applied sciences

MDPI

Article

Air to Water Generator Integrated System Real Application: A Study Case in a Worker Village in United Arab Emirates

Lucia Cattani [1], Paolo Cattani [2] and Anna Magrini [3,*]

[1] Technical Office, Société de l'Eau Aérienne Suisse (SEAS SA), Via dell'Industria 13/A, 6826 Riva San Vitale, Switzerland
[2] Freelancer Engineer and Developer, Via Piermarini 4/L, 26900 Lodi, Italy
[3] Department of Civil Engineering and Architecture, University of Pavia, 27100 Pavia, Italy
* Correspondence: magrini@unipv.it

Abstract: The water crisis is currently affecting billions of people. To mitigate the issue, unconventional water sources should be taken into account. Among them, atmosphere is a promising possibility, but it is still considered a novel source, and more studies, based on real results concerning the behaviour of the Atmospheric/Air-to Water Generator (AWG) systems, also known as Atmospheric Water Harvesting (AWH) systems, are needed to prove the water extraction sustainability. The current research work describes the real application of an integrated AWG system, based on a thermodynamic reverse cycle, designed to extract water from air and take advantage of the other useful effects of the cycle at the same time. The integrated machine was placed in Dubai, in a worker village, and tested. The machine is able to provide, at the same time, with the same energy consumption, water, heating and cooling energy. On the basis of onsite measurements, calculations about the efficiencies, using the Water Energy Transformation (WET), plastic savings, due to bottled water avoidance, and economic sustainability were carried out. The work answers to research questions concerning the potentiality of integrated systems in Heating Ventilation Air Conditioning (HVAC) plants revamping, the economic sustainability of water extraction from air and the lack of tests on real AWG machines of thousand-litre production capability (large size).

Keywords: atmospheric water harvesting (AWH); air to water generation (AWG); water extraction efficiency; water extraction sustainability; water energy transformation (WET); energy saving; integrated systems

check for updates

Citation: Cattani, L.; Cattani, P.; Magrini, A. Air to Water Generator Integrated System Real Application: A Study Case in a Worker Village in United Arab Emirates. *Appl. Sci.* **2023**, *13*, 3094. https://doi.org/10.3390/app13053094

Academic Editors: Agostino Marcello Mangini and Michele Roccotelli

Received: 1 February 2023
Revised: 20 February 2023
Accepted: 23 February 2023
Published: 27 February 2023

Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Today, the water crisis affects billions people: two billion face high water stress, as reported by the United Nations' (UN) World Water Development report [1], while four billion suffer water scarcity for, at least, one month a year [2]. The UN quoted document depicts a situation that will rapidly worsen, as the yearly water demand, today evaluated at about 4400 billion cubic metres [3], is expected to increase, between 20 and 30%, by 2050. At the same time, climatic changes and water pollution are exacerbating the crisis, because:

- 1.8 billion people already use contaminated water [4];
- water-related disasters between 2001 and 2018 were estimated to be accountable for around 74% of natural disasters, expected to increase in the next few years [5].

To face the issue, strong requirements are represented by better hydric resource management, wastewater treatments, water recycle and reuse practices [6]. Additionally, new fresh water sources, achievable and sustainable, are needed [7].

In such a context, in the last decades, air has been rediscovered as a water source. In ref. [8], the possibilities to employ atmospheric water harvesting in order to enhance the water supply resilience were explored. One idea, from this perspective, is the recovery of condensate coming from air conditioning systems. In ref. [9], a review of the potentialities of such an approach was presented. Nevertheless, water quality plays a fundamental role. In particular, water coming from air conditioning systems can be affected by heavy metals and microbiological pollution [10]; thus, its legal employment normally is confined to uses not related to humans, as underlined, for example, in Dubai regulations [11]. Moreover, air conditioning systems are usually designed to minimise condensation, as the latent heat is perceived as an energy waste, because the condensate is normally treated as a polluted liquid to be disposed of. In this perspective can be ranked the use of desiccants on the inlet environmental air and the vapour disposal into the environment, by means of the hydrophilic substances regenerative air stream [12].

A more dedicated way to extract water from the air is represented by Atmospheric/Air to Water Generator (AWG) systems, also known as Atmospheric Water Harvesting (AWH) systems. The research in this field has been particularly active in the last few years, and various processes of water extraction have been explored. For example, in ref. [13], the available technologies were presented, and the research gaps were underlined, while the review presented in ref. [14] focused on the most promising techniques for water extraction in arid zones. The work described in ref. [15] collected the findings concerning systems that employ a passive approach. In the current work, a brief description of the state-of-the-art AWGs is reported in paragraph 2. It is worth noting that one of the main research questions concerns the need for more field tests about real machines of medium–large sizes (from hundreds to thousands L/day) that, up to today, are comparatively few, as underlined in ref. [13]. The same lack of tests—in particular, for Middle East regions—was also underlined in ref. [10]. As a matter of fact, it is possible to find some data coming from tests about little size systems capable of producing some litres per day up to a few hundreds. For example, in the review of [10], concerning the Middle East, the maximum water extraction test, performed by AWGs, gave a production of about 232 L/day. In ref. [16], a prototype able to produce up to 8 L/day in arid conditions was described. In ref. [17], there was a comparison of different models of machines able to provide less than 20 L/day. Studies based on desiccant materials or on thermoelectric coolers are normally sized to produce few litres per day; thus, tests carried out on prototypes of such kinds of machines describe productions that go from a few grams to a few kilograms of water per day, as it is reported in refs. [18,19]. Real production tests about larger sizes, capable of more than one thousand litres per day, are currently very few. As far as the authors' knowledge goes, the only examples about large-sized machines are:

- the case study described by authors in ref. [20], which provided a methodological approach refined and used in the current study;
- the experience reported in ref. [21], which used the same machine subject of the current work but only for water quality analyses purposes;
- the test performed in ref. [22], where it was tried to improve the water yield, increasing the vapour content in the air by means of adiabatic cooling.

Another lack of research concerns economic considerations about water coming from the air in order to determine its sustainability, taking into account AWG integrated machines, which are an AWG evolution, and also considering the possible plastic saving due to the onsite water production and distribution, as declared by [23]. Moreover, HVAC plant sustainable retrofitting analyses, with a particular attention to water coming from the air, are also needed [24]. The scope of the current paper is to contribute to the scientific knowledge providing new results focused on the said lack. The research questions to be answered concern:

- more data about large-sized integrated AWG real tests;
- HVAC retrofitting potentialities by means of integrated AWG;
- extended economic evaluations, taking into account the water quality and the particularity of the integration (HVAC contributions);
- considerations about plastic saving.

In order to answer to the research questions, this paper presents a test carried out on an integrated AWG machine placed in a worker village in Dubai. Starting from the results coming from such a test and data concerning the existing HVAC plants serving the village, the current research work studies:

- the machine behaviour during an entire year, tuning the physically based model used in ref. [20];
- revamping potentialities of the existing HVAC plant;
- economic analyses, carried out considering the integration advantages and the quality of the produced water;
- plastic savings potentialities.

To address the above topics, the research work is developed as follows: a brief description of the AWG machines technology, with a particular attention to integrated AWGs (Section 2), the applied methodology (Section 3), the case study (Section 4), the machine behaviour (Section 5), economic evaluations (Section 6) and, finally, considerations about plastic savings (Section 7) and results discussion (Section 8).

2. AWG Technologies

Water extraction from the air, up today, can be carried out principally by means of humidity condensation. Vapour contained in the breathable air is forced to change its state into liquid. Different techniques can be used in foggy climates, where fog nets permit water extraction from air directly collecting the fog aerosol by means of coalesce [25].

In the other cases, the humidity contained in air must be captured from the atmosphere and transformed toliquid by means of thermal and/or chemical–physical processes. Such an operation can be carried out by means of refrigeration of the air under its dew point. The condensate is then collected and treated in order to achieve the required quality. Vapour-harvesting processes can be classified into passive and active. The processes that do not need an artificial energy input are defined passive [8], and an example of such an approach is represented by the radiative cooling, such as that employed in the dew plant described in ref. [26], where panels with a particular emissivity and geometry are installed in the open air. The temperature gradient, caused by irradiation, between the environmental air and the panel surfaces, permits vapour condensation. The main advantage of such a process is that it does not require an artificial energy input. The disadvantages are that: it can be carried out only in particular climates, it strongly depends upon weather conditions and requires large spaces to collect meaningful water quantities, usually represented by a few litres a day for a squared metre [8]. In the active processes, there are comprised AWGs based on a thermodynamic reverse cycle. Those that employ a compressor represent the most diffused and scalable technology, as stated in ref. [13] and confirmed by consulting [27]. The working principle is the following. Environmental air is forced to flow into an evaporator coil, where a refrigerant at a low pressure and temperature is flowing as well. The heat is removed by the refrigerant, and the air is cooled under its dew point. Condensate is collected and the processed air is disposed into the environment. The refrigerant, compressed, passes through the condenser coil, where it exchanges heat with the external environment and returns, after the lamination valve, to the starting conditions of the cycle. The main advantages of such an approach are the comparative high yields (up to thousand L/day), the compactness (dimensions comparable to those of an air conditioner chiller) and the possibility to operate the machine in a wide temperature and relative humidity range (even when the dew point is low, with defrosting cycles). The main weak point is the energy consumption that increases when the dew point is under 4 °C [28].

The cooling effect can also be obtained using thermoelectric coolers [29], instead of the compressor. The main advantages of such an approach, in comparison to the compressor use, is the compactness of the devices, the absence of moving parts and the absence of any kind of refrigerant. The weak points are represented by a low efficiency thus, the energy consumption is higher than that related to compressor employment and by a difficult regulation and a low yield (few L/day) [30].

Another approach to water harvesting consists into increasing the vapour content in the air by means of materials able to adsorb, or absorb, part of the atmospheric humidity. Once such materials are saturated enough, they are forced to release the vapour into a controlled air volume or air flux, normally using a low temperature heat flux [31]. After that, the process continues with the air cooling that permits collecting liquid water. In the desiccant field, a very promising substance is a super moisture adsorbent gel [32], a material able to adsorb moisture and release a part of it, directly in the liquid phase, by means of low temperature heating. At any rate, this kind of material also requires a final air-cooling process in order to collect a meaningful part of water and to restore the material in its starting conditions. A promising approach consists of a mix between the desiccants oriented approach and the reverse cycle application, as the example described in ref. [33], where a thin layer of desiccant coats condenser coils. The condensation heat is used to extract humidity from the desiccant, while the absorption is performed on environmental air.

The sorption-based atmospheric water harvesting is currently mostly focused on the development of new materials, but paying less attention to the entire system that should embed them thus with no clear calculation of the real energy cost [34]. Actually, complete machines based on such an approach are comparatively few and at an early stage of development [35]. Moreover, desiccant based technology very often is not employed in complete passive devices, but it only tries to minimise the energy required to obtain the vapour condensation. Normally, water harvesting machines are equipped with fans that need the external energy input. The main advantage of the desiccant material approach is the possibility to harvest water in dry climates, as desiccants are able to capture water at low humidities (under 30%), avoiding defrosting cycles. Nevertheless, in this case, large spaces are also required if more than a few L/day are needed. It is worth noting that one of the tests most performing reports a yield of about 5 L/(day m^2) [10].

First rough attempts to make a comparison between a compressor-based solution and a desiccant based one, in water harvesting, were carried out in ref. [36]. However, in such a research, authors compared the behaviour of different types of dehumidifiers, instead of AWGs, as it was declared (and as it could be easily inferred by the quality of collected water). The results are not very meaningful for the AWG topic, as dehumidifier are not at all AWG machines, not from the point of view of employed materials, nor from that of the thermodynamic cycle set points design and control, and nor from the point of view of the quality of water, as underlined in ref. [37].

At any rate, when a considerable water harvesting is needed (exceeding few L/day), active technologies are required; thus, AWGs are affected by energy consumption that is related not only to the vapour condensation but also to the need to move the air inside the harvesting device, as said in ref. [37]. This last voice is very difficult to be avoided even if the condensation can be obtained by means of free cooling or other mechanisms, such as those employing new desiccant materials as that described in ref. [32]. When water production achieves the order of thousand litres a day, the energy consumption related to air moving can be very significant: several kWh a day [37]. Actually, the energy issue is one of the main concerns of the AWG technology. In particular, the energy consumption related to reverse cycle-based AWGs was estimated to be responsible for 50% of the entire cost of commercial water from air production [21]. One of the means to bypass such an energy issue is represented by AWG integrated machines, as said in ref. [23]. As described in ref. [38], an AWG integrated machine is a system able to extract water from air, by means of a compression reverse cycle, and, at the same time, to provide valuable side effects, coming from the water extraction process. The integrated machine can provide, with the same energy input (*en*), three useful effects:

- a certain quantity of condensed water;
- a cooled and dried airflow that can be directly employed as primary air or convoyed into an Air Handling Unit (AHU) of an air conditioning system;
- a flux of heating energy, which can be used to heat up, for example, domestic water.

A scheme of the process is reported in Figure 1, where it is possible to observe that the process is obtained applying a reverse cycle to the refrigerant and processing environmental air. In traditional AWGs, the colder and dryer air flux is discharged into the environment, as well as the heat flux, while, in AWG integrated machines, the system design permits employing them inside HVAC plants.

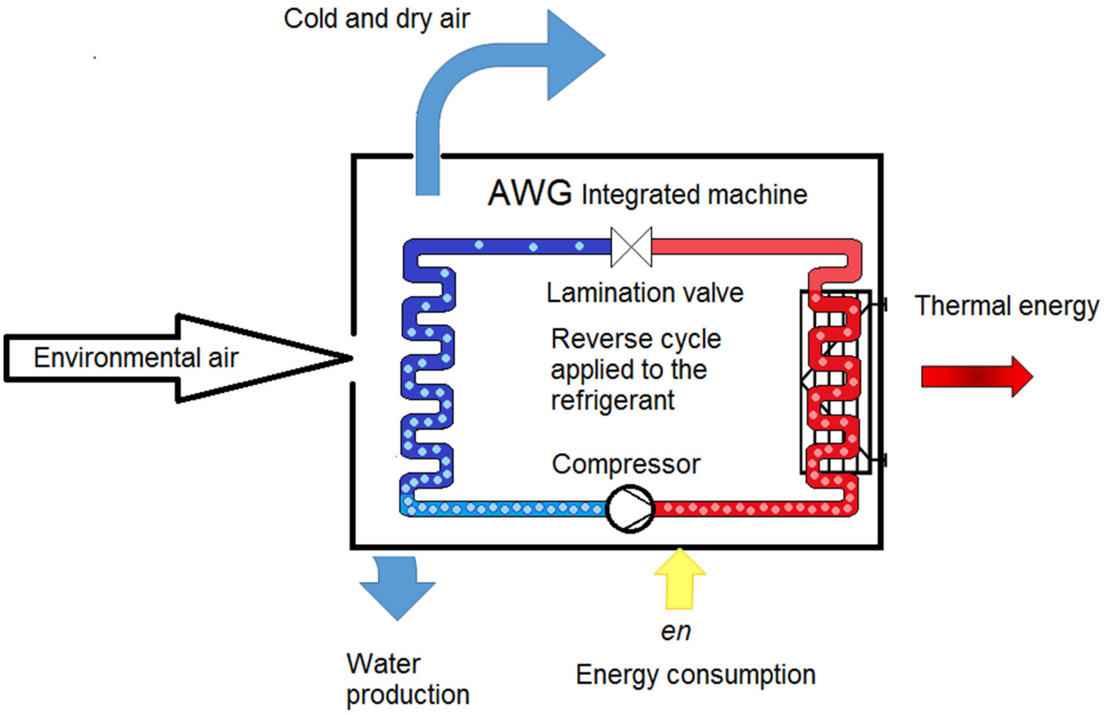

Figure 1. AWG integrated machine scheme.

A first example of integrated approach involving water from air production was described in ref. [28], where a comparison between a traditional air conditioning system and an integrated one, able to extract water from air, as well as to perform the same cooling of the traditional one, was carried out. In such a study, the integrated machine, with almost the same energy consumption, was able to provide a considerable ratio of the needed drinking water and to guarantee the desired inside temperature and humidity conditions.

Another example of water production during air conditioning was analysed in ref. [39], where a theoretical study of possible water recovery in a conditioned greenhouse was described. The study described in ref. [40] proposed a theoretical study about an integrated system able to collect water and to provide the flux of the treated air (colder and drier in comparison to the external air) to control the microclimate of an outside area; nevertheless, it is not clear where the heat flux is disposed.

The case study described by the authors in ref. [20] was the first and, up today, unique example of a real AWG integrated machine purposely designed to maximise the water production and, at the same time, to permit to use the other two useful effects of the reverse cycle. In that research, the integrated machine, whose configuration was similar to that of the machine used for the current paper, was installed on the roof of a hotel in Villahermosa, Mexico. The produced water was enough to cover drinking water needs, while the heat flux was enough to cover the domestic water heating. Savings due to the installed machine were calculated at about 80 thousand dollars/year. In such a test, the flux of dry and cold air was not used to help the existing air conditioning system but was delivered to the laundry, not served by the air conditioning system in order to mitigate the inside working conditions.

In the current study, another test was carried out on another integrated machine in a different climate and context. In this case, the study is oriented not only to provide further data about large size AWG machines but also to enhance the knowledge of the integrated approach potentialities, answering the lack of knowledge stated in the introduction.

3. Methodology

The study was carried out by adapting the methodological approach proposed in ref. [20]. In such a work, the method was intended to be a prevision process in order to decide, from a theoretical point of view, whether an installation of an integrated machine can be effective. In the current case, the method is applied on results coming from a real test in a worker village in Dubai, and it is used to define a revamping package suitable for a portion of such a worker village. To the initial procedure formulation, presented in ref. [20], some more steps are added in order to refine the approach from a sustainability point of view, such as the weather data frequency analysis, the economic indicators calculation and the possible plastic saving. The complete analysis flow is described below.

- Data collection: the case study section reports information about the test site and the characteristics of the possible buildings to be served by the integrated machine. Moreover, needs about drinking water, primary air and thermal heating for domestic water were described too. Data concerning the existing plants were also collected, as well as costs about drinking water and energy sources.
- Weather environmental conditions: statistical hourly data about temperature and relative humidity from a weather station placed in Dubai, at only 5 km from the installation spot, were collected in order to have the climatic conditions of an entire statistical year. A brief analysis of the weather data frequency was also added.
- Integrated system behaviour analyses: the behaviour of the machine, installed nearby the kitchens building, was monitored by the data collection in some time periods. On the basis of such data, the simulator, used in ref. [20], was fine-tuned and run using the Dubai climate conditions, collected by means of the said weather station in order to determine how the machine was expected to behave all over the year in terms of produced water, energy consumption, heating power/energy and cooling power/energy. In order to evaluate the energy efficiency of the machine, in terms of produced water and consumed energy, the Water Energy Transformation (WET) indicator was employed [37].
- Covered needs: matching the integrated machine behaviour in the Dubai weather and the needs (drinking water, primary air and domestic water heating), it was calculated how many buildings it was possible to serve.
- Economic evaluations: all the voices, positive and negative, related to the machine installation and its use, were collected and the Pay Back Time (PBT) calculated. Moreover, the Net Present Value and the actualised Pay Back Time were calculated, because the installation can be seen as a sort of investment.
- plastic savings: on the basis of the literature data, savings in terms of avoided plastic bottles were calculated.

4. Case Study

4.1. Geographical Site, Buildings, Existing Plants and Energy and Water Supply

In December 2017, an integrated AWG machine was tested in a worker village in the industrial side of Dubai. In Figure 2, the installation site is shown. The worker village is placed at about 15 km from the shore and 5 km from the weather station of the Al Makatoum International Airport.

The worker village is composed by tens of residential buildings, each of them housing 200 guests. There are various common kitchen buildings, where meals are prepared and served in turns. Kitchens are equipped by an air conditioning system, composed by fans, moving external air inside an air duct, air vents and splits. The fans work continuously during the year, providing about 12 m^3/h of fresh air, while the splits were estimated to work continuously only from April to October, with an average EER of 3.5, providing the air cooling and dehumidification. It was estimated that cooling starts working when the outside temperature is over 20 °C, because, due to internal loads, in such a case, air changes by themselves are not enough to give internal comfort.

Figure 2. Integrated machine installation site.

The tap water comes from the desalinisation system. Such a water is employed for domestic uses, such as showers, toilets and general washing, not for human consumption. It was estimated that each building, housing 200 guests, working in turns, needed to heat 18,000 L/day of tap water, from 10 °C to 50 °C. The installed heating plant is represented by 24 electrical boilers of 2 kW of power each, with an efficiency of 95% and about 18 h of daily work. Drinking water is provided to guests by means of bottled water. To each guest, 2 L/day of drinking water are supplied by means of half-litre bottles (four bottles/day).

The kitchen building is equipped by an LPG boiler of 125 kW, with a calculated efficiency of 70%, connected to a hot water tank of about 3 m^3. The daily provided hot water is between 20,000 and 22,000 L/day, and the required temperature is 50 °C. The cold water, for domestic uses, comes from the municipality, which delivers desalinated water by means of the aqueduct.

The test was carried out in a worker village, because such a kind of settlements are diffused in United Arab Emirates (UAE). Actually, Ministerial Resolution 44 of 2022 establishes that, whenever 50 or more workers, with earnings under 1500 AED/month, are employed, they must be accommodated in proper settlements that should answer to precise standards regulated by the law. In particular, besides proper room sizes, it is specified that the accommodations must be provided with drinking water, common kitchens, air conditioning and hot and cold domestic water [41]. Due to the technology peculiarities, described in Section 2, the integrated AWG machines employment can be particularly effective whenever more than one useful effect of the reverse cycle is required at the same time. In the case of the worker villages, all the potentialities of an integrated AWG machine can be required, because, following the Ministerial Resolution 44 of 2022 rules, there are needs of drinking water, cold and dry air and heating energy for domestic water, all at the same time. Thus, worker villages are a good benchmark for integrated AWG installation.

4.2. Bottled Water Cost

Taking into account data coming from [42], the average cost for a litre of water in United Arab Emirates is about EUR 0.37; that means, considering a currency conversion of 0.236 EUR/AED, which corresponds to the average value in the last 5 years [43], about 1.56 AED (Arab Emirates Dirham). In order to obtain safe results, for the current study, a beginning cost of 1 AED/L was considered, in compliance with the values applied in ref. [21]. A further reduction of 30% was applied in order to consider possible discounts applied to large stock orders; thus, the final considered bottled water cost is equal to 0.7 AED/L, that means 0.165 EUR/L.

4.3. Electricity Cost

On the basis of the worker village bills, electricity cost in 2017–2018 was equal to 0.44 AED/kWh, that means 0.10384 EUR/kWh. Such a price is in compliance with the official calculator results [44] that can be obtained taking into account a global consumption of about 4800 MWh/year, imputable to the only domestic water heating of the whole village.

4.4. LPG Cost

The worker village fee for LPG provision, in 2017–2018, was evaluated equal to 1.9 AED/L, taxes and transport included. In 2022, the costs are almost the same [45] for small provisions. In the current study, the above value of 1.9 AED/L, equal to 0.4484 EUR/L, was adopted.

4.5. Weather Conditions

In the following Table 1, there are the average temperature, t, and relative humidity (R.H.) data coming from the weather station of Al Makatoum International Airport. Averages are calculated on the basis of hourly samples collected in the last five years.

Table 1. Dubai climate, expressed in monthly averages.

Average	January	February	March	April	May	June	July	August	September	October	November	December
t (°C)	20.6	21.7	24.4	28.5	32.8	34.2	37.0	36.8	34.4	31.2	26.5	22.3
R. H. (%)	59.7	56.5	53.2	46.6	39.5	48.8	44.6	44.6	51.5	54.4	53.7	57.4

The Dubai climate is classified as BWh, tropical and subtropical desert, following the Koppen–Geiger classification [46]. The climate presents a colder period, from December to February, and a mild month, March. The rest of the year is almost hot. In the current research, weather data were used in order to extend the integrated AWG test results to the entire year. As discussed in ref. [47], for such a kind of climate, which is similar to that of Abu Dhabi, it is acceptable to consider the monthly average day (24 values of temperature and relative humidity for each month of the year, representing the average day of each month) to evaluate the AWG energy behavior. Nevertheless, an hourly frequency leads to more accurate results. In the current research, the analyses were carried out using both the frequencies; in particular, hourly data were used in order to determine the machine behavior and monthly average day data for the overall analyses.

5. Integrated Machine: Description, Plant Linking and Behaviour Analyses

5.1. Integrated Machine Description

The machine is the same used in the test described in ref. [21]. That research analysed data coming from a test carried out between 2018 and 2019. In such a period, the machine was moved from the worker village of Dubai to a desert area of United Emirates, and it was used only to produce water to be bottled. The said research goal was focused on the water quality and water from air bottling economic effectiveness in comparison to traditional bottled water. The results are very interesting as they report that the produced water quality is comparable to that of the main bottle labels sold in the UAE. Thus, such a water quality is also assumed in this study.

The current research is based on the data coming from the test outputs of December 2017. In that period, as said before, the integrated machine was placed in the industrial side of Dubai in a worker village. It is worth mentioning that, for water extraction from air, the worst period in Dubai is from December to March, as it was underlined also in in ref. [47]. The machine was connected to the existing heating and cooling plants of the village kitchens in order to test the integration potentialities, intended to enhance the energy efficiency of the existing plants while producing high-quality water.

The machine used in the worker village has the same features of that used for the test in Mexico [20]. The system is based on a thermodynamic reverse cycle, where the circulating coolant is R134a. The major items of the machine are described below:

- Air filters placed in the inlet section. The air coming from the environment is cleaned by means of a filtration stage composed by two filter arrays in series: the first composed by coarse filters followed by pocket filters in order to avoid pollution due to dust, sand, insects, bacteria and other particles.
- Evaporation and heat recovery coils. The cooling process is carried out by means of direct cooling on an evaporation coil combined with a heat recovery system. Both of them are made of food contact materials [48]. The airflow, after the cooling process, can be collected in a duct in order to be delivered to zones requiring cooled and dry air changes.
- Evaporation fans. The machine has centrifugal evaporation fans that can provide an average airflow, in Dubai conditions, of 10,000 m^3/h.
- Screw Compressor. The compressor running the thermodynamic reverse cycle is a screw compressor having, in Dubai environmental conditions, an average cooling and heating capacity, respectively, of 81 kW and 105 kW. The coolant is R134a.
- Condensation coils. The machine is equipped by two kinds of condenser: a finned air-cooled coil and a plate heat exchanger. The condensation heat is delivered to the domestic water by means of this second condenser, where the water flow is run by a pump, regulated by the setting temperature. When heating is not required, the condensation is provided by the fined coil, cooled by the environmental air. The plate heat exchanger works with a classic temperature difference of 5 °C. The domestic water heating was set to obtain a temperature difference of 40 °C and a maximum temperature of 50 °C.
- Water treatment unit. The condensate coming from the evaporator is collected in a tank in stainless steel. After that, the liquid is processed in a multistage system comprising mechanical filtration made by three stages with decreasing meshes, the last one having a mesh of 1 µm, activated carbon filter, adsorption resins, UV (ultraviolet) lamps, reverse osmosis and a mineralisation stage. The system is continuously monitored by means of a pH probe and a conductivity probe and a water meter dedicated to count the produced water.

Besides the probes required by the reverse cycle, the machine is equipped by temperature, relative humidity and pressure probes. In particular, the environmental air, as well as the airflow exiting the water extraction process, is continuously monitored by the temperature and relative probes. A Programmable Logic Controller (PLC) controls the machine working process and collects all the relevant data.

5.2. Integrated Machine Plant Linking

The integrated machine was linked to the air ducts of the kitchen building and to the drinking water tank housed in the courtyard of the same building and normally used for drinking purposes. The water was then delivered to a dispenser point. The system, for this test, was also connected to the domestic water heating plant of the kitchens. A scheme of the configuration is reported in Figure 3.

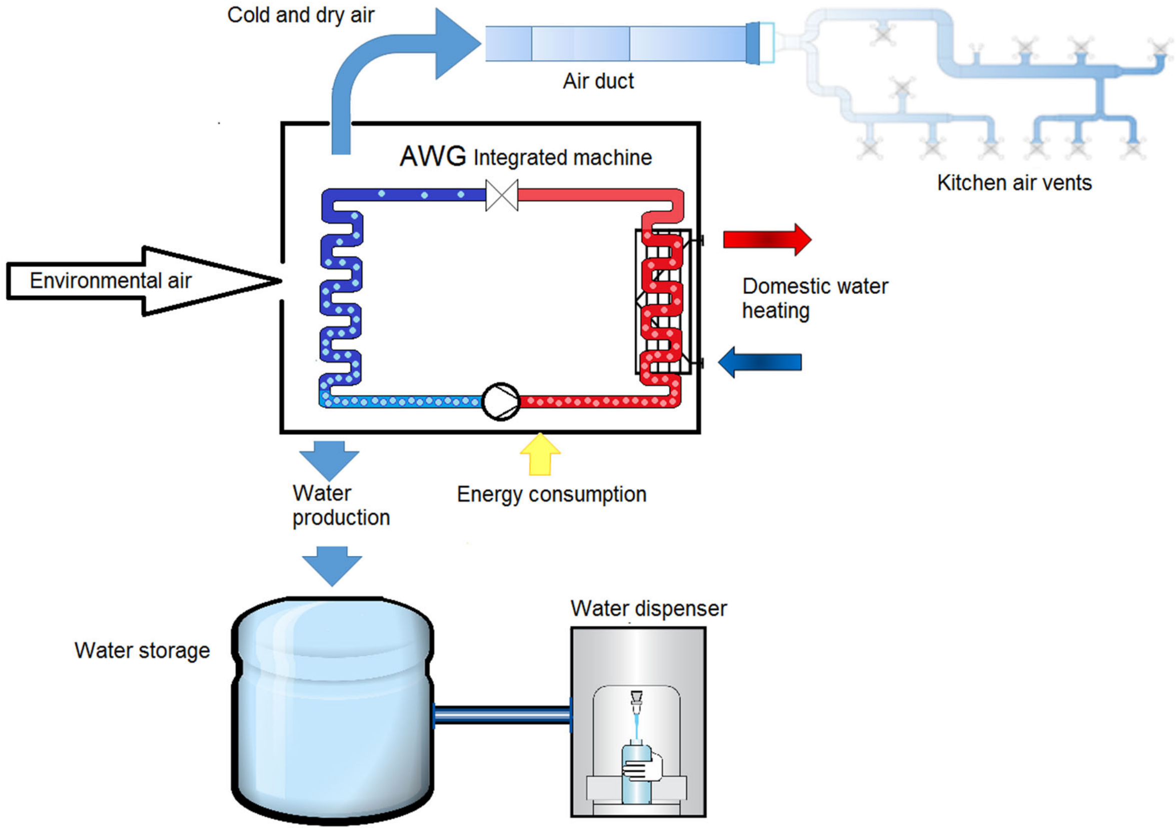

Figure 3. AWG integrated machine useful effects employment scheme.

As described before, the integrated machine houses a plate heat exchanger for domestic water heating, working on a classical temperature difference of 5 °C. In Figure 4, it is possible to recognise the green pipes connecting such a heat exchanger to the inside domestic hot water tank, visible in Figure 5.

The hot water tank was linked to the existing LPG boiler too, as can be seen in Figure 5. Such a boiler has a declared power of 125 kW. The efficiency (η) was calculated equal to 0.7 on the basis of the collected data.

During tests, part of the condensation heat was used for the domestic water. Due to such an operation, it was recorded a daily saving of about 216/day litres of LPG fuel. The saved heating energy, en_t, can be calculated using Equation (1), taking into account an LPG Inferior Calorific Power (ICP) of 6.67 kWh/L, called Cp, the said LPG saving, expressed as a volume, v, of 216 L/day and the said boiler efficiency:

$$en_t = \frac{Cp \cdot v}{\eta} \tag{1}$$

The calculation gives en_t = 1008.5 kWh.

The domestic water, coming from the water system of the worker village, was directly used inside the plate heat exchanger of the machine. A global efficiency of 0.95 was estimated in the heating operation. The machine, in such a period of the year, had a residual average heating capacity of 1472 kWh per day, considering said efficiency.

During the test, the fresh air was provided by the integrated machine. The kitchen fans were turned off, and the splits did not work, because the energy, given by the machine evaporation fans, was enough to win the resistance of the air duct and vents, and the overall air conditions were judged comfortable. Cooling and heating energy calculations, in detail, are reported in the next subparagraph.

Figure 4. AWG integrated machine installation.

5.3. Integrated Machine Behaviour and Needs Coverage

The behaviour of the machine was estimated using the test results data of December 2017 (10 days of test). Data were collected by means of onboard probes, whose readings were monitored by onsite personnel and also collected by the onboard PLC. The display of the machine gave various pieces of information, such as outside temperature and relative humidity, water production and energy consumption and domestic water heating. Water production was also recorded manually by the onsite personnel by means of a water counter.

In Table 2, probe types and their related uncertainties are reported.

Table 2. Main probes characteristics.

Physic Variable	Probe Type	Probe Error (in the Test Conditions)
Relative Humidity	Capacity hygrometer HTCT 01	±(1.3 + 0.003 measured r.h. value)%
Temperature	Resistance thermometer Pt100	±0.2 °C
Water flow	Oscillating piston water counter	±2% of the read value
Water weight	Electronic Pressure scale	±0.01 kg
Air Flow	Vane Anemometer	±1% of the read value or ±2% 0.02 m/s
Energy	Integrated Power meter	1% ± 2 words

Figure 5. Hot water tank and LPG boiler. In the image, green pipes, connecting the integrated machine to the hot water tank, can be seen.

The sampling frequency was 30 min; thus, the collected data for each testing day were 48. In Table 3, the most relevant experimental data, cumulated (water production and energy consumption) or averaged (temperature and relative humidity) for each day of the test, are reported.

Table 3. Experimental data.

Day of Test	Temperature	Relative Humidity	Water Production	Energy Consumption
	(°C)	(%)	L/Day	kWh/Day
1	19.6	63.2	1229	772
2	20.6	61.7	1215	793
3	21.4	59.8	1335	813
4	21.7	60.4	1392	848

Table 3. *Cont.*

Day of Test	Temperature	Relative Humidity	Water Production	Energy Consumption
	(°C)	(%)	L/Day	kWh/Day
5	21.7	62.6	1423	827
6	20.1	74.6	1777	846
7	21	73.2	1775	864
8	20.7	53.6	1544	847
9	19.8	64.2	1022	795
10	19.6	63.2	1253	826

During each day, the environmental air temperature and relative humidities varied. In the following graphs of Figure 6, there is an example of the weather behaviour (day 5).

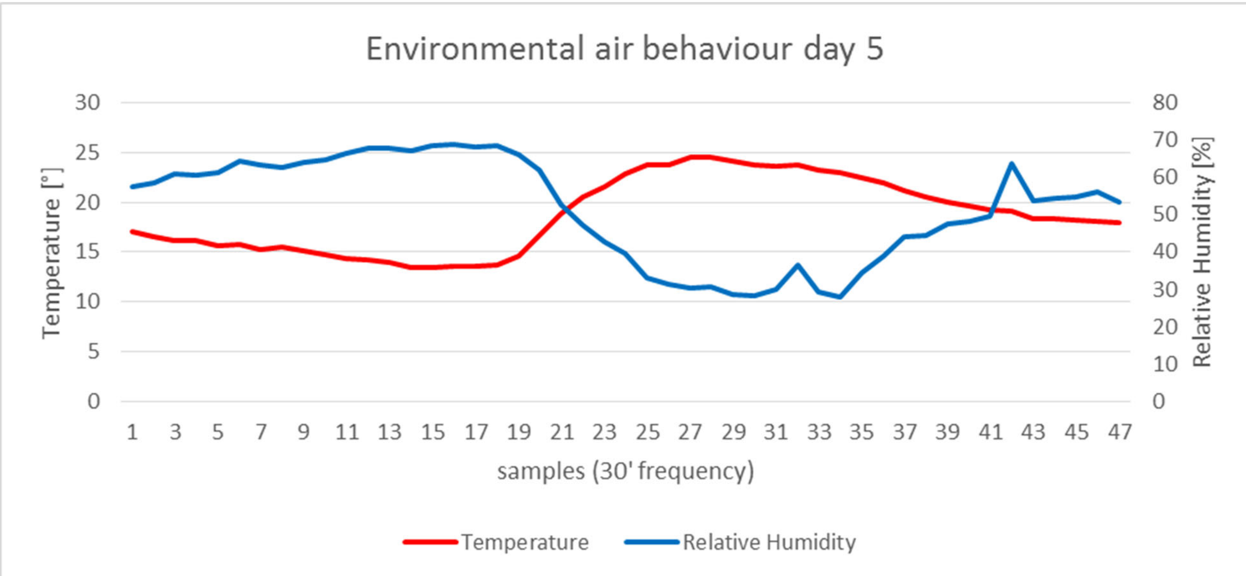

Figure 6. Environmental air temperature and relative humidity. Samples were collected with a frequency of 30 min (30′).

The collected data were used to tune and test the calculation model, which is physically based (the main characteristics are briefly reported in Appendix A). Such a model, described and used also in ref. [20] with good results, is a modular, real-time reverse thermodynamic cycle simulator, based on the principles of mass and energy conservation. The required input data are given by the environmental air conditions, expressed by means of the total pressure, the dry bulb temperature and the relative humidity. The simulation tool main outputs are water production and energy consumption. Using the weather data, collected during the test, and the production and consumption data, it was possible to tune and test the simulator behaviour.

Figure 7 reports a comparison between the real data and the calculated ones concerning water production. The average error is below 3%; thus, the simulated data were considered acceptable.

It is worth remembering that, on the basis of energy consumption data, it is possible to determine the WET indicator, which is one of the metrics used to measure the efficiency of an AWG machine. The indicator has the same structure of the Coefficient of Performance (COP) and of the Energy Efficiency Ratio (EER) and can be expressed as follows [37]:

$$\mathrm{WET} = \frac{Qc \cdot m}{en} \tag{2}$$

WET is defined as the ratio between the condensation energy and the whole energy input en (kJ) required to obtain it. The condensation energy is given by the product between Qc (kJ), the latent heat of condensation per mass unit, on average equal to 2460 kJ/kg, and the water mass unit m (kg). The water treatment unit of the machine has an average daily consumption of about 24 kWh. Such an amount was deducted from the whole energy consumption in order to calculate the WET indicator, as underlined in ref. [37].

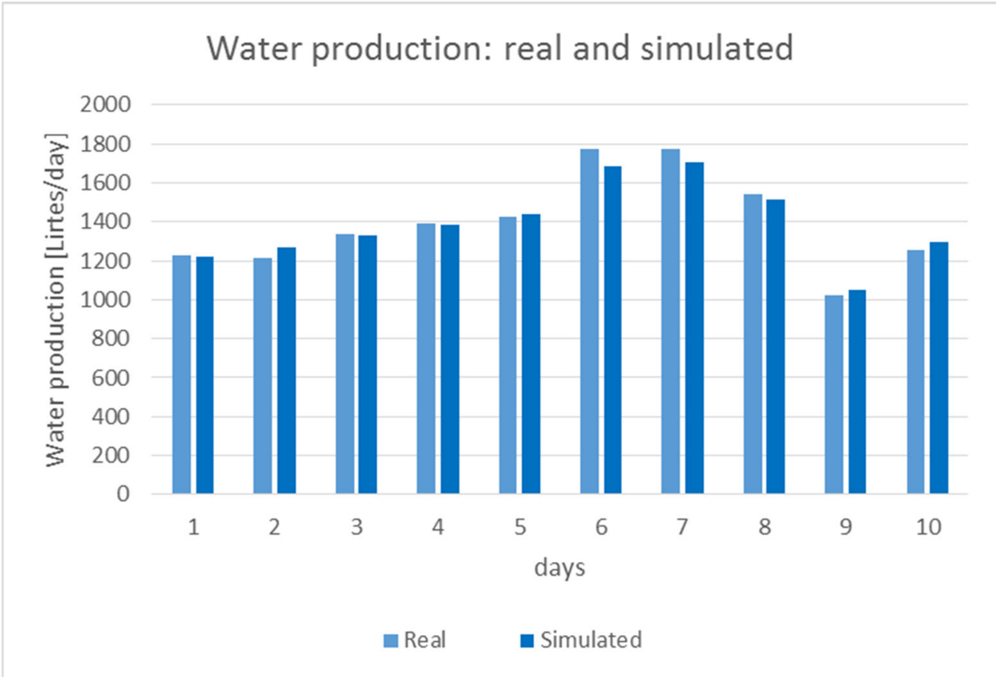

Figure 7. Daily water production: comparison between real and simulated data.

In Figure 8, the comparison between the WET results coming from, respectively, real and simulated data of energy consumption can be seen. The average error, in this case also, is below 3%; thus, the simulated data, about energy consumption, were considered acceptable.

Once fine-tuned and tested the simulation tool, it was possible to use it to determine the behaviour of the machine for an entire year with the hourly weather data coming from the weather station of Al Makatoum International Airport. Hour by hour, the simulation tool gave the water production, the energy consumption. As side outputs, the simulator gave the treated airflow, in terms of quantity, temperature and relative humidity after the treatment, and the heating energy available at the plate condenser.

A first application of the calculation model was carried out, forcing the plate condenser to provide domestic water heating at 40 °C. In this case, the machine average production of water was near to 1650 L/day. A second calculation was carried out, raising the water temperature to 50 °C. In this case, the average daily water production was 1585 L/day. Taking into account this second temperature setting, the average daily production, calculated on the basis of hourly data, month by month, is reported in the graph of Figure 9.

Taking into account the drinking water provision, given to each host, the produced water is enough to cover, on average, the needs of 792 persons. The total amount of produced water, considering the entire year and 120 h of machine stop, due to maintenance is equal to 825,543.5 L.

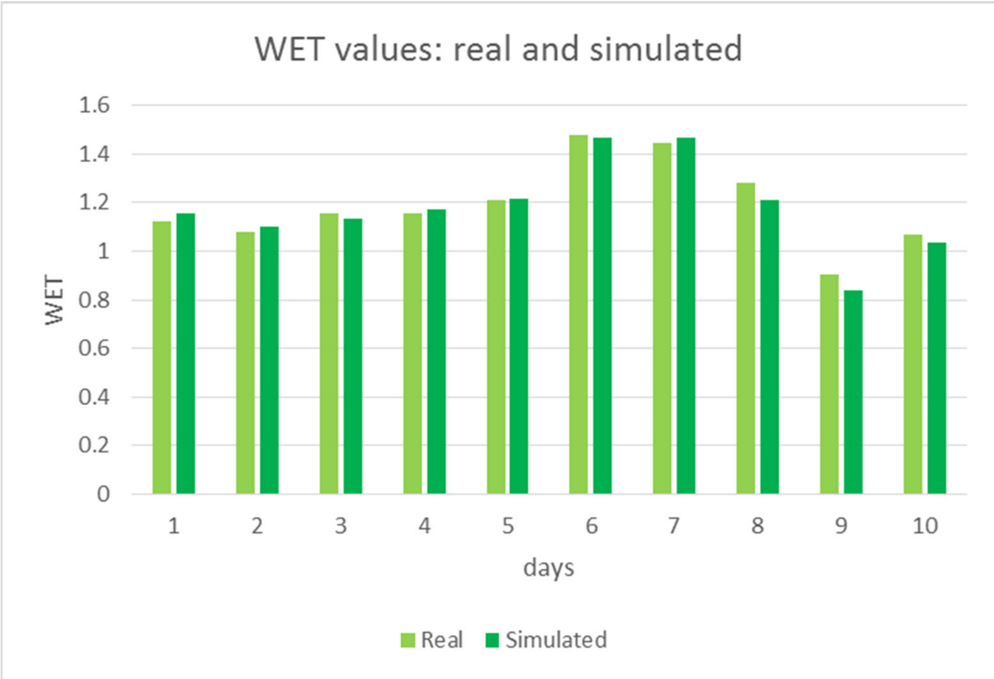

Figure 8. WET indicator: comparison between values coming, respectively, from real and simulated data.

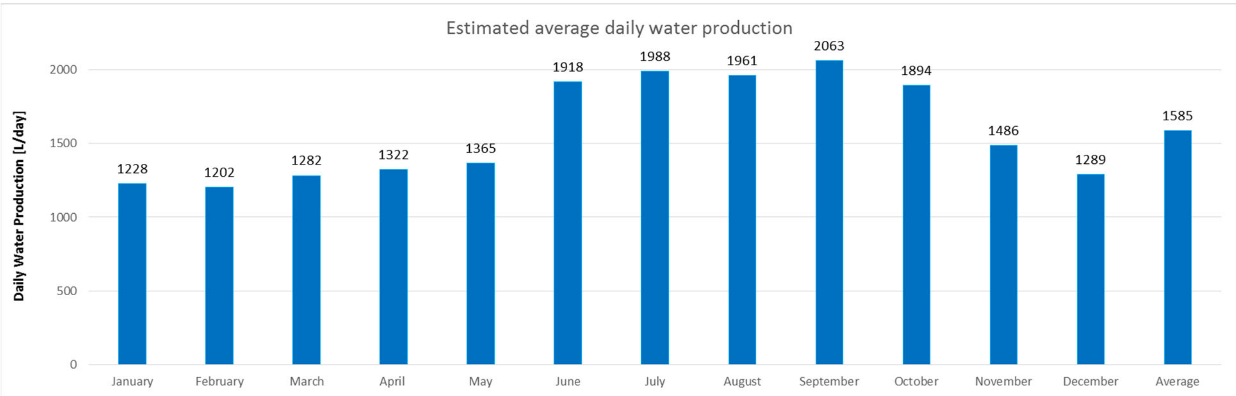

Figure 9. Average daily water production expressed in L/day.

The thermal heating energy, daily available for domestic water heating, is reported in Figure 10.

Considering the stop hours mentioned above, the heating energy available yearly is equal to 903,623.8 kWh.

Taking into account a direct heating into the plate exchange of the domestic water, as performed during the test, it was possible to determine the average daily water mass to be heated considering the following equation:

$$m = \frac{en_t}{C \cdot \Delta t} \tag{3}$$

where en_t, here expressed in kJ, is the heating energy coming from the coolant condensation, C is the water specific heat, equal to 4.186 kJ/(kgK), and the difference of temperature, Δt, is supposed to be equal to 40 °C, considering a set point temperature of 50 °C.

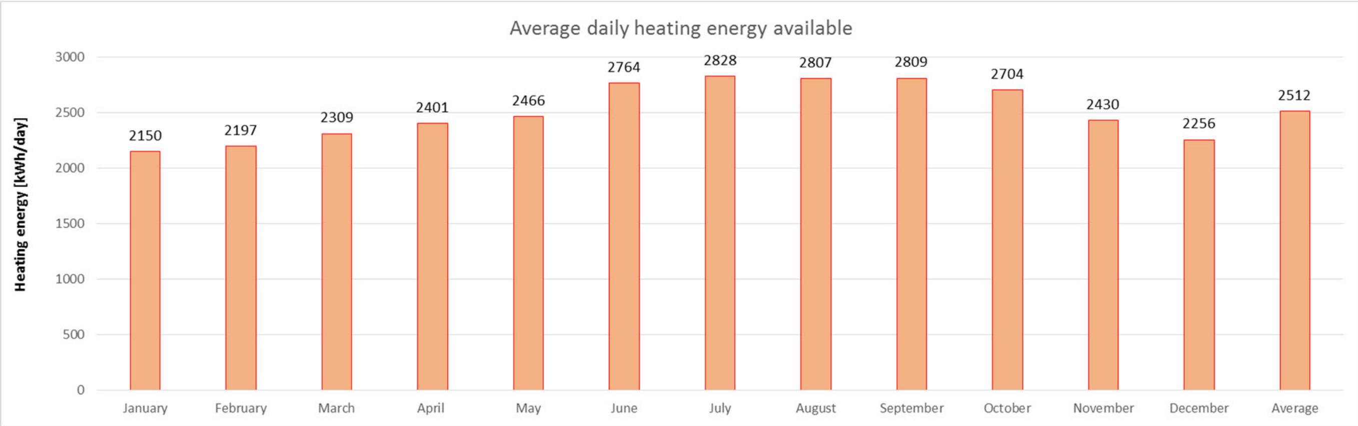

Figure 10. Average heating energy daily available at the plate condenser, expressed in kWh/day.

Applying Equation (3) and assuming a thermal losses coefficient equal to 5%, it was possible to obtain the domestic water amount that can be heated daily, for each month, Figure 11, corresponding to a delivered thermal heating energy equal to 858,442.6 kWh/year.

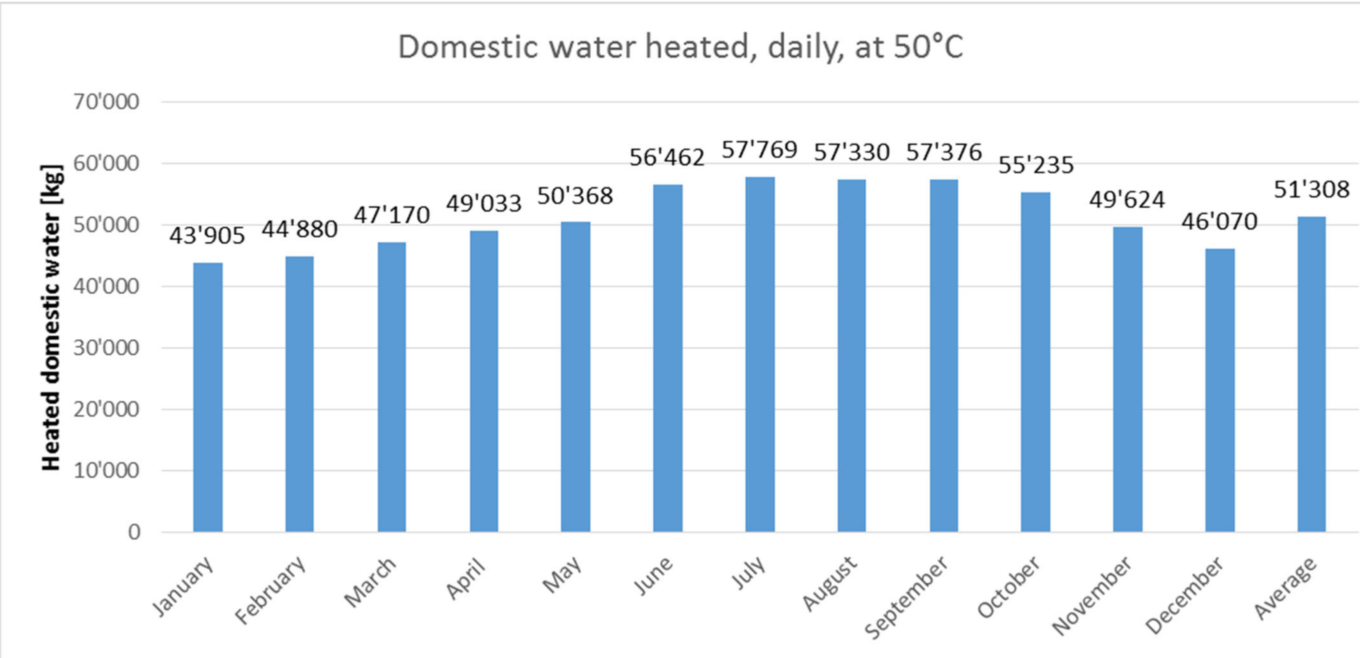

Figure 11. Domestic water mass that can be, on average, heated, daily, at 50 °C.

From these results, it is possible to infer that one integrated AWG machine can totally cover the domestic water heating required by two buildings (36,000 L/day, remembering thatwater density at atmospheric pressure is 1 kg/L) and, partially, cover the demand of the kitchens, which is, on average, 21,000 L/day. The monthly coverage percentage is indicated in the graph of Figure 12.

Thus, the integrated AWG machine can provide a saving of electrical energy en_{el}, related to the building boilers avoided activity, that can be calculated with:

$$en_{el} = \frac{en_t}{\eta} \tag{4}$$

where η is the boiler efficiency, equal to 95%, and $en_{t,}$ the daily heating energy, which can be calculated using Equation (3) with 36,000 kg as the water mass. Considering a conversion factor of 3600 from kJ to kWh, the daily electrical energy saving is equal to 1762.5 kWh, as reported below:

$$en_{el} = \frac{4.186 \frac{\text{kJ}}{\text{kgK}} \cdot 40 \text{ K} \cdot 36,000\text{kg}}{0.95 \cdot 3600 \text{ kJ/kWh}} = 1762.5 \text{ kWh}$$

The yearly savings, considering 120 h/year of machine stop due to maintenance operations, are equal to 634,509.5 kWh.

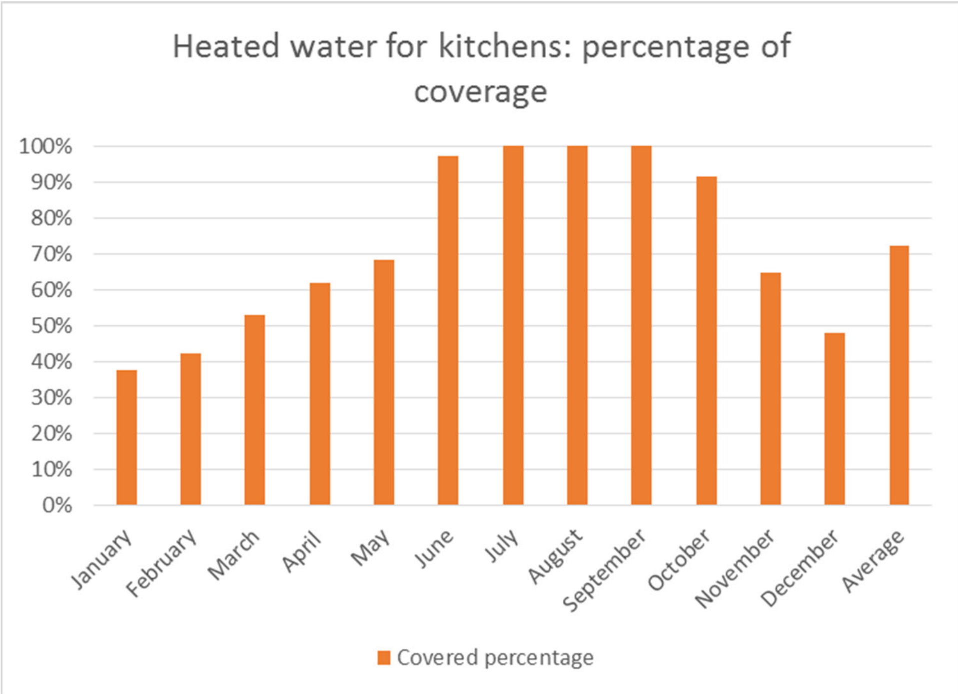

Figure 12. Heated water, required by kitchens, coverage percentage.

As already said before, the air, dried and cooled, coming from the water extraction cycle, was connected to the system of kitchen cooling as a thermal contribution to the fresh air, namely 12 m^3/h. In Figure 13, it is possible to observe the differences between the average conditions of the external air and the airflow coming from the integrated machine after treatment.

It is worth remembering that it was estimated that the cooling system starts working when the outside temperature exceeds the 20 °C threshold because of the internal loads.

The treated airflow varies between 11,680 (in January) and 9200 (in September) m^3/h, corresponding, respectively, to 3.85 and 2.9 kg/s, depending upon the environmental conditions. The treated air coming from the machine can cover, on average, 87% of the required fresh air. The comparison, given as monthly averages, between the required fresh airflow and the available treated airflow coming from the machine, is reported in Figure 14.

It is worth remembering that, during the test, all the air coming from the machine was delivered to kitchens, and auxiliary fans, used to provide fresh air from the environment, as well as the splits, were turned off.

In order to provide the energy saving calculations related to cooling, it was considered that the fresh air coming from the integrated machine will be used only when fresh air is also cooled by the splits, which happens when the outside temperature is above 20 °C. To evaluate the contribution of the integrated machine, the enthalpy difference between the outside and the treated air conditions was calculated using the t and R.H. data of the average monthly day. Taking into account the mass flow of the treated air, it was possible to obtain the cooling energy. Figure 15 represents, month by month, the cooling contribution, in terms of the cooling energy and electrical energy, to the air conditioning system provided by the integrated machine.

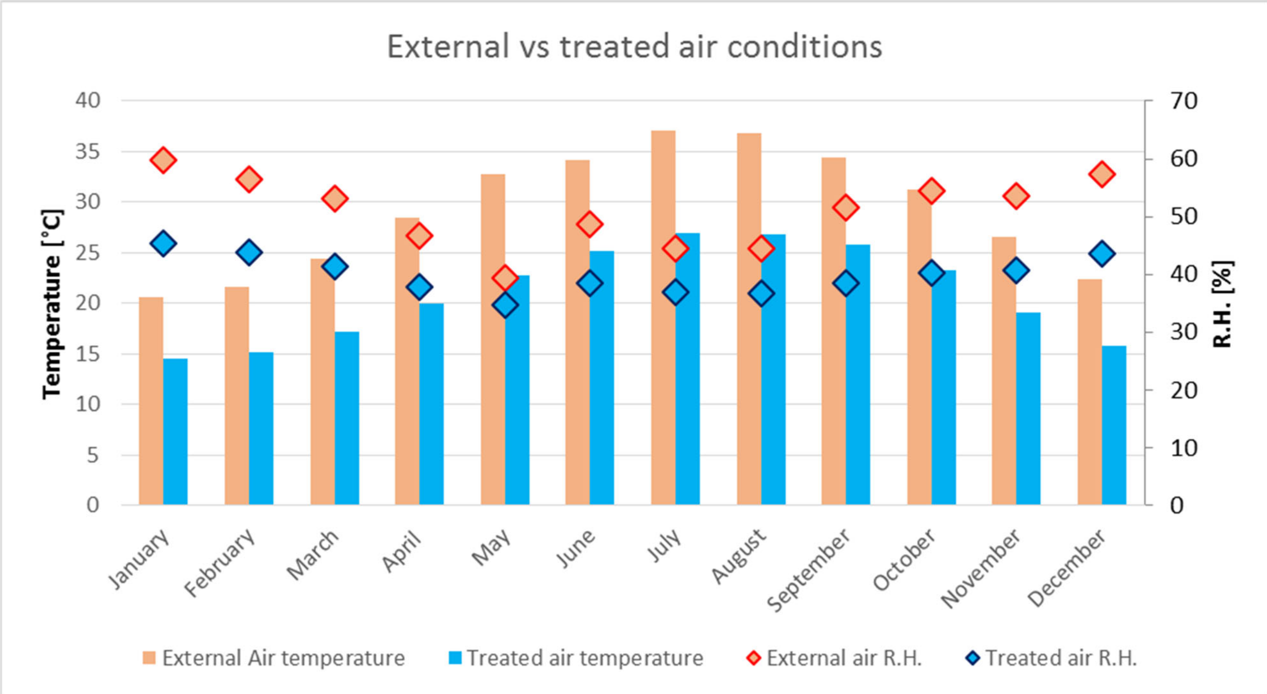

Figure 13. Treated air characteristics in comparison to external air.

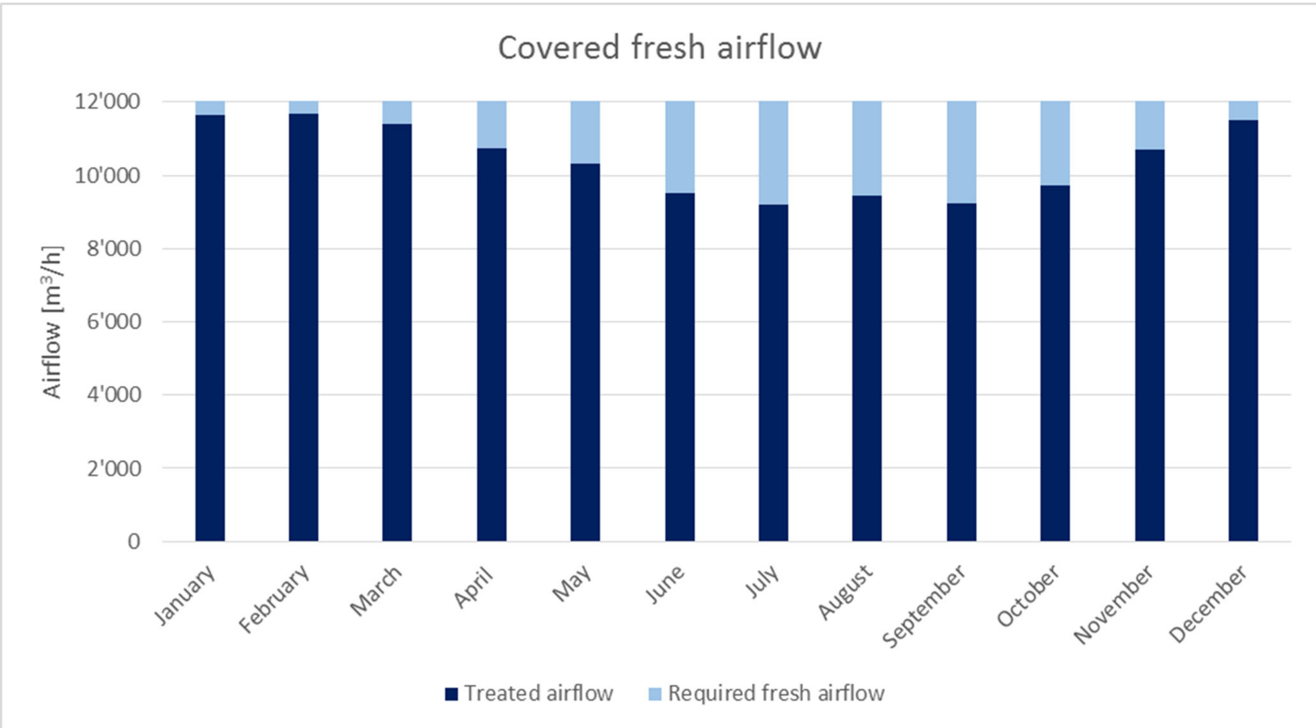

Figure 14. Comparison between the treated airflow, available and required fresh airflow.

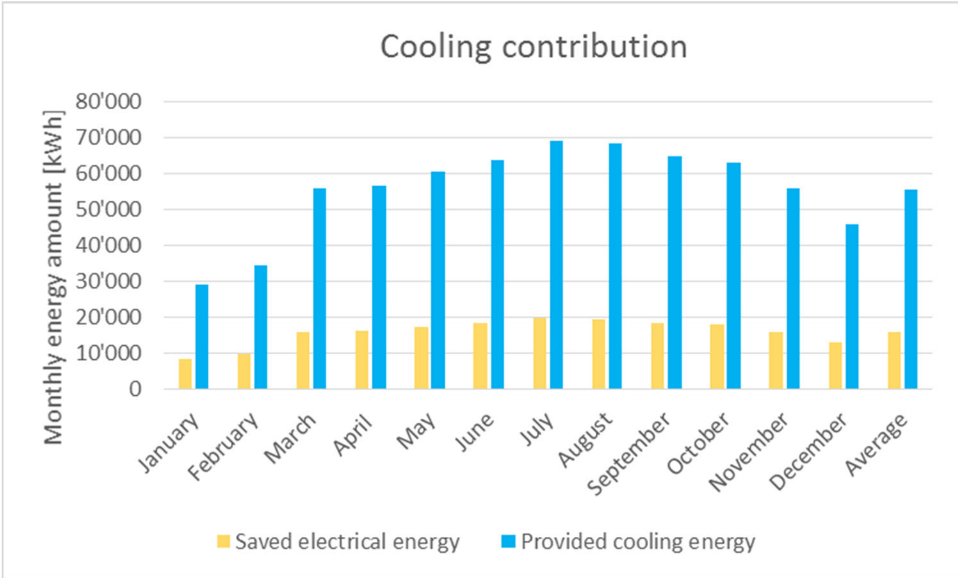

Figure 15. Energy saving due to the employment of the integrated machine as a support for the existing air conditioning system.

The total electrical energy saving is equal to 190,259.5 kWh, corresponding to 665,908.4 kWh of cooling energy, which already considered the stop machine hours due to maintenance. It is worth mentioning the energy consumption of the machine, providing all the above useful effects, including the water treatment unit, which can be seen in Figure 16.

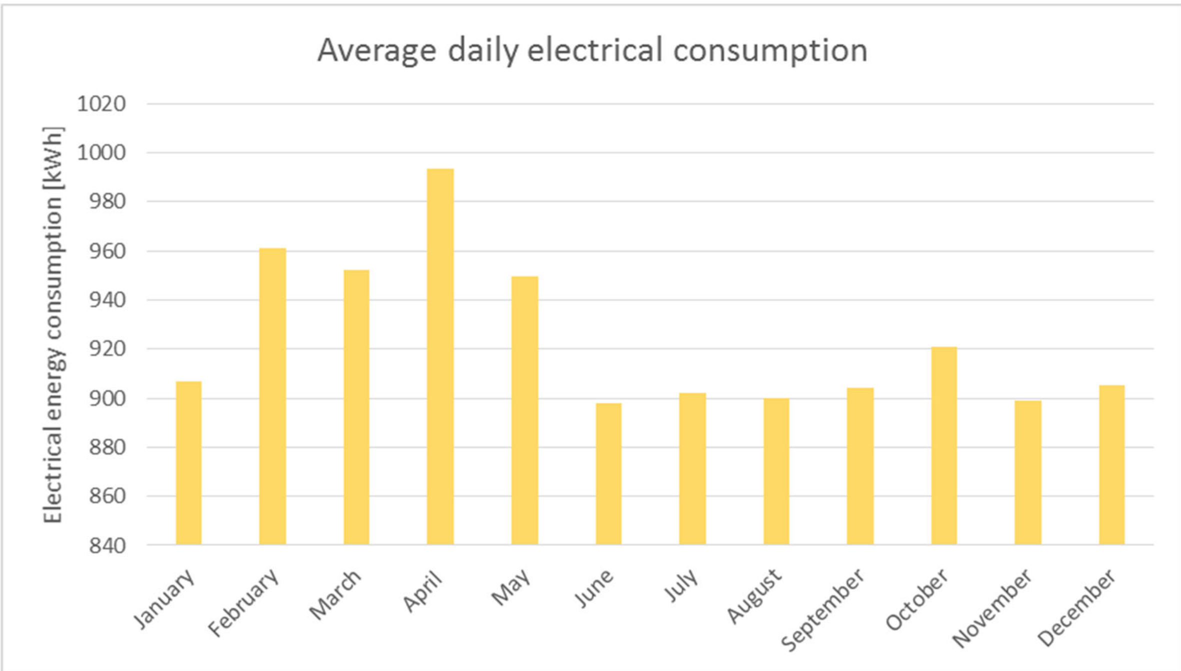

Figure 16. Daily average energy consumption, month by month.

The electrical energy required by the integrated machine for the whole year, considering the hours of stop, is 323,135.1 kWh, which becomes 331,775.2 kWh when including the action of the water treatment unit.

Summarising the results, it can be said that the integrated machine can improve the existing HVAC plant as follows:

- It covers entirely the heating needs of domestic water of two residential buildings, substituting the electrical boilers and providing, in such a way, an electrical energy saving of 634,509.5 kWh/year, which is 100% of the whole energy consumption;
- It covers partially the kitchen heating needs of domestic water, providing an average of 70% of the required heating, leaving to the LPG boiler the residual heating work, giving, thus, LPG saving of 54,426.1 L/year;
- It helps the air conditioning system, providing a treated airflow and giving a cooling energy equal to 665,908.4 kWh, providing, in this case, an electrical energy saving of 190,259.5 kWh/year and 87% of the required fresh air.

Moreover, the machine can produce 570,614.8 L/year of drinking water.

The integrated AWG machine can thus revamp the domestic water heating of two residential buildings and the LPG boiler of the one kitchen building. Moreover, it can also help the air conditioning system of one kitchen building.

6. Economic Evaluations

As described in the previous sections, the integrated AWG machine is able to give an important contribution to energy savings of existing HVAC plants in hot climatic conditions. Nevertheless, it is interesting to understand whether the investment, comprising integrated machine cost, installation and maintenance, has a positive return in an acceptable period. The costs of the entire installation, included the integrated machine, piping, pumps, links, manpower and transport, were equal to EUR 292,170. The maintenance and the consumables, including the water treatment unit, were calculated equal to 12,000 EUR/year. The revenue of the investment is the expected money saving related to the avoided consumption of bottled water, LPG, electricity employed for domestic water heating and electricity employed for primary air cooling. On the basis of the previous results, taking into account costs and prices of each voice and the currency conversion of 0.236 EUR/AED, the following Table 4 can be edited.

Table 4. Savings, costs and net revenue of the investment related to the integrated AWG machine.

Savings		**Unitary Costs**	**Yearly Savings (EUR/Year)**
LPG (L/year)	54,426.1	0.4484 EUR/L	24,405
Electricity due to boilers (kWh/year)	634,509.5	0.10384 EUR/kWh	65,887
Electricity related to air conditioning	190,259.5		19,757
Bottled water (L/year)	570,614.8	0.165 EUR/L	94,151
Costs		Unitary Costs	Yearly costs (EUR/year)
Integrated AWG machine electricity consumption (kWh/year)	331,775.2	0.10384 EUR/kWh	34,452
Maintenance and consumables (EUR/year)	12,000	-	12,000
Net revenue (EUR/year)			157,748
Starting investment (EUR)			292,163
Pay Back Time (years)			1.85

In Table 4, the Pay Back Time (PBT) was calculated without actualisation, simply dividing the total investment by the yearly net revenue. In order to provide a more precise calculation, it was decided to carry out the Net Present Value (NPV) and the actualised PBT evaluation.

The following well-known equation describes the NPV:

$$\text{NPV}\ (i, N) = \sum_{\tau=0}^{N} \frac{Cu_\tau}{(1+i)^\tau} + \frac{V(N)}{(1+i)^N} \quad (5)$$

N is the time horizon and was set, in this case, equal to 10 years, even if, thanks to the robustness of the components and of the employed technology, the expected useful life of the integrated machine is 20 years. The limited time horizon is a mean to provide safer results. The time period, τ, is equal to 1 year.

Cu_τ is the net cash flow. At year zero, it is negative and equal to the entire investment cost: EUR 292,170. As described in previous sections, the integrated machine use is the mean of the savings given by the avoided purchase of bottled water, electricity for boiler and air conditioning, and LPG for domestic water heating. The sum of those savings gives a positive cash inflow. The sum of the maintenance operations, consumable items and consumed electricity for the machine work costs gives a cash outflow that is negative. In order to provide safer results, the cash outflow was also charged, yearly, with 0.5% of the entire investment amount, equal to EUR 1461, to take into account possible machine component failures and replacement costs. Table 5 shows the cash flows.

Table 5. Yearly cash flow.

Cash Inflow	**EUR/Year**
Electrical energy saving	85,644.0
LPG saving	24,405.0
Water saving	94,151.0
Cash outflow	**EUR/year**
Electrical consumption	−34,452.0
Consumables and maintenance	−12,000.0
Component replacement	−1461

The actualisation rate, i, is the sum of inflation and discount rate. In this case, the discount rate was set equal to 4.5%, the value of the Emirates Bond rate. It was chosen as an investment to be compared with, because it requires a minimum investment of the same magnitude order as that related to the integrated machine, and it has a confrontable time horizon (12 years instead of 10) [49]. The inflation rate chosen for Dubai is 2.83% for 2023 and 2% for the next 9 years, in compliance, for the first 5 years, with the statistical prevision taken from [50]. In the current document, the LPG, water, electricity, maintenance, consumables and component replacement costs increase with inflation during the time horizon. In order to provide safe results, the residual value of the machine, $V(T)$, was set equal to zero after the time horizon.

It is worth remembering that the actualised PBT is the time when the sum of actualised net cash flows achieves the initial investment or, in other words, the instant when the NPV is equal to 0. In Figure 17, the NPV behaviour in the 10 years horizon is shown.

From the above calculations, it was possible to determine that the NPV is above EUR 958,000, and the actualised PBT is 2 years.

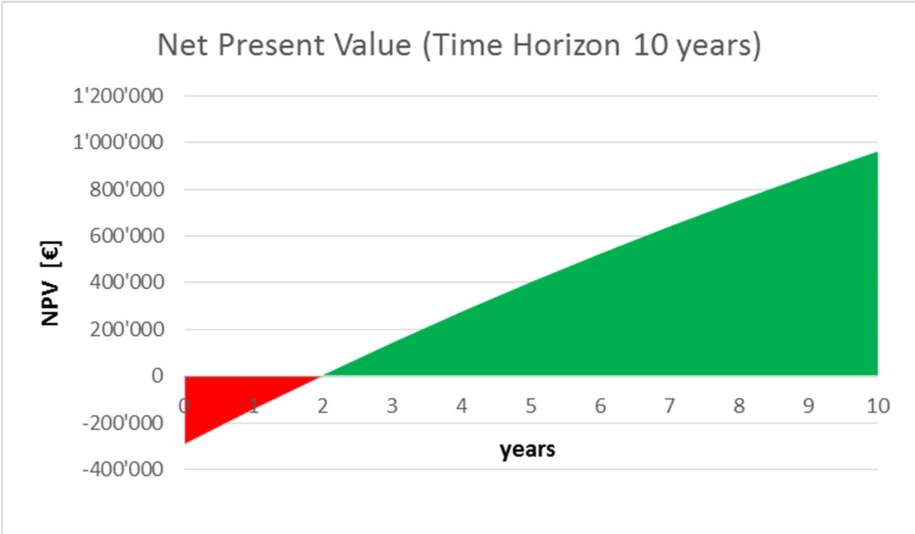

Figure 17. NPV evolution in the time horizon of 10 years. The positive return is underlined by the green colour.

7. Plastic Saving

Usually, in UAE accommodations, drinking water is provided by means of half a litre plastic bottles in order to be easily distributed to people. It is not uncommon, for example, to find in hotel rooms two or four half litre bottles a day for each guest. The water coming from the integrated machine can avoid the plastic consumption related to such a habit, because it has two advantages. First, it is locally produced; therefore, it does not need to be transported and thus packed. Second, it can be directly linked to water dispensers or to internal sinks, as it happened in the described test; thus, it can be easily accessed onsite and collected into jugs, or reusable bottles, without the need of single use plastic bottles. As already underlined, the quality of the water coming from the integrated machine is comparable with that of the most known bottled labels. In the current example, it was distributed using jugs, avoiding plastic bottles. It must be said that small bottles are less efficient considering the ratio between the water capacity and the Polyethylene Terephthalate (PET) quantity, and thus, they are the most impacting in waste production [51]. On the basis of the previous results, given a system average water production of 1585 L/day, it can be estimated that 3160 half litre bottles a day can be avoided. That means, considering the 120 h of machine stop for maintenance, a plastic saving of about 11.4 Mg (tons) a year, taking into account an average mass of plastic of 0.01 kg [51] for each half-litre bottle production, cap excluded. It is worth noting that, beside the mere plastic saving, other positive effects can derive from the integrated AWG use: the fuel saving related to the avoided bottle transportation and the environment impact saving due to the avoided used plastic bottle disposal and/or recycling treatments.

8. Discussion, Implications and Future Developments

The analyses provided in the current research gave an example of integrated AWG machine application and its potentialities to cover two issues at the same time: to offer an alternative source of drinking water and to provide a HVAC plant revamping. The results show that such a kind of machine, in Dubai, was able to produce meaningful water quantities, more than one thousand and half litres a day, overcoming, at the same time, the energy consumption issue, related to water extraction from the air, by means of a smart use of the by-side products of the water extraction cycle. Taking into account the economic considerations, it is easy to calculate that, even if the water would not be evaluated, thus given for free, the actualised PBT would be about 5 years. It is worth mentioning that the hypothesis of 120 h of machine stop is a very conservative one, because such a machine requires a maintenance comparable to that of the chillers of equal cooling power. The main research implication is that the water extraction from air could already be effective if the integration approach is pursued. Lately, the atmospheric water harvesting research field has been concentrating on desiccant substances study and on passive systems. Nevertheless, as already remembered in Section 2, with such an approach, specific yields are comparatively low, some litre day per squared mater of plant and, when desiccants are employed, often the energy consumption remains an issue. The integrated approach can be a mean to provide meaningful quantities of water, thousand L/day, with a comparatively low space requirement, overcoming, at the same time, the energy issue. The water extraction from air sustainability, that is one of the current research questions, can be actually pursued with such an approach.

Nevertheless, more studies are required, not only to extend the results to other cases and climates but also to explore other potentialities of the integrated approach in water extraction for uses such as agriculture, industrial, etc., different from human consumption. For the current case study, the economic sustainability is clear enough; thus, it would be very interesting to understand how such a solution could be extended to other similar building installations, worker villages, in other climatic regions. Such a hypothesis will be the object of a future study, which will be developed also with the help of the Global Efficiency Index (GEI) [38] calculations in order to provide a comparison metric between the existing and the improved (adding the integrated machine) plant configuration. The study could be a mean to define a sort of revamping standard based on the integration approach that considers water as important as energy efficiency.

Other future developments will concern the possibility to equip such dwellings with photovoltaic fields, covering at least a part of the electrical energy demand, whose cleaning could be carried out by means of part of the water coming from the integrated system, as described in ref. [52]. Finally, further evaluations about the environmental impact will be carried out considering the CO_2 emissions that can be avoided with the integrated approach.

9. Conclusions

The current paper presents a real case study concerning an integrated AWG machine of large size production, more than one thousand litres per day. The test of a real machine was carried out in a worker village placed in Dubai, where the drinking water provision is a current issue. The machine was linked to the existing HVAC plants by means of a pipe circuit and of an air duct and was able not only to produce drinking water but also to provide a flux of fresh air, cooled and dehumidified, and to heat domestic water. On the basis of real results, it was possible to calculate that the machine can cover the daily drinking needs of 792 persons and avoid, yearly, the plastic consumption of more than 11 Mg (tons) due to the avoided bottled water use. Moreover, the heating energy coming from the machine was calculated to be enough to cover the heating needs for the domestic water of two buildings, housing about 200 guests each, and 70% of the heating needs of one of the kitchen buildings. The cooled and dry air, coming from the water extraction cycle, can cover 87% of the fresh air required by common kitchens. The integrated AWG machine, on the whole, was evaluated to be able to provide the following savings: electrical energy equal to 824,769 kWh/year and LPG equal to 54,426.1 L/year. The water production exceeds 570 m^3 per year. An economic evaluation, to test the system sustainability, was also carried out. The investment, equal to about EUR 290,000, comprising the machine cost, materials for linking to the existing plants, manpower and transport, has a Net Present Value, after a time horizon of 10 years, of more than EUR 958,000 and has an actualised PBT of 2 years, while the simple PBT is less than 2 years.

Author Contributions: Conceptualization, A.M.; methodology, L.C. and A.M.; software, P.C.; validation, L.C. and P.C.; formal analysis, L.C.; investigation, L.C.; resources, L.C.; data curation, L.C. and P.C.; writing—original draft preparation, L.C.; writing—review and editing, L.C., P.C, and A.M.; visualization, L.C.; supervision, A.M.; project administration, A.M.; funding acquisition, A.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: not applicable.

Informed Consent Statement: not applicable.

Data Availability Statement: no further data are available.

Acknowledgments: The worker village data, test data and photographs were provided by SEAS, Societè de l'Eau Aerienne Suisse.

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

Abbreviations

Acronyms

AED	ISO code for Dirham
AHU	Air Handling Unit
AWG	Air to Water Generator
AWH	Air Water Harvesting
COP	Coefficient of Performance
EER	Energy Efficiency Ratio
HVAC	Heating Ventilation Air Conditioning
ICP	Inferior Calorific Power
LPG	Liquid Petroleum Gas
NPV	Net Present Value
PBT	Pay Back Time
PET	PolyEthylene Terephthalate
PLC	Programmable Logic Controller
WET	Water Energy Transformation
UAE	United Arab Emirates
UN	United Nations
UV	Ultra Violet

Symbols

a	dry air mass flow (kg/s)
C	water specific heat, 4.186 kJ/(kgK)
Cp	Inferior Calorific Power (kWh/L)
Cu	net cash flow (chosen currency)
en	energy (kWh) or (kJ)
en_t	heating energy (kWh) or (kJ)
en_{el}	electrical energy (kWh) or (kJ)
i	actualisation rate (%)
j	calculation model node number
m	water mass (kg)
N	time horizon (years)
q	water mass-flow (kg/s)
Qc	condensation energy (kJ)
R	coolant mass (kg)
r	coolant mass flow (kg/s)
R.H.	relative humidity (%)
t	dry bulb temperature (°C)
$V(N)$	residual value of the considered good at after the time horizon (chosen currency)
v	LPG volume (L)
η	efficiency (−)
τ	time period (year) or time step (s)
φ	energy flux (kW)
z	index of the mass flow or energy flow exchange in the node

Appendix A

The AWG integrated machine, in the calculation model, is represented by a network of interlinked nodes, dynamically assembled, instead of a whole, monolithic system. Each node is the mathematical counterpart of each of the main real-life components of an integrated machine (compressors, pumps, heat-exchangers and so on). Each node is designed as a "black box" to the other parts of the system (using the strong paradigm of "object-oriented" approach) so that, at any time, it is possible to expand the model by adding new node types. The model calculates how the different fluids (air, coolant and water) traverse the network of nodes, delegating to each component the actual calculation of how energy is exchanged between fluids. Fluids are bonded to follow the mass conservation (mass entering a component must equal mass exiting plus mass "storage"), and the same holds true for energy fluxes entering/exiting each component. Thus, for each node "j", the following four equations must hold true:

$$\sum_z \varphi_{zj}\,\Delta\tau = \Delta en_j \quad \text{(A1)}$$

$$\sum_z a_{zj}\,\Delta\tau = 0 \quad \text{(A2)}$$

$$\sum_z q_{zj}\,\Delta\tau = 0 \quad \text{(A3)}$$

$$\sum_z r_{zj}\,\Delta\tau = \Delta R_j \quad \text{(A4)}$$

where, in Equation (A1), the sum of the energy fluxes, φ_j, integrated by the time step, $\Delta\tau$, are equal to the energy variation of the node, Δen. Equation (A2) describes the fact that the dry air mass flows, a_j, are not accumulated in any node, as well as for the water mass flows, q_j, as described in (A3). The last Equation (A4) describes the coolant mass flows, R_j, exchanges in each node. Additionally, in this case, it is possible that, in some nodes, such as the heat exchangers, there could be a coolant mass variation, ΔR.

Such a calculation is iterated at each time step, Δ (the time step is user-adjustable), from the starting conditions. At each node, the model stores energy, (A1), and/or coolant mass, (A4), the simulation is able not only to calculate the steady-state performance of the machine but also the transient behaviour of the system when it is started/stopped or when the external conditions dynamically change.

References

1. UNESCO World Water Assessment Programme. *UN World Water Development Report 2019: Leaving No One Behind*; UNESCO: Paris, France, 2019; ISBN 978-92-3-100309-7.
2. Global Land Outlook, United Nations Convention to Combat Desertification. 2017. Available online: https://knowledge.unccd.int/glo/global-land-outlook-glo (accessed on 27 December 2021).
3. Water Consumption. Available online: https://www.worldometers.info/water/ (accessed on 27 December 2021).
4. WHO Drinking Water. Available online: https://www.who.int/news-room/fact-sheets/detail/drinking-water (accessed on 15 February 2022).
5. UNICEF Stories, Water and the Global Climate Crisis: 10 Things You Should Know. Available online: https://www.unicef.org/stories/water-and-climate-change-10-things-you-should-know (accessed on 20 June 2022).
6. Water Economy Report UNESCO. Available online: http://www.unesco.org/reports/wwdr/2021/en/valuing-water-economy (accessed on 29 December 2021).
7. Karimidastenaei, Z.; Avellán, T.; Sadegh, M.; Kløve, B.; Haghighi, A.T. Unconventional water resources: Global opportunities and challenges. *Sci. Total Environ.* **2022**, *827*, 154429. [CrossRef] [PubMed]
8. Zhang, M.; Liu, R.; Li, Y. Diversifying Water Sources with AtmosphericWater Harvesting to Enhance Water Supply Resilience. *Sustainability* **2022**, *14*, 7783. [CrossRef]
9. Algarni, S.; Saleel, C.A.; Mujeebu, M.A. Air-conditioning condensate recovery, and applications—Current developments and challenges ahead. Sustain. *Cities Soc.* **2018**, *37*, 263–274. [CrossRef]
10. Ansari, E.; Ferber, N.L.; Milošević, T.; Barron, J.; Karanikolos, G.N.; Faisal AlMarzooqi, F.; Dumée, L.F.; Calvet, N. Atmospheric water generation in arid regions—A perspective on deployment challenges for the Middle East. *J. Water Process Eng.* **2022**, *49*, 103163. [CrossRef]

11. Government of Dubai. *Green Building Regulations and Specifications*; Dubai Electricity and Water Authority: Dubai, United Arab Emirates, 2011. Available online: https://www.dewa.gov.ae/~/media/Files/Consultants%20and%20Contractors/Green%20Building/Greenbuilding_Eng.ashx (accessed on 28 March 2022).
12. Purushothama, B. 11—Air-conditioning units. In *Humidification and Ventilation Management in Textile Industry*; Woodhead Publishing: Delhi, India, 2009; pp. 174–193, ISBN 9788190800129. [CrossRef]
13. Raveesh, G.; Goyal, R.; Tyagi, S. Advances in atmospheric water generation technologies. *Energy Convers. Manag.* **2021**, *239*, 114226. [CrossRef]
14. Wang, Y.; Danook, S.H.; Al-Bonsrulah, H.A.; Veeman, D.; Wang, F. A Recent and Systematic Review on Water Extraction from the Atmosphere for Arid Zones. *Energies* **2022**, *15*, 421. [CrossRef]
15. Liu, X.; Beysens, D.; Bourouina, T. Water Harvesting from Air: Current Passive Approaches and Outlook. *ACS Mater. Lett.* **2022**, *4*, 1003–1024. [CrossRef]
16. Pokorny, N.; Shemelin, V.; Novotny, J. Experimental study and performance analysis of a mobile autonomous atmospheric water generator designed for arid climatic conditions. *Energy* **2022**, *250*, 123813. [CrossRef]
17. Bagheri, F. Performance investigation of atmospheric water harvesting systems. *Water Resour. Ind.* **2018**, *20*, 23–28. [CrossRef]
18. Shahrokhi, F.; Esmaeili, A. Optimizing relative humidity based on the heat transfer terms of the thermoelectric atmospheric water generator (AWG): Innovative design. *Alex. Eng. J.* **2023**, *67*, 143–152. [CrossRef]
19. Wang, W.; Yang, T.; Pan, Q.; Dai, Y.; Wang, R.; Ge, T. All-day freshwater production enabled by an active continuous sorption-based atmospheric water harvesting system. *Energy Convers. Manag.* **2022**, *264*, 115745. [CrossRef]
20. Cattani, L.; Magrini, A.; Cattani, P. Water Extraction from Air by Refrigeration—Experimental Results from an Integrated System Application. *Appl. Sci.* **2018**, *8*, 2262. [CrossRef]
21. Mandal, C.S.; Agarwal, M.; Reddy, V.; Kudapa, V.K. Water from air—A sustainable source of water. *Mater. Today Proc.* **2020**, *46*, 3352–3357. [CrossRef]
22. Kgatla, L.; Gidudu, B.; Chirwa, E.M.N. Feasibility Study of Atmospheric Water Harvesting Augmented through Evaporative Cooling. *Water* **2022**, *14*, 2983. [CrossRef]
23. Moghimi, F.; Ghoddusi, H.; Asiabanpour, B.; Behroozikhah, M. Is atmospheric water generation an economically viable solution? *Clean Technol. Environ. Policy* **2021**, *23*, 1045–1062. [CrossRef]
24. Asim, N.; Badiei, M.; Mohammad, M.; Razali, H.; Rajabi, A.; Haw, L.C.; Ghazali, M.J. Sustainability of Heating, Ventilation and Air-Conditioning (HVAC) Systems in Buildings—An Overview. *Int. J. Environ. Res. Public Health* **2022**, *19*, 1016. [CrossRef]
25. Tu, Y.; Wang, R.; Zhang, Y.; Wang, J. Progress and Expectation of Atmospheric Water Harvesting. *Joule* **2018**, *2*, 1452–1475. [CrossRef]
26. Sharan, G.; Roy, A.K.; Royon, L.; Mongruel, A.; Beysens, D. Dew plant for bottling water. *J. Clean. Prod.* **2017**, *155*, 83–92. [CrossRef]
27. Atmospheric Water Generator or Water-from-Air Machine Suppliers Links. Available online: http://www.atmoswater.com/manufacturers-and-suppliers-of-atmospheric-water-generators--water-from-air-machines.html (accessed on 5 January 2022).
28. Magrini, A.; Cattani, L.; Cartesegna, M.; Magnani, L. Water Production from Air Conditioning Systems: Some Evaluations about a Sustainable Use of Resources. *Sustainability* **2017**, *9*, 1309. [CrossRef]
29. Milani, D.; Abbas, A.; Vassallo, A.; Chiesa, M.; Al Bakri, D. Evaluation of using thermoelectric coolers in a dehumidification system to generate freshwater from ambient air. *Chem. Eng. Sci.* **2011**, *66*, 2491–2501. [CrossRef]
30. Asham, A.D.; Abdelaal, W.G.A.; Mamdouh, W.M. A Novel Ambiently Adaptive Atmospheric Water Generator Using Maximum Production Tracking Algorithm. *Teh. Vjesn. Tech. Gaz.* **2022**, *29*, 797–805. [CrossRef]
31. Fathieh, F.; Kalmutzki, M.J.; Kapustin, E.A.; Waller, P.J.; Yang, J.; Yaghi, O.M. Practical water production from desert air. *Sci. Adv.* **2018**, *4*, eaat3198. [CrossRef] [PubMed]
32. Zhao, F.; Zhou, X.; Liu, Y.; Shi, Y.; Dai, Y.; Yu, G. Super Moisture-Absorbent Gels for All-Weather Atmospheric Water Harvesting. *Adv. Mater.* **2019**, *31*, 1806446. [CrossRef]
33. Shemelin, V.; Pokorny, N.; Novotny, J. Experimental investigation of silica gel and zeolite coated fin-tube heat exchangers under arid climatic conditions. *Energy Rep.* **2022**, *8*, 331–341. [CrossRef]
34. Yang, K.; Pan, T.; Lei, Q.; Dong, X.; Cheng, Q.; Han, Y. A Roadmap to Sorption-Based Atmospheric Water Harvesting: From Molecular Sorption Mechanism to Sorbent Design and System Optimization. *Environ. Sci. Technol.* **2021**, *55*, 6542–6560. [CrossRef]
35. Wasti, T.Z.; Sultan, M.; Aleem, M.; Sajjad, U.; Farooq, M.; Raza, M.H.; Khan, M.; Noor, S. An overview of solid and liquid materials for adsorption-based atmospheric water harvesting. *Adv. Mech. Eng.* **2022**, *14*, 1–27. [CrossRef]
36. Mulchandani, A.; Edberg, J.; Herckes, P.; Westerhoff, P. Seasonal atmospheric water harvesting yield and water quality using electric-powered desiccant and compressor dehumidifiers. *Sci. Total. Environ.* **2022**, *825*, 153966. [CrossRef]
37. Cattani, L.; Magrini, A.; Cattani, P. Water Extraction from Air: A Proposal for a New Indicator to Compare Air Water Generators Efficiency. *Energies* **2021**, *14*, 224. [CrossRef]
38. Cattani, L.; Cattani, P.; Magrini, A. Air to Water Generator Integrated Systems: The Proposal of a Global Evaluation Index—GEI Formulation and Application Examples. *Energies* **2021**, *14*, 8528. [CrossRef]
39. Pacak, A.; Jurga, A.; Drąg, P.; Pandelidis, D.; Kaźmierczak, B. A Long-Term Analysis of the Possibility of Water Recovery for Hydroponic Lettuce Irrigation in Indoor Vertical Farm. Part 1: Water Recovery from Exhaust Air. *Appl. Sci.* **2020**, *10*, 8907. [CrossRef]

40. Khalid, M.B.; Beithou, N.; Al-Taani, M.; Andruszkiewicz, A.; Alahmer, A.; Borowski, G.; Alsaqoor, S. Integrated Eco-Friendly Outdoor Cooling System—Case Study of Hot-Humid Climate Countries. *J. Ecol. Eng.* **2022**, *23*, 64–72. [CrossRef]
41. Labour Accommodation in United Arab Emirates. Available online: https://u.ae/en/information-and-services/jobs/labour-accommodation (accessed on 17 February 2023).
42. Mineral Water Cost in Emirates. Available online: https://www.globalproductprices.com/United-Arab-Emirates/mineral_water_prices/ (accessed on 15 March 2022).
43. Currency Rates. Available online: https://it.investing.com/currencies/aed-eur-historical-data (accessed on 28 March 2022).
44. Emirates Electricity Costs Calculator. Available online: https://www.dewa.gov.ae/en/consumer/billing/tariff-calculator (accessed on 28 March 2022).
45. ADNOC LPG Refilling Prices. Available online: https://www.adnocdistribution.ae/en/products-services/gas/liquefied-petroleum-gas-lpg/overview/ (accessed on 28 December 2022).
46. Weatherbase, Weather Data. Available online: https://www.weatherbase.com/weather/weather-summary.php3?s=49114&cityname=Dubai,+United+Arab+Emirates (accessed on 7 January 2022).
47. Cattani, L.; Magrini, A.; Leoni, V. Energy Performance of Water Generators from Gaseous Mixtures by Condensation: Climatic Datasets Choice. *Energies* **2022**, *15*, 7581. [CrossRef]
48. Food Contact Materials Definition, European Food Safety Authority. Available online: https://www.efsa.europa.eu/en/topics/topic/food-contact-materials (accessed on 16 December 2022).
49. Emirate Bonds. Available online: https://www.boerse-frankfurt.de/bond/xs0885065887-emirates-4-5-13-25 (accessed on 9 January 2023).
50. Inflation rate previsions. Available online: https://www.statista.com/statistics/297779/uae-inflation-rate/ (accessed on 28 December 2022).
51. Becerril-Arreola, R.; Bucklin, R.E. Beverage bottle capacity, packaging efficiency, and the potential for plastic waste reduction. *Sci. Rep.* **2021**, *11*, 3542. [CrossRef]
52. Cattani, L.; Cattani, P.; Magrini, A. Photovoltaic Cleaning Optimization: A Simplified Theoretical Approach for Air to Water Generator (AWG) System Employment. *Energies* **2021**, *14*, 4271. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.