

Article

Energy Performance of Water Generators from Gaseous Mixtures by Condensation: Climatic Datasets Choice

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Abstract: Due to the growing issues related to water scarcity and pollution, water extraction from gaseous mixtures, such as atmospheric air, or fumes from combustion, is acquiring increasing importance. Nevertheless, one of the main concerns is the energy consumption that affects the use of any kind of Air(/Gas) to Water Generator (AWG). Referring specifically to water extraction from humid environmental air, AWG behaviour depends upon the air thermo-dynamic conditions and thus upon weather data. To evaluate the water extraction energy efficiency, two interesting tools can be applied: the WET (Water Energy Transformation) indicator, concerning the specific AWG machine behaviour, and the MHI (Moisture Harvesting Index), focused on climate suitability evaluation. Those tools require the knowledge of weather data to be applied. When hourly data for the entire year are available, the application of these tools leads to reliable results. However, in many cases, only average climatic data are available. Today, there are no indications about the reliability of results coming from the use of those less accurate data sets: the research aims to provide a preliminary assessment of the conditions under which average climatic data can be employed without losing meaning. This target was pursued by calculating WET and MHI with three different data sets and five meaningful climate examples. By comparing results, it was possible to provide indications about the most suitable use of average data.

Keywords: water harvesting from air; meteorological conditions for water extraction from air; AWG Air to Water Generators; WET Water Energy Transformation; MHI Moisture Harvesting Index



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1. Introduction

The water vapour in gaseous mixtures can prove to be a precious resource, given the water scarcity worldwide [1]. Water vapour is present in large quantities in atmospheric air; it can be found in abundance in combustion processes of water-rich fuels such as woody biomass [2], and in some particularly closed environments, like greenhouses, where it can also be harmful to the correct plant growth [3]. Given the scarcity of water, now clearly attested not only in arid areas but also in many parts of the world [4], it is important to improve the knowledge about not conventional water sources, such as atmospheric water [5]. Moreover, it is important to determine the most effective technologies that permit water extraction [1]. Vapour extraction can take place through processes that use thermal flows. In such a context, one of the main issues is the definition of the energy performance of the Air to Water Generator (AWG) machines in order to understand when and where it is effective for producing water by means of such a technique and to find the best solution [6]. During the decision-making stage, which occurs before any possible installation, designers are called to carry out preliminary analyses, based on energy performance calculation tools. Such analyses are carried out with the help of indexes and indicators. In particular, the followings are the most common or new:

- The Moisture Harvesting Index (MHI) [7] is used when the most diffused approach of water extraction from the air is addressed (machine based on a reverse cycle employing a compressor) in order to decide whether a climate is suitable or not;
- The Specific Energy Consumption (SEC) indicator [8] represents the specific energy consumption related to water production and, even if it presents a series of drawbacks [6] in its calculation, it is currently used in technical datasheets;
- The Water Energy Transformation (WET) indicator [6] that, given the required system (whatever AWG technology employs), provides the machine coefficient of performance in terms of efficiency in water making expressed as an energy ratio (a-dimensional), overcoming the issues of SEC.

The calculation of all the metrics that permits the water extraction efficiency evaluation depends, in general, on the climatic data [8], mostly when environmental air is involved. This dependence is more or less evident if it is considered, for example, the process of air cooling and vapour condensation for extracting water from the air or the process of cooling combustion fumes up to the water vapour condensation. In the latter case, the climatic conditions affect the process indirectly, as they are mainly linked to: the vapour content in the combustion air, the influence on the moisture content of the fuel in the storage, and to the modalities of the combustion process itself. It is worth anticipating that if the combustion is related to house heating, and if, for the fume water content calculations, design outside air temperatures equal to or less than 0 °C are considered, the water content in the oxidising air has an incidence of a few percentage points in comparison with the vapour coming from the combustion reaction. Nevertheless, when the heating process is carried out for other purposes, such as industrial ones (cement production, hot water production, etc.) that are, thus, operated in any possible climate, or when the outside temperature is above the design temperature, and the relative humidity is comparatively high, the water content of the oxidising air can be more meaningful. For example, referring to the Table 5 of [2] (Table 5), a mass of 469.2 kg of air is required to burn 23.35 kg of diesel oil. In that case, the water produced by the combustion, without considering the water content of the oxidation air, is 31.6 kg. If the oxidation air temperature is 0 °C and its relative humidity is 50%, given a total pressure of 101,325 Pa, the hygrometric degree x (the ratio between the masses of the vapour content and the dry air) is equal to 0.0019 kg_v/kg_a, which means about 0.89 kg of the water contained in the 469.2 kg of air. Such a mass is around 2.8% of the water coming from combustion. Nevertheless, if the oxidation air temperature is 15 °C and the relative humidity is 100%, the hygrometric degree becomes 0.0106 kg_v/kg_a, which means 4.97 kg of vapour. Such a value is more than 15% of the total water coming from the combustion. Thus it is not negligible in the final amount of the vapour content in fumes.

In general, all the calculation methodologies related to the energy efficiency evaluation concerning water extraction consider the use of climatic data but do not specify with what precision and accuracy such data must be provided, as will be underlined in the next paragraph. In other words, there are no indications about “when and where”; for example, hourly values, average day of the month, monthly data, or yearly averages can be used and the possible result error linked to the chosen approximation. Intuitively, the higher the steadiness of the weather conditions, the higher can be the approximation, but until now, no analyses have ever been carried out about the magnitude of the error related to the various climatic possibilities, and in which cases the various approximated datasets would be acceptable or not. Without any indication of the possible error related to the approximation, the risk is that it would be impossible to correctly estimate the underrating/overrating of the water production from gaseous mixture effectiveness. In other words, the unknown error related to the chosen weather dataset and, thus, its possible wrong choice, could lead to the wrong decision about the use of such an unconventional water source.

The current study intends to give an answer to the said research gap. In the paper the question that will be analysed concerns the efficiency metrics calculation reliability in connection to the climatic data used (hourly–daily–monthly). This assessment represents

the first step in a broader investigation and preliminarily takes into account only one of the various processes that permit the extraction of water. In particular, in the current work, reference is made to the cooling processes for the extraction of water from atmospheric air, considering the most diffused technology for water extraction from the air, as it will be remembered in Section 2, where a brief excursus about the most diffused AWGs will also be presented. In further studies, on the basis of the results obtained, aspects relating to the extraction of water from biomass combustion fumes will be investigated.

In order to estimate the possible errors which can occur in the preliminary evaluation stage of AWGs use, the incidence of the weather dataset on MHI and WET results have been considered. They will be calculated starting from the climatic conditions of five locations characterised by different climates. It is worth noting that not only dry areas, or wet regions lacking fresh water, have been considered in the study, but also other climates, comprising those related to temperate zones. Water stress and droughts are becoming more and more dramatic in the last few years, affecting places traditionally rich in surface water [9]. Due to climatic changes, the scenario will worsen in the future because water-related disasters, droughts and floods, and consequent water contamination, are expected to increase [10]. The comparison between five different climatic situations represents a starting point for a more extensive and systematic investigation with reference not only to a greater number of locations but, if appropriate, to different indices and indicators.

Therefore, the current research is developed as follows: starting from a literature overview concerning water extraction from the air and the research gap statement, a short description of the methodology is outlined, comprising a brief summary of the employed evaluation metrics and the chosen climates and datasets. After that, the calculation result report and its discussion will be presented.

Results will give a first way to judge when and where different weather datasets can be used and the magnitude order of the possible error that is related to the choice for the water extraction efficiency evaluation.

2. Water Extraction from Air and the Research Gap Related to Climatic Data

In the water cycle, the atmosphere is the direct receiver of evaporation [11]. Thus it is not surprising that the water content in the atmosphere is of the same order of magnitude as the fresh water contained in all the Earth's rivers and swamps, which means about 12,900 km³ [12]. The idea of exploiting such a water source for human uses by means of artificial humidity condensation is not new. First attempts to obtain it with free cooling were performed by F.I. Zibold, in 1905 [13], who tried to build a sort of an "open-air" condenser, basing his experiment on an old myth concerning ancient Greeks of the sixth century BC dwelling in Theodosia. Such a myth reported that the population was able to cover their water needs by means of dew condensation. Even if the myth is not to be relied upon, and the Zibold experiment was not successful [13], the idea of forcing humidity condensation from the air was considered interesting. These first experiments were performed in the 1930s. In the 1960s, water extraction from the air was obtained in the laboratory using a thermodynamic reverse cycle [14] that cooled the air under its dew point and collected the condensate instead of disposing it into the environment. However, the energy requirement was too high, caused by the low efficiency of the reverse cycle applied to the technology of the period and the idea was put aside for a while. Due to the advancement of the reverse cycle technology and the increasing issues related to scarcity, pollution and depletion of traditional water sources [15], water condensation from the air has become a reality. Nowadays, it is possible to find tens of companies that build and sell Air to Water Generator (AWG) machines [16] based on such a principle. Currently, there are three main approaches to obtaining air vapour content condensation:

- (i) Air cooling by means of a reverse cycle employing a compressor [1]. The working cycle can be described as follows. An environmental airflow passes through the evaporator coil of a thermodynamic reverse cycle. The heat passes from the airflow to the refrigerant. In such a way, the airflow is cooled under its dew point, and part

of the humidity content condenses and thus can be collected. The heat is disposed into the environment by means of the condenser coil, where the refrigerant, after the compression, exchanges energy with the external environment. A working scheme of such a technology is reported in Figure 1. This process is the most diffused in existing AWGs that can produce from tens to thousands of litres per day [17]. Such an approach is often employed when the dew point temperature is above 4 °C [7], but it can also be used when such a temperature is below the said threshold, employing defrosting cycles for the coils [18];

- (ii) Thermoelectric Coolers (TEC), based on Seebeck (or Peltier) effect [19]. The working cycle, whose scheme can be seen in Figure 2, differs from the previous one in the part concerning the system employed to cool down the environmental air, which, in this case, is provided by a TEC module instead of by a compressor and its related coils. Such a technique has the advantage of being compact and almost free of moving parts. Nevertheless it is not very efficient and not very adaptable to environmental conditions variations. It is mostly used whenever very small equipment is required as well as low water production (few litres/day) [20];
- (iii) Desiccant substances employed to artificially enhance the water content in the treated airflow [21]. Desiccants are able to absorb a part of the vapour content of the air, even if the relative humidity is low. In order to release the vapour, desiccants require thermal energy. The cycle can be described as follows. An environmental airflow passes through a layer of desiccant material and releases a part of the humidity that migrates inside the layer. After that, a heat source is applied to the desiccant that releases the vapour inside a closed volume of air or a controlled airflow. The volume of air, or the airflow, is then cooled under its dew point, which, compared with the environmental air, is now higher. A possible scheme of a working cycle is reported in Figure 3.

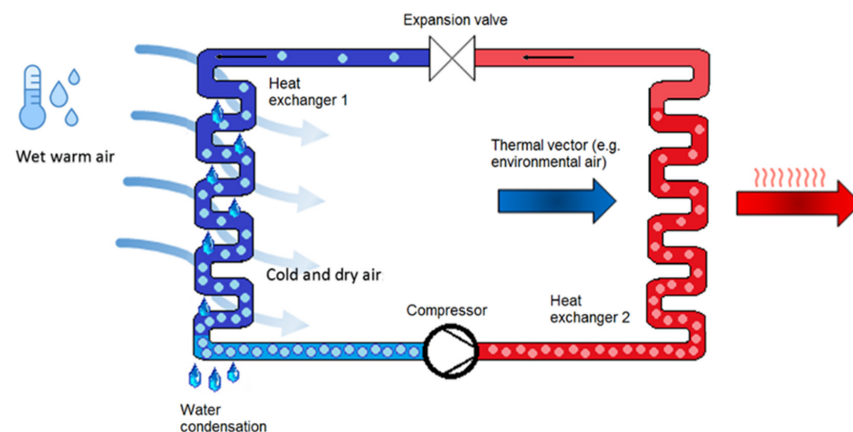


Figure 1. Reverse cycle-based AWG working scheme, image from [6].

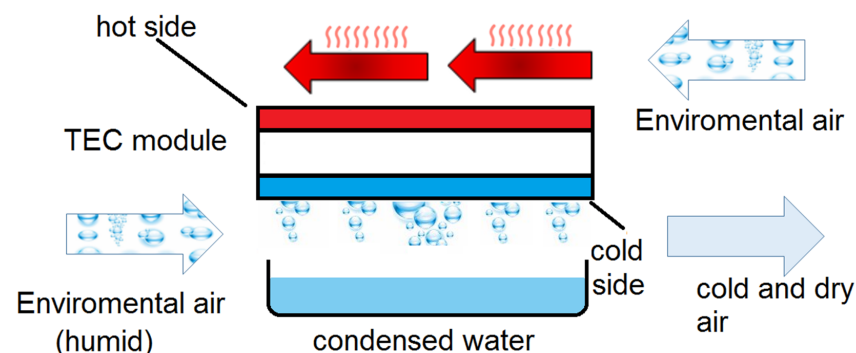


Figure 2. Thermoelectric cooler-based AWG working scheme.

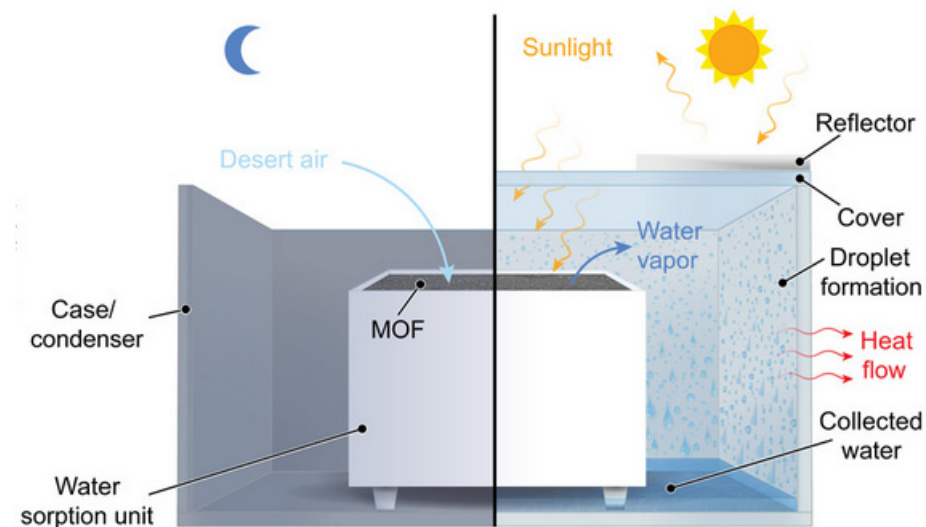


Figure 3. Desiccant-based AWG scheme, image adapted from [22].

The process permits the extraction of water while consuming less cooling energy, but the complete balance, including the heating energy, is not favourable in comparison with the reverse cycle technique. Nevertheless, if free cooling and/or free heating can be employed, and/or natural temperature differentials can be used, the process can be effective [21]. Moreover, the technique can be interesting in cold zones where environmental air presents a dew temperature equal to or less than 4 °C, providing an alternative method to extract water that avoids defrosting cycles for the coils. Up until today, the desiccant-based approach has been used when a few litres per day of production is needed because it requires large spaces to usefully embed the desiccants [21]. It is worth noting that a new approach has been proposed lately. It can be called a “hybrid solution” because it couples the desiccant technique and the reverse cycle. For example, in [23], desiccants coat the condenser coils, and the heat released by the refrigerant is used to regenerate them. In [24] desiccants were gathered into a rotating wheel placed at the air inlet section of the reverse cycle after its passage on the condenser. In such a way, the air gathered humidity from the desiccant and was then cooled by the evaporator. Desiccants are charged by environmental air. The process of humidity harvesting and releasing is carried out continuously. This approach, which needs more study cases and real applications, is promising as it could reduce the energy required to produce water compared with the above-mentioned AWG technologies [24].

As a matter of fact, whatever the employed technique, one of the main concerns about water extraction from the air, is always the energy cost of the operation [25]. Water condensation is an exothermic process that releases about 2460 kJ, which is the average value of the latent heat of condensation, Q_c , in the working range of the most diffused AWGs [6], for each kg of vapour mass condensed. If the air is not in saturation conditions, it is required that, besides the condensation heat, the sensible heat needed to achieve the saturation curve will also be removed. Moreover, if the condensation is performed where the hygrometric degree x is lower than 4 g_v/kg_a, the latent heat of condensation is rather high [26]. Besides what has been said above, the lower the air’s water content, the higher the required air volumes to obtain the same condensed water will be, and, thus, also the energy consumption due to moving such air from outside through the treatment section [6].

As can be inferred from the above description, also remarked in [27], the water extraction process deeply depends upon the thermo-hygrometric conditions of the air that is going to be treated to obtain the condensate. In particular, not only the extractable quantity of water but also the energy required to carry out the process are strongly related to the state of the treated air [28]. Thus, AWG behaviour, whatever the technology employed in it, can be evaluated only by knowing the state of the inlet air, as highlighted in [6]. AWGs behaviour, and in particular their energy consumption, is of the utmost importance in

order to understand when and where such an approach can be employed to obtain fresh water, and many papers focused on such a topic, considering the weather conditions of various climates. For example, in [29], the extractable water in India's coastal regions was theoretically calculated using, as input, the monthly average dry bulb temperatures and relative humidities of nine different cities.

In [30], yearly averages of relative humidity and environmental temperature were used to give a first estimation of the most suitable technology to extract water all over the world. In the limitations of the study, it is acknowledged that taking into account daily and seasonal variations would provide better results. In [18], calculations about an AWG system behaviour were carried out on the basis of hourly data in Kathmandu, India.

It can be observed that, for the various calculations and tests reported in the quoted literature, different kinds of dataset were used, in particular, the yearly averages, the average months and the hourly data of the entire year. In [31] it was shown that the climate of the analysed location was very stable all over the year. Thus even the yearly average was meaningful for some considerations.

As a matter of fact, in the quoted papers, there is a lack of knowledge concerning the discussion about the reliability of results coming from different weather datasets. Such missing information is of the utmost importance when results have to be generalised.

Generally, hourly data are considered a reference of good frequency sampling in the energy calculations referred to the annual behaviour of buildings and their technical plants. They are adopted by building energy simulation tools, comprising humid air transformations and related equipment, such as Energy Plus [32]. Thus, it is reasonable to consider such a degree of frequency sampling a possible reference also for calculations concerning water extraction from the air, as they treat humid air transformations as well. Nevertheless, in many places in the world, weather data with such a frequency are not available. The weather dataset of Energy Plus (hourly data) covers only 3034 locations all over the world. Weatherbase [33], a worldwide weather database, reports data concerning about 42,000 locations, but only a part of them are provided with hourly data, while many places, in particular if in remote areas, are provided only with monthly averages of one value of temperature and one of relative humidity for each month of the year (twelve values for each variable). Sometimes, in weather databases, it is also possible to find the average day of the month: twenty-four values of temperature and twenty-four of relative humidity, describing the average day of each month (288 values for each variable). As described in [31], there are places where the climate is almost steady, from the point of view of water extraction, all over the year, but there are others, as underlined in [6], where it varies, and AWG performances vary in consequence. In these cases, it can be inferred that the use of approximated weather data can affect results. In [34] the global potential of a hypothetical solar-driven atmospheric water harvesting device was mapped, and hourly data of temperature and relative humidity were specified, coming from weather simulation ERA5-Land [35]. Nevertheless, even in this case, there was no discussion of the possible error related to input data approximation and the possible use of real data, characterised by a less sample frequency versus more accurate but calculated ones.

As far as the authors' literature knowledge goes, there are no studies giving any general indication related to the Earth's climates about how the use of approximated weather datasets can affect AWGs behaviour calculation results. Today, one of the indirect effects of such a lack of information is the diffused practice of declaring AWGs energy consumption considering only one condition of environmental air, as can be ascertained by examining the commercial AWGs data sheet [16]. Such a practice, as discussed in [6], can lead to very misleading judgments.

As the first answer to such a research gap, in the current work, there is a first attempt to understand what kind of error is related to the differently approximated weather datasets when calculations concerning water extraction from the air are carried out, considering different climates. This approach is a novelty because, even if in [30] it was inferred that

higher precision corresponds to more reliable results, a systematic study about the issue has never been carried out. The error entity, due to approximation, has never been identified.

As already underlined in the introduction, as energy consumption is one of the main concerns in the AWG field, the incidence of the different datasets will be analysed, taking into account two metrics involving energy consumption: the WET indicator and the MHI index. In the current paper, the SEC will not be used because the terms involved in the calculation of such an indicator are not well defined, as discussed in [6]. Thus its definition presents some weak points that invalidate its applicability.

Results of the current work will be considered a starting point also for a deeper investigation of the condensation of the vapour content in the gaseous products from fuel combustion, in particular related to biomass boilers, such as described in [2]. Even in this case, as mentioned above, the climatic conditions would play a meaningful role in the collectable amount of condensed water. The current research step will be, thus, employed in a further paper in order to evaluate the accuracy level of results related to the weather dataset assumed in calculations concerning the water extraction from fumes.

3. Methodology

As declared above, the current study is focused on water extraction from the air and, in this first research step, the energy efficiency analysis takes into account the most diffused AWG technology, which implements the thermodynamic reverse cycle driven by compression.

In this section, the metrics used to evaluate the system performance, WET and MHI, are outlined, and the climatic input data chosen for the analyses are indicated. In particular, in this research, the hourly weather data are considered as the reference. Thus results coming from their application will be the benchmark, while the approximated weather datasets will be the average month day and the monthly averages.

3.1. WET (Water Energy Transformation) Indicator

The WET indicator is a metric that measures the energy efficiency of any kind of system able to extract water from the air. It represents the ratio between the wanted effect, the water extraction from the air, and the effort required to obtain it; both expressed in homogenous terms.

In order to obtain the required homogeneity, the water extraction is expressed as energy by means of the latent heat of condensation. Thus the WET is an energy ratio between the energy amount needed to condense a mass of water m [kg] divided by the entire energy required by the investigated AWG machine to produce such an effect. The expression of the indicator is the following:

$$\text{WET} = Q_c \cdot mw / E \quad (1)$$

where:

Q_c = the latent heat of condensation per unit mass [kJ/kg]

mw = mass of condensed water [kg]

E [kJ] = the energy required by the chosen AWG to produce the wanted effect.

The WET formulation is general and represents an efficiency evaluation tool, which can be used independently from the machine working principles, applying the same concept at the base of the Coefficient Of Performance, COP [36], and of the Energy Efficiency Ratio, EER [37], formulations. The higher the WET value, the higher the energy efficiency related to water extraction. It is important to underline that the E term comprises the energy consumption by all the components involved in water production, such as fans, pumps, compressors, heating sources, etc. The water treatment energy consumption is excluded because it is not directly related to water production, and thus it is beyond the WET scope [6]. Using its definition, WET overcomes the issues related to SEC. Moreover, it can be directly aggregated with EER and COP to define the GEI index [38] for the integrated

AWG machine evaluation. Moreover, it is worth noting that WET can be applied to all AWG machine types, simple or integrated, employing desiccants or not, using combustion smoke, etc., working outdoors, or even indoors.

The value of Q_c in the WET indicator formula, in first approximation, can be set as a constant, whose value is 2460 kJ/kg, as discussed in [6], because it is representative of the most diffused AWGs working points.

In the current paper, the above approximation was used.

WET values depend upon the behaviour of the machine, which, as already remembered, strongly depends upon environmental air thermo-hygrometric conditions.

3.2. MHI (Moisture Harvesting Index)

The MHI [7] is a metric designed to roughly evaluate the different climates from the point of view of the effectiveness of water extraction from the air, where such extraction is supposed to be obtained by cooling the air under its dew point.

The index is given by the ratio between the possible condensation energy and the theoretical specific energy (enthalpy difference) required to obtain the described process. The condensation energy is given by the difference of the hygrometric degree multiplied by the latent heat of condensation.

The index expression is the following:

$$\text{MHI} = \frac{x_i - x_0}{h_{e_i} - h_{e_0}} Q_c \quad (2)$$

where

x = hygrometric degree [kg_v/kg_a]

h_e = specific enthalpy [kJ/kg_a]

Q_c = latent heat of condensation [kJ/kg_v]

(i = inlet, 0 = reference point, v = vapour, a = dry air)

The main hypotheses [7] for its application are that:

1. The water extraction is performed by a machine that provides only water extraction by air cooling;
2. The cooling process is normally not performed under the dew point of 4 °C, which corresponds to a hygrometric degree of 5 g_v/kg_a, representing the reference point for the index calculation;
3. The latent heat of condensation can be considered a constant, equal to 2492 kJ/kg.

Analysing the above conditions, some index limits can be identified:

- Hypothesis 1 excludes processes based on: integrated machines, hybrid machines employing desiccants, and water extraction from smoke coming from boilers used for heating, and thus reduces the power of the index to be a general effectiveness metric for water extraction from the air.
- Hypothesis 2 is objectionable because there are cases in which it can be interesting water extraction even under the said limit, employing defrosting cycles. As a matter of fact, MHI authors declare that it is possible to change the reference point in compliance with the real machine behaviour, nevertheless to know such a parameter is not an easy challenge, even for manufacturers, because it is not always a design parameter [6];
- Hypothesis 3 is acceptable enough even if, as discussed in [6], the most suitable average value of Q_c for the water extraction range should be 2460 kJ/kg_v.

Analysing Equation (2), it can be easily ascertained that the MHI index is based on the air thermo-hygrometric conditions, given by h_e and x , known as the total air pressure. Thus its values can be calculated taking into account dry bulb temperature and relative humidity, stating the total air pressure, of a certain climate, in order to determine whether the water extraction process, remembering the above-described limits, could be effective or not.

Due to the formulation, the index is always under 1, and its authors set the value of 0.3 as the discriminant to decide whether the climate is suitable for water production. The

higher is MHI, the more suitable the climate. In general, it can be said that high MHI values represent very humid and warm environmental conditions, while low values characterise environments that require high sensible heat to condense water.

3.3. Input Data: AWG Characteristics

In the current work, the WET values are calculated taking into account the behaviour in the chosen different climates, described in the following subparagraph, of a machine having similar characteristics to that described in [31], functioning only as an AWG, thus simply producing water, as reported in [38].

Thus, the machine has the following main characteristics:

- It is based on a reverse cycle, equipped with a screw compressor of 100 kW cooling capacity.
- It has an air treatment unit equipped with fans able to provide an average airflow of 8000 m³/h, an evaporation coil, where the water condensation takes place, and a heat recovery unit.

In the current study, the machine was configured to work with an inferior cooling limit of about 1 °C of dew point and a working range that stops the machine when the environmental air dew point is below 3.5 °C. The machine was designed to give the best performances in hot-humid climates.

3.4. Input Data: Chosen Climates and Data-Sets

In order to provide preliminary evaluations concerning the influence of the different weather datasets on WET and MHI results, five locations, characterised by five different Köppen–Geiger climate classifications, were chosen. In Table 1, the climates, and related locations, are shown:

Table 1. Climate classifications and related locations.

Climate Classification	Climate Definition	Location	Weather Station	D (km)	H (m)
Aw	Tropical Savanna	Havana (Cuba)	Jose Marti international airport	6	64
Af	Tropical Rainforest	Singapore	Singapore Changi international airport	0	6.7
BWh	Hot Desert	Dubai (UAE)	Dubai Al Maktoum international airport	6	8
Csa	Hot Summer Mediterranean	Rome (Italy)	Fiumicino international airport	20	4.6
Cfb	Oceanic (marine)	Paris (France)	Paris Montrouge	0	77

Arranging results coming from [39], main climate groups A, B and C cover 65% of the dry land of the Earth while taking into account the subgroups, Aw, Af, BWh, Csa, Cfb, the total coverage amounts to the 35.75% of the whole dry land. If group E is excluded because it represents polar regions where water extraction from the air is almost meaningless, the coverage increases to 41.5% of the remaining lands.

For each location, hourly weather data concerning dry bulb temperatures, t , and relative humidities, $r.h.$, averaged on the last five years' hourly sampling, were collected, considering the weather stations reported in Table 1.

All the weather stations are placed at a height above the sea level inferior to 100 m. Thus the total air pressure was assumed to equal 101,325 Pa and considered constant, as its influence, due to its expected variation, on the thermo-hygrometric variables is negligible. Due to the total pressure constancy, the t and $r.h.$ values are enough to define the air state (Gibbs phase rule applied to wet air [40]).

On the basis of such hourly data, the two approximated weather datasets were calculated. Summarising, the chosen datasets used for the analysis of WET and MHI results are:

- The average hourly values of the average year (used as the reference sampling frequency, 8736 values for each variable).
- The average month day values of the average year (288 values for each variable).
- The average monthly values of the average year (12 values for each variable).

For each dataset described above, the WET indicator and the MHI index were calculated by applying Equations (1) and (2). After that, two differences were calculated:

- ✓ “d-h”, that is the difference between results coming from the use, as input, of the average month day data and the hourly data;
- ✓ “m-h”, that is the difference between results coming from the use, as input, of the average monthly data and the hourly data.

Moreover, the percentage of the said differences was calculated, which can be seen as the committed percentage error, remembering that the reference results are those obtained using the hourly data.

Results are reported in graphs by comparing, month by month, the found values.

It is important to note that an average error equal to or inferior to 5% could be assumed acceptable because temperature and relative humidity instrument uncertainties range from 2% to 5% [41].

A further step of the research will expand the climate analysis taking into account other places in order to obtain a wider coverage of the dry land climates and considering a further dataset, representing the whole average year in terms of t and $r.h.$ (only one value for each variable to describe the entire average year).

4. Calculation Results and Discussion

In the following sub-paragraphs, climates analyses and result reports are discussed for each chosen location. In particular, for each case will be provided:

- a short climate description, with the graphical help of the behaviour of the monthly average;
- the WET values variation and percentage error calculation in the function of the different datasets;
- the MHI values variation and percentage error calculation in the function of the different datasets.

4.1. Climatic Dataset—Havana (Aw)

In Figure 4, Havana’s climate is summarised using monthly averages.

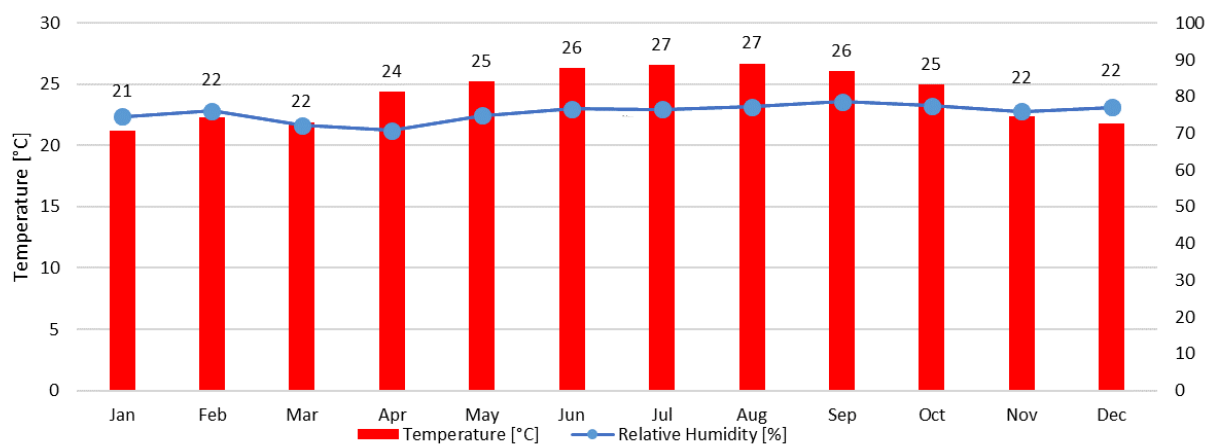


Figure 4. Havana, t and $r.h.$ during the average year.

It can be observed that

- Maximum temperature excursion is less than 6 °C;
- Relative humidity range has a very low variation: min 70% max 79%;

- It is possible to distinguish two periods: a colder one, from November to March, and a hotter one, from April to October.

In Figure 5A, WET results calculated taking into account the three different datasets are summarised: the highest water extraction efficiencies are achieved from May to October. The lowest is in March, followed by that of January. The indicator has the same trend, using the three different datasets, but results, coming from the application of the less accurate weather dataset, always overestimate the efficiency.

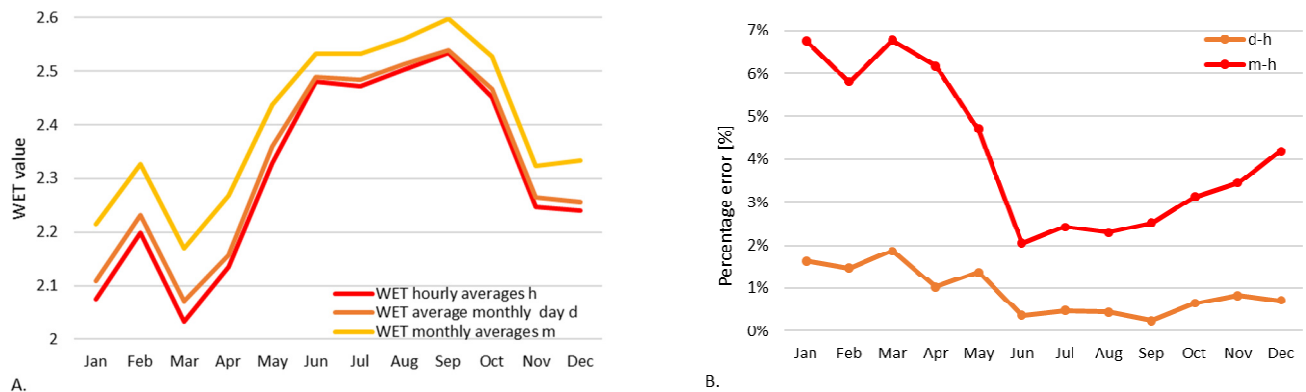


Figure 5. Havana WET values (A) and percentage error (B).

The graph in Figure 6B describes the WET error in percentage and its trend, for the different datasets, month by month.

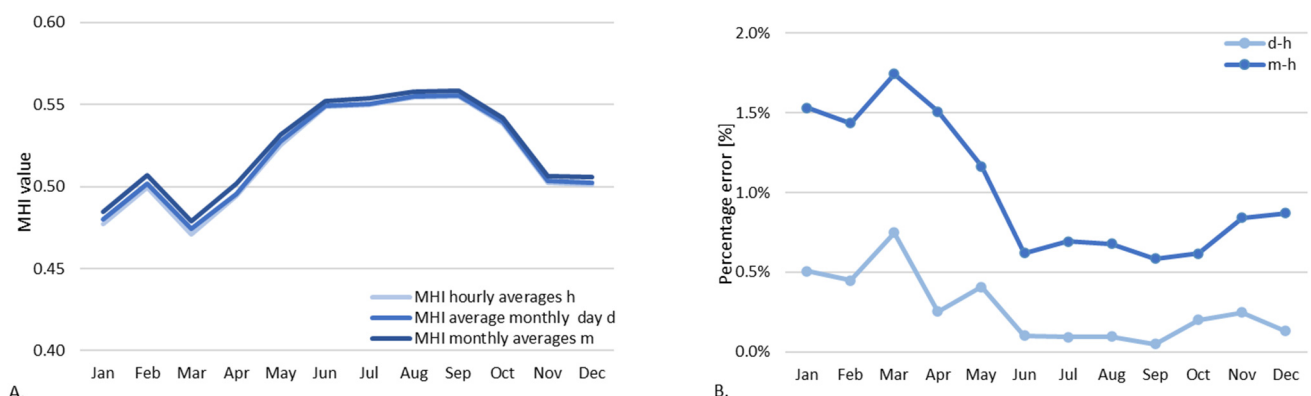


Figure 6. Havana MHI values (A) and percentage error (B).

Analysing the graph it is possible to infer that in the Havana climate, for the WET calculation:

The average month day data use (curve d-h) gives:

- An error range of: 0.4–1.9% (avg 0.9%), the error is always negligible;
- A maximum error in March (that is the month characterised by the lowest temperatures and relative humidities).

The average monthly data use (curve m-h) gives:

- An error range of 2.1–6.8% (avg 4.2%, lower than 5%, thus considered almost acceptable);
- A peak error of 6.8% occurring not only in March but also in January.

Analysing the error trend, month by month, it can be seen that the two datasets have different behaviour in May, September, and December.

In Figure 6A MHI value calculation results are summarised. In the Havana climate, the MHI index is high and always above 0.46, but there is a huge difference between the colder period, also including April, and the hotter period, in this case from May to October,

where the index exceeds 0.5. As well as what happens for the WET indicator, the MHI value has the same trend using the different datasets.

In Figure 6A the percentage error and its trend, related to MHI, for the two comparisons, d-h and m-h, are reported.

Analysing the graph, it is possible to infer that in the Havana climate, for the MHI calculation:

The average month day data use (curve d-h) gives:

- An error range of: 0.05–0.7% (avg 0.3%), the error is always negligible;
- A maximum error in March (0.7%).

The average monthly data use (curve m-h) gives:

- An error range of: 0.63–1.7% (avg 1%), the error is always negligible;
- A peak error, also in this case, in March (1.7%).

The MHI error trend presents almost the same differences observed for the WET results, except July. As a matter of fact, as well as it happened for the WET a different behaviour coming from the two datasets can be seen in May, July, and December.

4.2. Climatic Dataset—Singapore (Af)

In Figure 7 Singapore's climate is summarised by means of monthly averages.

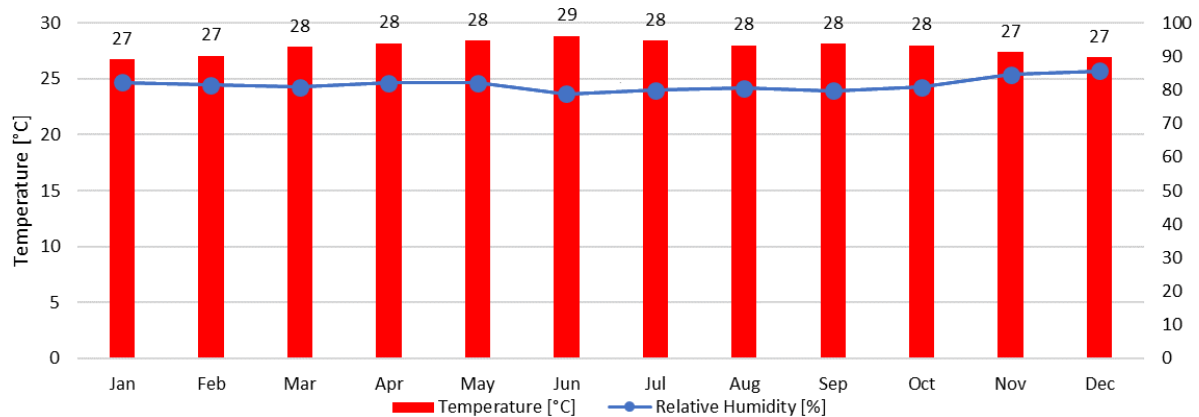


Figure 7. Singapore, t and $r.h.$ during the average year.

It can be observed that:

- The maximum temperature excursion is less than 2 °C;
- The relative humidity average values always remain between 79% and 86% (very low variation);
- It is not possible to determine a colder or a hotter period.

In Figure 8A, WET is calculated for the three different data sets. It is possible to observe that the highest water extraction efficiencies are achieved in November and December with values of 2.80 and 2.83 (values obtained using the “hourly averages h” dataset). The lowest value is in June, followed by the ones in July and August.

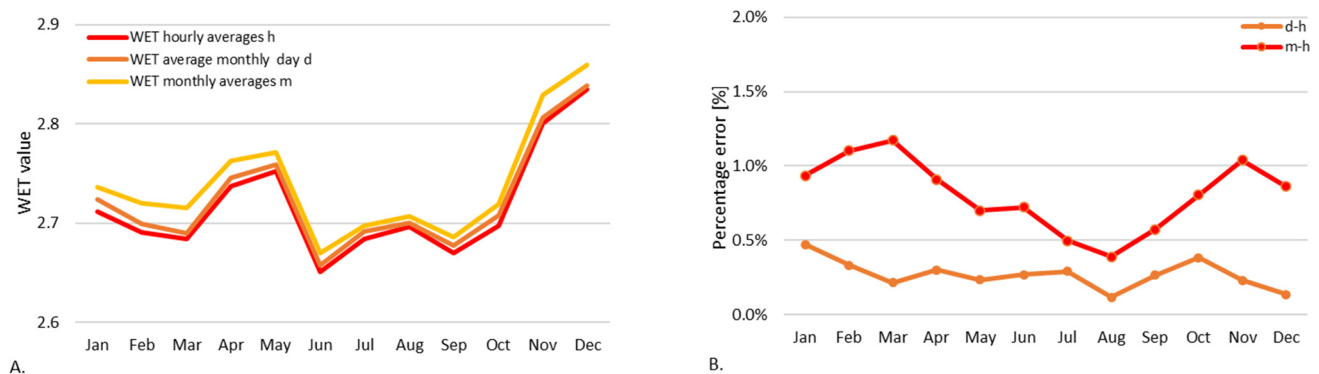


Figure 8. Singapore WET values (A) and percentage error (B).

The indicator has the same trend, using the three different datasets, but results coming from the application of the less accurate weather dataset always give a slight overestimation of the efficiency.

Analysing the error curve d-h, Figure 8B, it is possible to infer that in the Singapore climate for the WET calculation:

The average month day data use (curve d-h) gives:

- An error range of: 0.1–0.5% (avg 0.3%), thus the error is always negligible;
- A maximum error in January (that is the month characterised by the lowest temperatures).

The average monthly data use (curve m-h) gives:

- An error range of: 0.4–1.2% (avg 0.8%), the error is always negligible;
- A peak error of 1.2% is no more in January but occurs in March. Moreover, in February and November, the error is above 1%, while in January, it is under 1%. All the errors are always negligible, but it is important to underline how the higher approximation shifts the error peak.

Analysing the percentage error trend, it can be seen that the two datasets present different behaviour in February, March, and November.

In Figure 9A, MHI calculation results are summarised. It can be observed that the year presents an index value above 0.575, but there are two pairs of months, April and May and November and December, in which there are peaks of values above 0.59. Even in this case, the MHI value has the same trend using the different data sets.

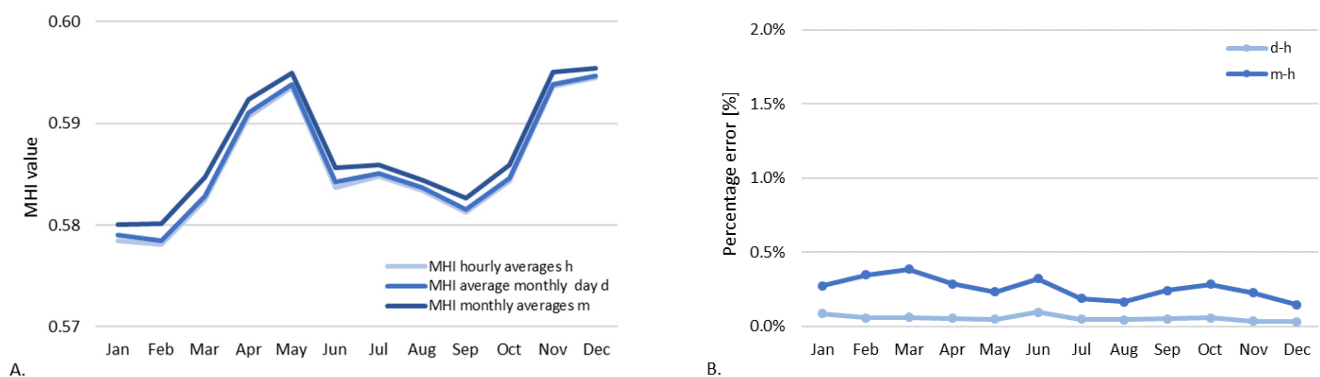


Figure 9. Singapore MHI values (A) and percentage error (B).

In the Singapore climate, Figure 9B suggests that for MHI:

The average month day data use (curve d-h) gives:

- An error range of: 0.03–0.1% (avg 0.06%) always negligible;
- Maximum errors in June and January, respectively 0.1% and 0.09%;

The average monthly data use (curve m-h) gives:

- An error range of: 0.15–0.39%, (avg 0.26%) always negligible;
- A peak error in March (0.39%).

The MHI error trend presents almost the same differences observed for the WET results of m-h. While for the WET d-h and MHI d-h a very different behaviour is observed.

4.3. Climatic Dataset—Dubai (BWh)

Dubai climate is shown by means of its monthly averages, calculated on the basis of hourly data, in Figure 10.

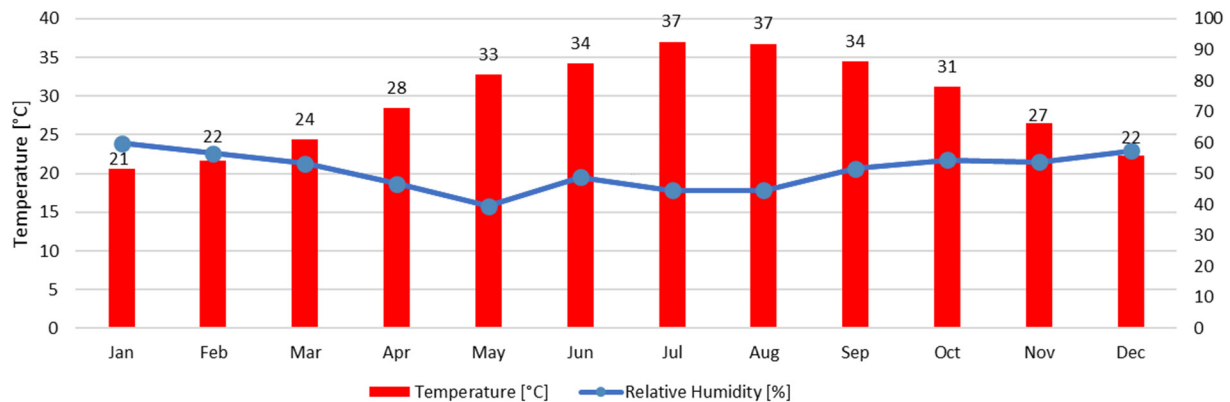


Figure 10. Dubai t and $r.h.$ during the average year.

It can be observed that:

- From December to January, temperatures are lower in comparison to the other months of the year, while relative humidities are higher;
- Temperatures have a variation range wider than 16 °C, while the maximum relative humidity difference reaches about 20 percentage points;
- The temperature trend has a bell shape, while that of the relative humidity has an almost specular behaviour.

In Figure 11A, WET results, calculated taking into account the three different datasets, are summarised. The water extraction efficiency of the considered machine is not constant during the year, presenting its peaks during June, September and October and its minimum in May, while in January, August, July and December, the values are near the average one, equal to about 1.6. Even in this case, the indicator has the same trend, using the three different datasets. Moreover, the results coming from the application of the less accurate weather dataset always overestimate the efficiency.

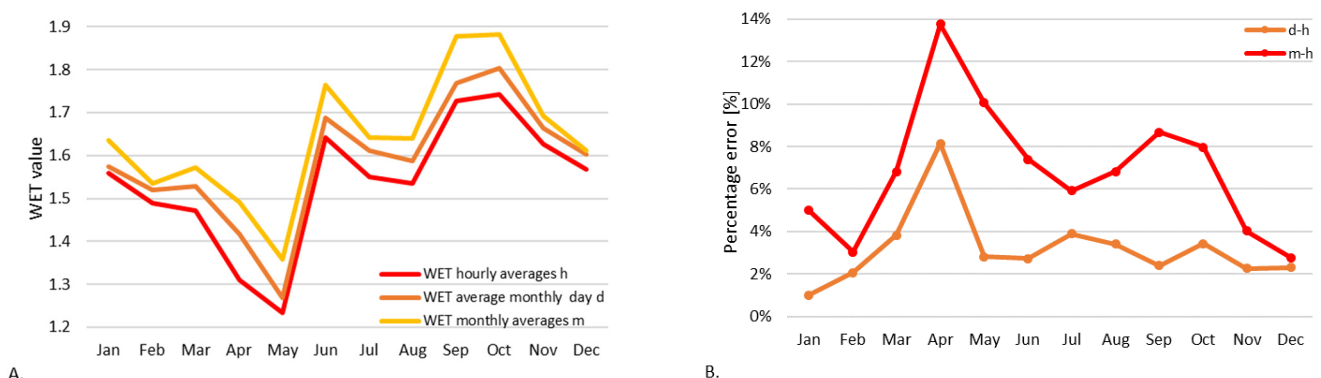


Figure 11. Dubai WET values (A) and percentage error (B).

Analysing Figure 11B, it can be seen that in the Dubai climate, for the WET calculation: The average month day data use (curve d-h) gives:

- An error range of 1–8% (avg 3.2%), the error is always under 10%, and the average error is under 5%. Averagely the error percentage can be considered acceptable;
- The maximum error is in April; in all the other months, the error is under the 5% threshold.

The average monthly data use (curve m-h) gives:

- An error range of 2–14% (avg 6.9%), such an error is far higher than that found with curve d-h; it exceeds 10%, thus results can be objectionable;
- A peak error in April, followed by that of May.

The differences between the error trend are not negligible in February and from June to October.

In Figure 12A,B MHI calculation results are summarised.

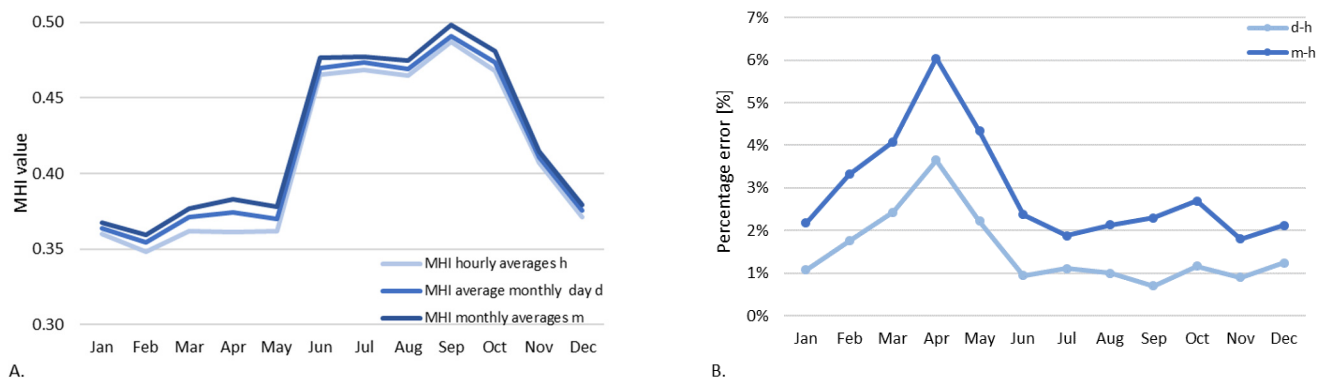


Figure 12. Dubai MHI values (A) and percentage error (B).

In Figure 12A, it can be seen that the year presents an index value above 0.3, but there is a huge difference between the first five months of the year and the months from June to October. Even in this case, the MHI value trend has the same behaviour using different datasets.

From Figure 12B, it can be understood that:

The average month day data use (curve d-h) gives:

- An error range of: 0.7–3.7% (avg 1.5%), the error is always under the 5% threshold;
- The maximum error is in April (3.7%), not misleading.

The average monthly data use (curve m-h) gives:

- An error range of: 1.8–6% (avg 2.9%), the average error is under 5%. Overall, the percentage error can be considered acceptable.

A peak error in April followed by May (4.3%).

For the MHI, the error trend is almost the same using the two different datasets, with slight differences in February, July, and September.

4.4. Climatic Dataset—Rome (Csa)

In Figure 13 Rome's climate is summarised by means of monthly averages.

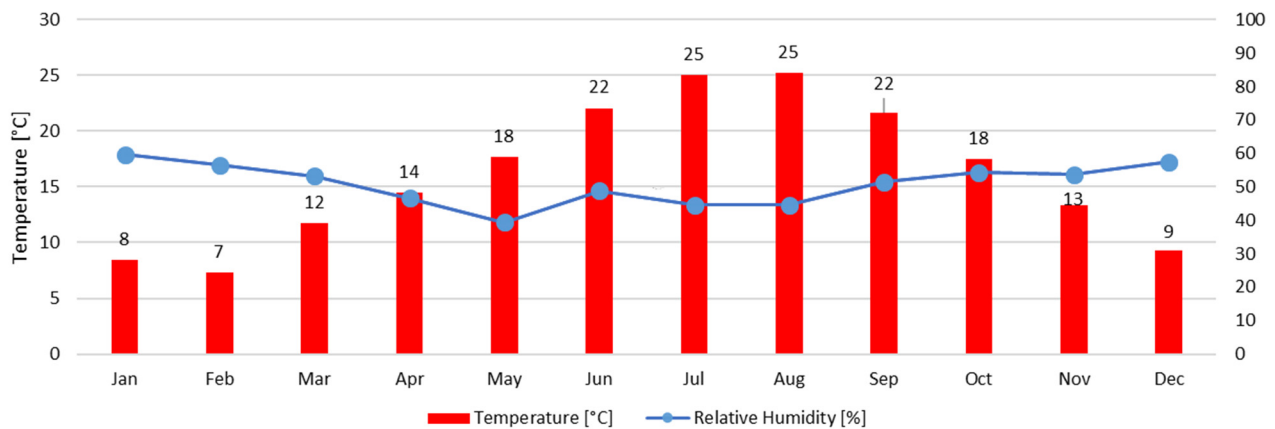


Figure 13. Rome t and $r.h.$ during the average year.

It can be observed that:

- The maximum temperature excursion is around 18 °C, from winter to summer;
- The relative humidity average values are comprised in only 10 percentage points;
- The average temperature trend shows a bell shape, with peaks in August and July;
- The climate has a cold and humid winter, while presents a warm and humid summer.

In Figure 14A, WET results are summarised, calculated taking into account the three different datasets. The graph highlights that from December to February, on the contrary of what it was observed for the previous climates, the use of the average monthly day and the monthly average datasets underestimates the water extraction efficiency.

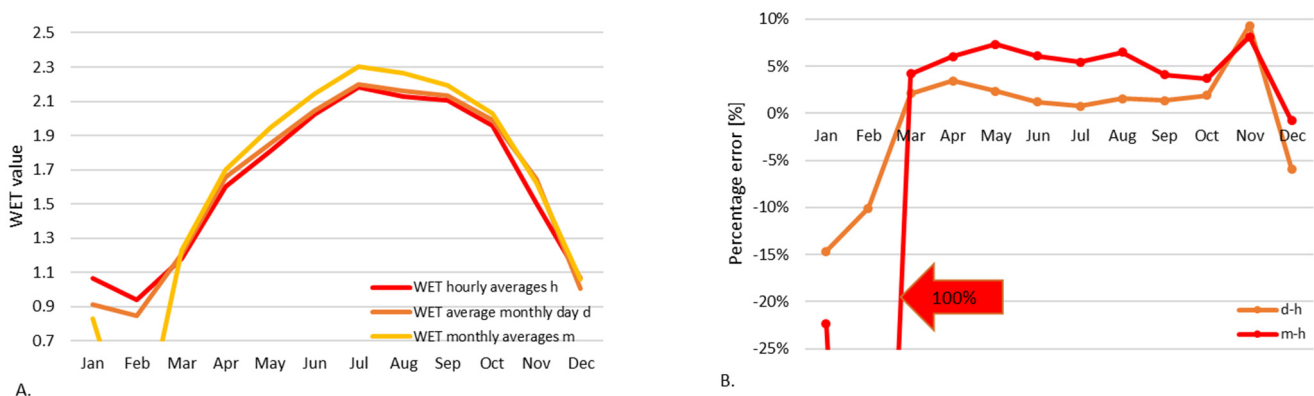


Figure 14. Rome WET values (A) and percentage error (B).

In particular, in February, the use of the monthly averages brings us to the wrong conclusion that the AWG machine cannot work. This is because the approximation of the monthly average is too strong. As a matter of fact, during February, there are days and hours compatible with the working range of the considered AWG machine (that, as said before, stops when the environmental air dew point is below 3.5) but the average values cut all those periods. The same reasoning can be used for the other winter days. There are many hours compatible with the machine working range, but the average month days and the monthly averages hide such information. It is curious the December month, where WET result coming from the monthly average is nearer to that given by the hourly dataset than that related to the average month day. Even in this case, the result is due to the approximation, which, accidentally, returns, for the considered month average, a value nearer to the baseline.

Analysing Figure 14B, it can be seen that in the other months of the year, the monthly averages give an error that goes from -0.8% to 8.1% , with an average value of 5.2% . Taking into account the average month day data, the highest error is in January, when its absolute

value is near 15% (underestimation). Excluding the winter time, the error decreases to an average value of 2.7%, with a peak of 9.3% in November and a minimum in July, when its value is 0.8%.

The main differences in the error trend occur in February, May and October. Moreover, there is an inversion in November and December, when the error related to the average month day dataset is higher than that related to the monthly averages.

In Figure 15A, MHI calculation results are summarised.

Even for MHI value calculations, it is possible to observe that results, coming from the average month day and the monthly average datasets, in February and in January are misleading and underestimate the possibility of water extraction, Figure 15A. As a matter of facts, during those months MHI is under 0.3. Even during December and March the index is under such a threshold, but the error related to the use of the two different datasets is less stressed, even if in March it is misleading as it will be discussed in the following.

In the Rome climate, the use of the monthly averages, instead of the hourly data, for the MHI calculation can be misleading not only during January and February, as it happened for the WET, but also for March and December. As a matter of facts, those months are characterised by a low MHI index, under 0.3. Nevertheless, in March the two said datasets give a MHI value very near to that threshold which, it is worth remembering, in the index intents is the discriminant that suggests whether it is effective water extraction or not. The error, thus, even if less pronounced in comparison to January and February, is more impacting, from the point of view of the index intents.

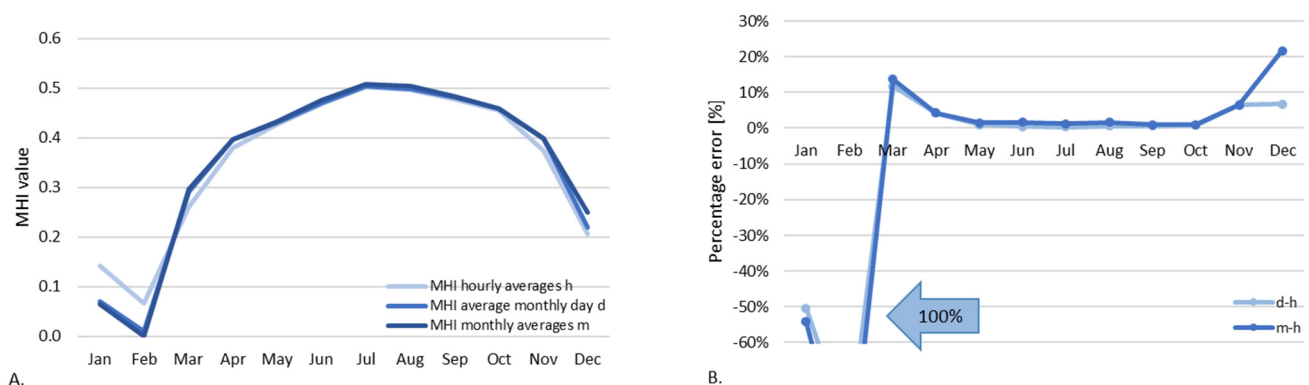


Figure 15. Rome MHI values (A) and percentage error (B).

Analysing Figure 15B, that represents the percentage error, from April to November, the monthly averages use gives an error that goes from 1% to 6.5%, with an average value of 2.3%.

Taking into account the average month day data, the maximum errors, in absolute value, are in February, 85%, and in January, 50%, followed by March, 11%, while considering the other months, the average error is 2.4% and goes from 0.3% to 6.7%. Excluding all the months with an MHI well under 0.3, the average error is equal to 3.6%, using the monthly averages, and to 2.9% using the average month days. For the MHI, the error trend is almost the same using the two different datasets, with slight differences in June and September, while the most evident difference is in December.

4.5. Climatic Dataset—Paris (Cfb)

In Figure 16 Paris climate is summarised by means of monthly averages.

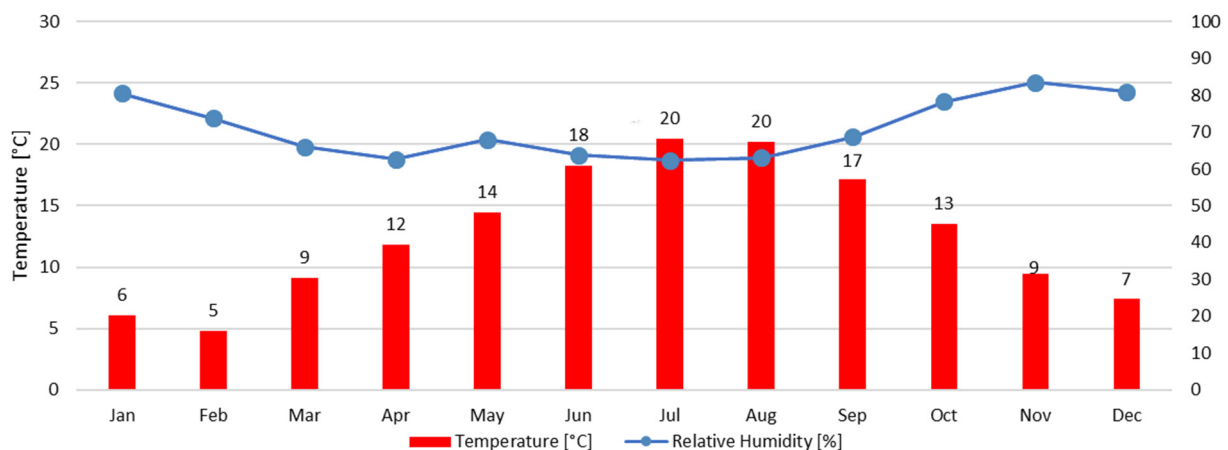


Figure 16. Paris t and $r.h.$ during the average year.

It can be observed that:

- The maximum temperature excursion is around 15 °C;
- The relative humidity average values are comprised of 20 percentage points, far more than the 10 of Rome's climate;
- The average temperature trend shows a bell shape with peaks in August and July, almost the same trend as that of Rome, but shifted down, as the minimum temperature is 4.8 °C instead of 7.3 °C, and the bell is less pronounced because the temperature range is around 15 °C, instead of 18 °C;
- The climate has a cold and humid winter while it presents a warm and rather humid summer.

In Figure 17A, WET results, calculated taking into account the three different datasets, are summarised. The graph highlights that from December to April, as well as what happens in Rome from December to February, the use of the average monthly day and the monthly average datasets underestimates the water extraction efficiency. In particular, in January, February and March, the use of the monthly averages and the average month days brings to the wrong conclusion that the AWG machine cannot work. Even in this case, the reason is that the approximation of the two said datasets are too strong, and the hourly weather dataset is the only one that can give a real idea of the machine functioning.

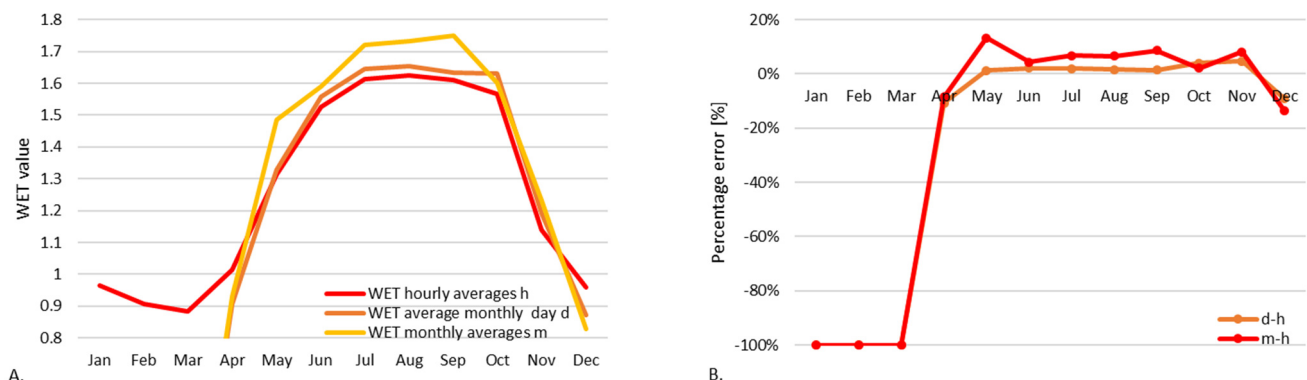


Figure 17. Paris WET values (A) and percentage error (B).

Figure 17B represents the percentage error related to the WET calculation.

In the Paris climate, the use of the monthly averages, instead of the hourly data, can be objectionable in general, as the absolute value of the error is always above 5%, excepted in June and October cases. From January to March, results are misleading.

Taking into account, now, the average month day data, it can be observed that, also in this case, from January to March results are absolutely misleading, while in December

and April, they can be objectionable, as the absolute value of the error is above 10%. In the remaining months, it is under 5% and thus almost acceptable.

The main differences between the error trends are in July, September, and October. Moreover, there is an inversion in April and October, when the error related to the average month day is higher than that related to monthly averages.

Figure 18A summarises MHI value results. Even for the MHI, it is possible to observe that results coming from the average month day and the monthly average datasets from January to March declare the impossibility of water extraction; that is not true, even if it must be said that the values calculated with hourly data are very low. With hourly data, MHI is under 0.3 from November to May. Nevertheless, during May and November, calculations made with the average month day and the monthly average datasets provide a value above the very threshold that is considered the discriminant for water extraction; thus, during those months, the error is particularly misleading. Moreover, in December and in April, MHI is underestimated if the approximated datasets are used.

The above observations are underlined if the percentage error is considered: in Figure 18B, in the Paris climate, the use of the monthly averages, instead of the hourly data, for the MHI calculation gives the same errors seen for WET from January to March. After that, it can be observed that the error, in absolute value, is higher in December, November and April in comparison with the remaining months. At any rate, as already underlined for the MHI value, the error committed in May and November is probably the most impacting. From June to October, the dataset can be used with an accepted error of a maximum of 2.5%.

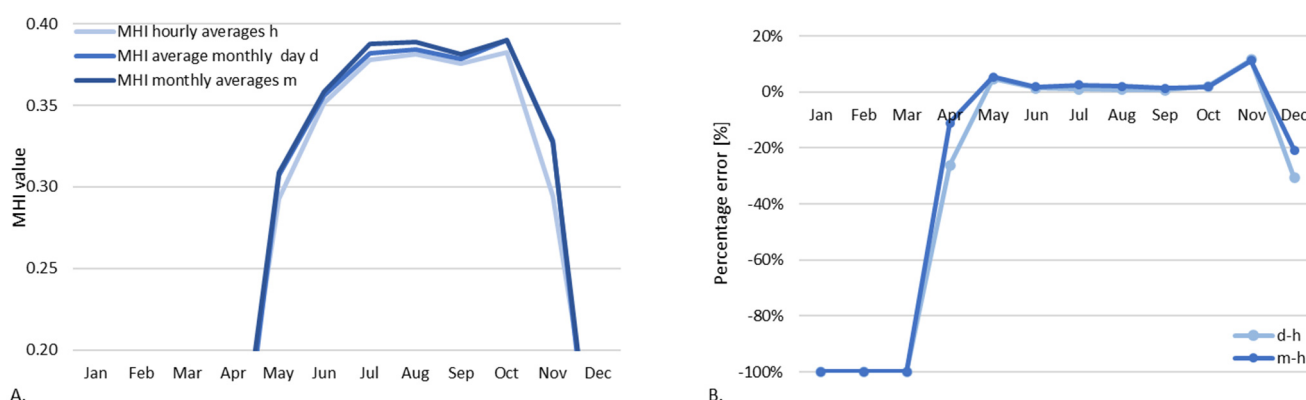


Figure 18. Paris MHI values (A) and percentage error (B).

Taking into account, now, the average month day dataset, it can be observed that, from January to March, results give the same problems described for the monthly averages. In December and April, the absolute value of the error is above 25%; in November it is over 11%, while in the other months, it is under 5%. Even in this case, the error committed in May and November is probably the most impacting because declaring an MHI value above 0.3, says that the periods are suitable for water extraction, while results coming from the more accurate calculation say exactly the opposite.

Excluding all the months with an MHI well under 0.3, the average error equals 2% using the monthly averages and 1.2% using the average month days. The MHI error trend is almost the same using the two different datasets, with only one difference that occurs in July.

4.6. Summary Report

In Table 2, error results are summarised, in terms of maximum, minimum, and average values, for both the metrics: WET and MHI. Those values are reported for each considered location.

Table 2. Percentage error: maximum, minimum, average values.

Location	WET			MHI		
	Max	Min	Avg	Max	Min	Avg
Havana d-h	1.9%	0.2%	0.9%	0.7%	0.0%	0.3%
Havana m-h	6.8%	2.1%	4.2%	1.7%	0.6%	1.0%
Singapore d-h	0.5%	0.1%	0.3%	0.1%	0.03%	0.06%
Singapore m-h	1.2%	0.4%	0.8%	0.4%	0.1%	0.3%
Dubai d-h	8.1%	1.0%	3.2%	3.7%	0.7%	1.5%
Dubai m-h	13.8%	2.8%	6.9%	6.0%	1.8%	2.9%
Rome d-h	9.3%	−14.7%	−0.6%	11.7%	−85.4%	−8.6%
Rome m-h	8.1%	−100%	−6.0%	21.7%	−100%	−8.3%
Paris d-h	4.6%	−100%	−25.2%	11.6%	−100%	−27.9%
Paris m-h	13%	−100%	−23%	11%	−100%	−25%

Note: h = hourly average; d = average monthly day; m = monthly average.

It is worth noting that, in Rome and Paris climate, the maximum error, in absolute terms, corresponds to an underestimation of the water extraction possibility for both metrics.

5. Overall Discussion

Observing the previous analyses, it can be said that, for the considered locations, the absolute value of the error given by the MHI calculation, using both the average month days and the monthly averages, is generally inferior in comparison to the WET one, during those months where MHI value is well above 0.3. This is because the MHI was not designed in order to provide an accurate picture of the real efficiency of a machine. In fact, MHI does not take into account the different behaviours of the compressor or the heat exchanger or of the employed desiccants, etc., in the function of the weather conditions, and it is not intended for such a scope. The said index gives only an indication of the climate suitability for water extraction under the hypotheses remembered before. It is interesting to observe that its results are less sensitive to the used weather dataset until its values are near the threshold of 0.3 or under it. When the index is evaluated near the said discriminant threshold, the sensitivity of the different datasets increases. In particular, it can be said that in those months when the index, calculated on an hourly basis, gave a value under the very threshold, the other two datasets gave a more favourable result, providing a wrong indication, from the point of view of MHI intent, about the suitability of such months for water making. Thus, in such cases, only hourly data are suitable to obtain reliable results. When the MHI is low, equal or under 0.2, the more approximated calculations give errors very high in percentage. Still, their impact is less significant, as, taking into account the index intent and hypotheses, such periods of the year are, at any rate, not suitable for water extraction.

The WET indicator, as remembered before, is based on the chosen AWG machine's real working behaviour. Thus it is correct that the indicator is more sensitive to the approximations related to the weather dataset. If an average error of 5% is accepted, for Havana and Singapore climates, the two approximated datasets can be used. For the Dubai one, only the month average days give reliable results. For the climate of Rome and Paris, analyses must be carried out only using hourly data. In particular, it must be observed that when temperature and relative humidity fluctuate under and over the machine start and stop threshold, approximations can be very misleading because compressing data in averages hides the possibility of water extraction during those hours compatible with the machine working field.

Further Developments

These results are interesting because they provide the first discriminant for the weather dataset use in preliminary analyses concerning AWGs efficient employment and even the AWGs design stage. Moreover, the climatic conditions dataset represents an important step for defining the input of different systems, and in particular, it will be considered a starting point also for analyses concerning the water extraction from exhaust products from combustion of boilers. In particular, when combustion is related to industrial processes or uses that can be carried out in all the world zones and/or all over the year, weather conditions could play a not negligible role in the final water content.

The next step of the research will extend the considered weather range, going more in deep with the weather analyses, and will also take into account the GEI index. Such an index was developed in order to evaluate the global efficiency of integrated machines that are multipurpose machines, able to provide more than one useful effect, included water extraction, using the same energy input. Such a kind of advanced AWG machines can overcome the energy consumption issue related to water extraction from air [39]. Taking into account GEI makes it possible to include in the analyses the boilers used not only for heating but also for water recovery from fumes.

A further research step will consider, also, an even more approximate data-set, yearly averages, for those locations where the weather conditions are particularly steady, as those described in [31], and will study how to manage monthly data in order to extend the possibility to use them, having the availability, beside averages, of the maximum and minimum values. It will be studied whether an equation that, with the employment of such values, tries to provide the daily fluctuations of temperature and relative humidity can be effectively used in order to obtain reliable results for the chosen indicator and indices.

6. Conclusions

The work, here presented, represents an absolute novelty because it addresses an issue that has never been analysed before: the error related to weather dataset choice when water extraction from air, or from other gaseous fluids, is considered. In particular, it is the first assessment of the series of climatic data that can lead to a reliable evaluation of performance indicators for extracting water systems, by cooling. In this phase, the study refers to the process of condensation of water from atmospheric air and represents a first step for a broader investigation that is aimed to define when and where different climate datasets (on a monthly, daily, or hourly basis), for the calculation of indices and indicators, can be used with an acceptable approximation degree.

In particular, these first evaluations analysed the reliability of the values concerning: an indicator, WET, and an index, MHI, both related to water extraction from air. WET is based on the real functioning of a general AWG machine, while MHI gives an idea of the suitability of a climate for water extraction, but only using a reverse cycle and, generally, stopping the cooling process at 4 °C of dew point. As reference weather values, assumed to give the highest reliability, the hourly data describing an average year were taken. The other two datasets were, respectively: the average month day, (24 values for each month, 288 for each variable per year) and the monthly averages (12 values for each variable per year). In this first evaluation, five locations, representative of five different climates, were taken into account: Havana, Singapore, Dubai, Rome, Paris. Using the Koppen-Geiger classification they can be described, respectively, as follows: Aw, Af, BWh, Csa, Cfb. Analyses results showed that the MHI is less sensitive to the used dataset in comparison to the WET, until its value is well above the discriminant threshold of 0.3. When results are near or under such a threshold, the MHI is more sensitive than the WET. In particular, for the MHI evaluation, it was found that for the climates of Havana, Singapore and Dubai, the use of the average month day gives an error that is always below 5%, while the average error, both for average month days and for monthly averages, is under 3%. In all the said cases, the error overestimated results. For the Paris and Rome climates, during the winter months and the spring, when the MHI value is near 0.3, in order to avoid misleading results, it is

required a higher frequency in the weather dataset, and only hourly data can be used. It was also found that the WET, in general, requires more accurate data, and such a result is an expected one because it is based on the real behaviour of an AWG machine. In the climates of Havana and Singapore, if an average error of 5% is accepted, the two approximated datasets for the analysed case can be used (average month days and monthly averages). In particular, the average month day dataset gives negligible errors. In Dubai, only the average month days can be used with the same accepted average error. In all the said cases, the error overestimates WET results. In Rome, in order to avoid misleading results which underestimate the water extraction possibilities, hourly data are required for the evaluation of winter months and in November. In Paris, besides winter months, also March and April require such an accuracy degree to avoid misleading errors. In the other months, the month average days give an error consistently below 5%, while the monthly averages give a higher error. In general, it can be said that when the weather data fluctuate under and over the machine start and stop threshold, the hourly data must be used to avoid underestimating water extraction possibility.

Overall, it can be said that the WET and MHI evaluation for the analysed locations, characterised by climates Aw, Af, BWh, admits the use of the average month day, while for the climates Csa and Cfb evaluation the hourly data are often required. Further steps of the research will take into account the index GEI and will extend the analysis to other climates and other gaseous sources of water, in particular combustion fumes.

The current work represents a first step to understand when and where weather datasets, with a different accuracy degree, can be used and the possible error related to the different data approximations, considering water extraction from air. The study is also a first step for climate analyses related to the water extraction from fumes condensation coming from boilers.

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Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

a	dry air
avg	Average
AWG	Air to Water Generator
d	average monthly day
E	the energy required by the chosen AWG to produce the wanted effect [kJ]
m	monthly averages
mw	mass of condensed water [kg]
MHI	moisture harvesting index
i	Inlet
h	hourly averages
he	specific enthalpy [kJ/kg _a]
Qc	latent heat of condensation [kJ/kg _v]
SEC	Specific Energy Consumption [kWh/kg]

<i>r.h.</i>	relative humidity [%]
<i>t</i>	dry bulb temperature [°C]
<i>v</i>	Vapour
WET	water energy transformation
<i>x</i>	hygrometric degree, the vapour content in air, expressed as a mass ratio [kg _v /kg _a]
0	reference point

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