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Integrated Atmospheric Water Generators for Building Sustainability: A Simulation-Based Approach

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Abstract: This paper presents the first results of a broader study aimed at considering atmospheric water generation as a viable option within sustainable building design strategies. In particular, the focus is on integrated systems in which atmospheric water generator (AWG) machines, in addition to producing water, support HVAC systems. The research focuses on the combined use of two different simulation tools: a commercial tool designed to study the energy balance of buildings and a custom-developed software for AWG modelling. This is the first step of a more complex procedure of software integration that is aimed to provide designers with a method to implement AWGs in the design process of buildings, both residential or industrial. This preliminary procedure is applied to a case study concerning the link between an advanced integrated AWG and a building housing inverters and transformers that belong to a photovoltaic field. The scope of the integration consists in enhancing the energy sustainability of atmospheric water intended for hydrogen production and panel washing by means of the dry and cold air flux that comes from the cycle of vapour condensation. The results highlight the potentialities of the integrated design, which includes AWGs, to enhance the final efficiency of sustainable housing. In particular, the joint action of the simulation tools used in this study provides insights about the possibility to reduce the size of traditional chiller that serve the building by an order of magnitude, and to achieve an energy saving of 29.8 MWh a year.

Keywords: atmospheric water generators; building sustainability; energy efficiency; water savings; sustainable atmospheric water harvesting

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1. Introduction

The availability of fresh clean water is an increasing global concern, driven not only by continuous population growth and industrialization [1], but also by climate change, which is altering weather patterns [2] and exacerbating extreme events such as droughts and floods. According to the United Nations (UN), over 2 billion people experience high water stress [3], and research indicates that 4 billion face severe water shortages for at least one month a year [4]. Moreover, it is estimated that, by 2050, water needs will increase significantly, worsening the associated challenges [3]. Among the possible solutions, comprising reuse, recycle, distribution efficiency, and better management, a role can be played by unconventional sources like atmospheric water [5], which is currently recognised as a possible means to address the "Blue Deal" (a term encompassing the water-related issues [6]). Research interest on this topic has grown significantly in recent years,

as evidenced by the increasing number of published studies on the topic [7] and by the foundation of the International Atmospheric Water Harvesting Association (IAWHA) [8]. Air is the first receiver of the natural water cycle, and the air is estimated to contain as much water as all the rivers and swamps on Earth [9]. The majority of the atmospheric water, 98%, is in vapour form [10] and its quantity varies as a function of the weather conditions, ranging from fractions of grams, in the coldest regions, to some tens of grams in hot and humid climates.

Atmospheric water can be used for various purposes, ranging from use as drinking water to industrial and agricultural applications [11]. In particular, due to the decentralised nature of its source, atmospheric water could be a means to enhance hydric resilience, which is the capability of the system to overcome extreme events [12]. However, it should primarily be reserved for high-value or "noble" uses, such as direct human consumption [13], high-tech industry and photovoltaic plant maintenance [14], and high-tech agriculture [15], primarily because producing one cubic meter of water requires treating approximately one hundred thousand cubic meters of air, and even moving such an air flux requires energy [16].

In addition to the production magnitude, energy sustainability itself is one of the primary concerns related to atmospheric water. It is important to note that water quality is another critical topic of discussion [17]. Atmospheric water generally offers superior quality compared to some traditional sources, such as surface water and shallow aquifers. Nevertheless, it presents challenges, primarily due to the technologies employed for its extraction [11]. It should also be noted that atmospheric water production depends on climatic conditions [10]. There is a strict relationship between the water yield and the physical parameters of temperature and relative humidity, given the total air pressure, because these parameters determine the vapour content in air [18]. Therefore, the issues pertaining to atmospheric water can be summarised as follows: yield, energy consumption, and achieved quality [8,19].

Vapour compressor refrigeration cycles (VCRCs) are recognized as the most effective techniques for achieving the highest and cleanest yields [20]. However, the main drawback of this method is the significant energy consumption associated with the process [21]. One approach to achieving energy sustainability is the employment of integrated advanced atmospheric water generators (AWGs). These systems are based on VCRC technology and provide water, heating, and cooling effects using the same energy input [16]. Such an approach is recommended for achieving sustainable atmospheric water production [20]. Previous research has demonstrated the effectiveness of connecting advanced integrated AWGs with existing heating, ventilation, and air conditioning (HVAC) systems. For example, in [22], a test was performed in a hotel where a machine supplied drinking water for kitchen uses and the guests' consumption, heated domestic water, and delivered a cooled and dry air flux to mitigate the environmental conditions of the laundries. In that case, the energy contribution enhanced the existing plant efficiency, resulting in estimated cost savings of 80,000 USD per year. Similarly, [23] describes a test involving the installation of an integrated AWG in a workers' village. The system provided drinking water for the residents while supporting the existing boilers and air conditioning system. This solution was proven to be sustainable, with the energy savings allowing the system to pay for itself within two years.

It is important to underline that the quality of the obtained water was not only in compliance with the local laws and standards, but also comparable with that of bottled mineral water [24].

As previously stated, incorporating atmospheric water generation into residential and industrial buildings serves as an effective means to enhance hydrological resilience. Simul-

taneously, when an integrated AWG system is considered, energy sustainability can also be achieved. To support the perspective of water and energy savings—characterised by the possibility of including advanced integrated AWG systems in building plant configurations—an appropriate design tool is required. In other words, considering that these machines offer a pivotal opportunity to improve the water and energy efficiency of buildings, it is of the utmost importance to equip designers with tools that enable the integration of this technology into their projects. In the literature, there are some efforts to define models that describe the behaviour of AWGs. For example, [25] presented a neural network model trained on data from a commercial AWG which was designed for water production only. The validity of the obtained relations was circumscribed to the tested conditions and to the considered machine. At any rate, the approach could be interesting whenever more real-life data become available.

In contrast, the authors of the current study used a custom-developed physically based model, AWGSim [26], which was tested in a previous study [22] and was applied in various other researches such as [23], which provides satisfying results about the behaviour of integrated AWG machines, given, as input, the environmental conditions of temperature (t) and relative humidity ($r.h.$). Such a model, which has lately received increased functionalities, can be applied to different AWG configurations to predict the main outputs of the considered machines [26]. A brief description of the main features of AWGSim can be found in Appendix A of [23].

Nevertheless, no available tools or procedures can be found to assist designers in incorporating AWGs into building plant configurations at the planning stage.

This knowledge gap demands urgent attention if meaningful and widespread actions to counteract water scarcity are to be effectively implemented.

A first step in this direction is represented by the current research, which proposes the combined use of the custom-developed AWG model, previously mentioned, and a commercial simulation tool based on EnergyPlus [27]. The latter focuses on both the passive and active energy behaviour of buildings, allowing users to define the most suitable plant configuration or to provide energy diagnosis by testing existing solutions. Moreover, it can simulate the water use in buildings, a pivotal feature that is useful in understanding how to decrease water consumption. The aim of this research is to achieve an initial integration between the two tools in order to include AWGs in energy evaluation, while providing results about the atmospheric water production of AWGs. The key factors that this approach aims to address are:

- The identification of the most efficient equipment configuration by assessing the energy consumption across different scenarios (with and without the advanced integrated AWG system);
- The potential water savings, which can also be translated into plastic waste reduction, as demonstrated in [25], when the produced water serves as a substitute for bottled water;
- The optimization of equipment operation to maximize both energy efficiency and water yield.

The integration method is applied to a case study, adopting the multipurpose approach recommended by [21], further developing and enhancing the research described in [11]. That previous study explored the application of an integrated AWG to a photovoltaic field with the dual purpose of producing green hydrogen as an energy reservoir and supporting panel cleaning. In the current research, the cooling contribution coming from the AWG is delivered into the building housing inverters and transformers that serve such a photovoltaic plant. This study analyses the building energy behaviour by combining the existing air conditioning (AC) system with the AWG capability of providing cooling energy.

This paper represents a first attempt to include AWGs in the building design process in order to support water savings alongside energy savings; the research results are presented according to the following steps:

- A short summary of the most widespread techniques of atmospheric water harvesting (AWH), focusing on the peculiarities of integrated AWGs;
- The methodology description, with a brief recapitulation of the main characteristics of the two software programs;
- A case study description, accompanied by a short recall of the previous analysis, the obtained results, and a discussion of the results;
- Some considerations and future developments;
- The conclusions.

This study directly addresses the gap in the literature regarding the integration of AWGs into building plant configurations at the design stage. While previous researches have examined the performance of AWGs and their impact on energy and water efficiency, no comprehensive methodologies or tools have been developed to support designers in incorporating this technology within building systems. By proposing an innovative integration of AWGSim with EnergyPlus, this study provides a practical framework for assessing AWG implementation in real-world scenarios.

This methodological advancement lays the foundation for future studies aimed at refining AWG integration strategies, ultimately contributing to the broader effort to enhance water resilience and sustainability in the built environment.

2. Atmospheric Water Harvesting: A Summary of the Most Widespread Techniques

The atmosphere is a ubiquitous source of water [21], even if atmospheric water is not distributed with the same density all over the world—in fact, the air water content varies as a function of different climates [28]. Depending on the desired quantity and quality of the obtained water [11], as well as the thermo-hygrometric environmental conditions of the considered site [29], it can be harvested through several techniques. Numerous review papers, such as [20,21], provide a comprehensive overview of the state of the art on this topic. Therefore, this section aims to offer only a brief summary of the most widespread techniques, with a particular focus on integrated AWGs, which are the type of machine used in the case study. To date, there is still no full agreement on the terms identifying the process of atmospheric water collection, as underlined on various occasions by the IAWHA [30,31]. Similarly, there is no univocal classification for the various techniques [32–34]. Nevertheless, one of the most widespread classifications relies on the energy source employed to harvest the liquid from the atmosphere [6], thus categorising the different approaches into passive, active, and hybrid. In particular:

- Passive systems exploit natural phenomena, such as temperature gradients or direct solar radiation, and do not require high-grade power sources. The yield of these systems is not programmable because it is strictly dependent on environmental conditions;
- Active processes, on the other hand, require electricity or other high-grade power sources. They can produce on demand within the environmental conditions allowed by their working range;
- Hybrid systems combine the two approaches, aiming to minimise high-grade energy consumption while simultaneously overcoming the operational limitations associated with reliance on natural phenomena.

Following the above classification, a short summary of the most diffused techniques is reported below.

2.1. Passive Systems

Fog nets [20] are devices that consist of net frames which are strategically placed in areas where natural fog occurs. The material composing the net captures tiny mist droplets and facilitates the coalescence phenomenon. Once the droplets reach a critical size, they fall due to gravity and are collected. Modern fog nets are often made with nature-inspired materials and structures—such as spider silk, desert beetles, cacti [35]—and are designed to enhance water collection efficiency. Under optimal conditions, impressive yields can be achieved, around 10 L/(m^2·day), but only in specific geographic areas where fog or mist are consistently present [20]]. Additionally, there are ongoing concerns regarding the quality of the collected water [36].

Radiative panels [20] are based on the use of radiative sky cooling to achieve temperatures below the environmental dew point. In such a way, part of the air vapour content condensates on the surfaces of the panels. The inclination of the panels, alongside their surface coating, enables them to collect the liquid through gravity. The effectiveness of this approach depends on environmental factors such as the air humidity, cloud cover, wind speed, and temperature, as well as on the material properties of the panels. Recent research has focused on optimizing the optical properties of the surfaces to enhance the radiative effect and on improving the hydrophobic-hydrophilic coatings of the panels to increase their water collection. The largest radiative panel installation, built in India in 2006, collected a total of 6545 L over one year using 850 m^2 of panels, demonstrating that smaller systems can often achieve higher efficiency compared to larger installations. The water quality can be an issue, because the panels are directly exposed to the outdoor environment, without any protection.

2.2. Hybrid

Sorption-based atmospheric water generators (AWGs) [20] employ desiccant materials that adsorb or absorb water vapour directly from the air. They can operate at very low relative humidities, as low as 10% [37], depending on the materials employed in their fabrication. The water harvesting process consists of three main stages:

- The sorption stage: The desiccant material is exposed to an environmental air flux, where adsorption or absorption occurs (an exothermic process);
- The desorption stage (or sorption material regeneration): Once the desiccant reaches saturation, vapour release is begun through the application of an external heat source. The heat breaks the bonds between the desiccant and the water vapour, which is then released into a closed air volume or a controlled air flux, increasing its vapour content. This stage essentially acts as a vapour concentrator;
- The condensation stage: The vapour-rich air is cooled so that part of thewater condensates and can be collected in liquid form.

When the required energy (for both heating and cooling) is supplied by solar energy and/or by natural temperature gradients (e.g., day–night cycles), the system can be classified as passive. Conversely, if energy is provided by a vapour compression refrigeration cycle (VCRC) powered by electricity or other high-grade power sources, the system falls into the active category. Moreover, if the air flux is driven by electrical fans, even if the sorption–desorption–condensation process occurs passively, the device cannot be fully classified as passive.

The research in this field is extensive, and has a particular focus on sorption materials, ranging from metal–organic frameworks (MOFs) to hydrogels [37]. These efforts aim to develop high-performance desiccants capable of exhibiting hydrophilic behaviour during the sorption phase and hydrophobic properties at low regeneration temperatures.

The main drawbacks of these techniques include comparatively low water yields and the requirement for large quantities of desiccant materials, which are often expensive. In fact, efforts are currently being carried out to find low cost substances which can be used as desiccant materials [38]. Additionally, there is a lack of studies concerning the quality of the obtained water, because research often focalizes on the mere water yield.

2.3. Active

VCRC-based AWGs are the most widespread active technique represented by the machines based on VCRC. Some real market solutions are already available. Some real market solutions are already available and the overall offer has been growing over time [39]. As mentioned, VCRC-based machines are currently recognised as the technology that can provide the highest and cleanest yields, given that the materials composing the machine do not release pollutants [15] and that correct air filtration and water treatment is carried out by these machines [40]. The working scheme of VCRC-based machines can be described as follows [6]. A refrigerant operates in a reverse cycle, extracting heat from an environmental (humid) air flux to force the condensation of part of its water content. The evaporator coil allows the refrigerant to change its phase from liquid to gas at low pressure that corresponds to a temperature lower than the dew point of the treated air. In this way, heat flows from the air to the coolant. After that, the refrigerant is compressed to a higher pressure that corresponds to a temperature higher than that of the surrounding environment. The heat is then discharged into the outside environment through a second coil, the condenser, where the refrigerant condenses from gas to liquid, exchanging heat with the surrounding air. Figure 1 illustrates the working scheme of a VCRC-based AWG.

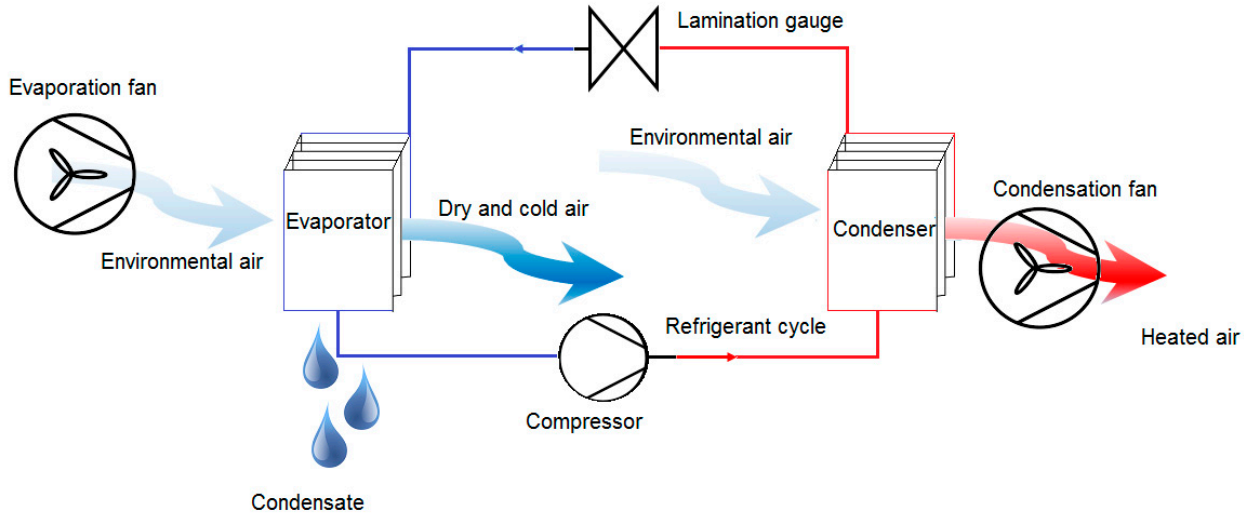


Figure 1. VCRC-based AWG working scheme. Environmental air is forced to pass through over the evaporator coil where it is cooled by a refrigerant that is below its dew point, causing vapour condensation. The coolant is then compressed and releases the heat into the external ambient air through the condenser coil. The refrigerant is brought back to the starting conditions of the cycle by an expansion (lamination) valve (the original drawing was presented by the authors in [6]).

Thermo-electric cooler (TEC) AWGs [32] are based on the Peltier effect: an electric current flows through a junction of two different conductive materials, causing heat to be absorbed on one side and released on the other. Vapour condensation occurs on the cooled side when the dew point temperature is achieved. The main advantage of this technology is its compactness and the elimination of both the refrigerant and the compressor, meaning that the only mechanical components in motion are the fans. However, there are notable drawbacks, such as the comparatively low yields and the difficulty of controlling

the cell temperatures. Additionally, the cooling efficiency of TECs is significantly lower compared to that of a compressor-based reverse cycle system [20]; thus, the specific energy consumption is higher.

Advanced integrated AWG machines represent a pivotal approach which can enhance the sustainability of atmospheric water [33]. This technique is based on the concept of global efficiency, which refers to the overall optimization of the performance of the system rather than focusing on individual aspects in isolation. Developed from a system integration perspective, integrated AWGs are an example of multipurpose machines through which global efficiency is achieved. These devices, based on VCRC technology, are specifically designed not only to produce atmospheric water but also to contribute to heating and cooling needs with the same energy consumption, thereby improving the overall efficiency of the process. Certainly, the main objective is the water yield. In fact, the cycle is optimised from this perspective and all the components intended for water contact are made of food-grade materials [23]. The working scheme of these machines is similar to that described for the simple VCRC-based AWGs. The key difference is that the treated air flux, which is colder and dryer than the environmental air, can be ducted and delivered to enclosed spaces that require cooling. Additionally, instead of being discharged outdoors, the condensation heat can be transferred to a thermo-vector fluid, such as water, to support domestic water heating or low-temperature heating systems. As mentioned, such an approach plays a crucial role in enhancing the sustainability of atmospheric water, as it is centred on the multipurpose and integration concepts [6]. In other words, while producing atmospheric water, the system simultaneously delivers two additional useful outputs with the same energy input, significantly enhancing the overall efficiency of the entire HVAC system. Figure 2 represents the energy input and the energy outputs of an integrated AWG machine.

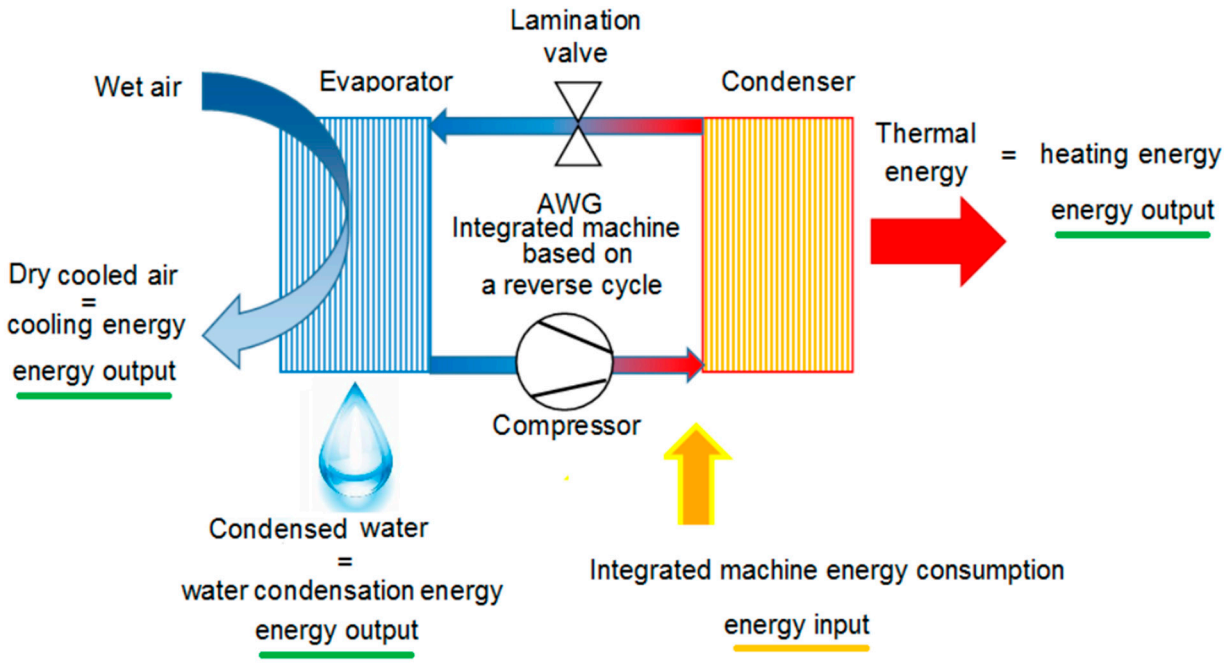


Figure 2. Energy input and outputs of an advanced integrated AWG machine (drawing based on an image presented by the authors in [16]).

From a holistic perspective—where water and energy savings are considered together as part of an integrated system—this type of machine represents a viable and sustainable solution for improving the overall efficiency of buildings. Therefore, it is essential to enable designers to incorporate such technology into their projects by providing them with simulation tools to assess their choices.

The next section describes the methodology that was developed to combine the use of the two aforementioned simulation tools aimed at calculating water harvesting, building energy behaviour, and the resulting potential energy savings.

3. Methodology

As previously mentioned, this research presents an initial method for importing the energy behaviour of an integrated AWG machine, calculated by means of AWGSim, into the DesignBuilder software. DesignBuilder (DB) (version 7.0.0.116) [41] is a graphical tool that integrates EnergyPlus (version 24.2.0), a powerful simulation engine for modelling building energy performance and water usage. DB performs dynamic, whole-building simulations, including the analysis of HVAC systems, thermal comfort, and natural ventilation, providing various output parameters such as indoor temperature, relative humidity, and energy consumption.

The simulation tool allows users to define the building model based on its geometrical and thermal characteristics. The input data are the materials and the thickness of each envelope component and internal frame, along with their thermal properties and shape. In addition, surroundings modelling is required, in order to define possible interactions with the analysed building (i.e., shading), as well as it is required defining its geographical location. Detailed hourly climate data—including temperature, relative humidity, solar irradiance, and wind speed—serve as the driving variables governing energy exchanges between the building and the external environment. Internal loads and HVAC systems can be defined using templates and scheduling. Due to the novelty of the technology, advanced integrated AWGs are not yet included among the available options of possible plant configurations.

In the current research, the method applied to include such a machine within the DB software is as follows.

Case study selection: In first instance, a suitable case study was chosen, which involves: an application requiring high-quality water, a location where traditional water sources are unavailable, and a building that needs at least one of the other useful effects provided by the AWG. A previous study [11] about the integration of atmospheric water with hydrogen production was chosen as the starting point. The current research builds upon these previous findings, enriching the analysis by taking into account a building that houses inverters and transformers intended for the photovoltaic field of said project.

Building and equipment data collection and adaptation: As data on the specific building were unavailable, the authors gathered information on a similar structure that supports the photovoltaic field at Pavia University, which has an installed power of the same order of magnitude. Ancillary equipment characteristics—including the released heat loads of inverters and transformers, as well as the chiller features—were obtained from real-life data sheets. The original building, whose description is reported in Section 4.1, was resized to align with the photovoltaic field of the case study; the same resizing was carried out on the ancillary equipment effects (heat loads, chiller energy consumption, and cooling energy).

AWG implementation in DB: The implementation of the AWG in DB involved the use of AWGSim to determine both the water production and the thermal fluxes released by the advanced integrated AWG. These thermal fluxes were simulated in DB by arranging standard pieces of equipment from the library, including coils, fans, and chillers. These components were appropriately sized and scheduled for their operational modes to ensure that the thermal behaviour of the AWG was accurately calculated in DB. The scheme of the model is shown in Figure 3.

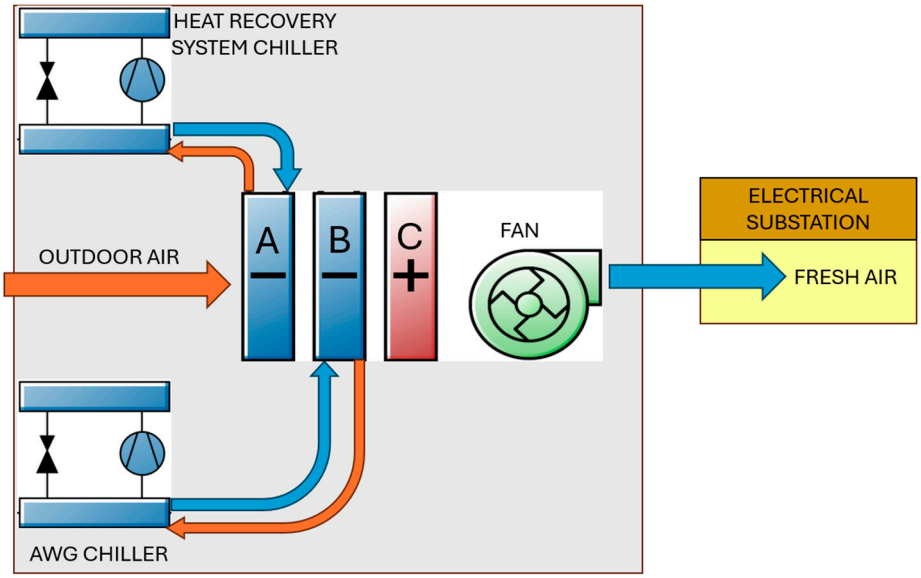


Figure 3. Integrated AWG scheme for DB modelling.

AWG model components: The AWG model consists of the following components:

- Heat recovery system: the real-life AWG features a heat recovery system that uses the fresh airflow, cooled by the AWG evaporator, to pre-cool the outdoor air flow. The corresponding model in DB consists of three elements:
  1. Coil A, which represents the pre-cooling effect;
  2. Heat recovery system chiller;
  3. Coil C, which models the post-heating effect.
- Coil B, which represents the real-life AWG evaporator, where the air flux is cooled and dehumidified;
- Fan, representing the existing fan set of the AWG;
- AWG chiller, which encompasses the VCRC of the AWG.

Simulation parameters and data sources: the effect of the integrated AWG was modelled in DB, with the following average hourly values being imposed:

- ➢ Hourly air flux moved by the fan;
- ➢ Temperature (t_1) and relative humidity (*r.h.*) of the outdoor environment, obtained from the weather data recording station located 37 km from the photovoltaic plant;
- ➢ t_2 and air water content, x_2, after Coil A;
- ➢ t_3 and x_3 after Coil B;
- ➢ t_4 and x_4 after Coil C.

The aforementioned values of t and x after Coil A, B, and C, as well as the air flux values, were obtained as output from a simulation conducted using AWGSim, version 1.02.d. As previously mentioned, such a software is a physically-based simulation tool specifically developed to dynamically simulate the behaviour of the integrated AWG on the basis of the temperature, relative humidity, and total pressure of the environmental air. The tool implements mass and energy conservation principles, modelling both the transient behaviour of the system and its steady-state operating conditions. An example of data, coming from the AWGSim model, intended for DB implementation is reported in Table 1.

Table 1. Example of AWGSim output results intended for DB implementation.

t_1	*r.h.*	t_2	x_2	t_3	x_3	t_4	x_4	v
°C	%	°C	kg/kg	°C	kg/kg	°C	kg/kg	kg/h
19.4	67.4	12.8	0.0095	4.3	0.0051	11.5	0.0051	13,944
21.9	73.9	16.0	0.0122	6.9	0.0061	14.7	0.0061	12,708
29.7	79.6	24.4	0.0211	13.8	0.0098	23.6	0.0098	10,038
29.5	71.3	22.8	0.0186	12.7	0.0091	22.3	0.0091	10,072

For the simulation of the integrated AWG monthly behaviour, average hourly values were used as input, calculated from hourly data recorded between 2018 and 2022 by the aforementioned weather station.

AWGSim accuracy: AWGSim has already been used in previous researches [22,23] that implemented the same AWG model analysed in this paper, with a very good match being obtained between the calculated results and the real-life test. In particular, an accuracy assessment of the model was discussed in [22]. For clarity, Figure 4 reports the graph comparing real-life tests of water production—carried out under 19 different environmental conditions, with temperatures ranging from 23 °C to 33 °C and relative humidities from 42% to 72%—with the simulation results. The average error is below 2%.

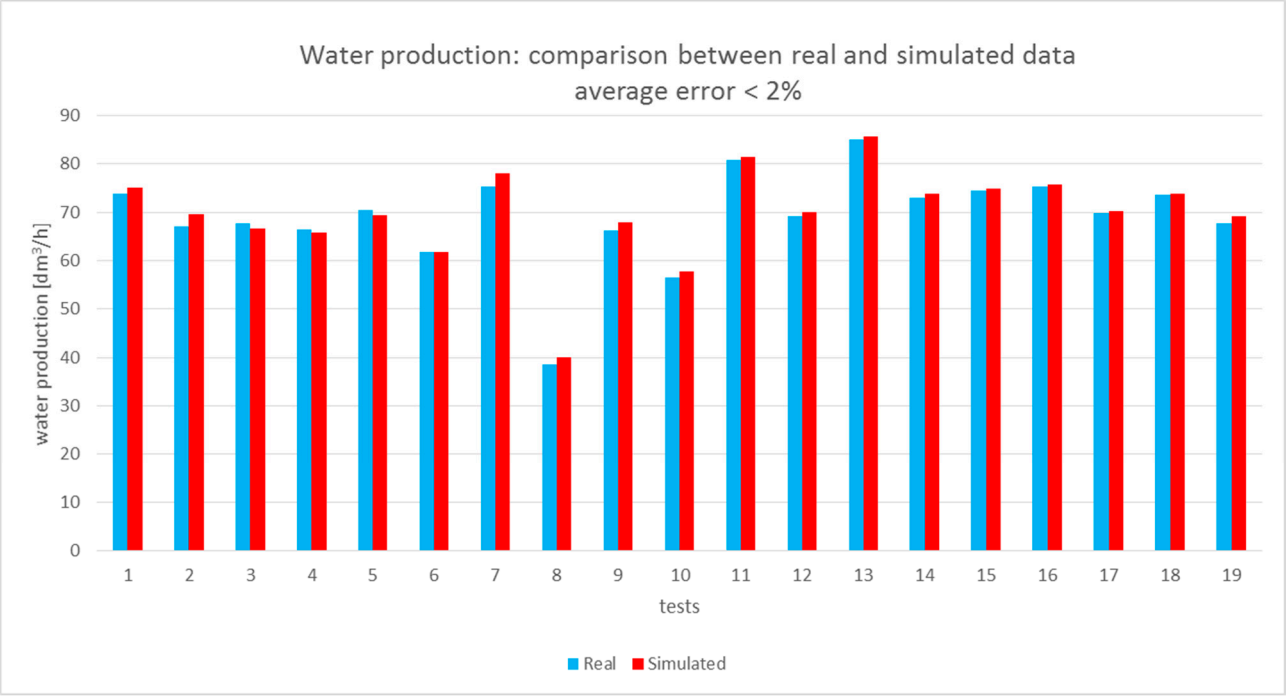


Figure 4. Water production: real-life test (in blue) and simulated (in red) results comparison. The average error is lower than 2% (figure comes from [22]).

Similarly, Figure 5 presents the comparison between the real and simulated energy consumption in terms of unit power consumption, defined as the ratio between the total energy required by the machine and the water produced [42]. In this case, the average error is below 5%.

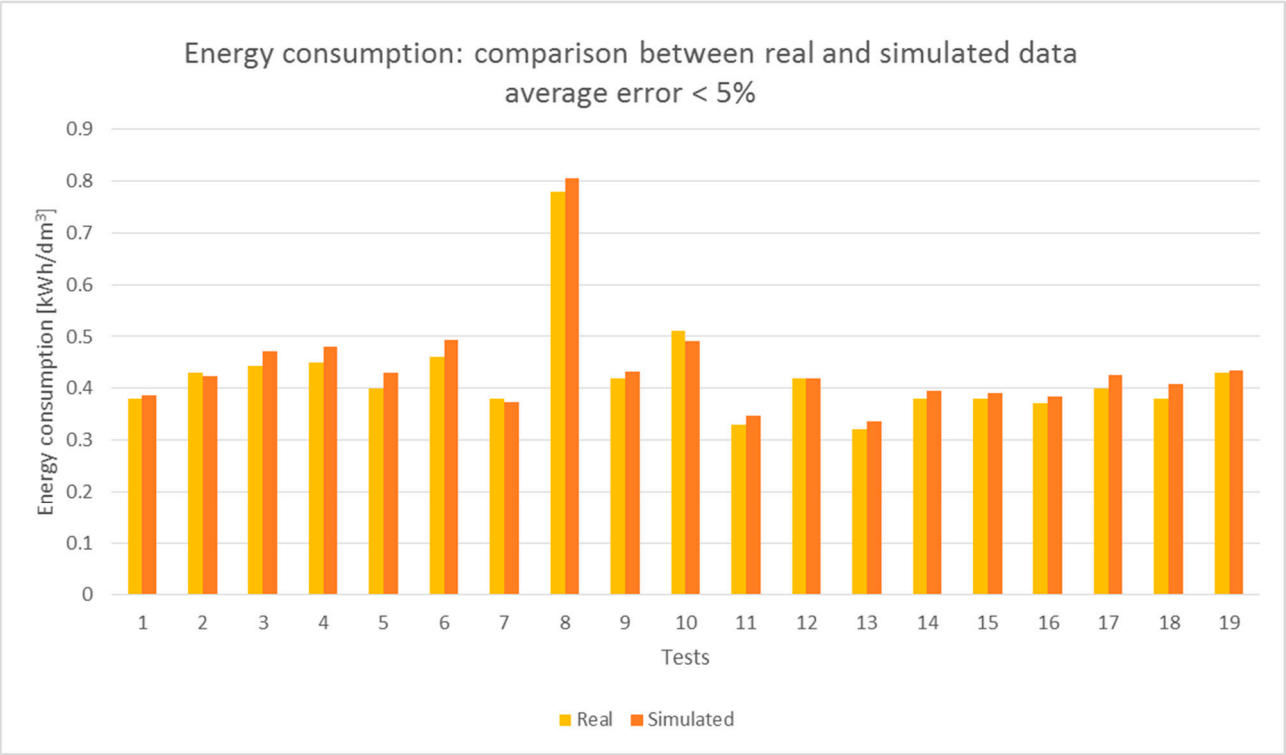


Figure 5. Energy consumption: real-life test (in blue) and simulated (in red) results comparison. The average error is lower than 5% (figure comes from [22]).

It is worth mentioning that temperature and relative humidity probes, normally used to assess environmental conditions, have an average error of 2% and 5%, respectively [43]. Given the good match between the real-life and simulated results, the AWGSim software was considered suitable for providing the necessary data to complete the AWG model in DB.

DB validation: The validation of the DB implementation of the AWG thermal effects was carried out by comparing the useful effect (cooling) calculated by both AWGSim and DB. Figure 6 shows the difference between the two results for 11 different environmental conditions. The average error is below 3%; thus, the model was considered reliable for simulating AWG thermal effects.

DB outputs limitation: It should be noted that, after integrating the AWG model as described above, DB was able to simulate the energy behaviour of the building, taking into account the AWG effect. However, DB did not output any data concerning water condensation resulting from the AWG use. To the best of the authors' knowledge, DB can provide information on water use within buildings, but not on potential water production from unconventional sources such as air. Consequently, these data were derived from the AWGSim results.

Ultimately, DB produced results regarding indoor building temperatures, required cooling energy, and electrical energy consumption, while AWGSim provided information on the air flux conditions exiting the AWG, the amount of water produced, and the associated energy consumption.

The next section presents a description of the case study, along with the simulation results and their contextual discussion.

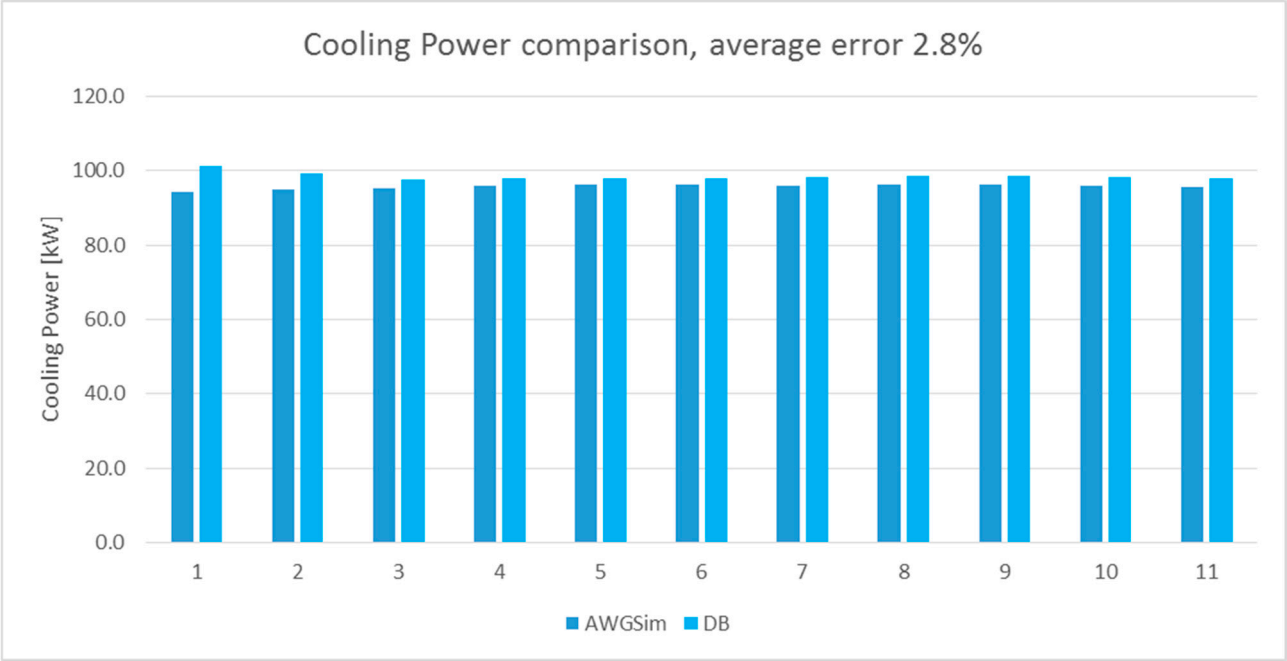


Figure 6. Cooling power calculation comparison: results are in dark blue for AWGSim and in light blue for DB.

4. Case Study Description and Simulation Results

The thermal energy simulation conducted in this study concerns a building housing inverters and transformers that are required as ancillary systems for the project of a 2 MW photovoltaic field described in [11]. This previous research analysed the use of a real-life integrated AWG machine—the very same model considered in the current study—in order to produce water for an electrolyser connected to the electricity production plant. The machine operated only during the specific daylight hours when the photovoltaic system generated enough energy to meet its power requirements. The photovoltaic field project was conceptualised for a Japanese island, Iriomote, which is a natural park. The produced electricity was to be used partly for green hydrogen synthesis, intended as an energy storage solution [44], and partly to directly meet the island's energy demands. The prior analysis focused solely on water production and the energy sustainability of the process. It was found that the harvested water was more than sufficient to meet the hydrolysis requirements, with a surplus that ensured effective panel cleaning. The calculated efficiency gain of the photovoltaic field, due to cleaning, was more than enough to cover the AWG power consumption, demonstrating the energy sustainability of such an installation.

The abovementioned study hinted at the possibility of exploiting the other potential benefits of the integrated AWG, namely its cooling and heating effects. In this section, the authors build on the previous results and expand the analysis to consider the cooling power of the AWG. Thus, AWGSim was used to determine the thermal contribution of the machine along with its water production and energy consumption. As described in the Section 3, once the AWG behaviour was determined, the data were used as input for DB to assess the contribution of the integrated machine to building temperature control. The scheme of the intended integration of the AWG in the whole plant can be seen in Figure 7.

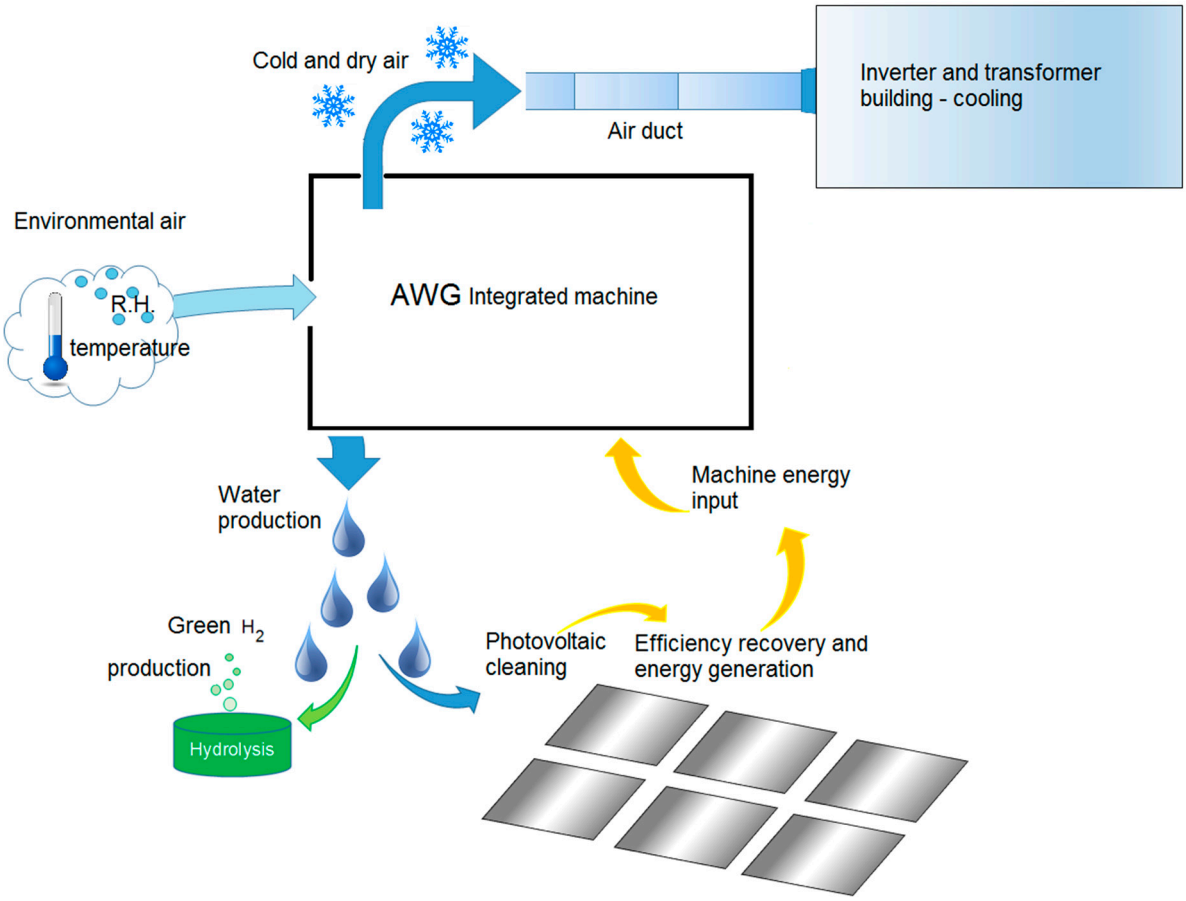


Figure 7. AWG integration in the plant.

As previously mentioned, in order to determine the cooling energy required by the substation housing inverters and transformers, a real-life similar existing plant and its ancillary devices were considered and rescaled to match the size of the Iriomote project. In the next subsection, the existing building and the connected equipment are described.

4.1. Building and Equipment Description

The real-life electrical substation building, used as the archetype for the DB simulation, is located at the University of Pavia (Italy). It houses inverter and power transformer systems that serve a 1.18 MWp photovoltaic field. The building is composed of masonry and its main geometric characteristics are summarized as follows:

- A rectangular layout with an area of approximately 35 m^2;
- A width of 3.50 m and a length of 12.70 m;
- An external height of 3.00 m and an internal height of 2.80 m;
- An internal volume of approximately 124 m^3;
- The building walls feature three doors, each 1.20 m wide and 2.15 m high, and 16 windows, each 1.20 m wide and 0.50 m high.

The main components of the building are described as follows:

- The perimeter walls are made of plastered heavyweight concrete blocks that are 0.1 m thick, with a transmittance of 2.07 W/(m^2·K);
- The ceiling consists of panels that are 0.20 m thick and has a transmittance of 0.35 W/(m^2·K);
- The cast concrete floor is 0.30 m thick and has a transmittance of 2.10 W/(m^2·K);
- The doors are made of plastic materials and have a transmittance of 2.82 W/(m^2·K);

- Each window consists of a metallic frame and a metallic grid; the openings collectively enable a natural air exchange rate of one volume per hour for the entire building.
- The scaled model for the 2 MW field has doubled dimensions and retains the envelope characteristics.

The heat load inside the building is generated by the inverters (Elvi Group QCC-250k-DCHV model) and power transformer systems (Tesar TRP-002-1250-0010-00 and TRP-002-2000-0010-00) housed in the electrical substation. In particular, the main heat release occurs during photovoltaic production hours, when the inverters and transformers are actively operating. A residual heat load remains during the inactivity hours of the plant, caused by transformer hysteresis and parasitic currents resulting from the grid connection. The heat release from the inverters and transformers, for the intended plant of Iriomote, can be estimated to be 4.2% of the produced energy and in an average energy flux of 3.8 kW during inactivity hours. These values were obtained from the real-life plant datasheets and can be scaled if needed.

It is well known that such a heat-load can potentially cause overheating and a decrease in inverter efficiency. For example, in [45], a 4% loss was found when the surrounding temperature exceeded 47 °C. According to various inverter producers, temperatures should not exceed 40–45 °C because, normally, over such temperatures, derating occurs. The optimal range would be 20–40 °C.

Additionally, in order to avoid other electrical issues, it is recommended to avoid temperatures below 5 °C.

The considered building has a chiller plant that ensures an upper temperature limit of 40 °C during the photovoltaic field operating hours.

The electrical substation was modelled using DB, considering the building features, including its geometry and envelope characteristics, the environmental and geographical conditions of Iriomote, the internal loads, and the cooling system.

Figure 8 depicts the three-dimensional representation of the building model in DB. Although the model is displayed in false colours, the actual radiative envelope characteristics are accurately considered in the calculations.

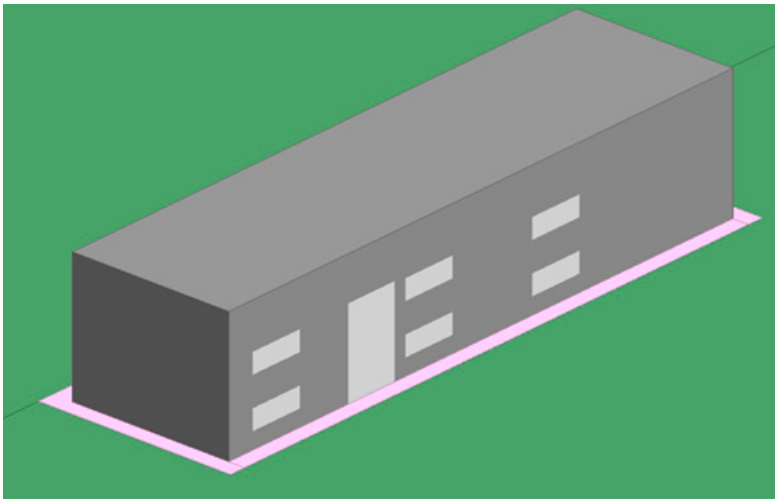


Figure 8. Electrical substation building, three-dimensional representation in DB.

Figure 9 illustrates the plant scheme used in the simulation, which includes the chiller and the associated emission system (fan coil). This setup is referred to as “configuration A”.

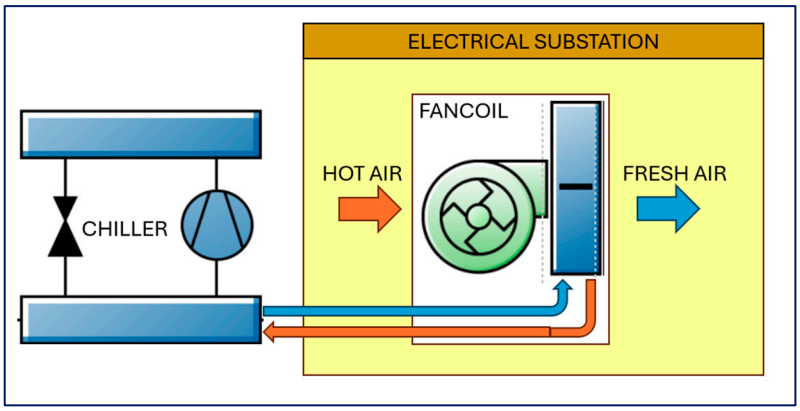


Figure 9. Configuration A: chiller serving the electrical substation building.

It is important to underline that the chiller serving the building uses technical water as the thermo-vector fluid. There is no specific requirement for fresh air exchanges to maintain indoor comfort, as the structure is designed solely to house inverters and transformers, with no permanent human presence expected. The chiller dissipates thermal loads through fan coils, ensuring that, during inverter operation, the temperature remains below 40 °C to prevent derating, with maximum allowable peaks of 45 °C when the photovoltaic system is not producing. Windows are kept open to support the active cooling of the chiller and are fitted with grids to prevent the entry of intruders and external pollutants.

4.2. Integrated AWG Machine Description

The considered AWG machine has the functioning scheme described in Section 2 and shown in Figure 2.

Its main characteristics are reported below:

- Evaporation fans serving the inlet section: the rotation speed of the fans is controlled by an inverter, allowing a programmable logic controller (PLC) to modify the air flux depending on the external conditions to enhance the efficiency of the machine. The inlet section is provided with two layers of filters to guarantee pollution removal;
- The fins and tubes of the heat exchangers and heat recovery system, composing the section where the air moisture condensation occurs, are made of food-grade materials to avoid any contamination of the condensate;
- Screw model compressor: its nominal cooling is 100 kW;
- The outlet section of the treated air flux (cooled and dried) can be connected to a duct to convoy the air flux;
- Double condenser coils: the coils include a plate one, intended for condensation heat recovery, and a fins and tubes one, cooled by dedicated fans, which is to be used when heat recovery is not needed;
- The atmospheric water piping circuit is made of food-grade materials;
- The water is stored in a stainless steel container;
- The water treatment unit is tailorable to achieve the required quality;
- The machine includes an on-board PLC that rules the entire machine, controlling the air speed, water production, and reverse cycle parameters;

Starting from the photovoltaic energy yields in Iriomote [11], shown in Table 2, it was possible to define the working hours of the integrated AWG machine.

Table 2. Energy yield during the average day of each month. In light blue the hours when the AWG machine works are highlighted (the table is an elaboration of the original data coming from [11]).

Hour of the Day	06:30	07:30	08:30	09:30	10:30	11:30	12:30	13:30	14:30	15:30	16:30	17:30	18:30	19:30
Month	**Photovoltaic Power Yield [kW]**													
January	0	0	90	286	508	692	818	876	795	737	149	0	0	0
February	0	6	140	375	607	824	958	1035	1008	936	793	66	0	0
March	0	33	199	442	691	887	1027	1083	1036	973	764	102	0	0
April	3	91	294	521	745	910	1046	1016	1029	936	723	112	0	0
May	15	138	346	577	785	989	1085	1154	1056	957	728	117	0	0
June	20	161	403	680	921	1100	1214	1251	1210	1111	903	407	36	0
July	12	139	379	646	895	1091	1238	1240	1203	1050	844	607	42	0
August	3	107	332	599	823	1029	1125	1164	1109	981	770	135	0	0
September	0	94	329	623	886	1094	1243	1225	1167	1031	848	84	0	0
October	0	59	271	550	818	989	1080	1097	1025	963	435	0	0	0
November	0	24	180	410	644	810	915	924	871	777	91	0	0	0
December	0	1	67	198	345	450	538	524	443	429	75	0	0	0

Simulations of the AWG behaviour were carried out using weather data for the machine working hours, referring to the average monthly day. It must be remembered that the climate of Iriomote is stable enough during each month of the year to justify such a simplification, as discussed in [11] and supported by the findings of [46].

The simulation tool outputted the AWG daily water production, shown in Figure 10, whose average value (Avg) was equal to about 940 L/day.

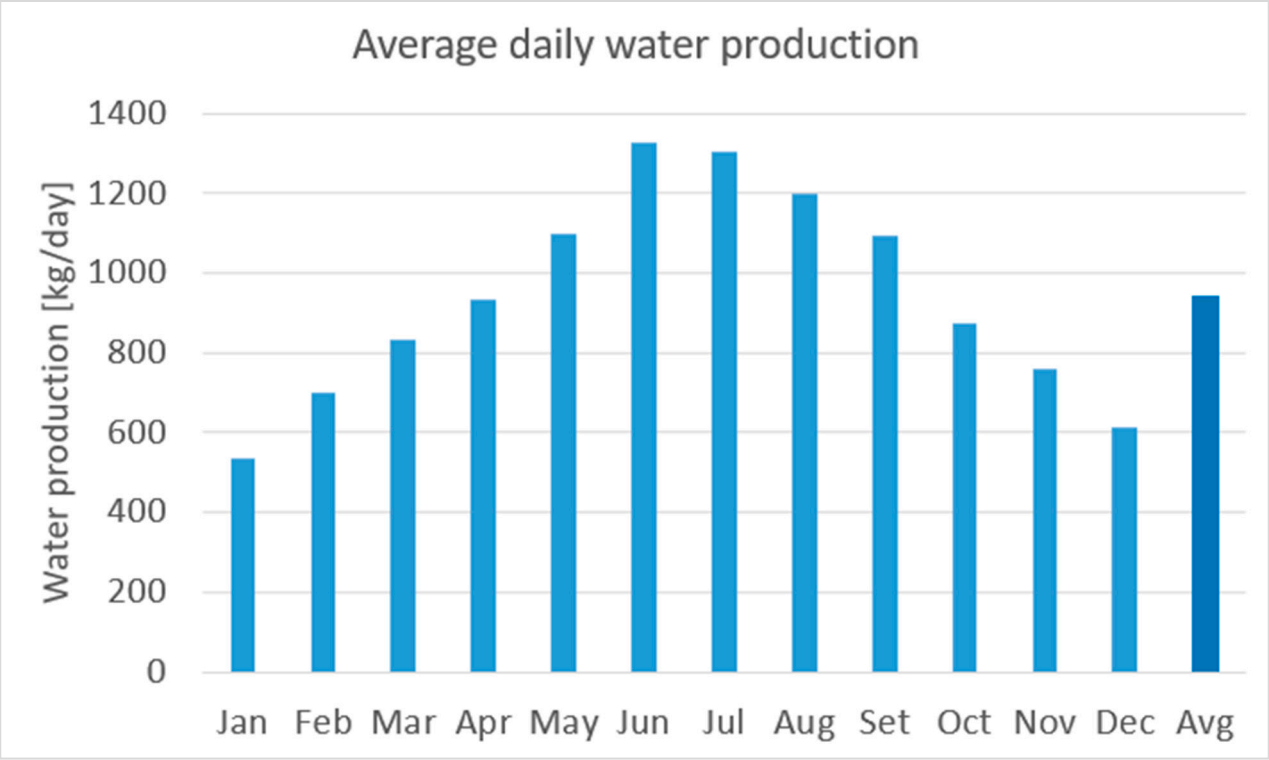


Figure 10. AWG daily water production.

As described in Section 3, the key feature of integrated AWGs is their capability to provide other useful effects, simultaneously to water production. In the analysed case, the

software outputted that the AWG was able to provide a cooled and dehumidified fresh air flux in a range from 14,000 kg/h to 10,000 kg/h, characterised by a temperature which goes from 11.5 °C to 23.9 °C, as can be seen in the graph of Figure 11.

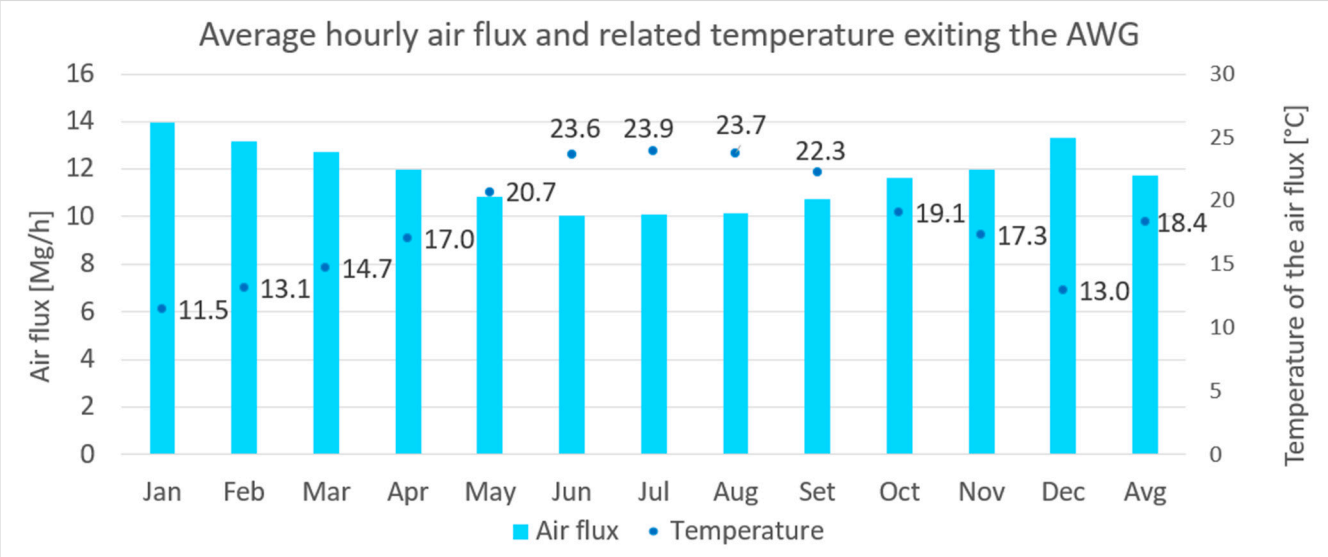


Figure 11. Average hourly air flux and related temperature.

The yearly energy consumption of the machine was confirmed to be equal to 108.3 MWh, a value lower than that of the recovered electrical energy, which is due to the efficiency improvement given by the periodical cleaning [11].

In addition to the air flux entity and temperature, it was possible to determine the air state at the various points required by the DB software (an example is reported in Table 1, Section 3). Once the aforementioned data were obtained, the effects of the AWG machine in terms of cooling were implemented in DB, as described in the methodology.

The plant setup called "configuration B" corresponds to the integrated solution, which is composed of a back-up chiller and the AWG contribution. The chiller has the same characteristics as the existing one, but with a lower cooling capacity, and it is equipped with a fan coil. The AWG contribution is represented by the cooled and dried air flux convoyed into the building.

Figure 12 represents the schematisation of configuration B inside the DB software.

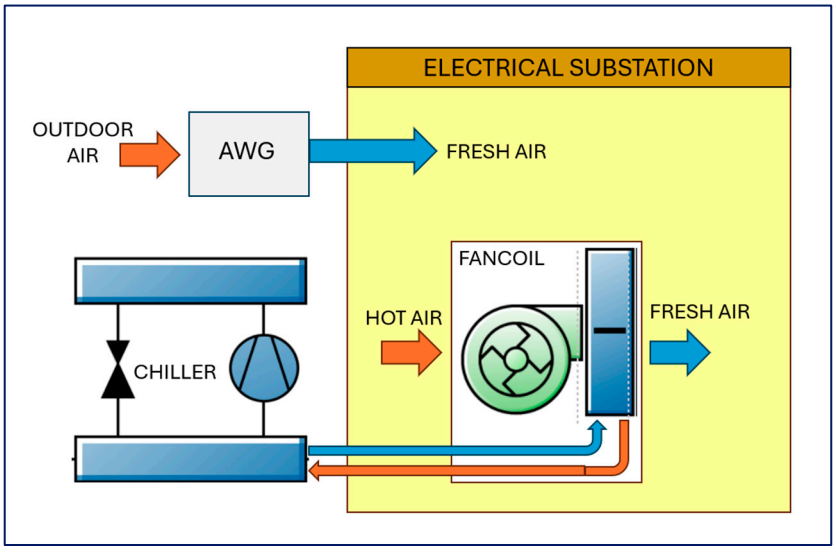


Figure 12. Configuration B: AWG contribution and back–up chiller.

4.3. Simulation Results of the Configuration A

The first DB simulation was carried out considering the energy balance between the indoor and outdoor environment, given the energy load, due to the inverters and the transformers, and the cooling power provided by the sole chiller. The set-point temperature was 40 °C. The air infiltration rate was set as equal to 1 volume/hour. For the simulation, the datasheet of a similar chiller installed in the University of Pavia was used, which has a nominal energy efficiency ratio (EER) of 2.5 and a cooling power of 52.4 kW.

Figure 13 reports the indoor air temperature behaviour, evolving over the 24 h of each average monthly day.

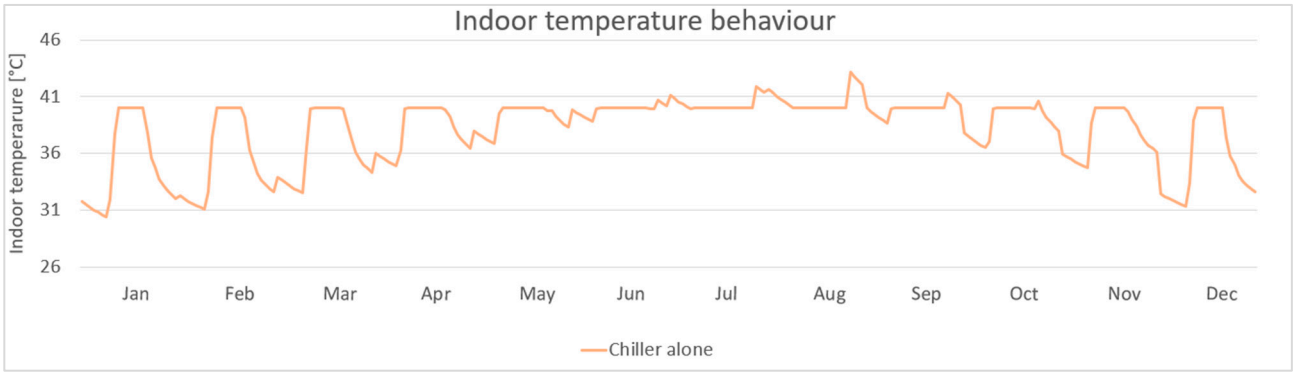


Figure 13. Indoor air temperature behaviour in configuration A during the average monthly day.

Observing the graph shown in Figure 10, some interesting insights can be inferred. The chiller is always able to avoid exceeding the maximum temperature allowed during the operating hours of the photovoltaic field.

During autumn, winter, and the first early spring, when the panels do not work, there is a fast temperature decrease inside the building. This is due to the external conditions, which are considerably lower in comparison to the internal ones, as can be deduced by observing Figure 14.

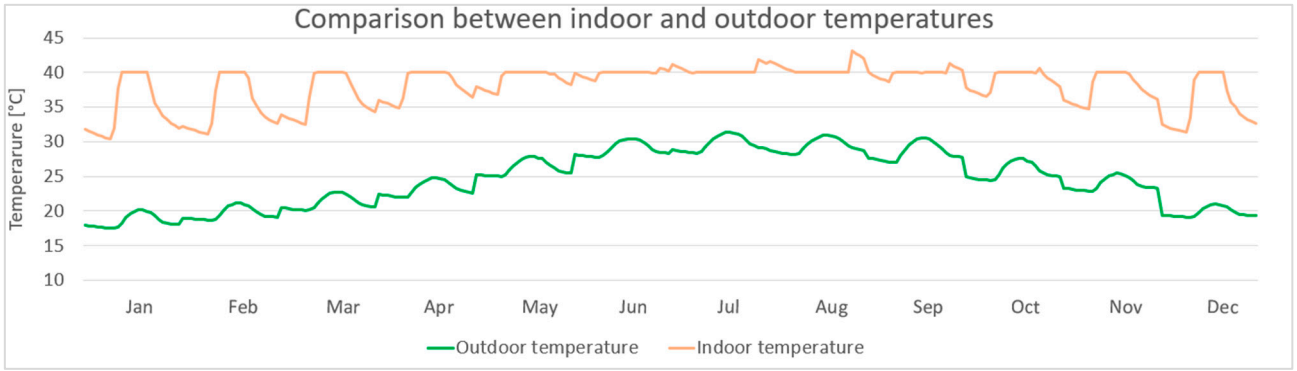


Figure 14. Comparison between indoor and outdoor temperatures during the average monthly days for configuration A.

In these periods, the residual heat load, given by the transformers, can be easily dissipated by natural heat exchanges.

Conversely, during late spring and summer, it is possible to observe that, when the photovoltaic yield stops and the chiller control system admits a higher temperature set point, the difference between the indoor and outdoor temperatures is lower, and the natural heat exchange is no longer enough to immediately dissipate the internal load; thus, the

indoor temperature increases. However, the building internal temperature never reaches 45 °C.

In Table 3, shown below, the cooling power provided by the chiller is shown.

Table 3. Cooling power provided by the chiller. The cells reporting the hours when the chiller works are in yellow, while the grey cells represent the hours when no chilling is required.

Hour of the Day	6:30	7:30	8:30	9:30	10:30	11:30	12:30	13:30	14:30	15:30	16:30	17:30	18:30	19:30	20:30
Month	**Cooling Power Provided by the Chiller Alone [kW]**														
January	0	0	0.2	3.9	9.9	14.6	16.4	14.4	9.5	3.7	0.1	0	0	0	0
February	0	0	0.1	2.8	7.5	12.3	14.6	13.7	11.0	6.1	0.9	0	0	0	0
March	0	0	2.7	8.9	16.3	22.7	25.6	23.3	17.6	10.1	2.8	0.1	0	0	0
April	0	1.9	8.3	15.9	21.2	25.4	25.9	21.4	17.3	11.9	5.3	1.0	0	0	0
May	0	1.9	8.3	15.9	21.2	25.4	25.9	21.4	17.3	11.9	5.3	1.0	0	0	0
June	1.4	6.7	14.7	21.5	27.0	31.3	32.4	29.3	23.8	16.4	9.2	4.3	1.9	1.1	0.8
July	1.9	7.8	17.5	25.6	31.7	36.9	39.4	38.6	32.7	22.8	13.0	5.9	2.9	1.9	1.6
August	1.6	7.8	18.3	29.0	39.4	46.9	48.1	41.5	34.2	24.5	13.6	6.1	3.1	2.3	0
September	0	5.3	13.2	23.0	31.3	38.6	41.3	36.9	28.9	18.9	8.5	2.9	1.8	1.2	0
October	0	1.8	8.5	17.4	24.5	30.3	31.9	27.9	21.3	12.3	4.2	1.0	0	0	0
November	0	0	3.9	10.3	16.6	21.1	21.1	17.8	12.1	5.1	0.6	0	0	0	0
December	0	0	0.9	5.2	11.8	17.0	18.8	15.6	9.5	3.2	0	0	0	0	0

Observing Table 3, it is possible to ascertain two insights: the maximum required cooling power exceeds 48 kW and the chiller is called to work during June, July, August, and September for some hours after the photovoltaic field has stopped producing energy in order to avoid exceeding the 45 °C threshold.

4.4. Simulation Results of the Configuration B

The second simulation was carried out to calculate the energy balance of the building with the same internal load and environmental conditions as in configuration A. In this, case, the cooling contribution of the AWG—given by the cooled and dried air flux—and the presence of an ancillary chiller—as a back-up, in order to avoid any possible exceedance of the threshold of 40 °C—were considered. It should be remembered that the AWG works only when the photovoltaic field provides enough energy to cover its needs.

Figure 15 reports the indoor temperature values coming from the DB simulation of configuration B.

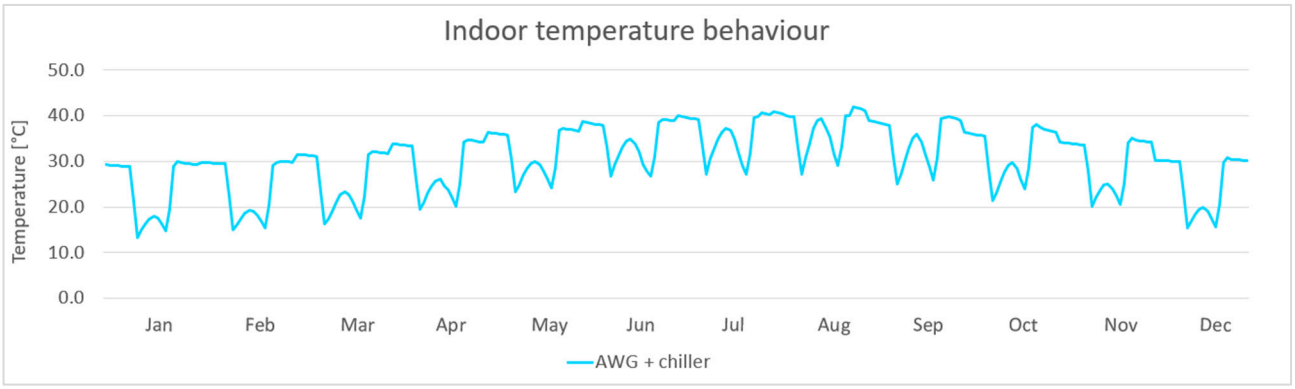


Figure 15. Indoor temperature behaviour in configuration B during the average monthly day.

Analysing the image above, it is immediately clear that the indoor temperature in configuration B is lower in comparison to that achieved in configuration A. This is because the cooling effect of the AWG is higher on average in comparison to that provided by the existing chiller. Such a behaviour is justified by the different scopes and settings of the two machines. The AWG is oriented to water production; thus, its cooling energy is a consequence of such a process, while the existing chiller is programmed to counteract only the ratio of the heat loads that cause the threshold to be exceeded.

Obviously, inverters perform better when temperatures are lower; however, the existing chiller is sized in order to minimise the energy consumption, and thus only grants the 40 °C threshold. This is because the only useful effect of such a machine is its cooling effect, and no other advantages come from its use. Therefore, its sizing should reflect a balance between the energy consumption for cooling and the energy consumption due to inverter possible efficiency loss. On the other hand, the main aim of the AWG is to produce water, which serves two purposes: improving the energy efficiency of the panel field through cleaning and providing the raw material for hydrogen production. Therefore, the higher cooling effect, exceeding the minimum request, is amply justified by the obtained atmospheric water. In such a way, the AWG not only covers the water needs of the plant, but also gives substantial help to the control of the temperature inside the building, permitting a better efficiency of the inverters.

Table 4 highlights the residual cooling power which must be provided by the ancillary chiller. In the table, the yellow cells represent the hours when the AWG is not working and the entirety of the cooling must be supplied by the chiller, while the green ones represent the periods when the ancillary equipment only provides support to the AWG. The blue cells represent the periods when the AWG cooling effect is enough to cover the building needs, and the grey cells indicates the times when no cooling is required.

Table 4. Residual cooling power provided by the ancillary chiller during the average monthly days. The colour of the cells has the following meaning: yellow signifies hours when the AWG is off and the ancillary chiller is cooling; green indicates periods when the ancillary equipment supports the AWG; blue shows times when the AWG alone meets the building cooling needs; and grey represents times when no cooling is needed.

Hour of the Average Day	**6:30**	**7:30**	**8:30**	**9:30**	**10:30**	**11:30**	**12:30**	**13:30**	**14:30**	**15:30**	**16:30**	**17:30**	**18:30**	**19:30**	**20:30**
	Residual Cooling Power Required to the Chiller in the Configuration Comprising the AWG Contribute [kW]														
January	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
February	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
March	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
April	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
May	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
June	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.02
July	0.7	0	0	0	0	0.02	0	0	0	0	0	0	0	0.5	0.8
August	0.3	0	0	0.5	2.6	2.7	1.6	0	0	0	0	0.3	1.7	1.6	0
September	0	0	0	0	0	0.02	0	0	0	0	0	0	0.3	0.3	0
October	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
November	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
December	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Observing the table above and comparing it with Table 3, it is clear that the cooling power required by the chiller is of very small proportions and is only needed for very few

hours over the whole year. Therefore, the ancillary chiller has a cooling capacity of only 3 kW, instead of the 52.3 kW required by configuration A.

Figure 16 reports the results of the comparison between the cooling power required by the chiller of configuration A and that of the one related to the equipment of configuration B. The graph shows clearly that, in configuration B, the chiller must work only for a little period and only during June, July, August, and September. Additionally, the required cooling power is a fraction of that provided by the chiller of configuration A.

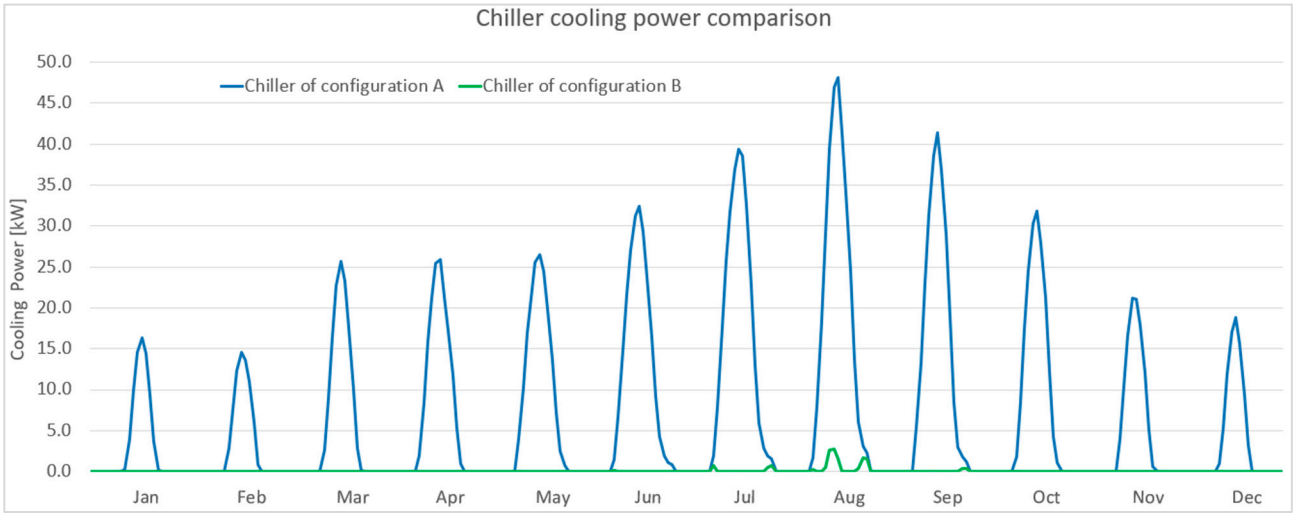


Figure 16. Comparison between the cooling power required by the two chillers in the two configurations: A, in blue; B, in green.

As for the energy savings, it must be remembered that the AWG energy consumption is entirely covered by the recovered efficiency of the panels, which is achieved thanks to the periodical washings enabled by the produced water. Thus, it can be said that, while configuration A has a net energy consumption that is determined by the employment of the existing chiller (characterised by a nominal cooling power of 52.3 kW), configuration B provides energy savings that are determined by the difference between the consumption of the existing chiller and the residual work of the 3 kW cooling-power ancillary equipment. Figure 17 reports the difference in the chiller energy consumption between the two configurations, which represents the possible energy saving.

The annual energy savings which can be achieved by the employment of the integrated AWG are about 29.8 MWh. It should be noted that such savings are due to the lower usage of the ancillary chiller, which is called to work only for a few hours during the entire period.

The next section discusses some final considerations about the results, along with future developments.

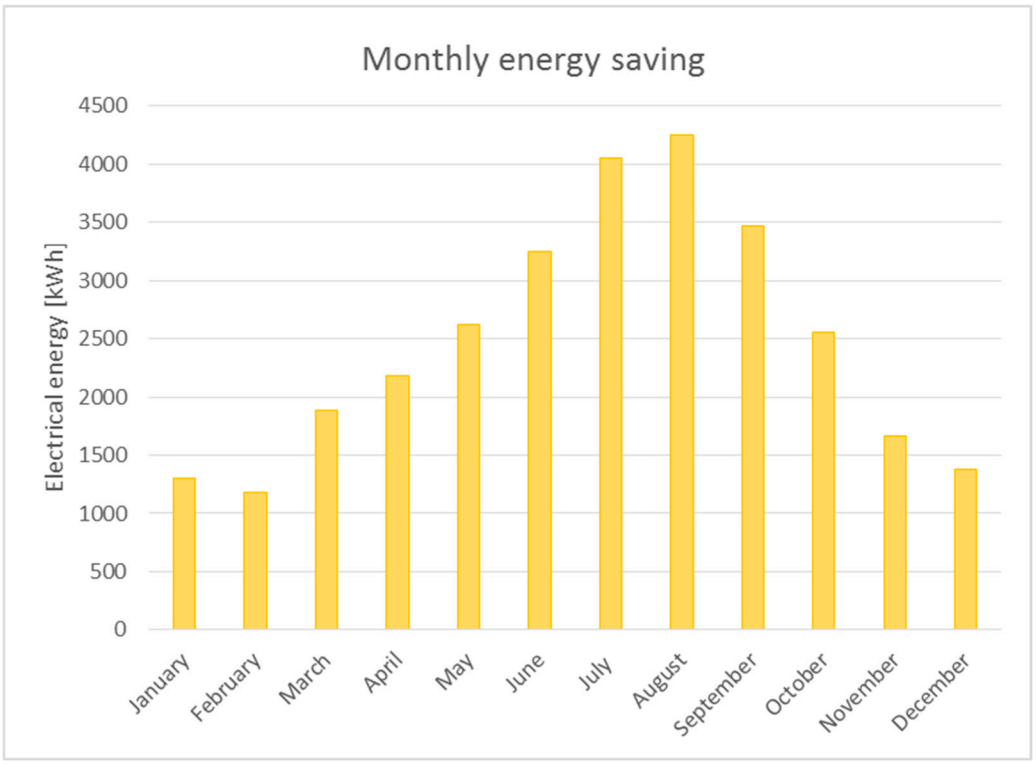


Figure 17. Energy saving given by the AWG integration.

5. Considerations and Future Developments

Comparing the simulation results, it becomes evident that the action of the integrated AWG can play a significant role in the overall energy balance of the photovoltaic plant.

The energy consumption of such equipment is higher than that of the dedicated chiller for the inverter building, because the primary scope of the machine is atmospheric water collection, rather than cooling. Additionally, the cooling effect inside the building is mainly given by the air changes provided by the AWG. Nevertheless, the simulations reveal that the dedicated chiller represents an additional energy cost, which can largely be avoided if the project incorporates the integrated system. The water production of the AWG is the key benefit, as it not only supplies the raw material for hydrogen synthesis but also enables panel maintenance, which is essential for achieving AWG energy consumption neutrality (the entire energy consumption of the machine is covered by the enhanced photovoltaic production due to regular cleaning). Additionally, the secondary cooling effect, resulting from atmospheric water extraction, does not incur additional energy costs and is almost sufficient to maintain the electrical substation temperature set-point. Moreover, the average indoor temperature during the AWG operation time is generally lower than the required set-point, further enhancing the inverter efficiency.

Enriching building simulations with a multipurpose machine, like the one analysed herein, enables designers to adopt an integrated approach that recognises the water-energy nexus [47]. By linking water management with energy efficiency, this holistic perspective supports both resource conservation and overall system optimisation.

In the case study, it was observed that the integration of the two simulation tools allows for the optimisation of the traditional cooling system, which can then be considered either as a final refinement or as a supplementary support to the cooling effect of the integrated machine. These initial results of the integration process were encouraging. Nevertheless, it should be acknowledged that the building analysed in the current case study was relatively simple. The main challenge in scaling this approach to more complex cases concerns the

complexity of the plant systems to be analysed rather than the architectural design of the building, as the former is directly influenced by the presence of the AWG. The method adopted in this paper is an analytical approach: the AWG effect was imported into DB as its cooling impact, providing the software with a structured dataset correlating external conditions with machine outputs. Applying this method to more complex buildings is certainly feasible, but it requires the inclusion of multiple scheduling lines. This process can be onerous and may also result in errors, as large amounts of data are handled. To overcome this issue, the next step in this research involves a deeper integration between the two software tools. Work is currently underway on developing a script that will enable the modelling of advanced AWG operation within DB using performance curves derived from AWGSim. This achievement will require the implementation of custom scripts within DB, a feature that is available to advanced users. This approach is expected to facilitate the implementation of integrated AWG systems in more complex buildings, making their adoption more practical and efficient.

However, even in the next development stage, water production will not be directly incorporated into DB results. A further development, currently under analysis, involves the direct integration of EnergyPlus to overcome this issue.

The ongoing case study explores a more complex application, focusing on a hospital building that, in addition to water, requires primary air cooling and domestic water heating. In particular, the AWG machine will serve the patient wing of the hospital, supporting its air conditioning system and domestic water heating boiler. It is worth mentioning that the water coming from the machine could be used not only for human consumption, but also for other hospital applications that require pure water. In particular, there will be a section focused on the quality of the obtained water and its possible uses. The hospital is located in Pavia. However, thanks to the described simulation tools, it will be virtually relocated to other parts of Italy that are affected by drought. It is worth noting that another important advantage of the simulation approach is its potentiality to extend study to different climates, allowing for a more comprehensive analysis of its application. In the next case study, the DB analysis will encompass all of the thermal potentials of the integrated machine. The joint action of AWGSim and DB offers a powerful tool for advanced energy design that fully integrates water management considerations. It is worth highlighting that advanced integrated AWG systems can be effective in all applications requiring, in addition to water, at least one of the useful effects provided by the machine—namely heating and cooling. This includes hospitals, hotels, industrial buildings, and residential buildings. The possibility of managing initial design and/or revamping project by integrating energy efficiency with water conservation can be an important step towards addressing the green and blue deals simultaneously and effectively. Moreover, DB allows users to integrate their projects with renewable energy production devices, such as photovoltaic panels and wind turbines. This additional capability can play a pivotal role in advancing the sustainability of atmospheric water, directly addressing the energy demand issue at the building design stage.

While this study primarily focuses on the technical aspects of integrating advanced AWGs into building projects through simulation tools, the economic feasibility of such solutions remains a crucial factor for real-world applications. In the design stage, assessing financial implications—including capital expenditures (CAPEX) and operational expenditures (OPEX)—is essential for informed decision-making. Advanced integrated AWGs have already proven effective in applications that leverage their multipurpose characteristics. For example, a hotel installation in Mexico, analysed by the authors [22], had a payback time of about two years. The economic evaluation of a case study concerning a worker village in Dubai was also extremely positive [23]. In this case, as well, the calculations provided a payback time of two years. Future research will focus on developing a structured

methodology to evaluate the economic benefits of integrated AWG systems, considering both direct cost savings (such as the reduction in bottled water procurement) and indirect advantages (such as enhanced system efficiency and the associated resource conservation). This approach will provide a more comprehensive framework for assessing AWG adoption across different building typologies and climatic conditions.

6. Conclusions

This research is the initial step in a broader study exploring the viability of integrating atmospheric water generation into building design strategies. In particular, the focus is on integrated AWG machines, which, in addition to producing water, can deliver energy benefits that support HVAC systems. These machines offer the dual advantage of contributing to atmospheric water sustainability while simultaneously enhancing energy efficiency.

For the first time, this study presents the combined use of two dynamic simulation software tools. The first, DesignBuilder (DB), is used to analyse the building energy performance, while the second, AWGSim, was used to evaluate the AWG performance. Their combined application was tested on a case study involving an integrated AWG and a building housing inverters and electrical transformers within a photovoltaic project. This research builds upon a previous study on the generation of hydrogen from atmospheric water.

The building model, including internal heat loads and the chiller required to control the internal temperature, was developed in DB, with external climate conditions serving as the forcing variables. The AWG effects, analysed using AWGSim, were then incorporated into DB, allowing the simulation to account for the cooling contribution of the integrated system. Two configurations were evaluated:

- Configuration A, which included the building and the dedicated chiller that was designed to maintain indoor temperatures below the required threshold;
- Configuration B, which integrated the AWG's cooling effects into the system.

The results demonstrated that the use of the integrated AWG could achieve energy savings of 29.8 MWh a year, as it supplied not only the water needed for maintenance and hydrogen production, but also nearly all the cooling power required by the building.

This study highlights the importance of adopting a holistic project approach that simultaneously considers water and energy aspects, as well as the crucial role of simulation tools in enabling such an integrated design process. Having a design tool that integrates systems addressing both energy efficiency and water resource management represents a significant step towards sustainability. By enabling the evaluation of multipurpose solutions from the early stages of the design process, this approach supports informed decision-making that maximize both water conservation and energy savings. Such a perspective addresses both the green and blue deals, promoting a more sustainable and resource-efficient built environment.

The promising results obtained from this initial attempt at software integration open new avenues for further research, particularly in enhancing AWG integration within building energy simulation tools.

In this context, future work will focus on refining simulation capabilities to better model the dynamic interactions between AWGs and building energy systems. This will ultimately contribute to the development of a more comprehensive tool for supporting sustainable architectural and engineering solutions, reinforcing the role of integrated approaches in addressing both energy and water sustainability challenges.

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Nomenclature

Acronyms

AC	Air Conditioning
Avg	Average
AWG	Air to Water Generator
AWH	Air Water Harvesting
CAPEX	Capital Expenditure
DB	DesignBuilder
EER	Energy Efficiency Ratio
HVAC	Heating Ventilation Air Conditioning
MOFs	Metal-Organic Frameworks
MUR	Italian Ministry of University and Research
OPEX	Operational Expenditure
PLC	Programmable Logic Controller
TEC	Thermo—Electric Cooler
UN	United Nations
USD	United States Dollar
VCRC	Vapour Compressor Refrigeration Cycle

Symbols

r.h.	relative humidity [%]
t	dry bulb temperature [°C]
v	air flux [kg/h]
x	water content [kg/kg]

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