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Experimental analysis of an atmospheric water generator coupled with a hydroponic greenhouse

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Abstract

Water scarcity and land degradation are issues involving millions of people around the world.
To guarantee access to safe drinking water and achieve food security in forecast of an increasing number of population during the next 30 years, alternative methods of producing water and food are gaining more and more attention.
In this work is analysed a Solar Atmospheric Water Generator (SAWG) constructed in the laboratory of the Energy Department of the Politecnico di Torino, based on an adsorption material technology that permits to extract water from air and to produce it locally where it is needed.
The generator is thought to be integrated with flat plate solar collectors that provide heat for the desorption of the material.
To characterize the functioning of the generator during a complete cycle of adsorption/desorption, laboratory tests were conducted with different regulations of the regeneration fan.
Starting from the results obtained, the adsorption phase was modelled to make an estimation of the water production in different locations.
Finally, was studied the possibility to integrate the SAWG with an experimental greenhouse based a on soil-less method installed in the garden of the Energy Center building in Torino.

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1. Introduction

As reported in the 2030 Agenda for Sustainable Development:

"We recognize that social and economic development depends on the sustainable management of our planet's natural resources. We are therefore determined to conserve and sustainably use oceans and seas, freshwater resources, as well as forests, mountains and drylands and to protect biodiversity, ecosystems and wildlife. We are also determined to tackle water scarcity and water pollution, to strengthen cooperation on desertification, dust storms, land degradation and drought and to promote resilience and disaster risk reduction. We commit to ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality" [1]

Guarantee the access to safe drinking water and sanitation for all, achieve food security and promote sustainable agriculture are only some of the goals fixed by the United Nations.
Following these guidelines, in this work will be presented an alternative way to produce water to sustain a hydroponic greenhouse in order to grow food in areas experimenting water shortages and soil degradation or desertification.

1.1 The problem of water scarcity and land degradation

Land and water resources are intrinsically linked to global challenges of food insecurity and poverty, climate change adaptation and mitigation, as well as degradation and depletion of natural resources.
Current projections indicate that world population will increase from the today 6.9 billion people to 9.1 billion in 2050. Together with the economic progress, mostly in the emerging countries, the demand for food will increase by 70% in the world and by 100% in the developing countries [2].
To guarantee an adequate food production agriculture needs to be highly intensified and to face the challenges of water scarcity and land degradation.

Nowadays, agriculture accounts for 38% of land use, 66% of water withdrawals and 85% of water consumption worldwide [3].
About 66% of the world population (i.e. 4.0 billion people) already lives under severe water scarcity at least 1 month of the year, 1.8 to 2.9 billion for at least 4 to 6 months per year, while half a billion all year round [4].

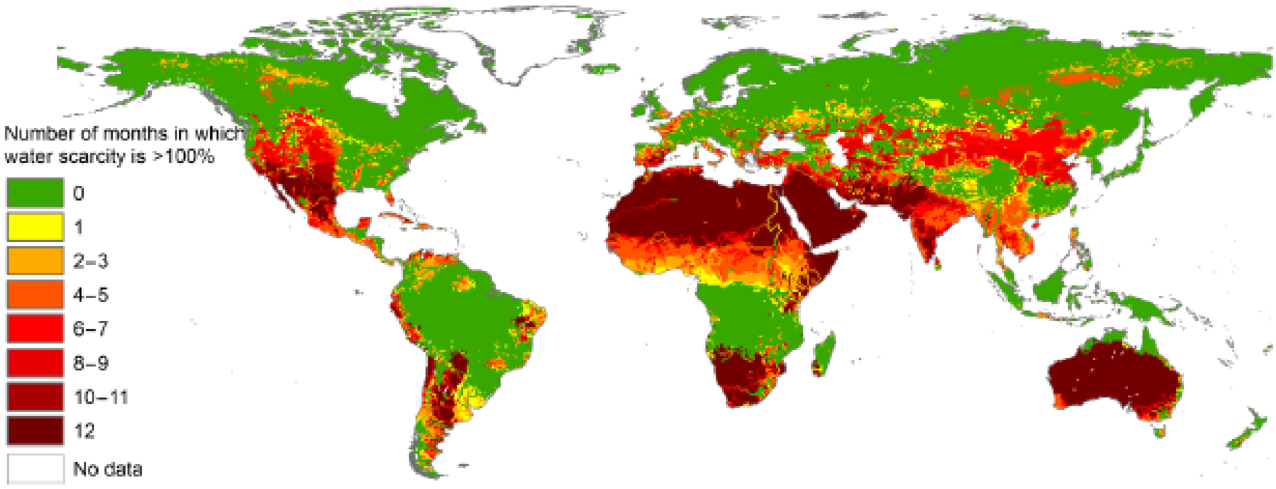


Figure 1. Number of months per year in which water scarcity exceed 100% [4]

As it is possible to notice from Figure 1 a great number of those half-billion people live in the so-called NENA (Near East and North Africa) countries that have some of the lowest levels of freshwater resources in the world, mainly underground and non-renewable, which are being depleted, with an amount of available freshwater reduced by 60% in the last 40 years and expected to fall a further 50% by 2050. In this region, agriculture accounts for 85% of this use and will take the hardest hit in shortages with serious consequences on rural livelihoods, economies and food security [5].
Land users, unable to respond to population increase and globalization are increasing the pressure on land in unsustainable ways, paving the way to desertification.
Up to now, drylands occupy 41% of Earth's land area and are home to more than 2 billion people, 90% of whom living in developing countries and estimated to further increase [3].

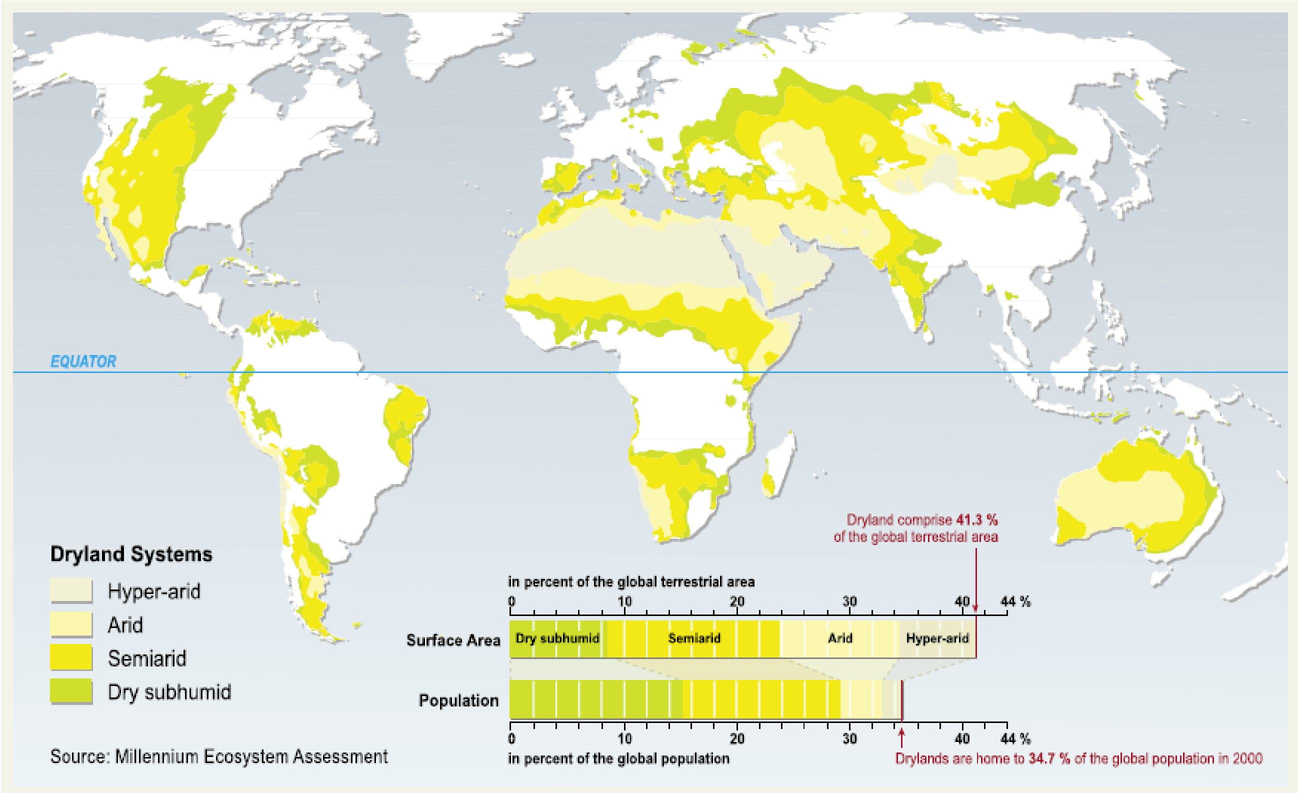


Figure 2. Maps if the distribution of the drylands and percentage of people living in them [3]

In this framework soil-less culture methods appear as an indispensable solution in arid and desert areas experimenting both land and water scarcity.

Soilless culture is the method of growing plants without the use of soil as a rooting medium, in which the inorganic nutrients absorbed by the roots are supplied via the irrigation water.

Thanks to its higher water- and fertilizer-use efficiency and to the high productivity for the small space required, soil-less agriculture is an interesting method for the development of micro-scale farming with zero food miles in both urban and suburban areas enhancing communities food security.

In this work a greenhouse based a on soil-less method coupled with a decentralized solution that produces water in order to sustain agriculture will be analysed.

Up to now the most diffuse approaches for generating new sources of fresh water are:

- transportation of water from other locations;
- groundwater extraction;
- desalination of seawater;
- extraction of water from the air humidity.

The last point, also known as Atmospheric Water Harvesting (AWH), seems to be the most promising solution when both transportation and desalination becomes too expensive and in regions where there's a lack of water resources. A brief overview of these technologies will be given in the chapter.

1.2 State of art on water extraction technologies alternatives to water harvesting from atmosphere

Currently the main alternatives to water harvesting from the atmosphere are sea-water desalination and groundwater extraction.
In the following section will be both discussed.

1.2.1 Sea-water desalination

According to World Health Organization (WHO) guidelines, the permissible limit of salinity in drinking water is 500 ppm and for special cases up to 1000 ppm (seawater normally has salinity in the range of 35000-45000 ppm). [6]
As 97.5% of the total global water reserves is in the oceans, the desalination of seawater has become one of the most important processes to provide fresh water for many communities and industrial sectors in a number of developing countries, especially in Africa and in the Middle East region.
The process separates saline water into two parts, one that has a low concentration of dissolved salts (fresh water), and the other which has a much higher concentration of dissolved salts than the original feed water (brine concentrate) [7].
The most widely applied and commercially proven technologies are the phase change thermal processes and membrane processes.
Thermal desalination is based on the principles of evaporation and condensation: water is heated until it evaporates, then the vapour is condensed to produce fresh water while salt is left behind.
Membrane processes use a relatively permeable membrane to move either water or salt to induce two zones of different concentrations to produce fresh water.
There are also alternative technologies like freezing and ion exchange, but they are not widely used.
All processes can be driven both by conventional and renewable energy sources.
In Figure 3 is presented an overview of the desalination processes:

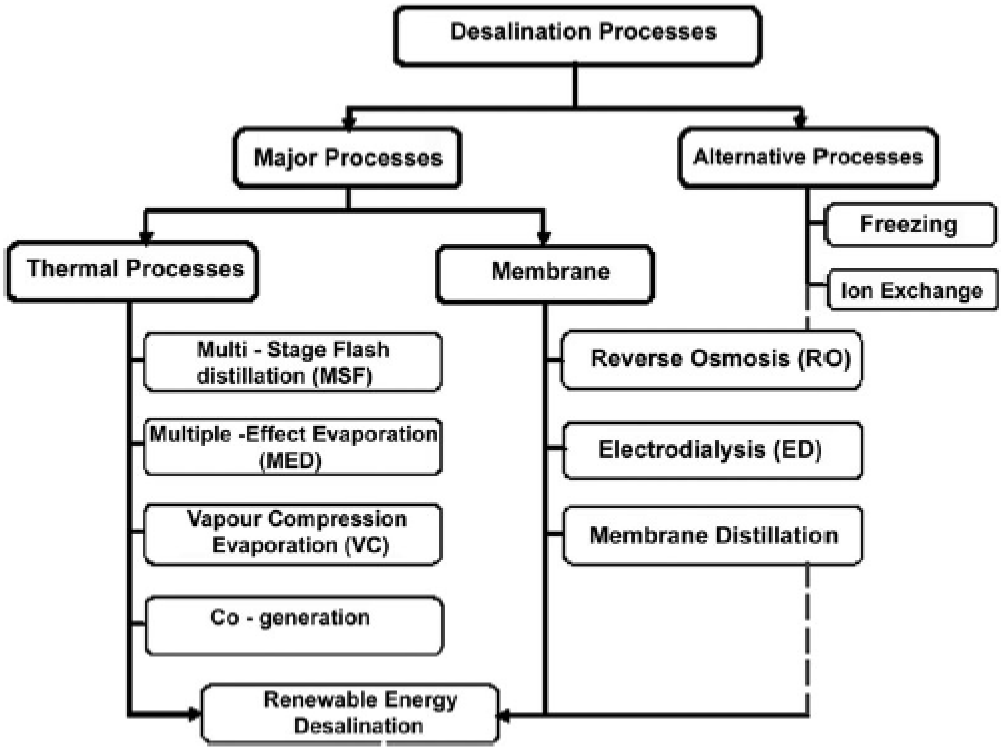


Figure 3. Water desalination technologies [8]

However, these plants are quite energy intensive and still mostly operated with fossil fuel leading to high operational cost and large carbon footprint on the resulting fresh water.

To solve water scarcity problem and reduce carbon dioxide emissions research and development programmes involving governments, industries and research institutions are required to further develop and promote desalination technologies powered by renewable energy sources.

This appears fundamental for remote areas that are distant from water resources and in most of the cases experience a shortage of fossil fuels and an inadequate electricity supply but have plenty of solar energy.

1.2.2 Groundwater extraction

Groundwater can be found almost everywhere beneath the land surface and it is contained in the aquifers which are geological formations of permeable materials water is able to freely move.

Water in aquifers is brought to the surface naturally through a spring or can be discharged into lakes and streams. Moreover, it can also be extracted through a well drilled into the aquifer and brought to the surface by a pump.

Some wells, called artesian wells, do not need a pump because of natural pressures that force the water up and out of the well.

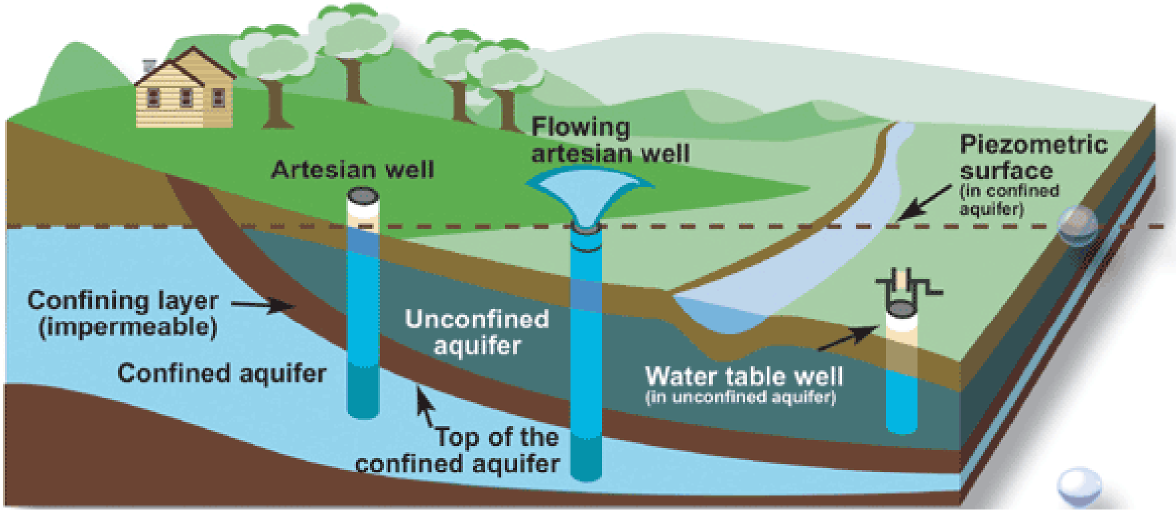


Figure 4. Groundwater extraction [9]

Groundwater is a convenient water supply and presents some advantages, such as:

- it is typically free of most pathogens and less vulnerable to surface-derived contamination;
- the losses due to evaporation are low and no land is used;
- it is a reliable supply being less susceptible to seasonal fluctuations.

For these reasons it is a very important natural resource and at world level its exploitation covers approximately [10]:

- 50% of drinking water needs;
- 20% of the demand for irrigation water;
- 40% of the needs of self-supplied industry.

In addition to human uses, many plants and aquatic animals depend upon the groundwater that discharges to streams, lakes, and wetlands.

Nevertheless, materials from the land's surface can move through the soil and end up in the groundwater: pesticides and fertilizers, sulphates, chlorides, nitrogen compounds, toxic substances from mining sites, and used motor oil. In addition, it is possible that untreated waste from septic tanks and toxic chemicals from underground storage tanks and leaky landfills can contaminate groundwater.

Another problem can be the intensive groundwater exploitation that exceeds recharge from precipitation and rivers with decrease in surface water discharge that can brought rivers and streams to dry up completely.
According to the so-called *"slow desiccation"*, between 15 and 21 percent of watersheds that experience groundwater extraction have already slipped past a critical ecological threshold and by 2050, that number could reach between 40 and 79 percent [11]:

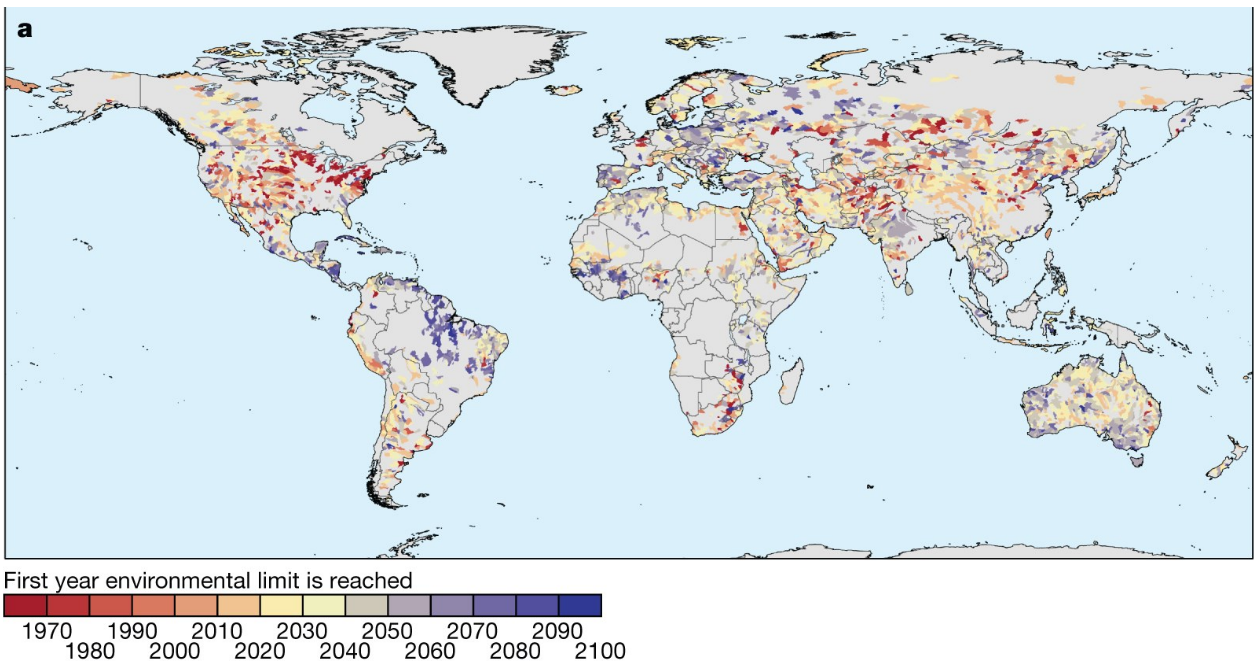


Figure 5. Estimated first time environmental flow limits have been or will be reached globally [12]

As can be seen in Figure 5 groundwater depletion hotspots were reached before 2010 in the High Plains aquifer, part of the Central Valley aquifer, parts of Mexico, and the Upper Ganges and Indus basins; before 2050 new regions will develop, in particular where the pressure on groundwater resources will increase owing to projected drier climate conditions that will cause an increase in irrigation water demand, such as in southern and central Europe and part of Africa.
It's clear that such intensive exploitation of groundwater resources is not affordable still for a long time and actions at national and local administrative level involving governments and stakeholders should be taken.
An example is given by France that introduced collective management bodies composed of stakeholders (agriculture chambers, irrigators, owners of irrigated lands, territorial associations) in charge of collecting water withdrawal requests

and set annual plans for the allocation of acceptable volumes of groundwater for pumping among irrigators [13].

1.3 Atmospheric Water Harvesting (AWH)

As already seen water scarcity problem is solved mainly by exploiting groundwater resources and desalination of the saline water.
Another possibility is represented by wastewater treatment.
Such innovative solutions become economically feasible for large plants only and in regions that have access to both fossil fuels and water to treat.
In many countries both the distance from brackish or polluted water resources and the insufficient existing budgets become an obstacle for these technologies.
Arid areas of inner region of North-Africa and the Arabic peninsula commonly face this problem.
The atmosphere, containing 13000 km^3 of fresh water in the form of water vapor could be a valid renewable alternative to this situation.
Humidity harvesting or Atmospheric Water Generation (AWG) describes the process of getting drinking water out of ambient air: when the air temperature reaches the dew point the atmospheric water vapor condenses into liquid.
Moreover, Atmospheric Water Harvesting (AWH) is accessible everywhere and can be easily co-operated with a renewable energy source (e.g., solar energy).
This possibility has been already studied and tested in different research activities ([14], [15], [16]) and up to now there are three main valid options:

- use passive systems as fog nets and radiative dew collectors, especially in humid climates;
- use a refrigeration cycle based on vapour compression heat pumps or absorption chillers, to cool the air under dew point and condense the moisture;
- use sorption materials to subtract the water vapour contained in the atmosphere. Heating the sorbent, water will evaporate and condense at ambient temperature.

1.3.1 Passive and refrigeration-based water harvesting

As already highlighted in previous section two valid options for AWH are: radiative (or passive) and refrigeration-based water condensers.
The former rely on exploiting the physical processes responsible for dew formation to collect dew water (typically within a range of 0.3-0.6 l/day/m^2 of surface area) without any additional energy input, while the latter is an alternative method that produces higher yields (within the range of 15-50 l/day for a small portable drinking water unit to up to 200000 l/day for larger agricultural scale designs) by using additional energy inputs [17].

The first technology proposed for passive extraction is fog harvesting.
A rectangular mesh is placed perpendicularly to the wind: water droplets are pushed against the net by the wind and become trapped. After successive impacts, the droplets grow by coalescence until they are large enough to fall by gravity, being collected and transported to a tank by a gutter.
At the Catholic University of the North in Antofagasta in northern Chile was conducted the first conclusive experiments reported in Figure 6:

Figure 6. "Atrapanieblas" or fog collectors in Alto Patache, Atacama Desert, Chile [18]

Several experiments following such ideas, but on larger scales, were conducted in many arid parts of the world such as the coastal deserts of West Africa

(Namibia), South America (Chile and Peru), and the Middle East (Saudi Arabia and Oman during the monsoon season) [19].
Typical results are liquid water harvested around 0.1-0.5 g/m^3, 40% fog immersion time, and 50% collection efficiency with 3 m/s wind speed.
Advanced systems using high-elevation fog have the water production ability of 3-7 $kg/day/m^2$ [20].
By the way, this technology presents some drawbacks:

- fog must occur frequently throughout the year, be persistent with a relatively high liquid water content and accompanied by wind in order to achieve a high efficiency;
- in most of the projects mentioned above the fog collectors were not assembled close to the users and the pipe costs and installation made the systems uneconomic and hydraulically difficult;
- low efficiency (defined as the ratio between the water reaching the collector's gutter and the liquid water flux normal to the collector's mesh).

Appears evident that fog collection can be a good supplementary water source in regions with favourable conditions but not a solution to water scarcity.

Another passive approach is represented by the dew water collection that is less affected by climatic and geographical constraints compared with fog water collection and also more cost-effective.
The condensers exploit the physical processes responsible for dew formation to collect water and consist basically in plane collectors thermally isolated from the ground and located at some elevation above it, tilted towards the direction of the dominant nocturnal wind.
They normally work during the night since the solar radiation in the daytime usually results in a higher surface temperature than the ambient temperature.
The surface is typically made of polyethylene foils pigmented with TiO_2 and $BaSO_4$ with a high emittance in the infrared region of the spectrum that allows it to cool faster than other surfaces at night-time.

Figure 7. Pilot dew condenser at Kothara (Northwest India) [21]

According to the radiative cooling ability available for condensation, the upper limit of dew yield is 0.8 kg/day/m^2.
However, the maximum recorded yields of dew water in arid and semi-arid climates typically fall within a range of 0.3-0.6 kg/day/m^2 of surface area [20] because the process is limited by the rate of radiative heat exchange, the weather conditions, and the surface properties. In particular, weather conditions dictate the ratio of latent to sensible heat exchange between the surface and the air.
Thus, passive dew water collection can be useful when small quantities of water are needed.
In order to enhance the harvesting yield is better to couple this technology to a refrigeration-based cycle as it will be discussed in the next paragraph.

Refrigeration-based condensers work in a manner similar to that of a dehumidifier to extract water from the air and can work in a wider range of environmental conditions.
Although they are more effective than the radiative condensers in terms of water yield per day, they require a source of energy which makes their operating costs higher.
However, recent active condensers are designed to minimize the energy required or make use of renewable energy resources integrated into the condenser itself. This type of devices has been widely analysed and are already available on the market.

An example is represented by a study conducted at the Simon Fraser University that assessed the performance of commercially available AWH systems under a variety of climatic conditions, using environmental chambers following relevant ASHRAE and ANSI/AHRI standards [15].

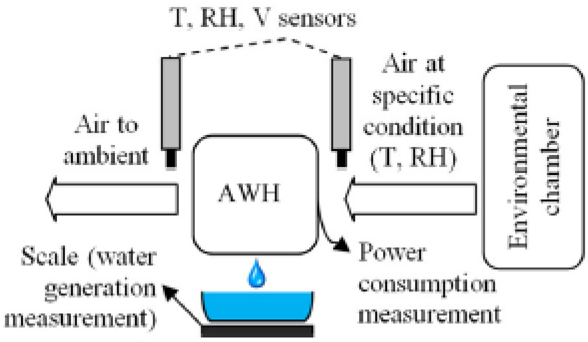


Figure 8. Test setup [15]

Three residential-size AWH with rated water generation capacity of 30 l/Day and 1500 W nominal power were tested varying the temperature and the relative humidity (R.H.) of the air entering the units in the ranges of 0-45 °C and 10-100%, respectively.
The different climatic conditions were assumed based on average monthly data for different cities in North America that can be comparable to similar climates in the world.
The results showed that an increase of the water content in the air or dewpoint temperature and a decrease of temperature enhances the water harvesting yield.
The average water harvesting rate varied in a range of 0.05 L/h for cold and humid to 0.65 l/h for warm and humid climates, while the average energy consumption changed from 6.23 kWh/l for the former and 1.02 kWh/l for the latter.

An issue related to active cooling is that a great part of the enthalpy change related to the process is attributed to the cooling of air, rather than to the condensation of water.
To reduce the energy demand it is possible to concentrate the water vapor separating it from air prior to the cooling process and then to cool it.
Vapor concentration can be achieved by using desiccants, as it will be discussed in the next section, or by using polymeric electrolyte membranes (Figure 9) or water vapor selective membranes (Figure 10).

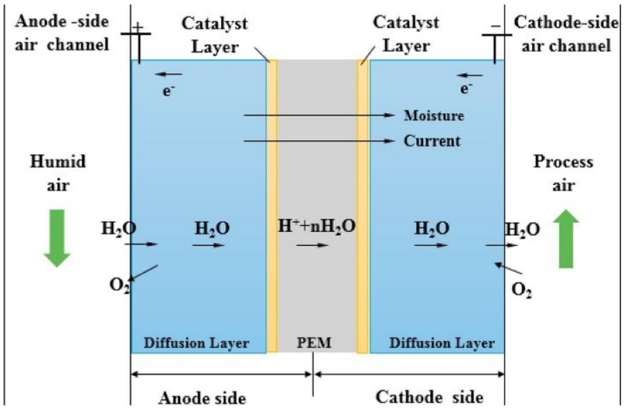


Figure 9. Polymeric electrolyte membrane

With regards to the PEMs a study has shown that when the inlet air humidity passes from 70 to 90%, the dehumidification rate increased about 1.5-2 times. However, only 30% of the total power input was effectively used by the polymeric electrolyte membrane to pump humidity, while the rest was wasted, leading to a relatively low COP (~0.33) [22]

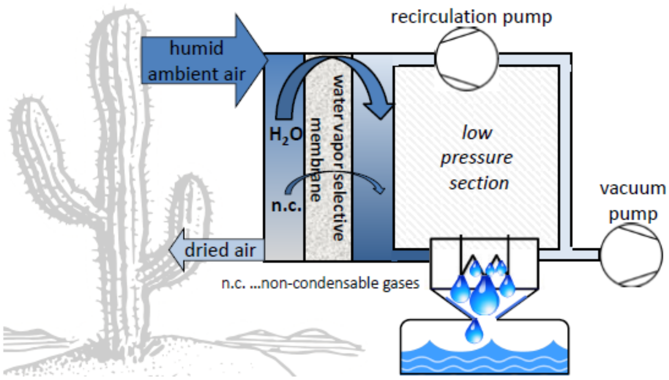


Figure 10. Schematic of the AWG based on water vapor selective membrane [22]

On the other hand, the use of water vapor selective membranes can reduce the energy requirement by more than 50%.

The driving force for the membrane permeation is the partial pressure difference, that is maintained with a condenser and a vacuum pump.

The pump removes the non-condensable gases that leak into the system and introducing a low-pressure, recirculated sweep stream, the total permeate side pressure can be increased without compromising the water vapor permeation. This measure lowers the power requirements of the vacuum pump and allows energy efficiency even in the presence of leakages.

It has been shown [23] that a prototype with a constant power of 62 kW could produce 9.19 m^3/day of water as compared to 4.45 m^3/day that can be condensed without membranes.

Thanks to the membrane the water generated in this manner is also cleaner and of higher quality than water condensed directly out of the air.

Another possible solution that has been investigated is the integration of an air-conditioning system and a water harvesting system to achieve optimized energy consumption and sustainable use of resources, especially in arid regions where refrigeration processes represent a basic need for indoor comfort.
Thus, condensed water coming from the dehumidification process become almost a free benefit instead of being wasted.
A study [24] has been conducted on a real installation and developed on the basis of the results of a previous research [25].
The integrated system was built and placed on the roof of a hotel in Villahermosa, Tabasco, Mexico in order to meet drinking water requirements, to provide domestic water heating and air for a non-conditioned zone (the laundry area of the hotel).
A schematic of the system is shown in Figure 11:

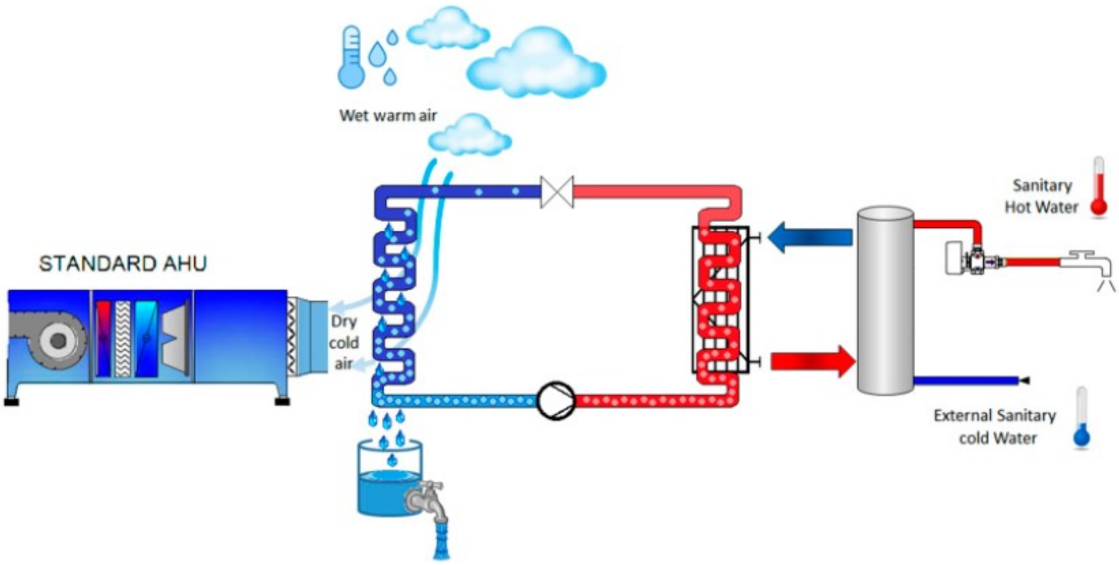


Figure 11. Scheme of the integrated system [24]

In addition, a condensed water treatment unit was designed in order to guarantee safety, healthiness and quality of the final product.
As the environmental conditions of the location are very steady during each month, the results obtained for the test period (the month of November) were taken as reference and a simulation for the whole year was carried out:

	Daily Savings	Avoided Costs	Daily Savings
Bottled water	160.5 dm^3	7 pesos/dm^3	1123.5 pesos
Kitchen water	1481.5 dm^3	1.4 pesos/dm^3	2074.1 pesos
LPG	166.4 dm^3	7.47 pesos/dm^3	1243.0 pesos
Electricity saving	494.4 kWh	0.8243 pesos/kWh	407.5 pesos
	Total		4848.1 pesos
	Daily energy consumption	**Energy cost**	**Daily cost**
Electricity consumption	0.5 kWh/L	0.8243 pesos/kWh	−676.75 pesos
Results			
	Daily saving		4171.35 pesos
	Annual saving		1,522,542 pesos
	Annual saving	Exchange rate 17.3735 pesos/USD	87,635.9 USD

Table 1. Water, energy and economic savings due to the integrated system

Another possible way to extract water from air is represented by thermoelectric coolers (TEC) that are devices based on the Peltier effect: by passing an electric current through them they produce a temperature difference resulting in a cooling effect.

In comparison with vapor compression and absorption refrigeration, TEC devices have no moving parts and require less maintenance becoming suitable for designing simple and portable AWG systems.

A recent study [26] considers a system composed of a number of thermoelectric coolers placed in series. Air flows through two channels on the hot and cold sides and heat sinks increase the surface of heat transfer. The required air flow is supplied by a fan and solar cells power the thermoelectric coolers and the fan.

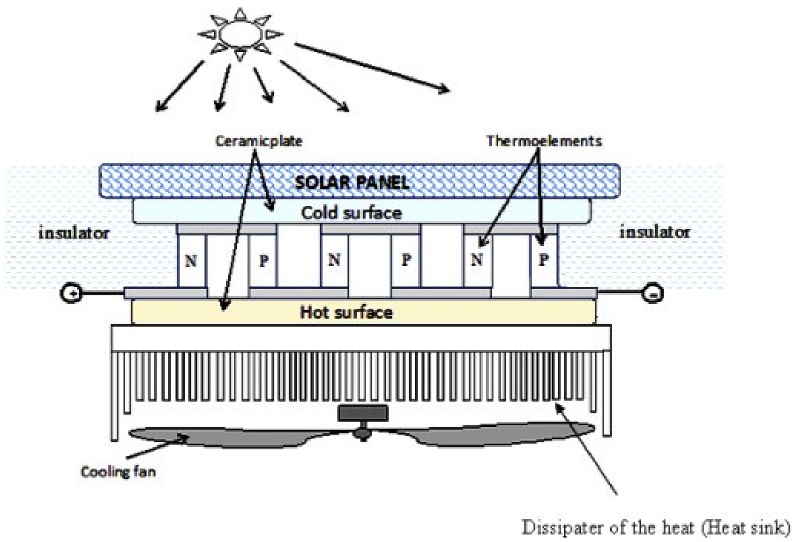


Figure 12. Schematic of the TEC [26]

The specifications of the system are: water production of 26 ml within 1 h from air with 75% relative humidity and temperature of 318 K by consuming only 20W of electrical power.
However, TECs are a good solution only for applications that need low water production providing limited cost and volume. An example is given by mini AWG based on the thermoelectric effect that have been used to provide the minimum amount of soil moisture needed by young trees for successful rooting while transplanted from the nursery into open fields, in dry-climate areas [27].

In conclusion it's crucial to observe that the energy consumption for water harvesting from the air dramatically increases as the humidity or ambient temperature decreases.
Desert and arid regions, unfortunately, have day-time relative humidity as low as 10% with a dew point that can be even below 0°C in extremely dry desert climate. At night even if the relative humidity can exceed 40%, the lower ambient temperature (~20 °C) prevents water harvesting with refrigeration-based AWGs [14].
As a result, atmospheric water harvesting by direct cooling is expected to be more cost-effective in tropical or coastal regions that enjoy warm and humid climate. Otherwise its practical implementation becomes infeasible with a huge energy requirement that would need a lot of PV plate with high cost and maintenance. Moreover, conventional refrigeration still uses chlorofluorocarbons (CFCs) which contribute to global ozone depletion [16].

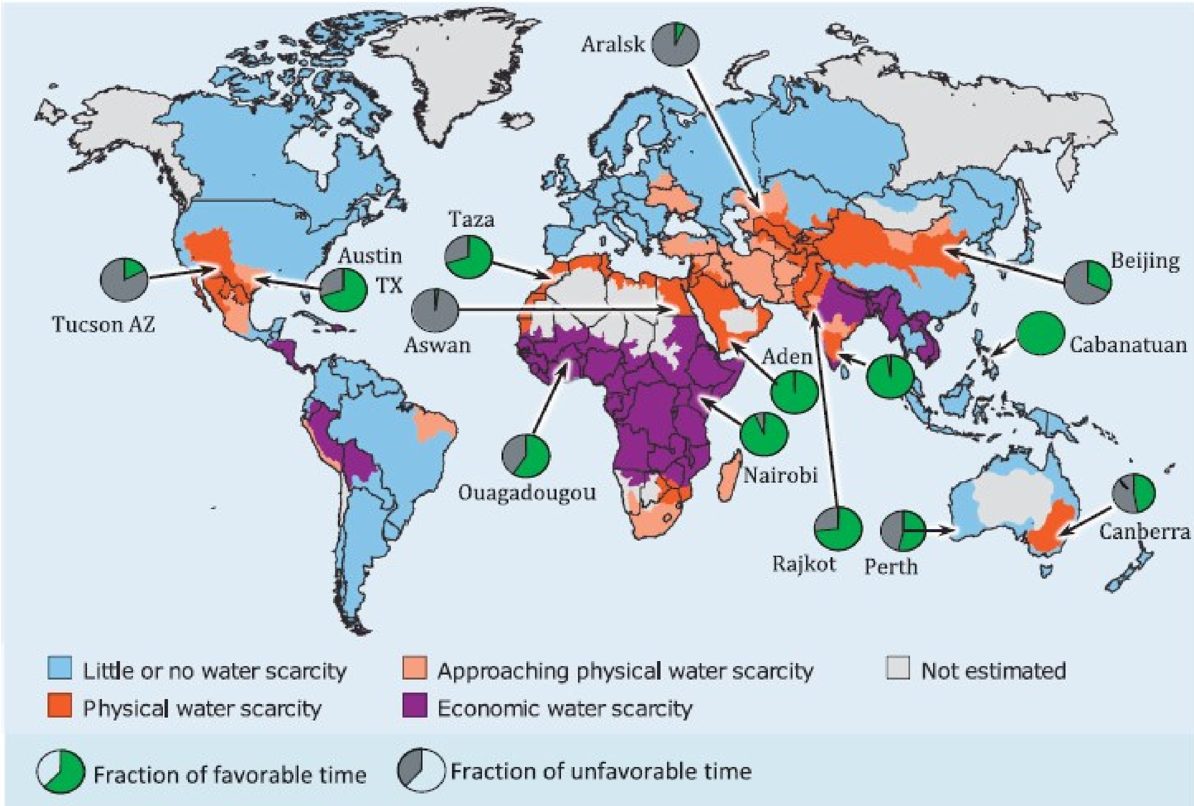


Figure 13. Fraction of the time out of the 10 years (2005–2014) meteorological data in which the ambient conditions were estimated to be suitable for AWH, overlaid on the physical and economical global water scarcity map [28]

1.3.2 Sorption material-based water harvesting

The use of desiccant is a promising approach for efficient atmospheric water harvesting thanks to the large water storage capacity in most climate conditions.

The process of absorbing and holding water vapour may be defined as either absorption or adsorption depending on whether the material undergoing chemical change on attracting moisture (absorption) or not (adsorption). Generally, a desiccant attracts between 10 to 1100% of its dry mass of water vapour depending on the moisture content available and the type of desiccant itself. Heating the material to temperatures from 50° to 260°C and exposing it to a regeneration airstream the moisture can be removed. After the desiccant is completely dried, it should be cooled so that it can attract water vapour again. Ideally, an AWH system should operate with a material that can take up and release water with minimum energy requirements and powered by low-grade energy sources, such as sunlight or waste heat.

It's clear that the choice of the sorbent is fundamental in order to efficiently harvest water even in low RH conditions.
Desiccant materials can be in the solid, liquid and composite form and in this section is presented an applicative example for each type.

Solid desiccant To harvest water with maximum yield and minimal energy consumption, an isotherm with a steep increase in water uptake within a narrow range of RH is desired.
According to studies in literature ([14], [29]) metal-organic framework materials (MOFs) exhibits such characteristics and recently special attention has been putted on MOF-801 ($Zr_6O_4(OH)_4(fumarate)_6$]) that is suitable for regions where RH is down to 20%.
The coupling with solar energy is particularly promising because sunlight is often abundant in arid regions with low RH where water resources are limited and where a natural diurnal temperature swing thermally assists the process.
A device based on this MOF has been studied [29] with a harvesting rate of 2.8 l/day of water per kilogram of MOF at 20% RH.
The critical step, that is the desorption, is driven by low-grade heat from sunlight below 1 sun (1 kW/m^2). After being desorbed at ~65°C, water is harvested using a condenser at ambient temperature.

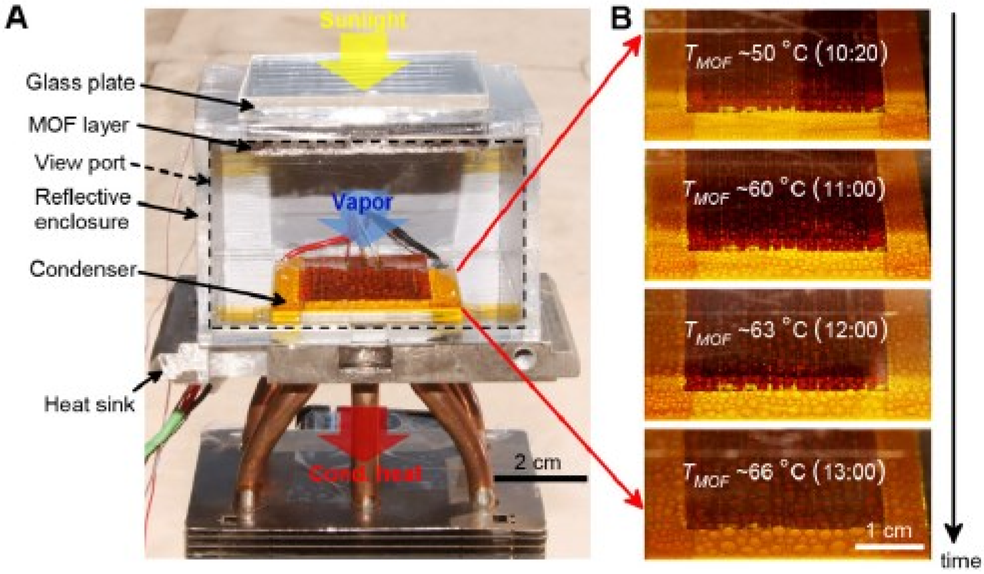


Figure 14. Image of the prototype (A) and formation and growth of water droplets as a function of MOF temperatures and time of day (B) [29]

The advantages of using MOFs for this type of application are:

- well-studied water adsorption behaviour on a molecular level;

- good performance driven by aggregation of water molecules into clusters within the pores of the MOF itself;
- stability and possibility of modulating their properties;
- wide availability of its constituents.

A schematic of the functioning is given in Figure 15:

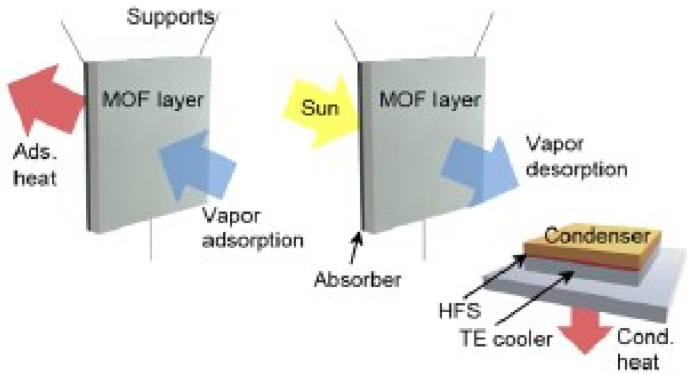


Figure 15. Schematic of the water absorption/desorption cycle [29]

Although the good performances, the synthesis of MOFs requires enormous effort and resources while exhibiting toxic and negative effects on human health and the environment [30].
It can also be corrosive thus current research interests should focus on the recycling, reuse, regeneration, and degradation of this material.

Liquid desiccant Some of the commonly used liquid desiccants, because of their low surface vapour pressure at low temperature and high concentration, are calcium chloride, lithium chloride, lithium bromide and triethylene glycol. One of the most promising sorbents is calcium chloride that can absorb more than 95% of its own weight in water and is a natural and industrial abundant resource.
An experimental work [31] conducted in Egypt has studied its application within an integrated desiccant/solar collector system for production of fresh water from atmospheric air.

Figure 16. Experimental apparatus [31]

To enhance the mass transfer surface, a thick corrugated layer of cloth was used as bed to carry the liquid absorbent.

During the night the glass cover of the collector is opened and water vapour captured by the bed thanks to either natural and forced convection. When absorption stops (at the end of the night), the cover and all other openings are closed.

During the day the bed, coated in black, absorbing the incident solar radiation, increases its temperature and makes the moisture evaporate and condense on the glass surface.

As reported in the study such system is able to provide about 1.5 l of fresh water per square meter per day with an efficiency of more than 17%.

Despite the good properties shown by liquid desiccant materials there are many drawbacks related to them.

In most of the cases the dehumidification process is carried out by direct contact between air and sorbent: air can carry some liquid desiccant droplets with it causing corrosion in the ducting and other equipment. This can increase the maintenance costs and decrease the equipment life and can affect the quality of the collected water. Direct contact type systems also require high fan and pumping power because of the higher pressure drop and continuous supply of desiccant solution [32].

Composite desiccant As already seen, apart from water harvesting through adsorption on the surface, it is possible to harvest water through absorption, e.g., hydration of salts.
As hygroscopic salts suffer from particle agglomeration during hydration, which reduces the gas permeability, composites materials have been studied: matrix materials adsorb water on their surface while the salts absorb water through hydration.
A study [33] has proposed the encapsulation of $CaCl_2$ into an alginate-based matrix in form of beads of the size of around 2 mm in diameter. Alginates have excellent features in terms of macroscopic shaping and are a cheap and non-toxic biomaterial widely used in various applications.
The final composite, referred to as Alg-$CaCl_2$, contains 76 wt.% of salt.

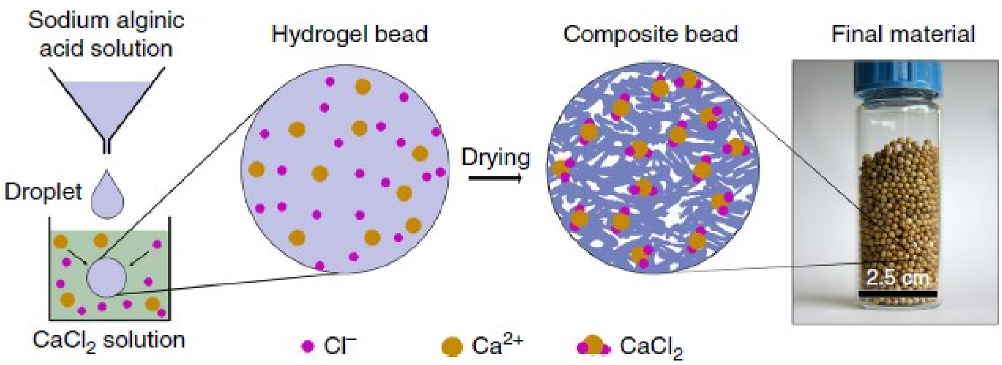


Figure 17. Scheme for the production of the composite beads [33]

The material was hydrated and dehydrated cyclically with the following results: it was able to adsorb 100% of its own weight in water from air at a water vapor pressure of 10 mbar with the capacity to release more than 90% of the adsorbed water at 100 °C and 100% at 150 °C. These temperatures can be provided by solar radiation, e.g., vacuum solar tubes.
Calculations from the bulk density of the material and the water uptake indicate that 660 kg of water could be harvested per cubic meter of composite material in a packed bed that makes Alg-$CaCl_2$ an interesting candidate for water harvesting.

1.4 Overview on hydroponic greenhouses

Starting from the title of this section, there are two words that need to be explained: hydroponics and greenhouse.

Hydroponics is a subset of hydroculture, which is a method of growing plants without soil by instead using mineral nutrient solutions in a water solvent. Plants may be grown with only their roots exposed to the nutritious liquid, or the roots may be physically supported by an inert medium (substrate).
A greenhouse is a metal, wood or plastic frame structure that is covered by transparent nylon, plastic or glass with the purpose of allowing solar radiation to enter and then become trapped to heat the air inside the greenhouse itself. As the sun begins to set, the heat is retained inside by the roof and walls, allowing for a warmer and more stable air temperature during a 24-hour period. Greenhouses provide general environmental protection from adverse meteorological conditions, let to extend the growing season by retaining ambient solar heat and can keep away animals and other pests.

Figure 18. Tomatoes hydroponic greenhouse

Therefore, a hydroponic greenhouse offers many advantages:

- possibility to sustainably cultivate crops and achieve high yields and good quality, even in saline or sodic soils, or in non-arable or arid lands with poor structure;
- precise control of nutrition that guarantees respect for environmental policies (e.g. reduction of fertilizer application and restriction or elimination of nutrient leaching from greenhouses to the environment);

- decrease in water usage for agriculture: to grow 1 kg of tomatoes in intensive farming requires 400 l of water, in hydroponics only 70 l [34];
- in some cases, perform a year-round production.

These features are fundamental for the future of harsh environments which don't have much accessible water or arable lands, to be able to grow their own food.

Soilless cultures are usually classified according to the type of plant support or in terms of management of the nutrient solution as either open- or closed-loop systems.

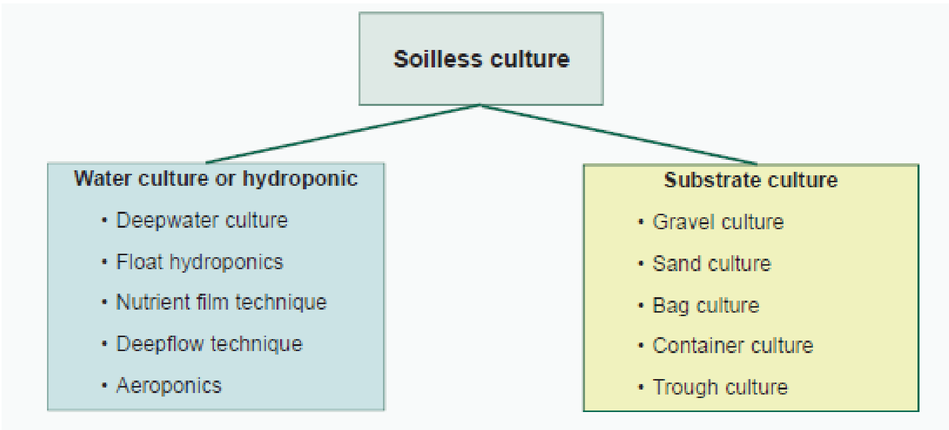


Figure 19. Classification of soil-les culture systems [35]

In open-loop systems the water and nutrients are supplied as for a conventional on-soil crop. The drained nutrient solution may be collected and reused to fertilize on-soil crops, but in most of the cases it is lost.

In closed-loop systems the drained nutrient solution is recovered, treated in order to restore its original composition and to remove any foreign substances and then recycled.

There are three main hydroponic methods: Deep Water Culture (DWC), Nutrient Film Technique (NFT) and the media bed.

Deep Water Culture (DWC) DWC was the first hydroponic method proposed commercially. It consists of a bucket filled with the nutrient solution, covered with a net and a cloth on which a thin layer of sand (1 cm) is placed to support the plants while the roots are suspended in the nutrient solution. Alternatively, the bucket may be covered with a lid and the plants, contained in net pots, suspended from the centre of the cover.

The main drawback of the system is the oxygen depletion occurring at root level. In order to avoid this aeration is needed so air stones are placed in the canals or Venturi siphons can be added to the water inflow pipes.

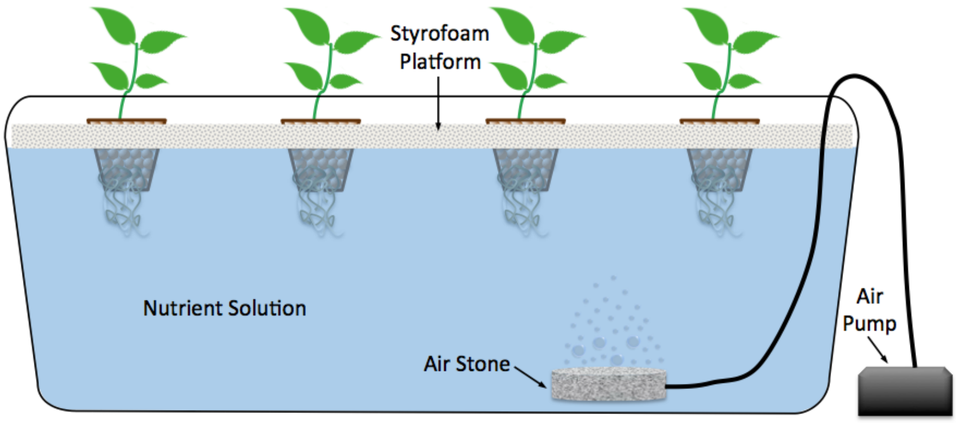


Figure 20. Schematization of a DWC system

Nutrient Film Technique (NFT) The NFT is a hydroponic method using plastic pipes each with a thin layer (film) of nutrient-rich water flowing through it. Plants are placed within holes on the top of the pipes that are on a slope of 1.2-3 %: nutrient solution is applied at the elevated end so that it flows down keeping the roots completely wet. This technique has very low evaporation because the water is completely shielded from the sun and the thin stream (1-2 mm deep) ensures sufficient oxygenation of the roots.

One of the benefits is that the pipes can be arranged in many patterns making use of vertical space, walls and fences, and overhanging balconies. Other advantages are the absence of substrate and the reduced volume of nutrient solution required, resulting in significant savings in water and fertilizers, reduced environmental impact and costs related to the disposal of the substrate.

In such a system special attention must be payed to the flow of the solution: if it stops, the roots will dry out and become stressed very quickly especially in hot weather.

Technically most crops could be grown in an NFT system, but it works best for short-term crops (30-50 days), because plants are ready to harvest before their root mass fills the channel.

Even if the NFT is a popular method for commercial operations because is financially more viable than media bed units when scaled up, it is far more complicated and expensive, and may not be appropriate in locations with inadequate access to suppliers. On the other hand, it is useful in urban applications, especially when using vertical space or weight-limitations are considerations.

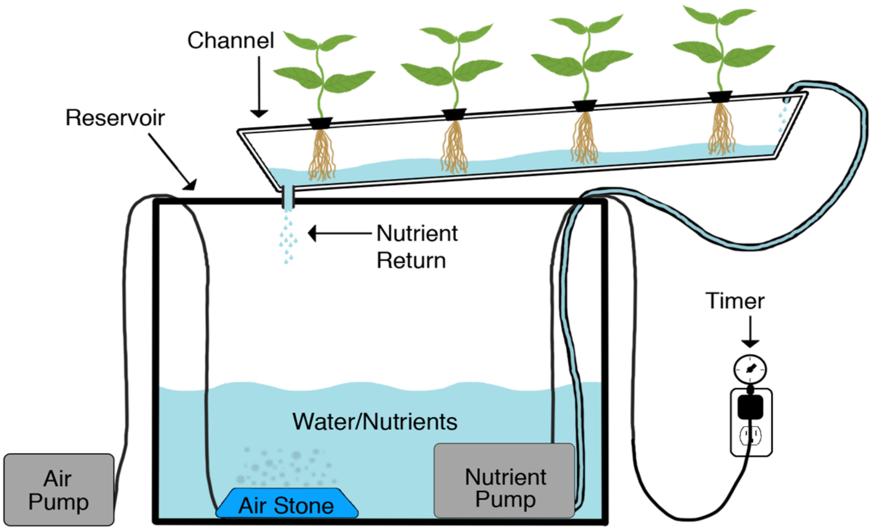


Figure 21. Schematization of an NFT system

Media bed culture The media bed technique refers to soil-less systems where a solid inorganic or organic medium offers support to the roots of the plants. It also functions as a filter, both mechanical and biological, as a reserve, retaining the nutrient solution, and as a protection against temperature fluctuations.
This type of system is very simple and is the most popular design for small-scale units, but at large scale can become expensive, heavy and unwieldy.
Some media beds are designed to flood-and-drain, which means that the water level rises to a certain point and then completely drains adding oxygen to the plant roots. Other irrigation methods use a constant flow of water, entering one side of the bed and exiting the other, or water distributed through a drip irrigation array.
Media beds suffers from water evaporation because of the high surface exposed to the sun.
The tank containing the bed can be made of plastic, fiberglass and even old bathtubs have been used in some “do-it-yourself” applications.

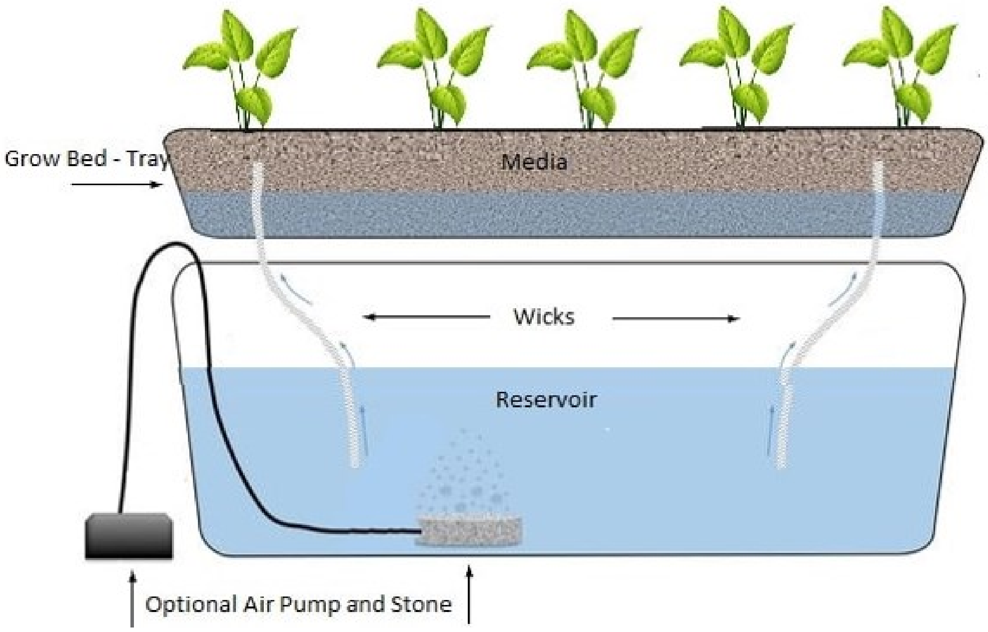


Figure 22. Schematization of the media bed culture

The choice of the media depends mainly the following criteria:

- large surface area for bacterial growth;
- neutral pH and inert (meaning the medium will not leach out any potentially toxic substances);
- good drainage properties;
- easy to work with;
- sufficient space for air and water to flow within the medium;
- available and cost effective;
- light weight, if possible.

In the table below are listed the main used media with the related characteristics:

Media type	Surface area (m^2/m^3)	pH	Cost	Weight	Lifespan	Water retention	Plant support	Ease to work with
Volcanic gravel (tuff)	300–400	Neutral	Medium	Medium	Long	Medium–Poor	Excellent	Medium
Volcanic gravel (pumice)	200–300	Neutral	Medium–High	Light	Long	Medium	Medium–Poor	Easy
Limestone gravel	150–200	Basic	Low	Heavy	Long	Poor	Excellent	Difficult
Expanded clay (LECA)	250–300	Neutral	High	Light	Long	Medium–Poor	Medium	Easy
Plastic bottle caps	50–100	Inert	Low	Light	Long	Poor	Poor	Easy
Coconut fibre	200–400 (variable)	Neutral	Low–Medium	Light	Short	High	Medium	Easy

Table 2. Characteristic of different growing media [36]

2. System description

In the present chapter will be given a brief description of the Solar Atmospheric Water Generator (SAWG) prototype and the hydroponic greenhouse in analysis.

2.1 SAWG

This work has the aim to implement and test the SAWG that has been assembled in the laboratory of Energy Department (DENERG) of Politecnico di Torino.
The prototype is contained in a cube of about 1 m^3 in order to be compact and easy to move.
The material chosen to harvest water from air is the Silica-gel because of its large water storage capacity in most climate conditions.
The SAWG is coupled with solar flat plate collector that supply the thermal energy needed for the desorption of water and is thought to work in real atmospheric condition, in particular arid climates.
The prototype has two batteries that work alternatively in order to optimize the process: when one is performing regeneration, the other is doing adsorption.

2.1.1 Components description

Inside the prototype is possible to distinguish between two circuits: the water and the air one.
The water circuit is divided into:

- solar water circuit, responsible of delivering the heat needed for the desorption process; the direction of the flux is decided by a motorized valve;
- condenser water circuit, which is a closed loop that cools down the hot and humid air stream during regeneration in order to extract water.

The air circuit is connected to a four-way valve that switches the air flux from the desorption closed loop to the adsorption loop and vice versa.
A brief description of the other components will be given below.

Solar collectors The solar collectors provide the heat necessary to drive the desorption process.

They consist in flat plate collectors with a gross area of 2 m^2 each and can be installed on the top of the SAWG with a tilt angle of 30°.

Batteries Two finned tubes heat exchangers are installed on the left and on the right side of the prototype respectively and are filled with 30 kg of silica gel beads with a diameter of around 2-3 mm.

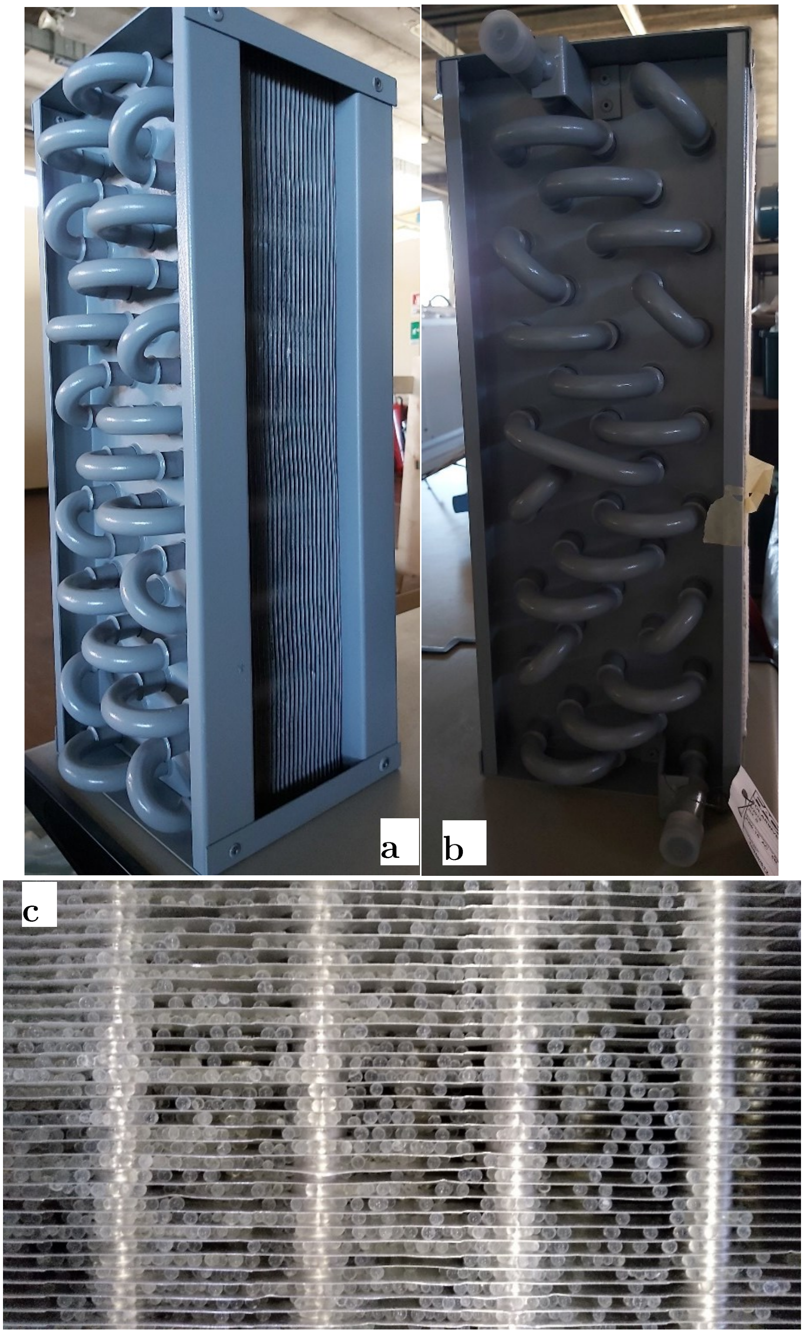


Figure 23. a-b) Front and back side of the heat exchanger c) particular of the battery filled with beads of silica gel

Condenser The condensation unit consists in an air to air heat recovery system and an air to water radiator.

The first cools down the air going to the proper condenser while recovers the condensation heat to pre-heat the air that is sent back to the battery performing the regeneration.
The second condenses the water present in the air stream and is connected to the external environment.

Fans Two big fans respectively blow air for regeneration (F2) and adsorption (F1) purposes with a maximum nominal power of 67 W. The fan F2 can be regulated.
Two axial fans (F3 and F4) are connected to the radiators of the condenser circuit and have a maximum power of 170 W with the possibility of being regulated.

Figure 24. Centrifugal fan used for adsorption and regeneration

Sensors On the prototype have been installed temperature and the relative humidity sensors.
The LM35 series are precision integrated-circuit temperature devices with an output voltage linearly proportional to the temperature.
To measure the moisture HIH-4000 Series Humidity Sensors are used which provide a linear voltage output.
All the sensors are connected to a microcontroller that receives as inputs analogical signals.
In the Table 1Table 3 a list of all the installed sensors is given:

NAME	FLUID	TYPE	LOCATION
TBD1	Air	Temperature	Inlet Bed Dx
TBD2	Air	Temperature	Outlet Bed Dx
TBS1	Air	Temperature	Inlet Bed Sx
TBS2	Air	Temperature	Outlet Bed Sx
TBD3	Water	Temperature	Inlet Bed Dx

TBD4	Water	Temperature	Outlet Bed Dx
TBS3	Water	Temperature	Inlet Bed Sx
TBS4	Water	Temperature	Outlet Bed Sx
TC1	Air	Temperature	Inlet Condenser
TC2	Air	Temperature	Outlet Condenser
TPD	Water	Temperature	Outlet Solar Collector Dx
TPS	Water	Temperature	Outlet Solar Collector Sx
RHBD1	Air	Relative Humidity	Inlet Bed Dx
RHBD2	Air	Relative Humidity	Outlet Bed Dx
TAMB	Air	Temperature	Ambient

Table 3. List of sensors

Double four-way valve It's a double valve that can switch the air flux going to the batteries when passing from desorption to absorption and vice versa.
It is moved by an actuator.

Figure 25. Double 4-way valve with its actuator

Load cell The load cell detects the weight variations of the battery under which is placed to control the amount of water adsorbed or desorbed.
It is used as a double check together with the relative humidity and temperature sensors.

Arduino DUE It is a microcontroller used to read the signals coming from the sensors.

Controllino It is a controller that receives analogical inputs and sends digital or analogical outputs to the components and it is implemented with a control logic to enhance the performances of the prototype.

2.1.2 Working principles

Each battery of the system can work alternating two successive phases as shown in Figure 26:

- Adsorption: the water vapour present in ambient air is adsorbed by the desiccant material;
- Desorption (or regeneration): the adsorbent is heated up using a low temperature energy source producing a hot and humid air stream.

The flux leaving the heat exchanger is then condensed in a dry cooler at ambient temperature.

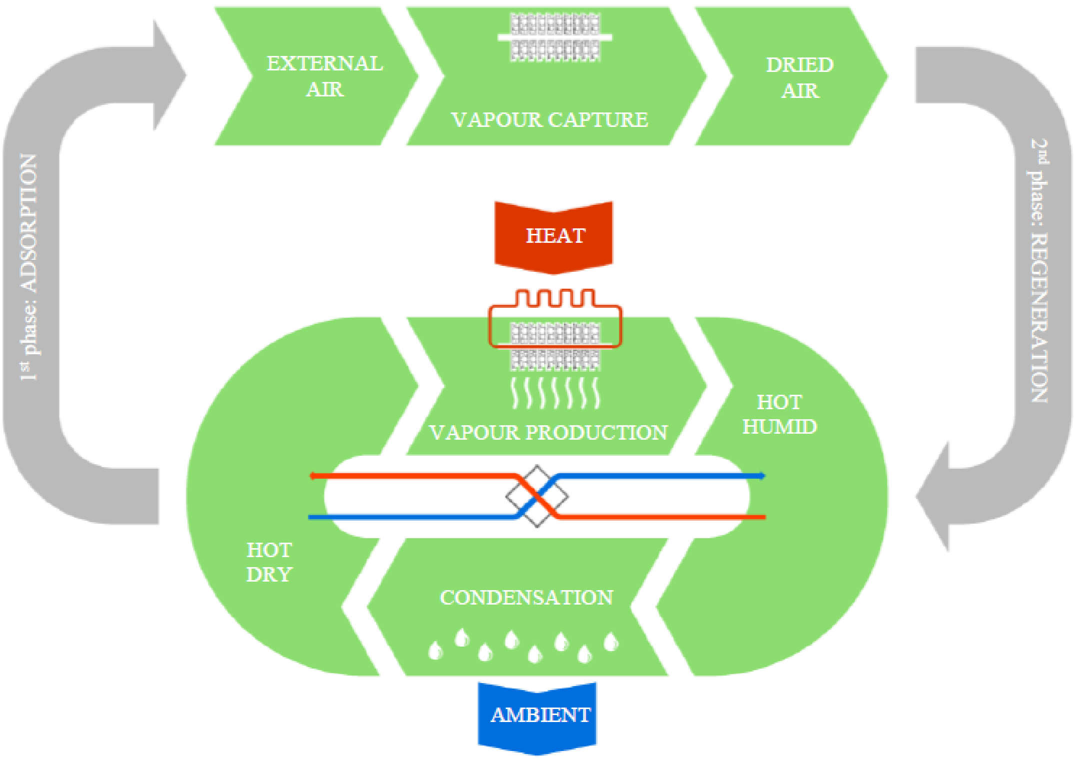


Figure 26. Scheme of the adsorption/desorption cycle [37]

To produce enough water during condensation it's necessary to have an air stream with certain levels of temperature and humidity so that the dew point temperature is higher than the ambient temperature. Humid air going through adsorption or desorption transformations moves along an isenthalpic line, which implies that during adsorption moisture content reduces and air temperature increases and vice versa during desorption.

Nevertheless, only a small amount of water can be produced through this kind of transformation and a condensing stream at ambient temperature of 35°C. As it is possible to observe in Figure 27, at 35°C the saturation point corresponds to about 36.5 g_v/kg_a (point 3). This means that with an isenthalpic transformation in order to reach points on the saturation line above point 3, desorption air must be at temperature around 50°C with the same moisture content of point 3 (point 1). However, just a reduced amount of water would be condensed (4-5 g_v/kg_a).

The solution is to perform an isothermal transformation (point 2 iso-T): starting from the same regeneration point (1) and following the isothermal line the humidity difference between point 2 and 3 will exceeds 40 g_v/kg_a.

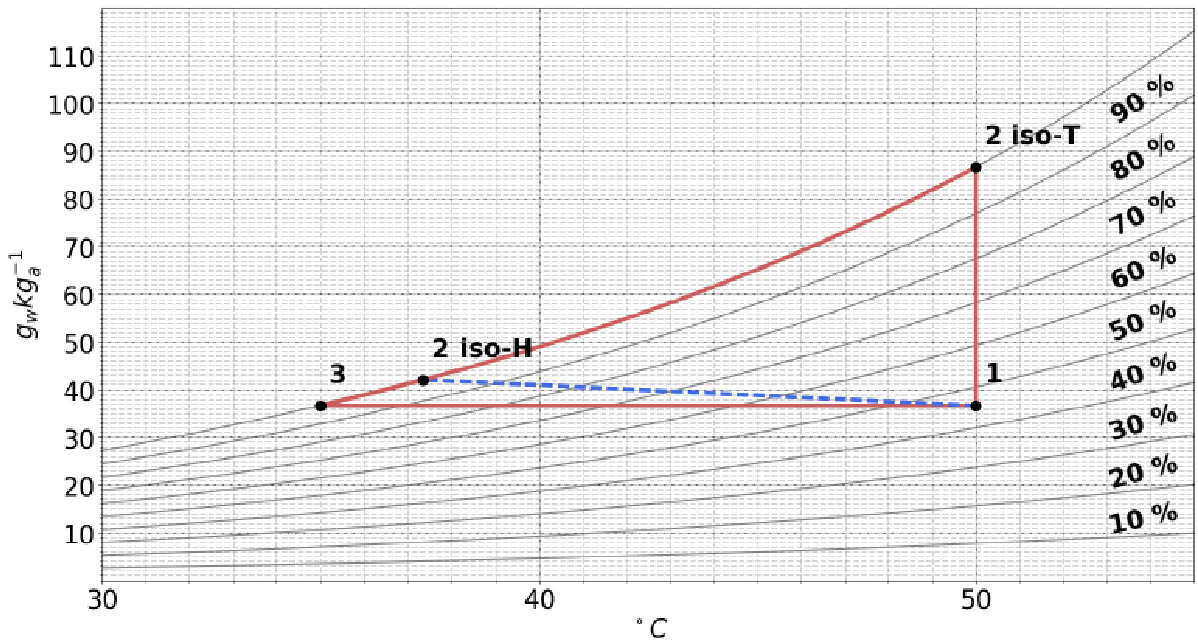


Figure 27. Comparison between a desorption with an isenthalpic (iso-H) and an isothermal (iso-T) transformtion [37]

It must be noted that to obtain the point 2 iso-T an amount of heat equivalent to the latent heat has to be supplied, but always at 50°C. On the contrary, if point 2 iso-T had to be reached by an isenthalpic line the heat supply temperature would be above 70°C. This gives important advantages in terms of efficient utilization of solar thermal source at low temperature (flat plate or evacuated tubes) and limits the design problem only to the thermal requirement from the source.

To realize an isothermal transformation is required a system that exchange heat and mass at the same time and it is possible thanks to a finned heat exchanger (HX-ADS) filled with the desiccant material.

2.2 The hydroponic greenhouse

The hydroponic greenhouse has been assembled and installed in the garden of the Energy Center building in Torino.

A functional scheme of the greenhouse coupled with the SAWG is given in Figure 28.

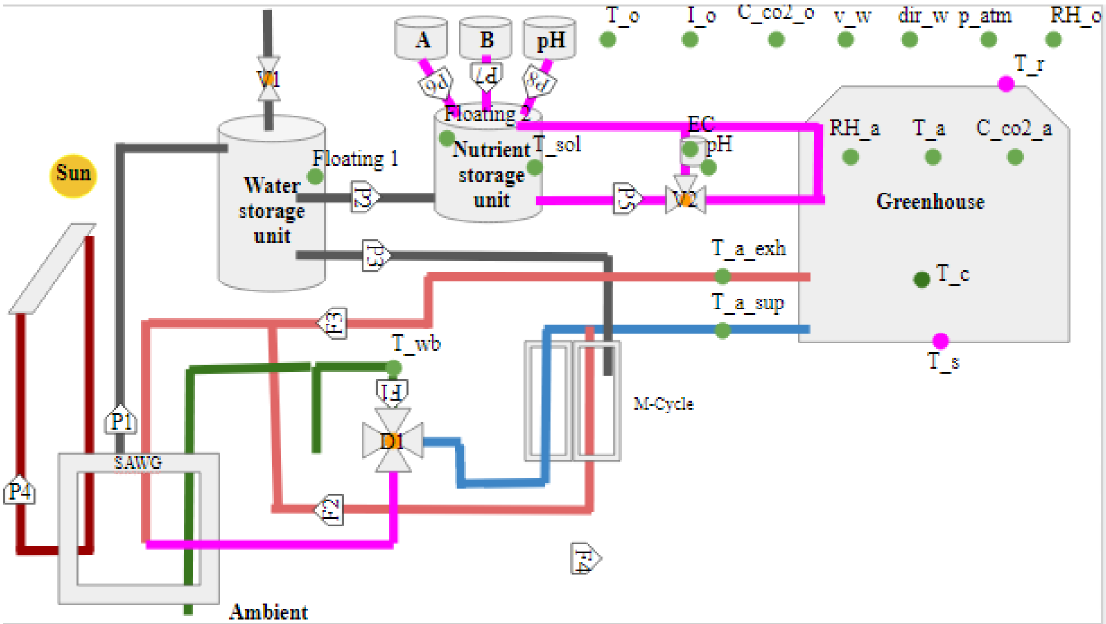


Figure 28. Functional scheme of the greenhouse coupled with the SAWG

The greenhouse consists in a metallic structure covered by a plastic sheet in which are placed two case for the housing of the plants.

The cases will hold small size plants irrigated thanks to the NFT method.

Figure 29. The greenhouse

The electrical panel and the mixing tank for the nutrient solution are placed in a metallic cabin.

3. Preliminary laboratory testing

While assembling the SAWG, several tests were performed in the laboratory of the Energy department at Politecnico di Torino on a test-bench prototype that works exactly like the SAWG with the aim of:

- define a working cycle suitable for extreme environments;
- investigate the dependencies between performances and environmental conditions;
- setup a theoretical model and a numerical solution that describe the behaviour of the system.

3.1 Working cycle

The test-prototype works exactly like the SAWG, alternating cycles of absorption and desorption by means of a desiccant material.
During the tests has been employed a battery filled with 27 kg of silica gel beads with 2-3 mm of diameter.
The energy needed for the diffusion of water inside and outside the porous structure of the sorbent depends on the material and is of the same order of magnitude of water latent heat. For silica gel is 2300-2500 kJ/kg.
The adsorption stage lasts around 15 hours and it is driven at ambient temperature (within 20-30°C) and dew point below 10°C.

The desorption (or regeneration) stage cannot exceed 10 hours and it consists in a cycle following four steps as shown in Figure 30:

- 1-2, the regeneration of the material is driven at temperatures below 60°C and powered with solar collectors following an isothermal transformation in order to have high dew points even at low humidity level;
- 2-3, the hot and humid air flux leaving the battery is cooled down using the external ambient air at around 30°C;
- 3-4, water condenses until air reaches the equilibrium with ambient temperature;
- 4-1, air is preheated recovering heat coming from vapour condensation, saving 24% of energy and increasing the efficiency of the system.

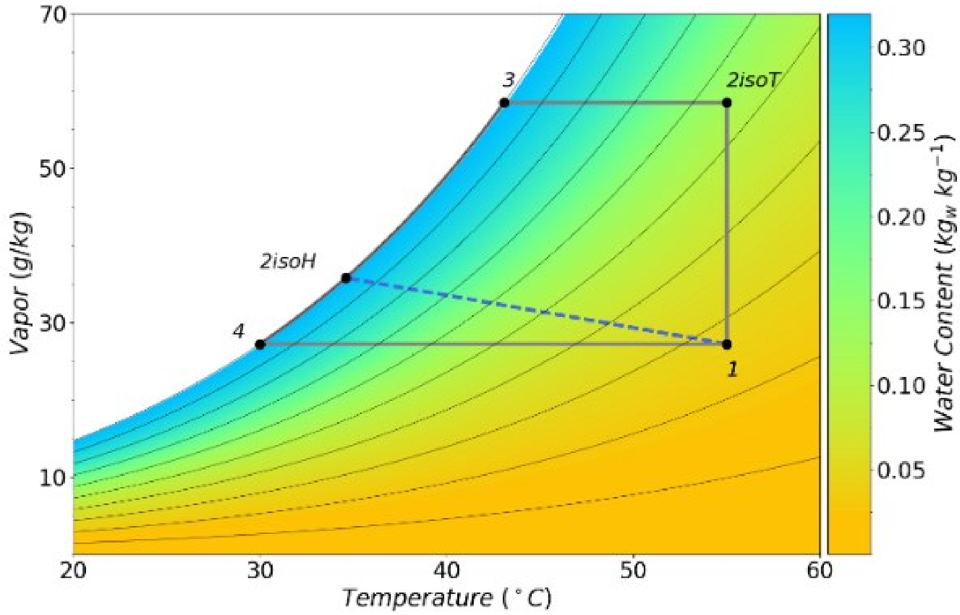


Figure 30. Desorption cycle on the psychrometric diagram

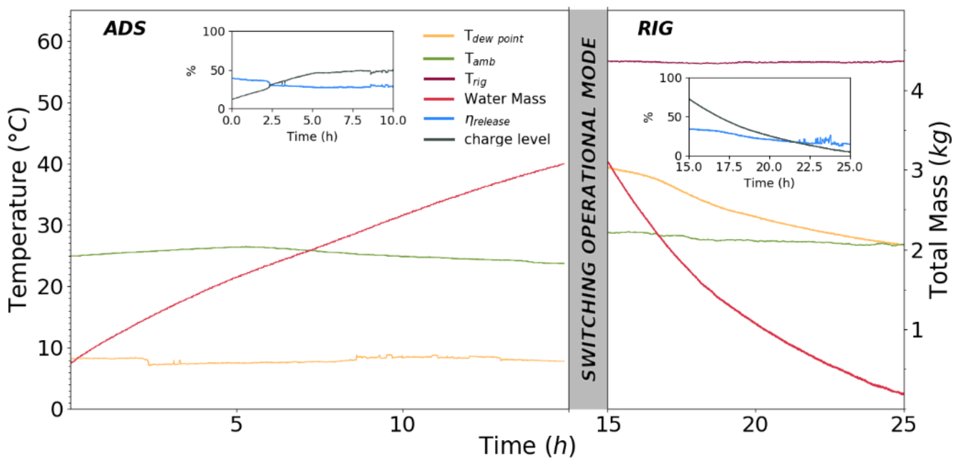


Figure 31. Example of a day/night water harvesting cycle

3.2 Experimental results

A number of tests were conducted keeping almost constant the temperature of the hot water supply at around 57°C and varying the environmental conditions between 20-35°C.
From the results has been observed that as the ambient temperature increases the water production decreases, passing from 3.3 l at 20°C to 1.5 l in the worst condition (35°C).
This drop has negative effect on the energy performance: the Specific Thermal Energy (STE) increases while the thermal efficiency decreases as reported in the table below.

Ambient temperature (°C)	**STE (kWh_{th}/l)**	**Global thermal efficiency (%)**
20	1.1	38
27	1.45	47
35	1.93	34

Table 4. Experimental results at different ambient temperatures

3.3 Theoretical model and numerical solution

In order to optimize the operation mode and to predict the performance in adsorption and regeneration, a theoretical was developed.
The model is made of a set of equations to evaluate the heat and mass transfer between water vapor-Silica gel-heat exchanger-water, the physical properties of air for each temperature and humidity level and the physical properties of Silica gel for each temperature and water uptake condition.
The hypothesis at the basis of the model are:

- adsorption/desorption processes involve only the water vapor and the sorbent;
- adsorption heat is generated inside the pores of the sorbent;
- adsorption/desorption processes are much faster than other phenomena (intraparticle diffusion, heat exchange);
- near the sorbent surface, the local vapor/sorbent equilibrium can be approximated with water-$SiO_{2 \cdot n}$(H2O) adsorption equilibrium curves;
- mono-dimensional phenomenon coherent with the air flow direction;

- the relevant heat transfer mechanism is convection (conduction and radiative exchange are neglected);
- due to the long duration of experiments, the vapor diffusion inside a particle plays a relevant role on the mass transfer mechanism;
- vapor mass transfer between air and $SiO_{2}\cdot_{n}$(H2O) is approximated with a Linear Driving Force (LDF) method;
- no thermal losses between the system and the external environment are expected considering the thermal insulation.

A comparison between experimental and simulated results was carried out focusing on air temperature, air humidity and water uptake, showing average errors below 10% which makes the LDF based algorithm a good compromise between reality and modelling.

4. Laboratory testing on the SAWG

In this chapter is described the experimental setup followed to perform tests on the SAWG and the results obtained.

4.1 Experimental setup

Before testing the on-field performances of the SAWG the following activities were carried out:

- enhancement of the thermal insulation of the prototype;
- optimization of the data acquisition system;
- elaboration of the data coming from the tests.

4.1.1 Thermal insulation

With the aim of avoid thermal losses toward the external environment the condenser and the batteries were insulated with the use of polystyrene sheets sealed with aluminium tape.

In addition, the tubes of the water circuit were coated with neoprene covered with aluminium tape.

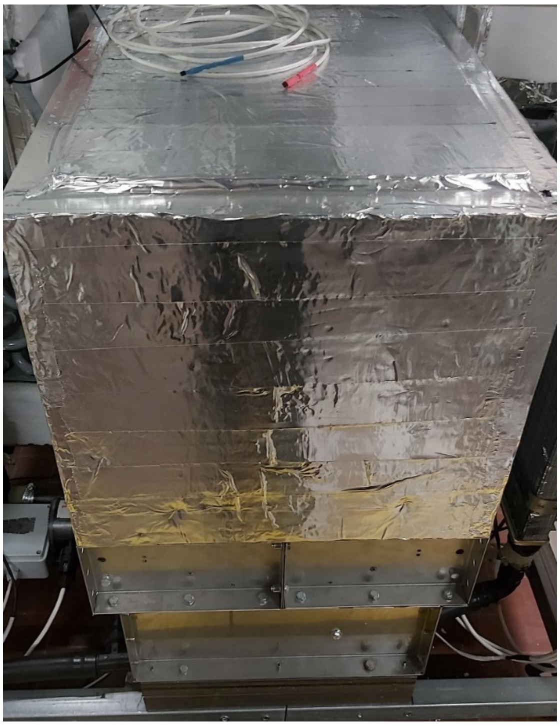


Figure 32. Insulation of the condenser

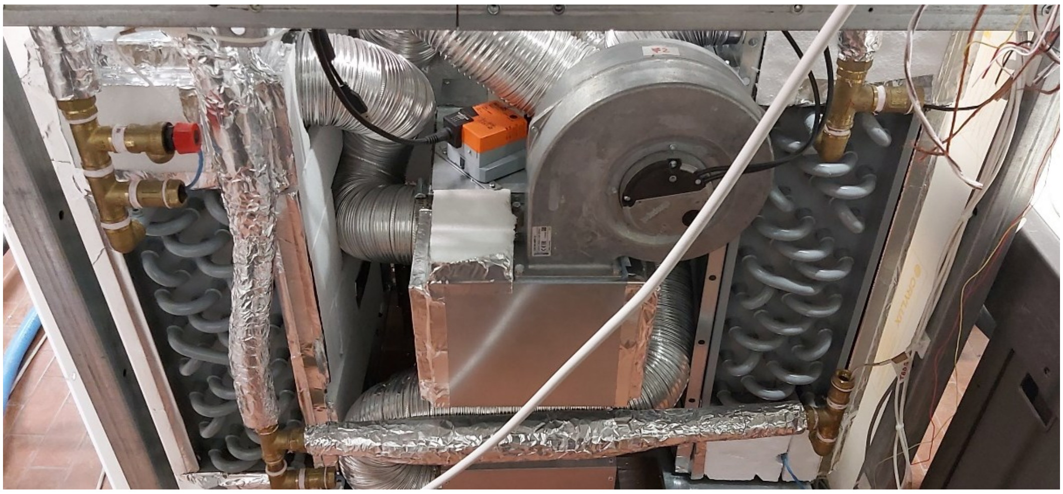


Figure 33. Insulation of the batteries and the tubes

4.1.2 Data acquisition system

As already mentioned in the previous chapter a number of temperature and relative humidity sensors have been installed.

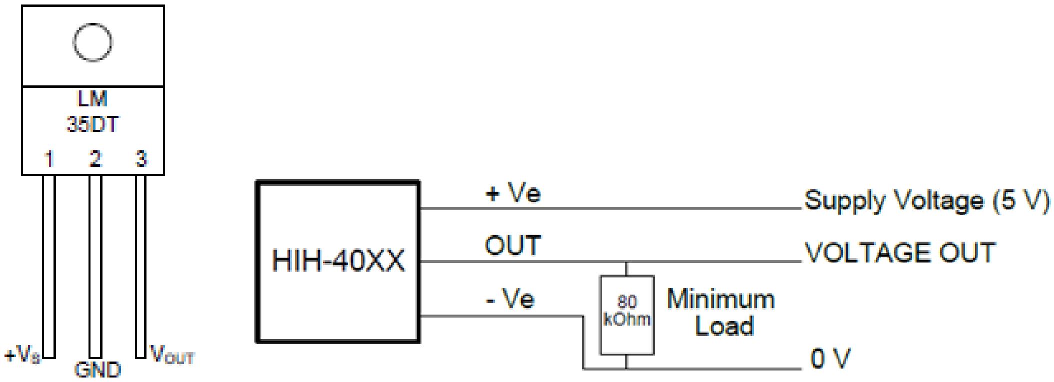


Figure 34. Schematization of the sensors

The temperature sensors (LM35CA) have an analogic output directly proportional to the temperature through the relation:

$$T = Vout \cdot 100 \frac{°C}{V} \quad [°C] \tag{4.1}$$

They do not require any calibration and provide accuracies of ±0.5°C at room temperature and ±1°C over a full −40°C to 110°C temperature range.
The devices draw only 60 µA from the supply thus have very low self-heating of less than 0.1°C in still air.
Like most micropower circuits, this type of sensors has a limited ability to drive heavy capacitive loads. Alone, it is able to drive 50 pF but in case of heavier loads the tolerance of capacitance can be improved with a series R-C damper from output to ground.

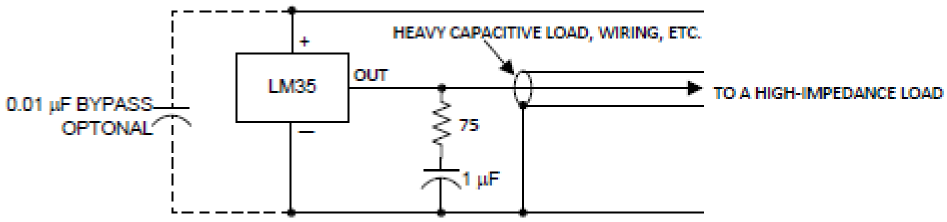


Figure 35. LM35 with a R-C damper

Even for the relative humidity sensors (HIH-4000 series) the voltage output is proportional to the relative humidity following the relation:

$$R.H. = \frac{V_{out} - zero\ offset}{slope} \quad [\%] \qquad 4.2$$

where the zero offset and the slope are given in the datasheet by the manufacturer.

The accuracy is of ± 3.5% with typical current draw of only 200 µA.

In the figure below is given a functional scheme of the SAWG together with the installed sensors:

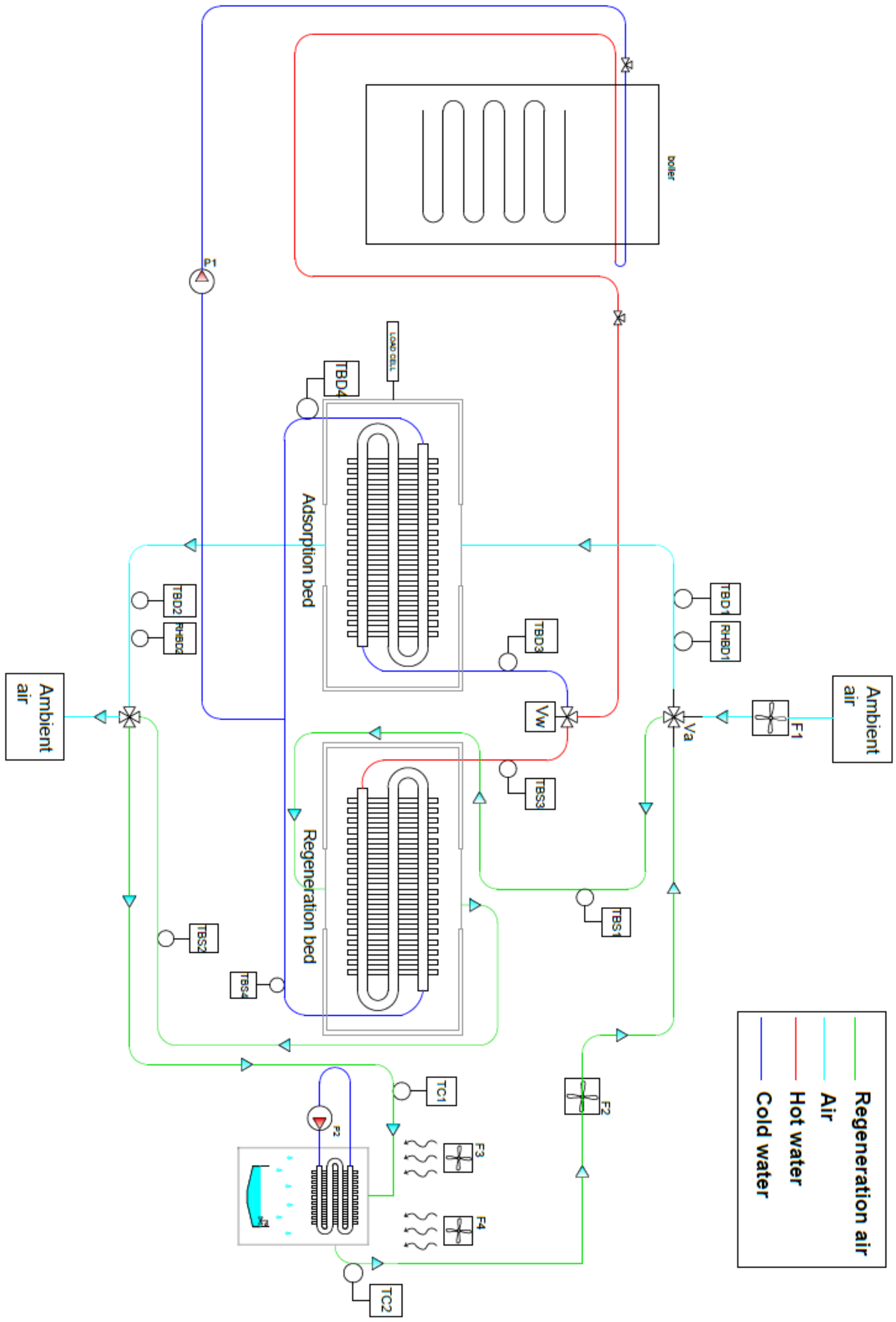


Figure 36. Functional scheme of the SAWG during laboratory testing

In the previous configuration the sensors were connected to the Controllino microcontroller together with the other components.

To decouple the control logic from the data acquisition system and to optimize the prototype a new microcontroller (Arduino DUE) has been installed and the sensors linked to it. A scheme of the new configuration is given in the figure below:

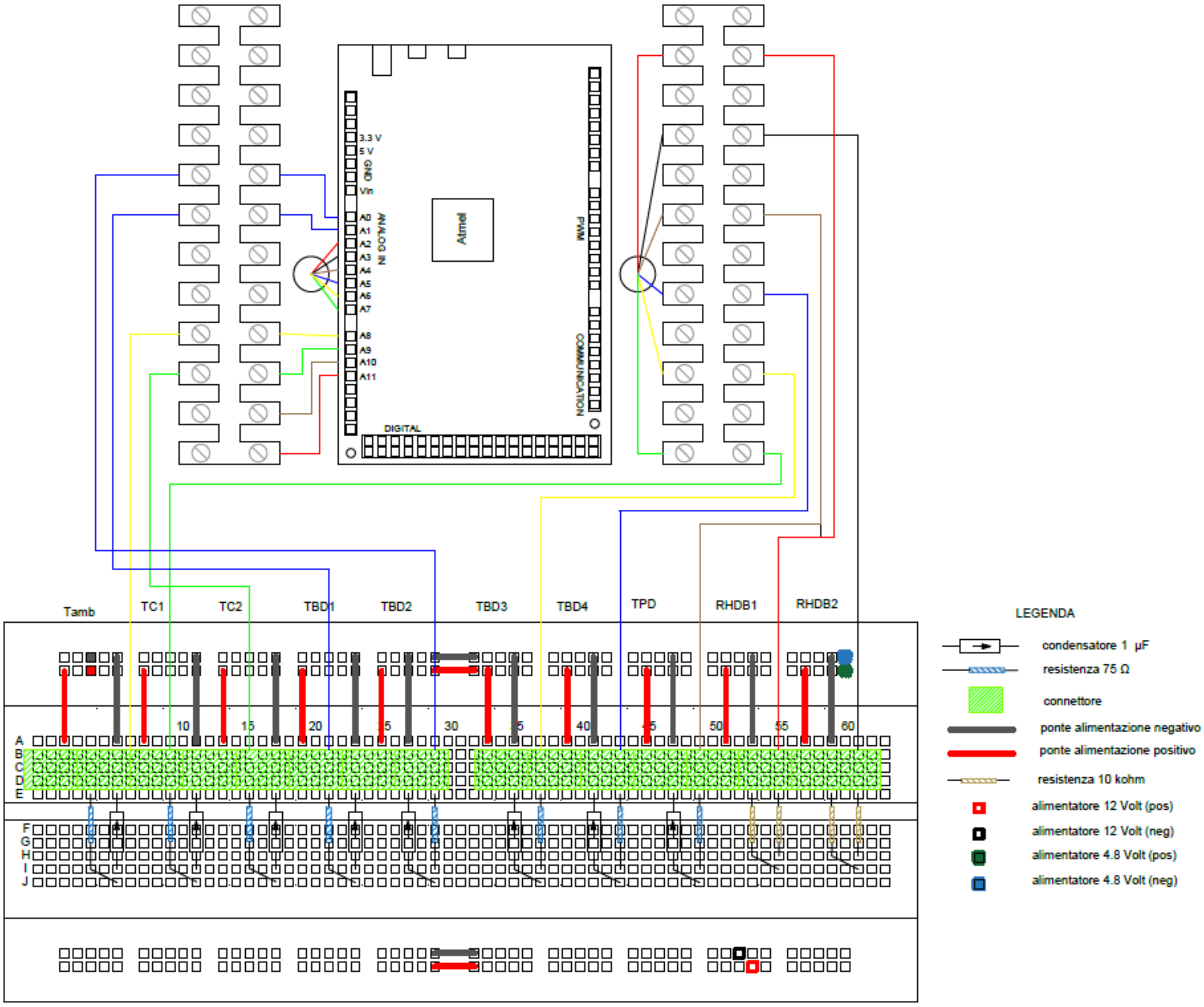


Figure 37. New configuration with Arduino DUE

The board and the sensors are powered by different voltage supply, 12 V and 4.8 V respectively.

The new microcontroller is connected via USB to a computer. Through the Arduino software the voltage output signals are sent to the Cool Term software that store them in a text file simultaneously opened in MATLAB environment. A code processes the data and on the PC monitor interface is displayed real time the evolution of the ongoing experiment.

Figure 38. Data acquisition architecture

4.2 Data analysis

From the temperature and R.H. values measured from the sensors it was possible to calculate the moisture content, the saturation pressure, the enthalpy, the air density and the dew point temperature of the inlet and outlet stream of the battery.
The saturation pressure is estimated using the Magnus equation:

$$p_{sat} = a \cdot \exp\left(\frac{b \cdot T}{c+T}\right) \qquad [Pa] \qquad 4.3$$

where the coefficients a, b and c are the so-called Alduchov and Eskridge coefficients, reported in the table below:

a	**b**	**c**
611.85	17.502	240.9

Table 5. Saturation pressure Alduchov and Eskridge coefficients

The absolute humidity is performed as:

$$x = 0.622 \cdot \frac{p_{sat} \cdot \frac{RH}{100}}{101325 - \left(p_{sat} \cdot \frac{RH}{100}\right)} \cdot 1000 \qquad \left[\frac{g_{water}}{kg_{air}}\right] \qquad 4.4$$

The enthalpy is:

$$h = cp_{air} \cdot T + x \cdot (cp_v \cdot T + hl_v) \qquad \left[\frac{kJ}{kg}\right] \qquad 4.5$$

where hl_v is the latent heat of vaporization.
The air density is:

$$\rho = \frac{1.293 \cdot 273.15}{273.15 + T} \qquad \left[\frac{kg}{m^3}\right] \qquad 4.6$$

The dew point temperature is calculated as a function of the saturation pressure for R.H=100%:

$$T_{dew} = \frac{c \cdot \ln\left(\frac{p_{sat,dew}}{a}\right)}{b - \ln\left(\frac{p_{sat,dew}}{a}\right)} \qquad [°C] \qquad 4.7$$

with:

$$p_{sat,dew} = \frac{101325 \cdot x}{0.622 + x} \qquad [Pa] \qquad 4.8$$

Finally, a mass balance is used to quantify the water absorbed or released by the Silica-gel:

$$m_{i+1} = m_i + dm \qquad [g] \tag{4.8}$$

dm, the amount of water adsorbed or desorbed at each time step, is equal to:

$$dm = (\rho_{out}(i+1)\cdot x_{out} - p_{in}(i+1)\cdot x_{in}(i+1))\cdot Q\cdot dt \tag{4.9}$$

being Q the air flow rate calculated according to the equations $air\ flow\ rate = \frac{-0.0042\cdot x^2+1.0017\cdot x-7.9956}{3600} \quad [\frac{m^3}{s}]$ 4.16-$air\ flow\ rate = \frac{-0.0029\cdot x^2+0.9621\cdot x-5.8062}{3600} \quad [\frac{m^3}{s}]$ 4.2 and the regulation chosen for the fan and dt the interval between two measurements.

In order to perform an accurate analysis on the data collected it is necessary to consider the error related to the measurements.

This value is well known for T and R.H. and is given by the manufacturer in the datasheet of the sensors:

$$\varepsilon_T = \pm 0.5°C$$

$$\varepsilon_{RH} = \pm 3.5\% \tag{4.9}$$

As p_{sat} is obtained starting from T, ε_T will influence the saturation pressure results. Similarly, the error related to the saturation pressure, together with ε_{RH} will affect the evaluation of the moisture content.

The same holds true for the enthalpy and the dew point temperature.

Considering that the treated quantities are not linear, to estimate the propagation of the error a Taylor expansion is performed, truncated at the first order term:

$$z(y) \cong z(\bar{y}) + \left.\frac{\partial z}{\partial y}\right|_{\bar{y}} (y-\bar{y}) \tag{4.10}$$

$$z(x,y) \cong y(\bar{x},\bar{y}) + \left.\frac{\partial z}{\partial x}\right|_{x} (x-\bar{x}) + \left.\frac{\partial z}{\partial y}\right|_{\bar{y}} (y-\bar{y}) \tag{4.11}$$

The variance is calculated as:

$$\sigma^2[z] = \sigma^2[z(y)] = E[(z(y)-E[z(y)])^2] \cong E\left[\left(z(\bar{y}) + \left.\frac{\partial z}{\partial y}\right|_{\bar{y}} (y-\bar{y}) - z(\bar{y})\right)^2\right] =$$

$$E\left[\left(\left.\frac{\partial z}{\partial y}\right|_{\bar{y}} (y-\bar{y})\right)^2\right] = \left(\left.\frac{\partial z}{\partial y}\right|_{\bar{y}}\right)^2 \cdot E[(y-y)^2] = \left(\left.\frac{\partial z}{\partial y}\right|_{\bar{y}}\right)^2 \cdot \sigma^2[y]$$

4.12

$$\sigma^2[z] = \sigma^2[z(x,y)] = E[(z(x,y) - E[z(x,y)])^2] \cong E\left[\left(\begin{matrix} z(\bar{x},\bar{y}) + \left.\frac{\partial z}{\partial x}\right|_{\bar{x},\bar{y}} \cdot (x-\bar{x}) \\ + \left.\frac{\partial z}{\partial y}\right|_{\bar{x},\bar{y}} \cdot (y-\bar{y}) - z(\bar{x},\bar{y}) \end{matrix}\right)^2\right]$$

$$\cong E\left[\left(\left.\frac{\partial z}{\partial x}\right|_{\bar{x},\bar{y}} \cdot (x-\bar{x}) + \left.\frac{\partial z}{\partial y}\right|_{\bar{x},\bar{y}} \cdot (y-\bar{y})\right)^2\right]$$

$$\cong E\left[\begin{matrix} \left(\left.\frac{\partial z}{\partial x}\right|_{\bar{x},\bar{y}}\right)^2 \cdot (x-\bar{x})^2 \\ + \left(\left.\frac{\partial z}{\partial y}\right|_{\bar{x},\bar{y}}\right)^2 \cdot (y-\bar{y})^2 \\ +2 \cdot \left.\frac{\partial z}{\partial x}\right|_{\bar{x},\bar{y}} \cdot \left.\frac{\partial z}{\partial y}\right|_{\bar{x},\bar{y}} \cdot (x-\bar{x}) \cdot (y-\bar{y}) \end{matrix}\right] \cong$$

$$\left(\left.\frac{\partial z}{\partial x}\right|_{\bar{x},\bar{y}}\right)^2 \cdot \sigma^2[x] + \left(\left.\frac{\partial z}{\partial y}\right|_{\bar{x},\bar{y}}\right)^2 \cdot \sigma^2[y] \qquad 4.13$$

The standard deviations, which represent the error, are:

$$\sigma[z] = \left.\frac{\partial z}{\partial y}\right|_{\bar{y}} \cdot \sqrt{\sigma^2[y]} \qquad 4.14$$

$$\sigma[z] = \sqrt{\left(\left.\frac{\partial z}{\partial x}\right|_{\bar{x},\bar{y}}\right)^2 \cdot \sigma^2[x] + \left(\left.\frac{\partial z}{\partial y}\right|_{\bar{x},\bar{y}}\right)^2 \cdot \sigma^2[y]} \qquad 4.15$$

The data coming from the tests are analysed in the following paragraph.
The adsorption and regeneration processes are treated separately.

4.2.1 Regeneration

The regeneration tests were performed regulating the fan at 100%,75%, 50% and 25% of its nominal power.
The corresponding air flow rate is calculated as follow:

$$air\ flow\ rate = \frac{-0.0042 \cdot x^2 + 1.0017 \cdot x - 7.9956}{3600} \quad [\frac{m^3}{s}] \qquad 4.16$$

A comparison on the results is made focusing on temperature, relative and absolute humidity and amount of water produced as shown in figure from Figure 39 to Figure 43.
The tests consist into two phases.

First the external water circuit is opened and the pump that circulates hot water switched on at its maximum flow rate. The battery is heated up until its temperature becomes uniform.
Once the equilibrium is reached, (the light blue and pink curves of Figure 39 reach a plateau) the proper regeneration starts turning on the fans and the pump of the condenser water circuit.
As it is possible to observe the temperature curves show a drop due to the fact that the hot water coming from the boiler passes from ~58°C to ~47°C after around one hour.
The relative and absolute humidity exhibit a similar behaviour showing a big difference and a fast reduction in the first part of the process when the water content inside the bed is still high.
The test stops when the curves between the inlet and outlet moisture content tend to converge, meaning that the Silica gel is completely desorbed.
It is worth noting that, increasing the speed of the fan, the duration of the test increases, passing from 4:05 h at 25% to 8:27 h at 100%, with a higher amount of water produced (~900 ml vs ~3 l).
Technically, when the dew temperature meets the curve of the ambient temperature, at which the condenser works, it is no more possible to extract water from the air.
This meeting point varies from test to test but, as it is possible to observe in Figure 43, is reached faster for lower regulation of the fan and increasing ambient temperatures.

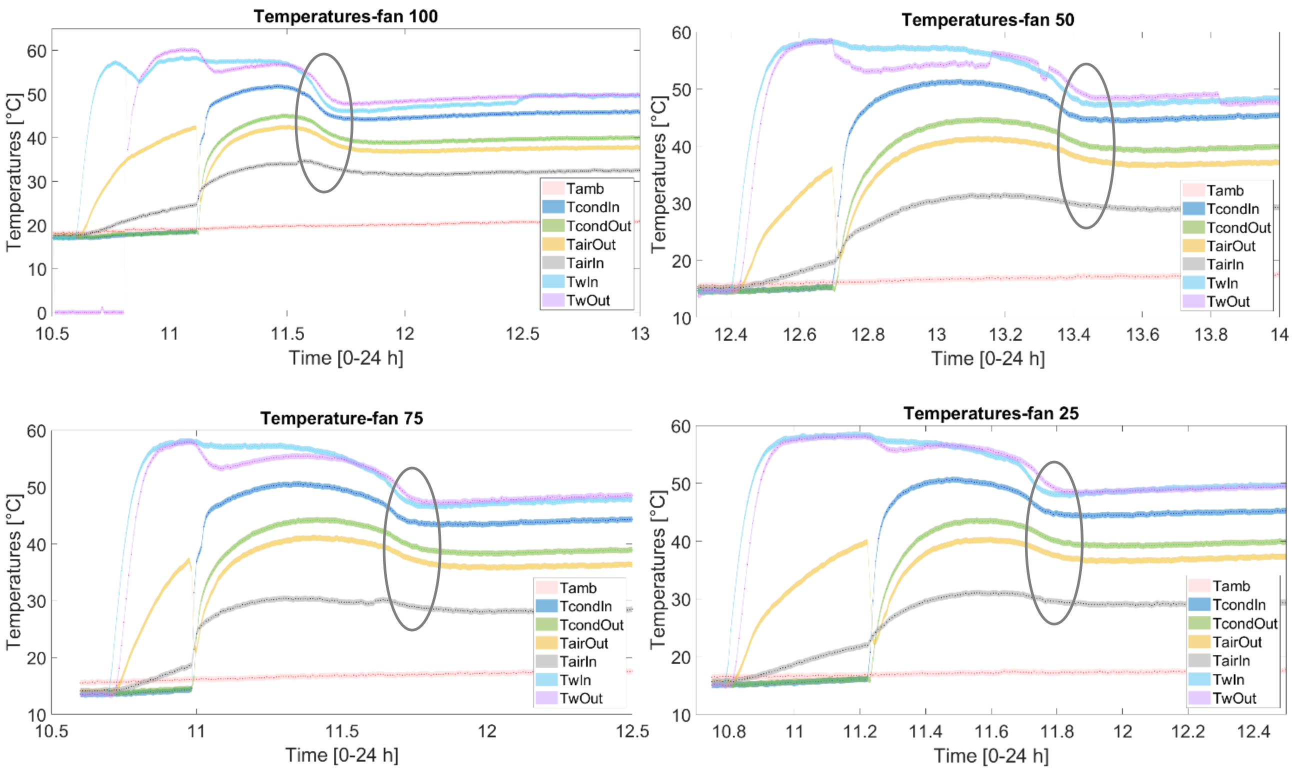


Figure 39. Air and water temperatures for different fan regulations

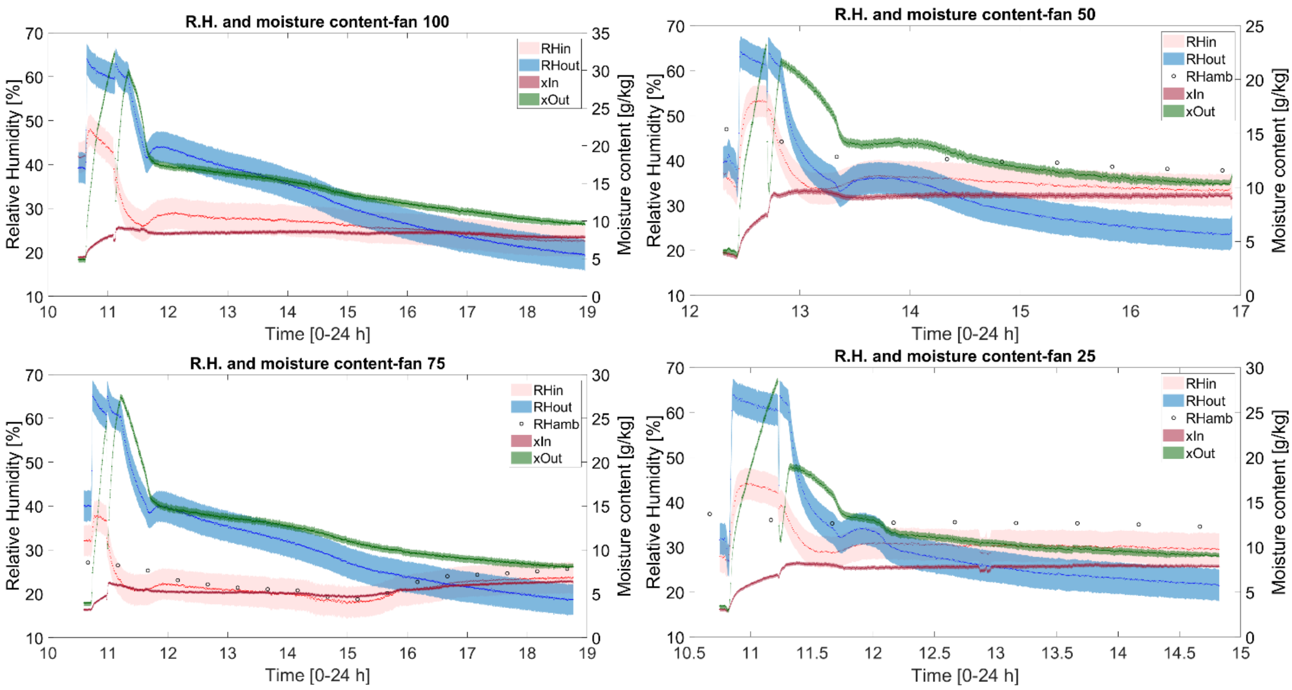


Figure 40. R.H. and moisture content for different fan regulations

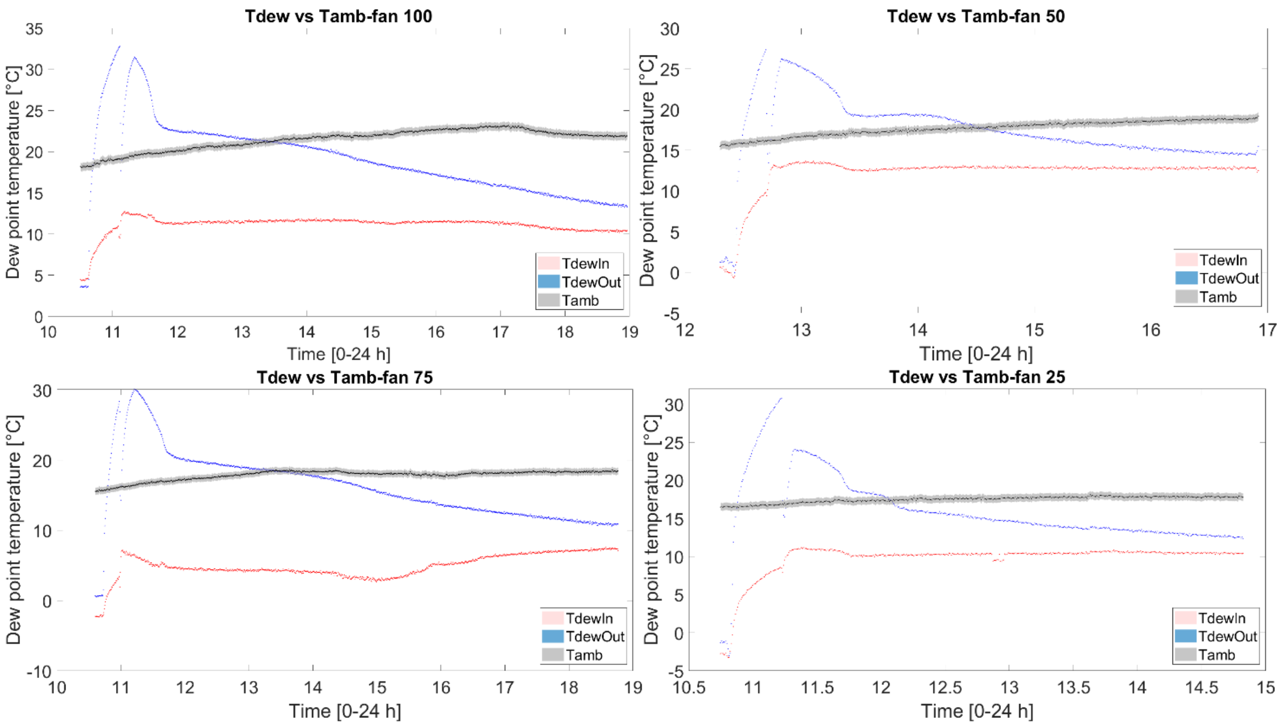


Figure 41. Tdew vs Tamb for different fan regulations

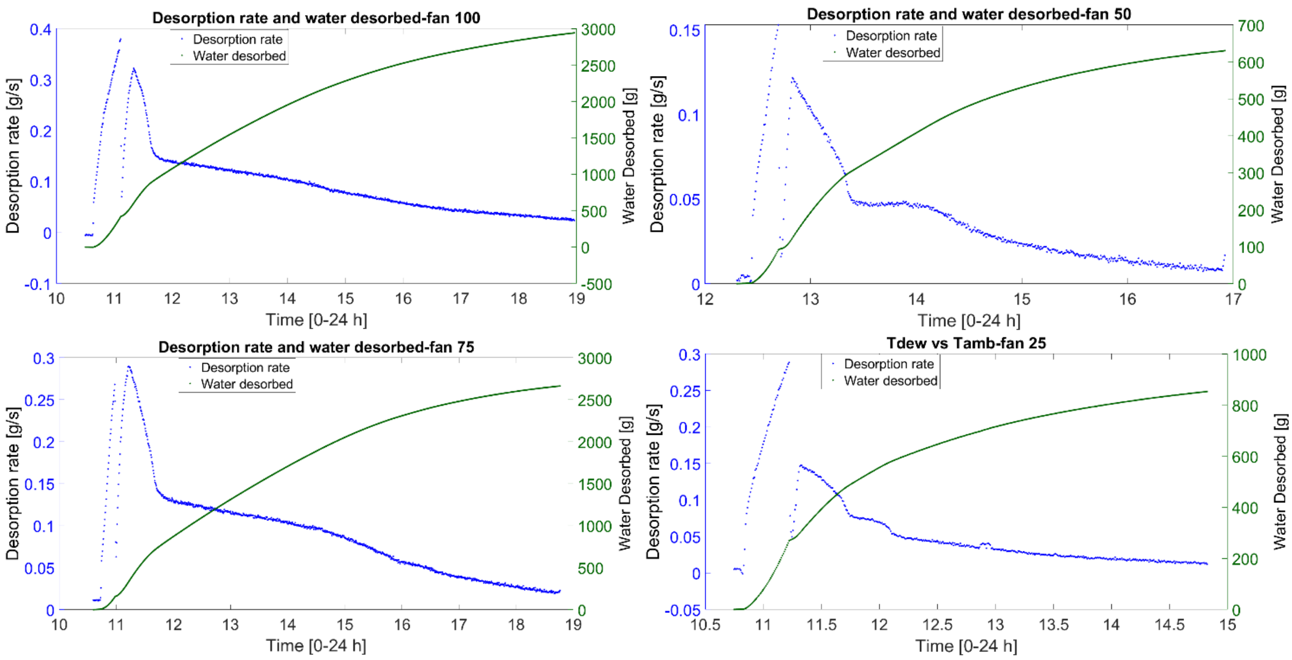


Figure 42. Desorption rate and water desorbed for different fan regulations

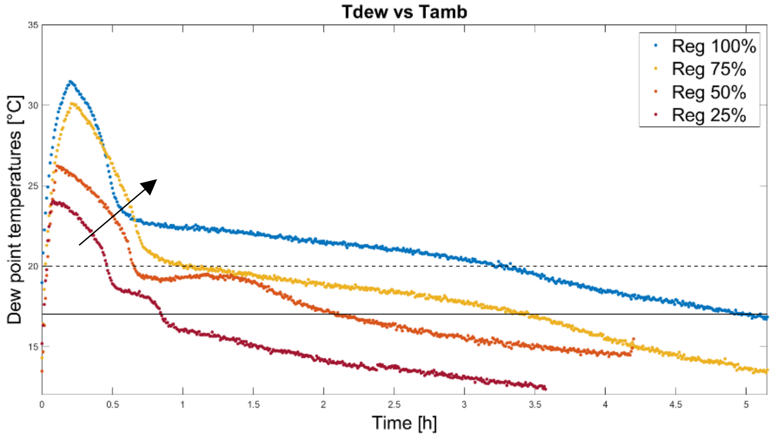


Figure 43. Tdew vs Tamb

To have an idea about the energy consumed to produce water among the different fan regulations, the specific consumption has been calculated:

$$e = \frac{P_{th-prim}}{Q \cdot (\rho_{out} \cdot x_{out} - \rho_{in} \cdot x_{in})} \qquad \left[\frac{kWh}{g_{H_2O}}\right] \tag{4.17}$$

being the electrical energy linked to the water circuit pumps and the fans negligible with respect to the thermal one.

The quantities at the denominator are referred to the air stream entering and exiting the regenerated battery.

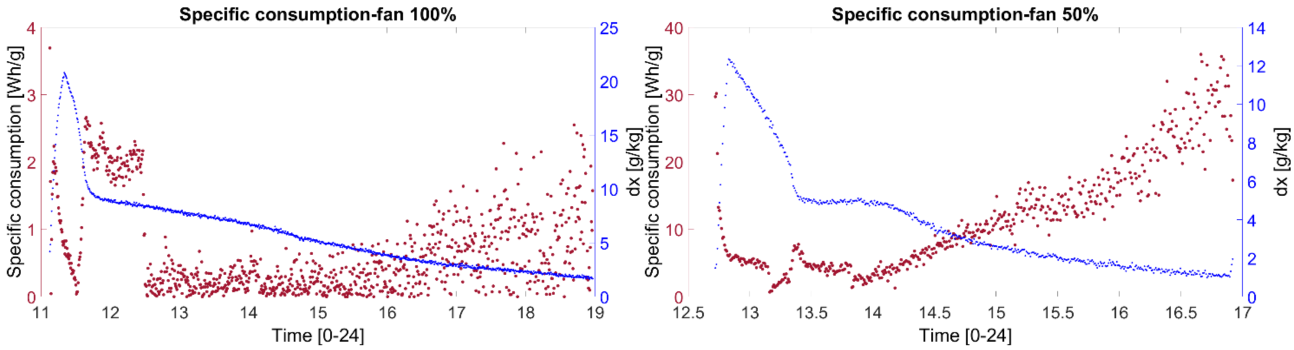
P_{th}, the thermal energy absorbed from the boiler, is equal to:

$$P_{th} = m_w \cdot cp_w \cdot (T_{in} - T_{out})_{prim} \qquad [kW] \tag{4.18}$$

This quantity has to be converted into primary source of energy according to the Authority for electric energy and gas (Autorità per l'energia elettrica e il gas) with "Delibera EEN 3/08 del 20-03-2008 (GU n. 100 del 29.4.08- SO n.107)".

The primary energy conversion factor is fixed at 0,187 10^{-3} tep/kWh. Being 1 tep equal to 41.860 GJ, $P_{th-prim}$ will be:

$$P_{th-prim} = P_{th} \cdot 0.187 \cdot 10^{-3} \cdot 41.860 \cdot 10^{6} \qquad [kW] \tag{4.19}$$



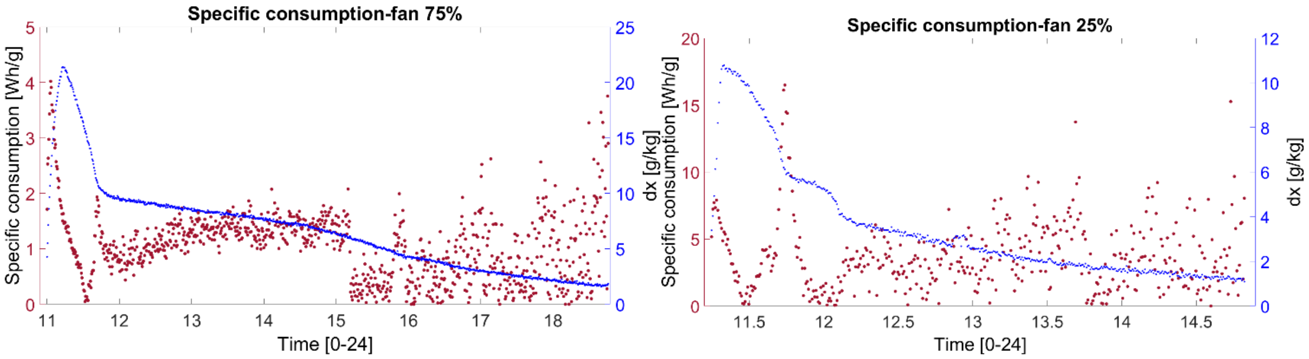


Figure 44. Specific consumption for different fan regulation

Despite the thermal power provided to the system is almost constant, the production of water has a decreasing trend, thus the specific consumption is not constant but an increasing function of the operating time.

From the results e is lower for higher regulation of the fan, i.e. more water is produced less specific energy is consumed.

4.2.2 Adsorption

The adsorption tests were performed without regulation and the air flow is calculated as follow:

$$air\ flow\ rate = \frac{-0.0029 \cdot x^2 + 0.9621 \cdot x - 5.8062}{3600} \qquad [\frac{m^3}{s}] \tag{4.20}$$

A comparison is made focusing on temperature, relative and absolute humidity and water produced during the regeneration.

The results are shown in figure from Figure 45 to Figure 47.

Being the process exothermic the temperature inside the bed tends to increase with a ΔT bigger when the difference of moisture content between inlet and outlet air stream is higher.

As for the regeneration, the curves of relative and absolute humidity have a similar behaviour tending to converge as the adsorption process goes on.

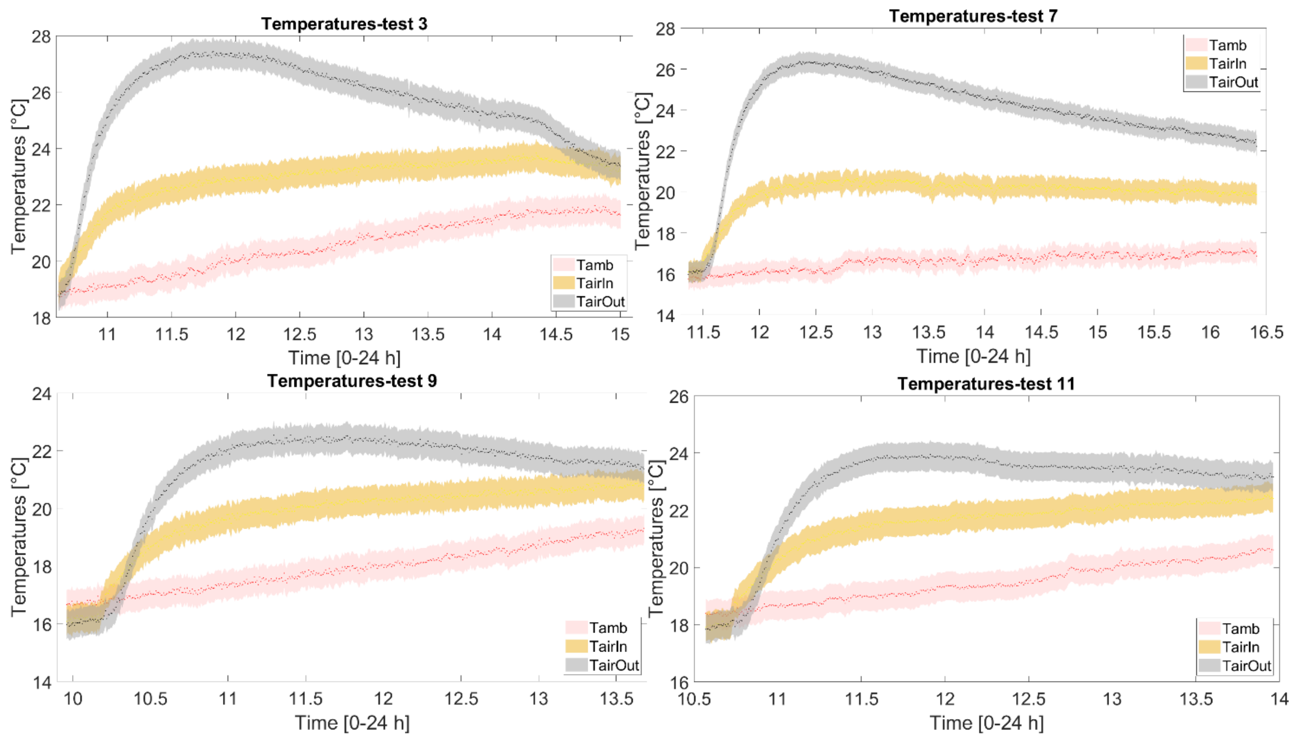


Figure 45. Air temperatures for different adsorption tests

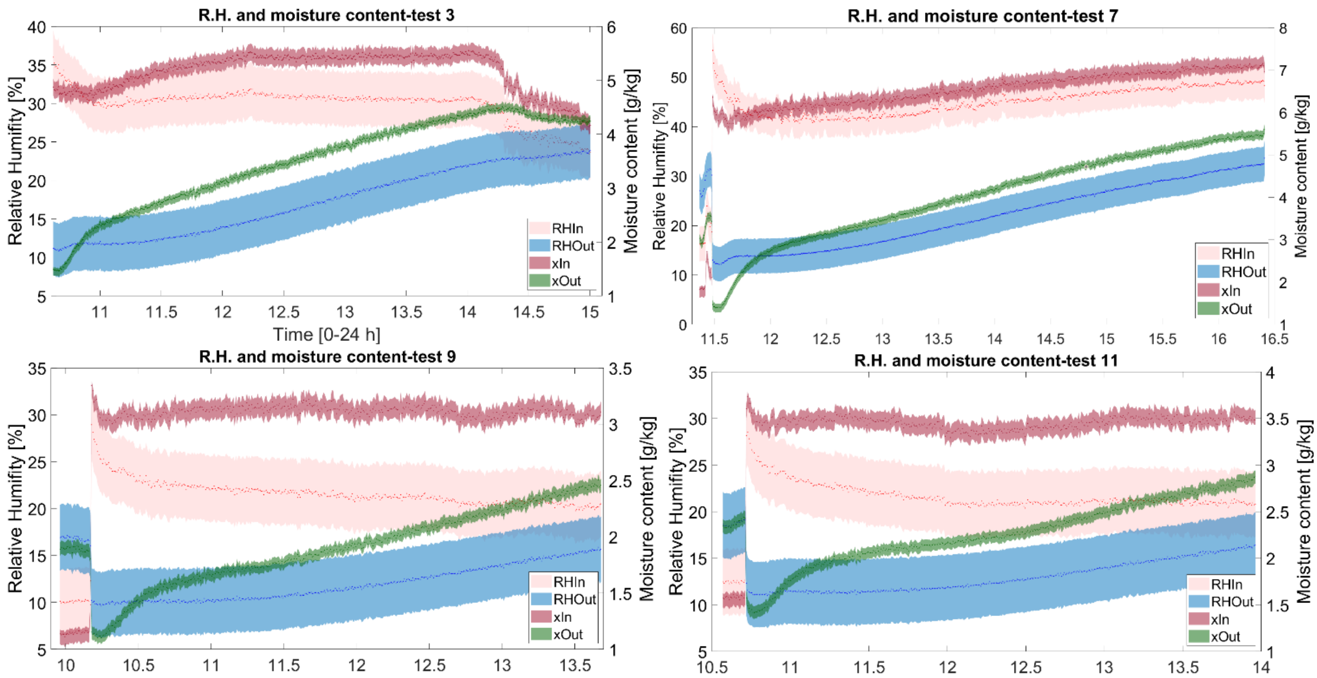


Figure 46. R.H. and moisture content for different adsorption tests

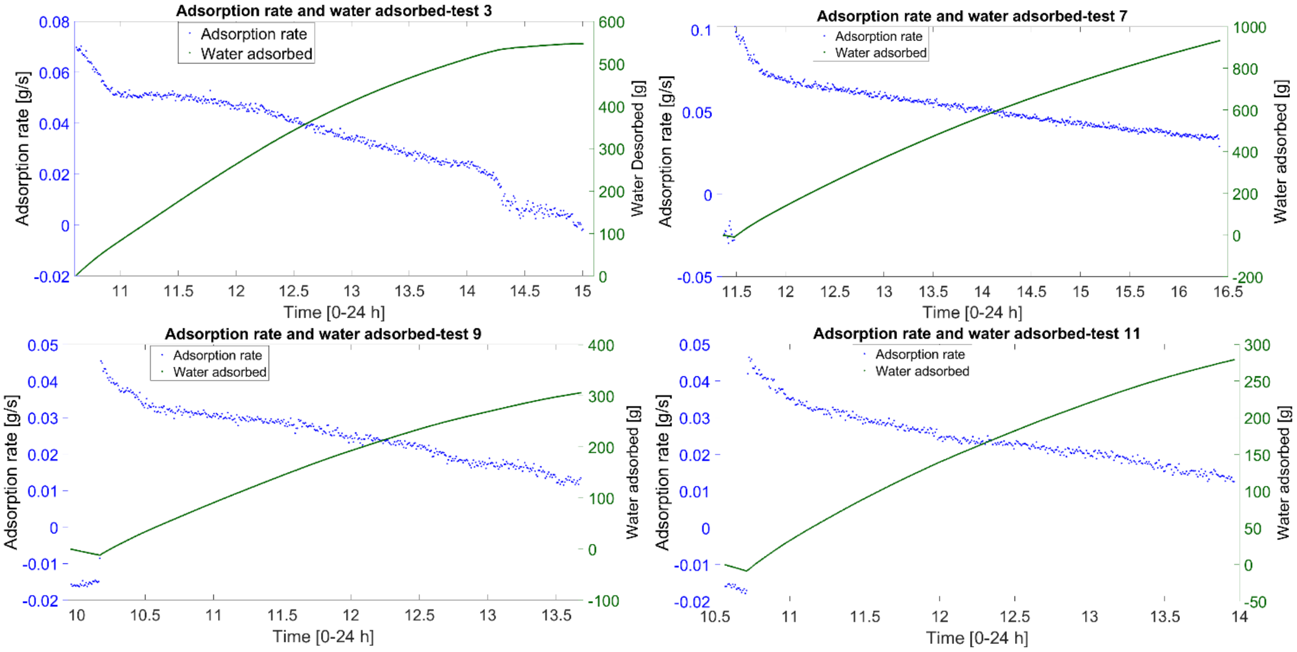


Figure 47. Adsorption rate and water adsorbed for different adsorption tests

5. SAWG water production forecast in different locations

Starting from the results of the laboratory tests, this chapter aim to make a forecast of the SAWG water production in different locations to concretize where the effective utilization of the prototype could be feasible.

In absence of a theoretical model able to reproduce the performance of the system, it was possible only to simulate the adsorption phase.

As shown in Figure 46, the green curves representing the moisture content of the air exiting the battery exhibit an initial steep increase of around 1 g_w/kg_a, followed by a linear raising trend. Additionally, a residual of ~1.5 g_w/kg_a has been observed at the beginning of each test.

Therefore, the adsorption curve has been approximated with a piecewise linear function and the results obtained have been compared to the experimental data.

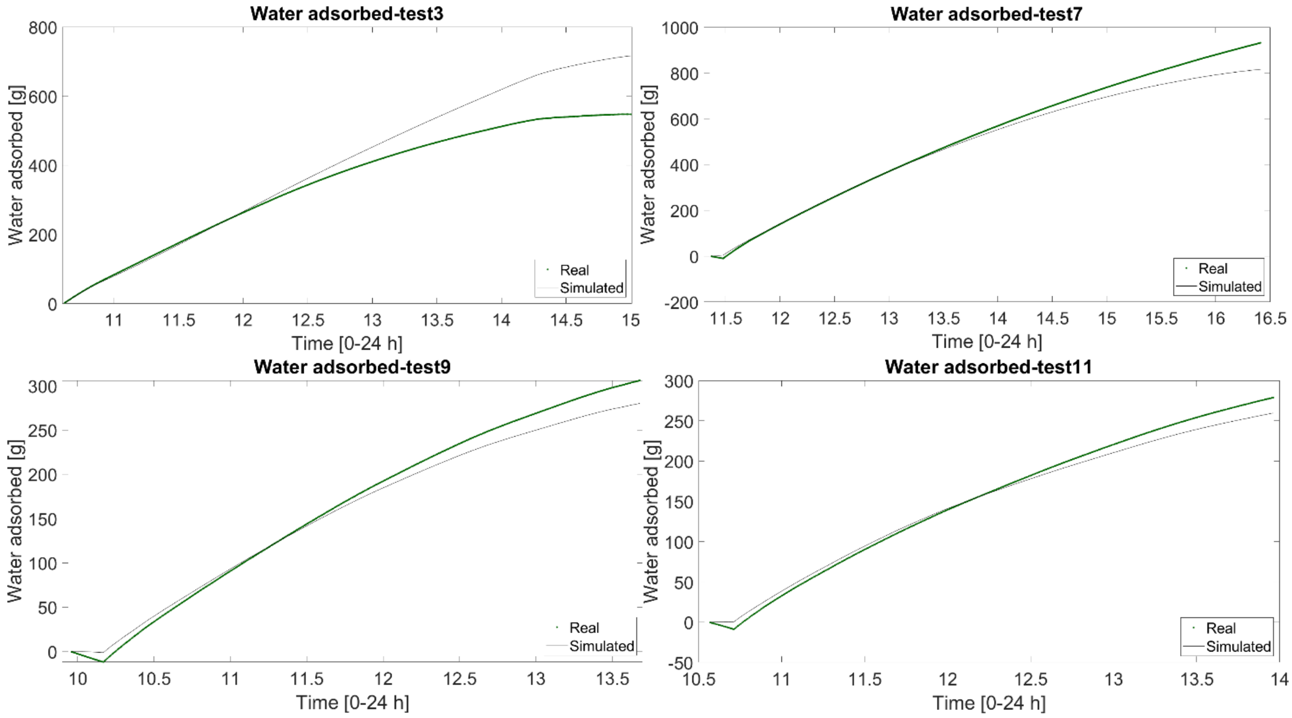


Figure 48. Water adsorbed during adsorption tests: real and simulated curves

The piecewise linear function gives good results with deviations within the 10%, thus it has been adopted to predict the potential productivity of the SAWG in different locations.

For the analysis were chosen three different cities located in areas experimenting water scarcity as seen in Figure 13: Tunis, Nairobi and Riyadh.

For each location four days representative of the four seasons are considered: the 15th of January, the 15th of April, the 15th of July and the 15th of October.

The climatic hourly data are available from the *EnergyPlus* and *Meteonorm* databases.

Temperature, relative humidity and atmospheric pressure are used as input to quantify the amount of moisture contained in the air entering the battery.

The duration of the adsorption phase has been set to 5 h and the starting time at 1:00 p.m. In this way, during the day the desiccant material can be regenerated taking advantage of the natural sunlight.

Supposing to have a control logic that stops the adsorption when the difference between the inlet and outlet absolute humidity reaches 0.5 g_w/kg_a, the results of the simulation are discussed below.

The attention has been focused on the amount of water that can be produced.

Moreover, on the graphs have been reported the average temperature and relative humidity during the chosen day since they help to get an idea of the quantity of moisture contained in the air.

Tunis: The city is characterized by a Mediterranean climate with dry summers and mild, rainy winters.
As it possible to observe from Figure 49 the water production varies significantly during the year, passing from 0.78 l/day during the coldest month to 1.89 l/day in summer.
Tunis shows an intermediate behaviour between Riyadh and Nairobi.

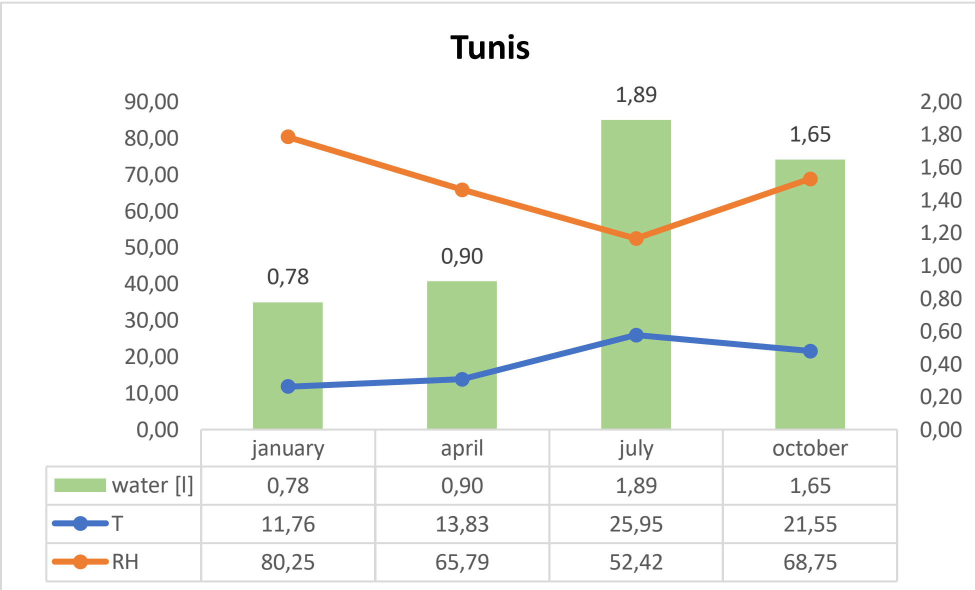


Figure 49. Tunis

Riyadh: Riyadh has an arid desert climate with a long and very hot summer and a short, mild winter.
The relative humidity is low throughout the year, which means that, despite a constantly high sunlight, very low amount of water can be produced.
It is evident that regions with this type of climate are unfavourable for the application of an atmospheric water generator.

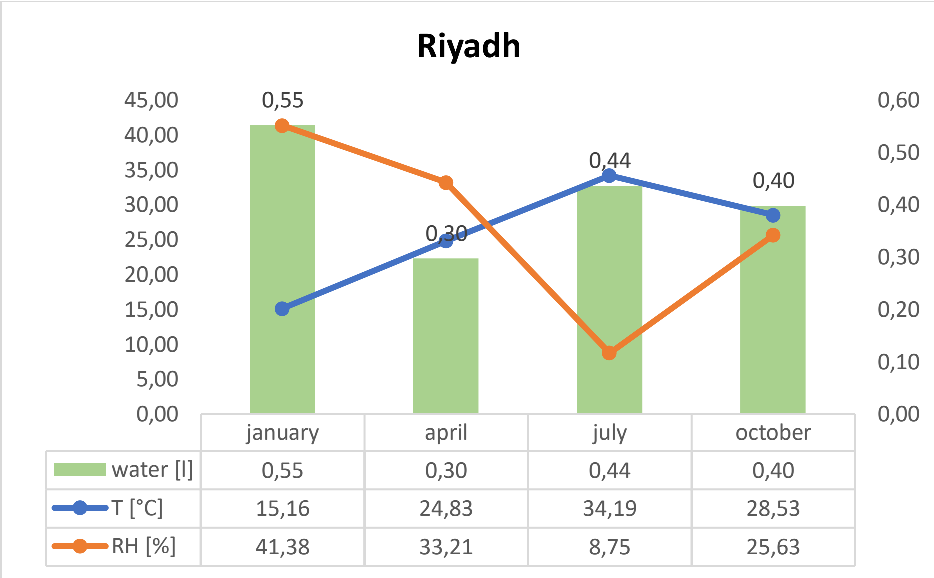


Figure 50. Riyadh

Nairobi: Nairobi has a subtropical highland climate experiencing spring-like weather with constant temperatures throughout the year.

This type of climate is characterized by a wet and a dry season and prevalently sunny days.

Thanks to the all year-round high humidity level the water production is not subjected to big variations, making this city a perfect candidate for the application of an atmospheric water generator.

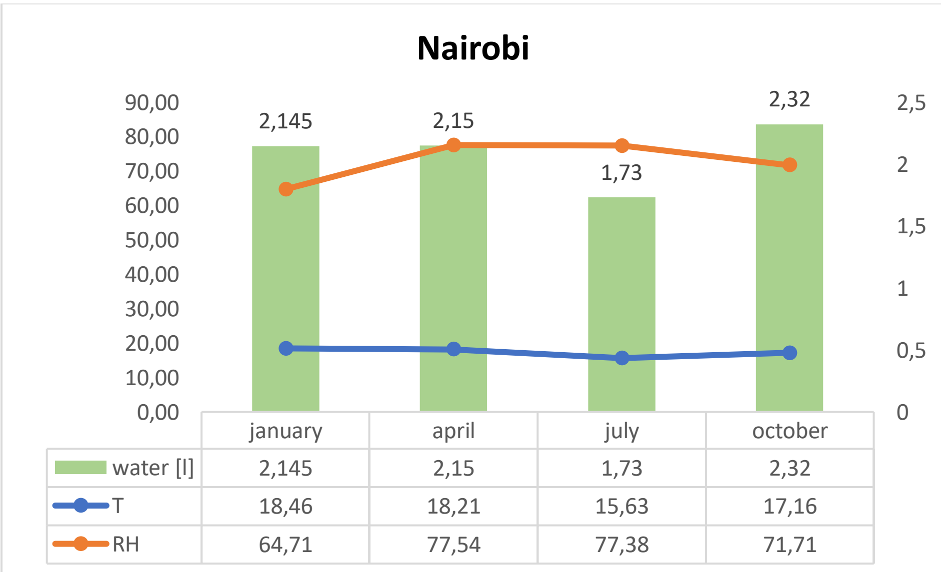


Figure 51. Nairobi

6. Analysis of the coupling of the SAWG with the greenhouse

In this chapter is investigated the possibility for the SAWG to provide water for agricultural purposes.

The attention is focused on the water requirements of an experimental greenhouse in which will be grown lettuce (*Lactuca sativa* L.) in hydroponics.

The plants will be held in two 3,7 m long cases and irrigated thanks to the NFT method in a closed loop. Considering a spacing between each plant of around 0,25 m is possible to place around 30 lettuces.

As reported in literature [38], from the planting to the harvesting each lettuce needs around 3 l of water, including the losses due to evapotranspiration.

The time span depends on the growing season and can vary from 45 days in winter to 20 days in summer.

Given a number of n_{plants}, a simple formula for the estimation of the Daily Water Requirements (DWR) of the plants is reported below:

$$DWR = \frac{n_{plants} \cdot W}{D} \quad [\frac{l}{day}] \tag{6.1}$$

where W is the specific water needs of the plant and D are the days between two subsequent harvesting.

Considering a growing season of 45 days, the DWR of the greenhouse under investigation will be equal to 2 l.

As already highlighted in the chapter 4, for lower regulation of the regeneration fan the dew point temperature reaches the ambient temperature faster, which means that less water can be desorbed.

This behaviour is confirmed by the results of the laboratory tests as reported in Table 6:

Test	**Fan regulation**	**Water produced [l]**
2	100%	2.9417
6	50%	0.6305
8	75%	2.6632
10	25%	0.8528

Table 6. Water produced during each test

To satisfy a DWR of 2 l it's more advisable a regulation of the fan in a range between 75% and 100% and climatic conditions similar to the Mediterranean and subtropical ones.
Nevertheless, in addition to the DWR must be considered the water requirement related to the NFT method.
From a study conducted at the Jordan University of Science and Technology [39] emerged that the ideal water flow rate in nutrient film technique systems that optimizes the nutrients uptake with growth of lettuce is of 20 l/h.
It is evident that the SAWG with the actual configuration cannot provide such quantity in a day. Two possible solutions can be adopted:

- run the generator alone until 20 litres of water have been stored and then couple it to the greenhouse;
- provide 20 litres from an external source and use the SAWG only to cover the DWR of the plants.

7. Conclusions

The aim of the work was to investigate the performances of a solar atmospheric water generator SAWG to examine the possibility of supply water for an experimental hydroponic greenhouse.
After enhancing the thermal insulation of the generator, the data acquisition system was optimized and several tests were performed under different regulation of the regeneration fan.
The attention was focused on the following variables: temperature, relative and absolute humidity, dew point temperature, mass balance and specific consumption.
The last quantity was used to investigate how different fan regulations affect the energy consumption of the SAWG and was highlighted that it decreases for higher regulation of the fan.
From the results was possible to model the behaviour of the adsorption phase with a piecewise linear increasing function and make a forecast of the SAWG water production in different locations.
It was seen how the water uptake varies according to the temperature and relative humidity, passing from 0.3 l/day in Riyadh to 2.32 l/day in Nairobi.

Finally, were investigated the daily water requirements of the experimental hydroponic greenhouse.
For the growing of lettuce, they correspond to 2 l/day for a lot of 30 plants.
The present work has been conducted considering only one of the two battery installed on the generator. Of course, the productivity of the system can be increased with the use of the two bed.
As future work it could be interesting to investigate the performances of the SAWG in such configuration, implementing a suitable control logic that aims to find the optimum between energetic consumption and water production.

Bibliography

[1] U. Nations, "Transforming Our World: The 2030 Agenda for Sustainable Development," *A New Era Glob. Heal.*, 2018.

[2] FAO, "The state of the world's land and water resources for food and agriculture (SOLAW) – Managing systems at risk."

[3] R. W. Zafar Adeel, Uriel Safriel, David Niemeijer, *Ecosystems and Human Well-Being Desertification synthesis*. 2005.

[4] M. M. Mekonnen and A. Y. Hoekstra, "Four billion people facing severe water scarcity," *Sci. Adv.*, vol. 2, no. 2, pp. 1–7, 2016.

[5] FAO, "Every drop counts | FAO Stories | Food and Agriculture Organization of the United Nations." [Online]. Available: http://www.fao.org/fao-stories/article/en/c/1111580/.

[6] "WHO/EU drinking water standards comparative table, Water treatment & Air purification and other supporting information."

[7] O. Buros, "The ABCs of Desalting," *Int. Desalin. Assoc.*, 1999.

[8] M. Shatat and S. B. Riffat, "Water desalination technologies utilizing conventional and renewable energy sources," *Int. J. Low-Carbon Technol.*, vol. 9, no. 1, pp. 1–19, 2014.

[9] "Groundwater Foundation." [Online]. Available: https://www.groundwater.org/.

[10] I. S. (Igorʹ S. Zektˆsˇer, L. G. Everett, and International Hydrological Programme., *Groundwater resources of the world and their use.* UNESCO, 2004.

[11] "We pump too much groundwater, and rivers are in danger." [Online]. Available: https://www.nationalgeographic.com/science/2019/10/groundwater-pumping-killing-rivers-streams/.

[12] I. E. M. de Graaf, T. Gleeson, L. P. H. (Rens) van Beek, E. H. Sutanudjaja, and M. F. P. Bierkens, "Environmental flow limits to global groundwater pumping," *Nature*, vol. 574, no. 7776, pp. 90–94, Oct. 2019.

[13] "The collective management approach for irrigation in France," 2017, pp. 93–98.

[14] H. Kim *et al.*, "Adsorption-based atmospheric water harvesting device for arid climates," *Nat. Commun.*, vol. 9, no. 1, pp. 1–8, 2018.

[15] F. Bagheri, "Performance investigation of atmospheric water harvesting systems," *Water Resour. Ind.*, vol. 20, no. June 2017, pp. 23–28, 2018.

[16] J. Y. Wang, R. Z. Wang, Y. D. Tu, and L. W. Wang, "Universal scalable sorption-based atmosphere water harvesting," *Energy*, vol. 165, pp. 387–395,

2018.
[17] B. Khalil *et al.*, “A review: dew water collection from radiative passive collectors to recent developments of active collectors,” *Sustain. Water Resour. Manag.*, vol. 2, no. 1, pp. 71–86, Mar. 2016.
[18] “Chile: los atrapanieblas que capturan agua en Atacama, uno de los lugares más secos del mundo - BBC News Mundo.” [Online]. Available: https://www.bbc.com/mundo/noticias/2015/05/150521_atrapanieblas_chile_desierto_lp.
[19] O. Klemm *et al.*, “Fog as a fresh-water resource: Overview and perspectives,” *Ambio*, vol. 41, no. 3, pp. 221–234, 2012.
[20] Y. Tu, R. Wang, Y. Zhang, and J. Wang, “Progress and Expectation of Atmospheric Water Harvesting,” *Joule*, vol. 2, no. 8, pp. 1452–1475, 2018.
[21] G. Sharan, “Harvesting Dew with Radiation Cooled Condensers to Supplement Drinking Water Supply in Semi-arid Coastal Northwest India,” *Int. J. Serv. Learn. Eng. Humanit. Eng. Soc. Entrep.*, vol. 6, no. 1, pp. 130–150, 2011.
[22] R. Qi, D. Li, and L.-Z. Zhang, “Performance investigation on polymeric electrolyte membrane-based electrochemical air dehumidification system,” *Appl. Energy*, vol. 208, pp. 1174–1183, Dec. 2017.
[23] D. D. Bergmair, *Design of a system for humidity harvesting using water vapor selective membranes*, no. 2015. 2015.
[24] L. Cattani, A. Magrini, and P. Cattani, “Water extraction from air by refrigeration- experimental results from an integrated system application,” *Appl. Sci.*, vol. 8, no. 11, 2018.
[25] A. Magrini, L. Cattani, M. Cartesegna, and L. Magnani, “Water production from air conditioning systems: Some evaluations about a sustainable use of resources,” *Sustain.*, vol. 9, no. 8, 2017.
[26] M. Eslami, F. Tajeddini, and N. Etaati, “Thermal analysis and optimization of a system for water harvesting from humid air using thermoelectric coolers,” *Energy Convers. Manag.*, vol. 174, no. March 2019, pp. 417–429, 2018.
[27] M. A. Muñoz-García, G. P. Moreda, M. P. Raga-Arroyo, and O. Marín-González, “Water harvesting for young trees using Peltier modules powered by photovoltaic solar energy,” *Comput. Electron. Agric.*, vol. 93, pp. 60–67, Apr. 2013.
[28] B. Gido, E. Friedler, and D. M. Broday, “Assessment of atmospheric moisture harvesting by direct cooling,” *Atmos. Res.*, vol. 182, pp. 156–162, 2016.
[29] H. Kim *et al.*, “Water harvesting from air with metal-organic frameworks powered by natural sunlight,” *Science (80-.).*, vol. 358, no. 6367, pp. 1–10, 2017.

[30] P. Kumar, B. Anand, Y. F. Tsang, K. H. Kim, S. Khullar, and B. Wang, "Regeneration, degradation, and toxicity effect of MOFs: Opportunities and challenges," *Environ. Res.*, vol. 176, no. May, p. 108488, 2019.

[31] H. E. Gad, A. M. Hamed, and I. I. El-Sharkawy, "Application of a solar desiccant/collector system for water recovery from atmospheric air," *Renew. energy*, vol. 22, no. 4, pp. 541–556, 2001.

[32] M. M. Rafique, S. Rehman, L. M. Alhems, and M. A. Shakir, "A liquid desiccant enhanced two stage evaporative cooling system-development and performance evaluation of a test rig," *Energies*, vol. 11, no. 1, pp. 1–17, 2018.

[33] P. A. Kallenberger and M. Fröba, "Water harvesting from air with a hygroscopic salt in a hydrogel–derived matrix," *Commun. Chem.*, vol. 1, no. 1, pp. 6–11, 2018.

[34] H. Zhang, A. Asutosh, and W. Hu, "Implementing Vertical Farming at University Scale to Promote Sustainable Communities: A Feasibility Analysis," *Sustainability*, vol. 10, no. 12, p. 4429, Nov. 2018.

[35] D. Savvas, G. P. Gianquinto, Y. Tüzel, and N. Gruda, *Good Agricultural Practices for Greenhouse Vegetable Crops. Principles for Mediterranean Climate Areas. FAO Plant Production and Protection Paper 217*, no. July 2013. 2013.

[36] C. Somerville, M. Cohen, E. Pantanella, A. Stankus, and A. Lovatelli, *Small-scale aquaponic food production.* 2014.

[37] V. Gentile, M. Simonetti, P. Finocchiaro, and G. V. Fracastoro, "Water production from the atmosphere in arid climates using low grade solar heat," *ISES Sol. World Congr. 2017 - IEA SHC Int. Conf. Sol. Heat. Cool. Build. Ind. 2017, Proc.*, pp. 984–995, 2017.

[38] H. R. Soares *et al.*, "Lettuce growth and water consumption in NFT hydroponic system using brackish water," *Rev. Bras. Eng. Agrícola e Ambient.*, vol. 19, no. 7, pp. 636–642, Jul. 2015.

[39] A. R. Al-Tawaha *et al.*, "Effect of water flow rate on quantity and quality of lettuce (Lactuca sativa L.) in nutrient film technique (NFT) under hydroponics conditions," *Bulg. J. Agric. Sci.*, vol. 24, no. 5, pp. 793–800, 2018.