable components in the considered climate zone. In the following sections, the feasibility analysis methodology is applied to various climatic zones worldwide to determine the most appropriate evaporative cooling system configuration.

## 3. Results

The results section is divided into three subsections. Section 3.1 evaluates the dependency of the repartition between the considered operation modes and the operating conditions of the building. Section 3.2 assesses the potential of desiccant evaporative cooling technologies worldwide and its evolution with global warming. Finally, Section 3.3 gives some recommendations regarding cooling system design in the chosen climate zones.

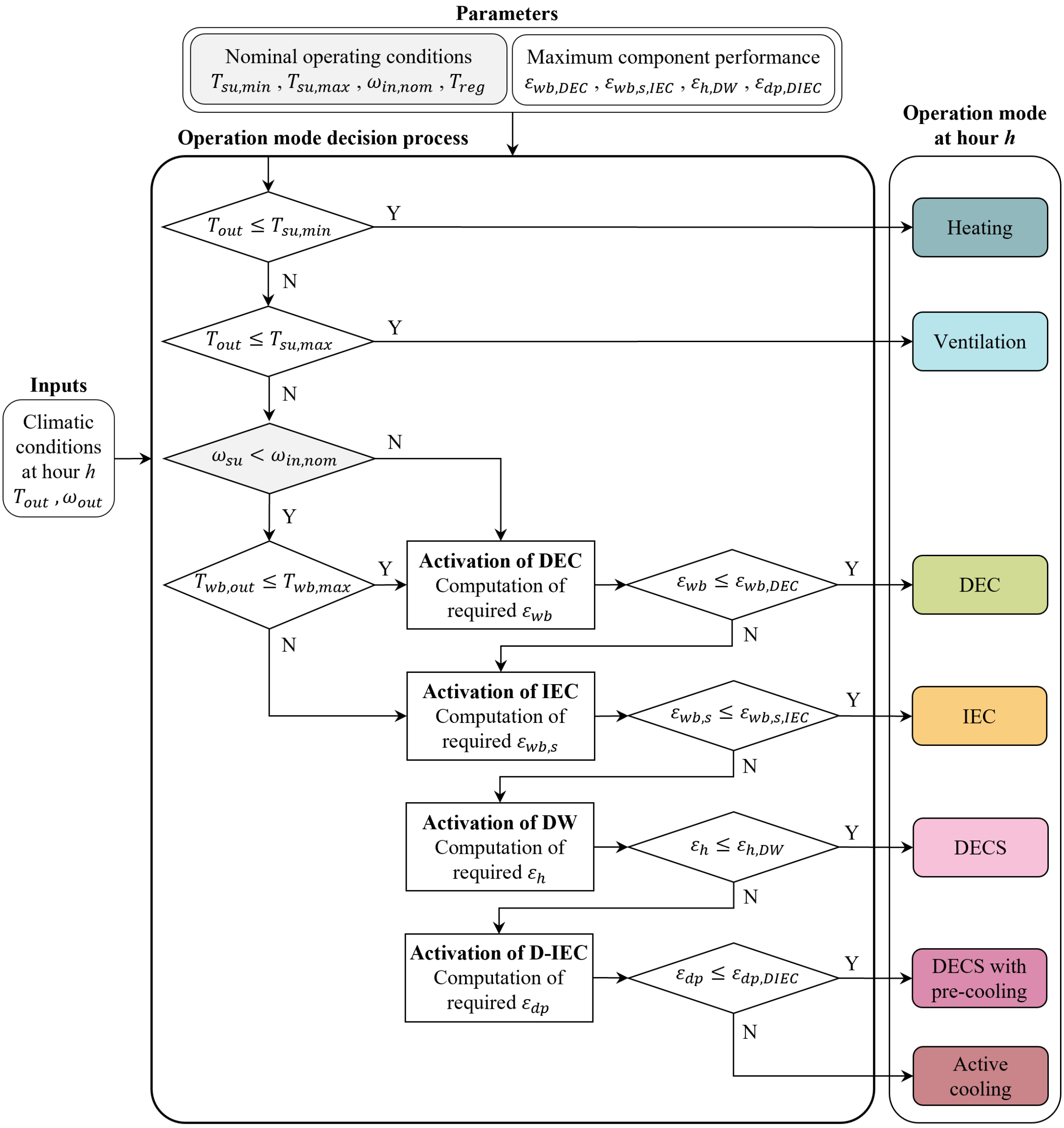



Figure 5: Flow chart representing the decision-making process of choosing the appropriate operation mode for a set of outdoor conditions.

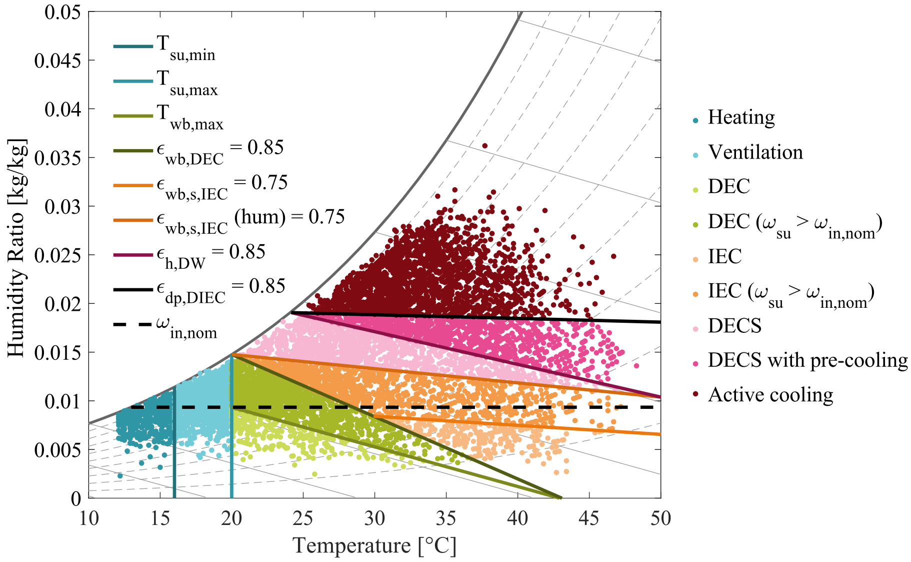



Figure 6: Example of application of the feasibility analysis methodology for the city of Abu Dhabi.

### 3.1. Sensitivity analysis to nominal operating conditions

The potential of desiccant evaporative cooling techniques has been evaluated under varying operating conditions. Since component limits depend on building indoor conditions, target supply air temperature range, and regeneration temperature, it is important to understand the dependency of the repartition between the different operation modes to these parameters. The effects of the operating parameters are summarized below by order of importance:

- The maximum supply temperature ($T_{su,max}$) influences the transition between ventilation and DEC modes. But it also impacts the position of the lines of constant wet bulb and secondary wet bulb effectiveness, hence the distribution of all operation modes (except heating mode). This parameter is expected to have the highest influence on the feasibility analysis.
- The regeneration temperature ($T_{reg}$) impacts the air temperature at the exhaust of the DW, hence before the IEC. It thus influences the repartition between DECS with and without pre-cooling and active cooling modes. All other modes are left unchanged.
- The nominal indoor specific humidity ($\omega_{in,nom}$) influences the indoor wet bulb temperature, hence the theoretical minimum outlet temperature of the IEC. It also impacts the distribution between the operation of evaporative cooling techniques with and without building humidification.
- The minimum supply temperature ($T_{su,min}$) influences the transition between heating and ventilation modes.

The last parameter has no crucial influence on the feasibility analysis of desiccant evaporative cooling techniques. Therefore, it has not been considered in the sensitivity analysis to building operating conditions. The values considered in the sensitivity analysis scenarios are summarized in Table 5.

The results of the feasibility analysis and their dependency on building operating conditions are shown in Figure 7. Results for Vancouver (4C) and Copenhagen (5A) have not been reported because conclusions are similar to Brussels (4A). Table 6 shows the decrease in the number of hours during which active cooling is necessary for each climate zone and scenario. Climate zones 3B, 4A, 4C, and 5A have not been reported because active cooling is unnecessary.

From the sensitivity analysis, it can be concluded that:

| Scenario | $T_{su,max}$ [°C] | $\omega_{in,nom}$ [g/kg] | $T_{reg}$ [°C] |
|---|---|---|---|
| **S0** | 18 | 9 | 60 |
| **S1** | 20 | 9 | 60 |
| **S2** | 20 | 10 | 60 |
| **S3** | 20 | 10 | 70 |

Table 5: Classification of test conditions for the sensitivity analysis

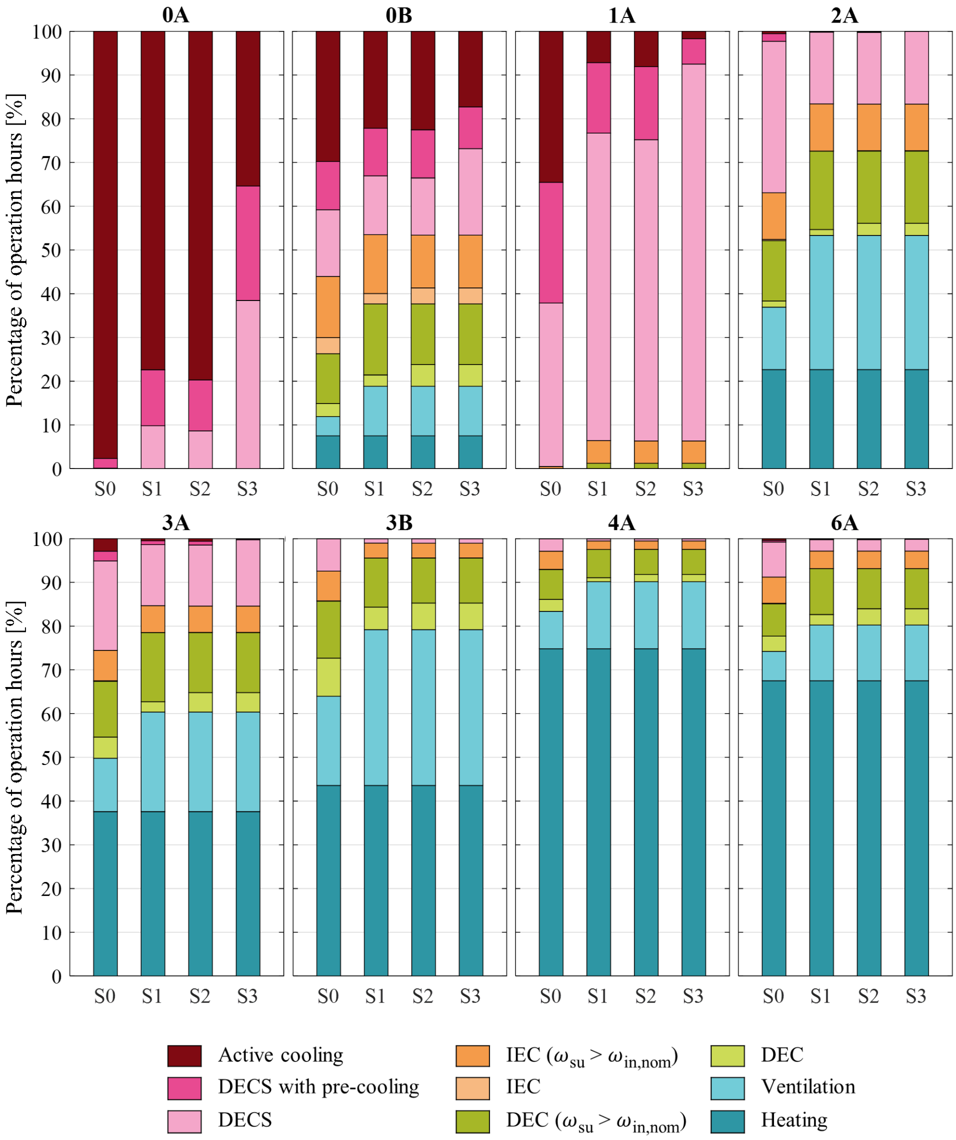



Figure 7: Results of the feasibility analysis of 8 climatic zones for varying building operating conditions.

- As expected, an increased maximum supply temperature influences the distribution of the number of hours of operation in each mode, significantly reducing the need for active cooling, especially in colder climate zones.
- The indoor conditions have a low influence on the results of the feasibility analysis. An increased indoor specific humidity leads to increased indoor wet bulb temperature, which slightly decreases the feasible zone

| Scenario | 0A | 0B | 1A | 2A | 3A | 6A |
|---|---|---|---|---|---|---|
| **S1** | -21% | -25% | -79% | -80% | -82% | -69% |
| **S2** | -18% | -24% | -77% | -78% | -80% | -63% |
| **S3** | -64% | -42% | -95% | -98% | -98% | -83% |

Table 6: Percentage of reduction in the number of hours of operation in active cooling mode compared to the reference set of parameters

of IEC. Nevertheless, the impact of the indoor wet bulb temperature is negligible compared to the one of the supply air conditions.

- The indoor specific humidity mainly impacts the distribution between the number of operation hours of evaporative cooling technologies with and without building humidification, which does not influence the overall results of the feasibility analysis.
- The regeneration temperature extends the feasible zone of the DECS operation mode. It has a major impact on the feasibility of DECS in very hot humid climate zones (0A and 1A).
- The combination of increased maximum supply temperature and regeneration temperature results in complementary active cooling systems to be necessary for less than 10% of operation hours in all climate zones except 0A and 0B which are considered extremely hot.

### 3.2. Potential evolution of DECS with global warming

The feasibility analysis has been performed for the 10 chosen climatic zones using current and future meteorological files to assess the impact of climate change on the feasibility of desiccant evaporative cooling technologies. For this analysis, the maximum supply temperature has been set to 20°C to account for the fact that in the future, indoor thermal comfort standards will tend towards higher temperatures. The regeneration temperature has been chosen to be 60°C to be compatible with low-temperature energy sources. The results of the feasibility analysis are shown in Figure 8. The current and predicted percentage of hours in each operation mode is shown for each climate zone. The main findings are summarized 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, the percentage of hours during which active cooling is necessary extends from 7% to 22%.
- 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 used only 23% of the time for TMY 2001-2020. And this proportion is likely to be less than 5% by 2050.
- 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 adequate supply air conditions while decreasing the energy demand of the system. However, the DECS should be coupled with an extra active cooling system to always guarantee good thermal comfort.
- 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 zones 3B and 4C, there will be a slight increase in the potential of DECS as they become necessary from 1 to 6% of the time.
- In the future, for climate zone 2A, the combination of desiccant evaporative technologies will become necessary for 67% of the time respectively versus 47% nowadays. The rest is covered by ventilation and heat recovery.

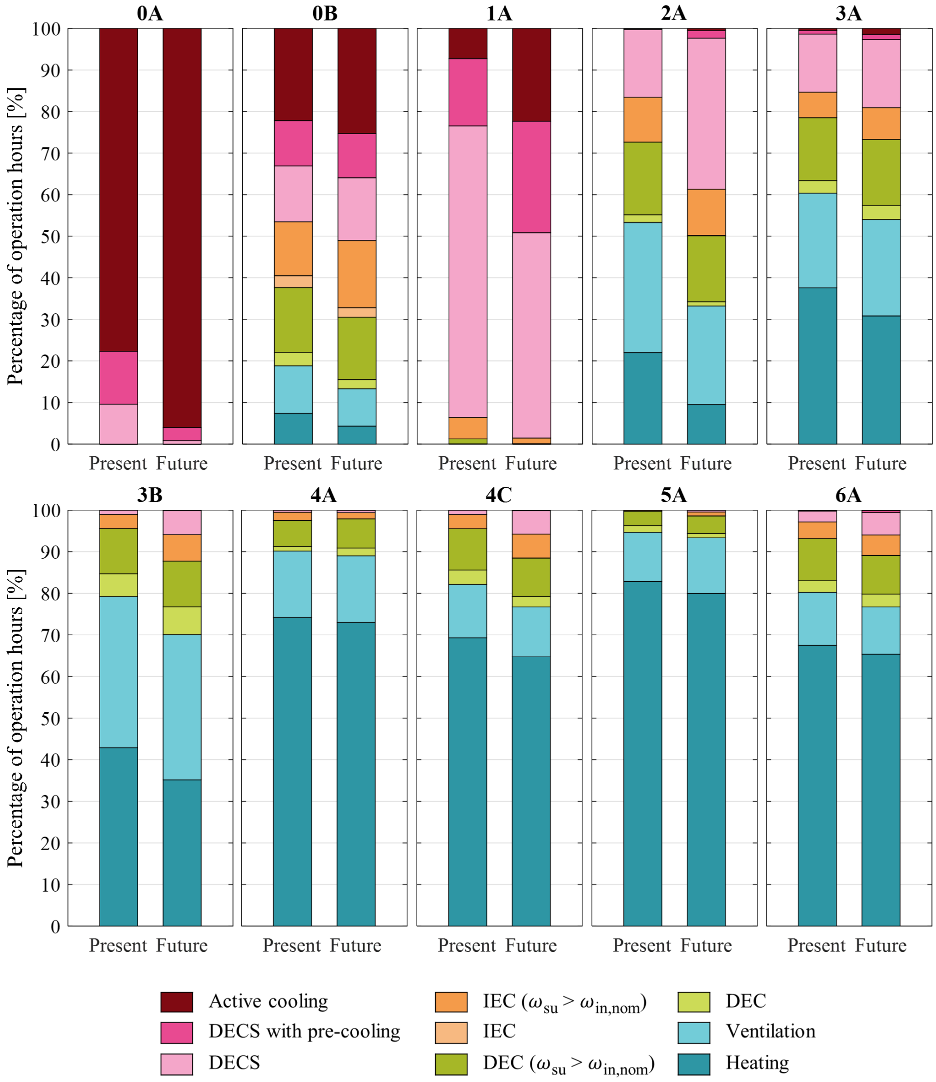



Figure 8: Impact of climate change on the percentage of operation hours in each mode in the ten considered climate zones.

- 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. In practice, this technology is not widely used since active cooling represents a major part of the market. 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.

### *3.3. Recommendation of DECS configuration worldwide*

From the considerations of the previous section, it can be concluded that desiccant evaporative cooling technologies are feasible in most climate zones around the world and 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 to determine the most suitable components to consider to ensure adequate supply air conditions throughout the year while limiting head losses in the installation. The results of the recommended systems in each climate zone and the expected percentage of discomfort hours are shown in Table 7 using current meteorological data. The meteorological files used in this work represent typical meteorological years, meaning that they are unlikely to contain heat wave episodes. Therefore, the most suitable system has been selected to remain below 150 hours of discomfort per year [71].

The feasibility analysis methodology and the component selection process have been completely automated. The resulting Python codes have been uploaded online as an open source tool to allow the user to perform a feasibility analysis in any climate conditions.

| Climate zone | Recommended cooling system | Expected discomfort hours | Hours of operation with all components activated |
|---|---|---|---|
| **0A** | Active cooling | NA | NA |
| **0B** | DECS with pre-cooling and complementary active cooling | NA | 954 |
| **1A** | DECS with pre-cooling and complementary active cooling | NA | 1419 |
| **2A** | DECS | 19 | 1434 |
| **3A** | DECS | 121 | 1223 |
| **3B** | IEC | 89 | 300 |
| **4A** | IEC | 45 | 178 |
| **4C** | IEC | 91 | 299 |
| **5A** | DEC | 24 | 442 |
| **6A** | DECS | 18 | 230 |

Table 7: Recommendation regarding DECS configuration depending on the considered climate zone.

## 4. Discussion and limitations

It is important to note that this work does not focus on a particular building and does not try to assess the performance of an actual 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.

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 an actual system. Additionally, actual 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 an actual existing system to determine a control strategy for the system operation. The control strategy plays a significant role in the system energy demand and in maintaining constant supply air conditions.

Further development of the feasibility analysis could involve combination with land indicators to 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.

## 5. Conclusions

A desiccant evaporative cooling system (DECS) is a combination of components that can modify the air temperature and humidity content. The primary air source of the DECS is outdoor air that should be conditioned before being supplied indoors. Thus, the performance of evaporative cooling systems is strongly dependent on outdoor conditions. A systematic methodology has been developed to assess the potential of desiccant evaporative cooling technologies based on the combination of standardized performance indicators for each component. The methodology has been applied to a generic system configuration using meteorological data from ten climatic zones to account for climate diversity worldwide. The considered climate zones range from extremely hot humid (0A) to cold humid (6A).

A sensitivity analysis was performed to evaluate the impact of the system operating parameters on the feasibility analysis results. The main conclusions of the sensitivity analysis are the following:

- The indoor conditions have a low influence on the system operation mode.
- The maximum supply temperature and the regeneration temperature shift the boundaries between operation modes, affecting the distribution of operating hours in each mode.
- The need for complementary active cooling systems can be decreased below 10% in almost all climate zones by increasing both the maximum supply temperature and the regeneration temperature. Active cooling systems remain necessary only in extremely hot climate zones.

The evolution of the potential of desiccant evaporative cooling technologies with global warming has been evaluated using projected meteorological data. The main findings of the feasibility analysis are the following:

- For very hot and humid climate zones (0A and 1A), the outdoor conditions are such that the desiccant evaporative cooling technologies can rarely supply air in a temperature range of 16-20°C. An active cooling system is currently necessary to maintain acceptable thermal comfort, and even more by 2050.
- 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 is likely to 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 in the desired temperature range. Therefore, this study demonstrates that there is a theoretical potential to use alternative cooling technologies, while active cooling currently dominates the market.

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## Appendix A. Temperature and humidity ranges of considered climate zones

Table A.8 gives the typical ranges for the temperature and humidity conditions of the considered climate types. The air-handling unit designer can use it to perform a simplified operation mode analysis for a given system configuration in a specified climate zone without the need to perform calculations using actual data. However, it should be noted that depending on the geographical location, data ranges may differ within a climatic zone.

| | **Present (2001-2020)** | | | **Future (2041-2060)** | | |
|---|---|---|---|---|---|---|
| | Temperature range [°C] | Specific humidity range [g/kg] | Cooling period duration | Temperature range [°C] | Specific humidity range [g/kg] | Cooling period duration |
| **0A** | 22.1 – 34.5 | 14.2 – 22.9 | 100 % | 22.5 – 35.4 | 15.2 – 26.0 | 100 % |
| **0B** | 16.0 – 48.3 | 2.5 – 36.2 | 93 % | 16.0 – 50.6 | 2.0 – 36.5 | 96 % |
| **1A** | 18.3 – 36.9 | 6.3 – 27.7 | 100 % | 21.2 – 38.7 | 10.4 – 24.7 | 100 % |
| **2A** | 16.0 – 35.2 | 1.9 – 20.5 | 78 % | 16.0 – 37.7 | 3.5 – 21.5 | 90 % |
| **3A** | 16.0 – 33.3 | 3.4 – 22.1 | 62 % | 16.0 – 32.8 | 4.2 – 22.0 | 69 % |
| **3B** | 16.0 – 36.6 | 0.6 – 15.7 | 57 % | 16.0 – 34.3 | 1.1 – 18.2 | 65 % |
| **4A** | 16.0 – 32.5 | 4.6 – 18.3 | 26 % | 16.0 – 33.2 | 4.0 – 19.4 | 27 % |
| **4C** | 16.0 – 32.3 | 2.5 – 17.0 | 31 % | 16.0 – 34.1 | 4.1 – 19.2 | 35 % |
| **5A** | 16.0 – 28.3 | 4.0 – 14.2 | 17 % | 16.0 – 30.2 | 3.6 – 17.8 | 20 % |
| **6A** | 16.0 – 33.3 | 2.5 – 23.9 | 32 % | 16.0 – 35.0 | 3.1 – 21.9 | 35 % |

Table A.8: Climate description of the 10 considered climatic zones according to the simulation results of Annex 80 Weather Data task force [36].

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