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# Liter-scale atmospheric water harvesting for dry climates driven by low temperature solar heat



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#### ABSTRACT

This experimental study demonstrates a thermodynamic cycle based on isothermal regeneration to enhance the exploitation of sorbents and low temperature energy sources, such as solar energy, for atmospheric water harvesting in dry climates. An experimental setup based on silica gel has been designed to produced liquid water with low regeneration temperatures for dry climates with dew points in the range of 2 to 8 °C and ambient temperatures between 20 and 35 °C. Experimental results demonstrate daily water production from 1.5 to 3.3 L day<sup>-1</sup> per square meter of solar field, with a maximum regeneration temperature of 57 °C, and ambient temperatures up to 35 °C. The thermal energy required to activate the cycle is between 1 and 3 kWh per liter of condensed water.

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#### 1. Introduction

Water is the essential component for living organisms, society, agriculture and industrial processes. As a matter of fact, the amount of water consumed per day by an individual can easily exceed 100 L in developed countries. On the other hand, 30 g of bread require as much as 40 L of water, taking into account the whole production chain [1,2]. Recent studies predict that the anticipated economic growth of developing countries combined with a dramatic increase of population will exacerbate stress on the natural cycle of water with possible consequences on society and economy, as already observed in different crises across the world [3-7]. To address the continuously growing water stress phenomenon throughout the world, research in academia and industry has been investing large amounts of resources into new technologies for more efficient processes for reclaimed water or desalination of seawater [8,9]. Among various alternative technologies, membrane separation is the most promising solution to provide large volumes of water on a daily basis for humans and industry. Nowadays, the major challenges related to membrane separation are system operational costs, intensive use of fossil fuels, limited lifetime of components,

and environmental issues related to salt concentrate disposal [10-13]. Moreover, the engineering complexity and geographical requirements of desalination techniques make their deployment difficult in certain regions of the world, such as dry climates, countries with no direct access to brackish or seawater.

The atmosphere contains around 13,000 km<sup>3</sup> of freshwater, which is an order of magnitude larger than rivers (primary source of fresh water), with a wider accessibility in all regions around the world [14]. Atmospheric Water Harvesting (AWH) is a promising alternative solution, especially in dry and remote regions. AWH takes place when the air temperature reaches the dew point, and atmospheric vapor condenses into liquid water. In humid climates, this can be achieved spontaneously using passive systems such as fog nets: when an exposed surface cools by radiating its heat to the sky, water vapor condenses at a rate greater than that of which it can evaporate, resulting in the formation of water droplets. The phenomenon is favorable when the dew point is close to ambient temperature, and mostly observable on thin, flat, exposed objects including plant leaves. Research is investigating these effects on water harvesting performances at relative humidity (RH)>85%, optimizing both the wettability of materials and meshing patterns of the condensing nets [15–17]. This investigation area takes inspiration from the natural dewing happening in numerous plants and animals, exploiting textural and chemical features on their surfaces to harvest this precious resource [18–23]. However, such a limited operative condition for this passive system reduces its applicability mostly to humid and mountainous regions. Examples



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of applications demonstrated a water production of  $1-2 \text{ L} \text{ day}^{-1}$  per square meter of net [15,24,25]. In less humid climates, the approach is different and requires active systems based on refrigeration or desiccant materials. Active cooling, based on mechanical vapor-compression refrigeration, is an effective solution already exploited at commercial level. But such a solution becomes power intensive at higher temperatures, and especially in arid climates with low vapor pressure. The energy consumption is indeed proportional to the difference between ambient temperature and dew point. Typical energy consumptions are between 0.33 and 0.5 kWh<sub>el</sub> L<sup>-1</sup>, and most of the cost per unit of produced water are attributed to energy consumption than capital costs [26–28].

The use of conventional desiccant materials is a promising approach for efficient AWH. The regeneration of solid desiccants is typically done with heat, under which the ambient vapor pressure increases, as well as the dew point, and creates a spontaneous condensing environment for water.

Metal-organic frameworks (MOFs) [29,30] are an example of this research branch in materials science, demonstrating gramscale water harvesting capabilities in the laboratory and on the field. These organic/inorganic materials present several advantages in terms of water uptake capacity and atmospheric vapor pressure condition. In particular, MOFs offer the possibility to be synthesized with a desired molecular structure for specific adsorption characteristics with more or less stressed "s-shape" in the adsorption isotherm curves (types IV and V) [31], giving a competitive advantage in very dry climates (negative dew points). Other alternatives consist in using of composite hydrogels [32–34], with hygroscopic salts [35–39]. Although intense research is on-going in this area, it is hard to find an affordable combination that satisfies all the requirements for a real application. Although materials such as MOFs or hygroscopic salts have higher moisture uptake capacities than silica gel [40–42], they generally require much higher regeneration temperatures (around 100 °C and above). In addition, they can be corrosive, and present risks of toxicity for the human body [31]. Similar concerns are about the use of hydrogels based on polymeric compounds that, up to now, did not demonstrate stable and safe water production over thousands of cycles, as required for a real and viable application.

Other major concerns that need to be addressed in this area include the energetic consumption of an AWH device, and the overall capital costs of the technology [43]. Most of the currently available technologies use solar energy for the regeneration of the material, but they mostly focus on demonstrating hygroscopic materials potential, and the final prototypes development lacks effective and efficient exploitation of the solar source.

In some of these studies, solar radiation is directly used to heat the sorbent up to its regeneration temperature, but the limitation in this case is that large water production will proportionally requires larger surface area of the device. Secondly, the copresence of two opposite phenomena, regeneration and condensation, in the same location results in a non-effective exploitation of the maximum potential of both processes. Indeed, most of the time, regeneration temperature is higher than 90 °C, thus requiring the use of solar concentration lenses, which in turn reduces the overall efficiency of the system. Alternatively, an electric resistor powered by photovoltaic panels can be used to overcome the thermodynamic constraints of regeneration temperatures. Nevertheless, such a practical solution, is energy intensive and suffers from the limited efficiency of solar cells: Photovoltaic technologies converts solar energy in the used form of power, and then into heat, with an efficiency of ~10–18% (commercial technologies). The same process done with a solar thermal technology (typical flat or evacuated tube solar collectors) has an overall efficiency ~50-70%, depending on the operative conditions. Finally, most limitations encountered in

real applications concern the condensation stage of the humid stream produced during regeneration. High ambient temperatures may reduce the possibility to directly reject the condensation heat, forcing the use of active cooling to reduce the operative temperature of the condenser. Therefore, the energetic costs per produced liter of water will rise.

Most of the research about AWH focuses the attention and efforts on typical topics of material science, with the result of pushing forward sorbent properties (moisture uptakes in dry climates, regeneration temperatures, long term stability, etc ...). This paper is oriented to push the optimization of the process and energy related aspects. Especially the effort is on to the optimization of the thermodynamic cycle in order to enable the effective integration of low temperature sources, such as solar thermal energy or waste heat from industrial processes. The experimental application demonstrated the main hypothesis: approaching the regeneration of the sorbent with an isothermal method, instead of the typical isoenthalpic strategy, leads to reduce both the energy consumption and the required regeneration temperature. Finally, a better exploitation of sorbent properties is achieved. Indeed, even if this study exploits standard quality silica gel as sorbent, performance indicators reveal better or equivalent performances when compared with AWH applications found in literature and involving much better and sophisticated sorbents.

Our results show that several liters can be produced in one daynight cycle, based on the energy consumption of a single solar thermal collector. The lab environment reproduced the conditions of hot and arid climates (dew point below 10 °C and ambient temperature above 30 °C) and demonstrated that water can be extracted from silica gel at a regeneration temperature around 50 °C and condensed at ambient temperature with a global maximum efficiency higher than what has been reported in the literature.

#### 2. Method

The energy needed for the process changes with material type and internal porous structure. This energy is comparable with latent heat of water: adsorption heat of Zeolite and MOF ranges between 4000 and 3000 kJ kg<sup>-1</sup>, and the one of for silica gel is 2300–2500 kJ kg<sup>-1</sup> [44–46]. This energy can be supplied converting solar energy into low temperature heat, with some constraints that follow the purpose of this research:

- i) regeneration temperature close to 50 °C to increase thermal conversion efficiency of solar energy (flat plate, evacuated tubes [47]);
- ii) the dew point generated through the regeneration must be higher than ambient temperature such that condensation heat is directly rejected to the ambient without any auxiliary refrigeration;
- iii) daylight duration limits heat availability to about 6–10 h per day.

The working cycle is a sequence of alternating stages in which the regeneration stage prevails:

 Adsorption: can be operated when there is no solar radiation. During this stage the system's air loop is open to the atmosphere to charge the sorbent with water vapor as much as possible. The energy cost associated with this stage is only dependent on the pressure drops generated by the air stream crossing the volume in which the sorbent material is disposed. Limiting factors for this stage are essentially generated by sorbent isotherms and working environmental conditions. • *Regeneration:* driven in presence of solar radiation. During this stage the air loop is closed, and the air recirculated between two environments at different temperature levels, the regeneration and the ambient temperatures.

The working cycle in Fig. 1 is defined by the regeneration temperature of 55 °C, and the ambient temperature of 30 °C. Through the isotherms of the sorbent media, silica gel, is possible to identify the achievable water uptake for each couple of air temperature and humidity. The transformation 1–2 represents the regeneration of the material throughout an isothermal desorption, operated with an adsorption-heat-exchanger (ADS-HX), described in the experimental section.

Through the step 2–3 the hot and humid air flux resulting from the regeneration of the sorbent is cooled down to the dew point. Condensation of water starts at point 3 and continues along the saturation line (relative humidity ~100%) up to the maximum exploitable potential. The minimum point is 4, with a temperature value in the ideal case equal to the ambient temperature, and RH = 100%. After this step the air stream is re-heated from 4 to 1, the regeneration can start again, and all the previous steps can be performed in series. Corresponding values of T, RH, x and enthalpy are reported in Table 1.

The isothermal regeneration (1-2) requires a system for a simultaneous exchange of heat and mass. Indeed, without a continuous supply of heat, during the regeneration the temperature will easily drop due to the endothermic nature of the desorption phenomenon. The point 2 is a function of the instantaneous value of sorbent water uptake and of vapor diffusion through the pores, that at equilibrium conditions is defined with adsorption isotherms of the sorbent (material properties are reported in appendix A).

The isothermal regeneration, driven at a maximum temperature of 55 °C, leads to higher dew points compared to conventional systems operating through a typical adiabatic regeneration (isoenthalpic). We can reach the dew point 3 at 43.1 °C with an isothermal desorption, against 34.6 °C for an iso-enthalpic one (point 2isoH). As a result, the water uptake required at the end of adsorption to achieve equilibrium points 1 and 2isoT are 0.318 and 0.125 kg<sub>w</sub> kg<sub>silo</sub>, respectively. Consequently, higher dew points are achievable even at lower humidity level through this desorption approach. For comparison, in the case of iso-enthalpic



**Fig. 1.** Desorption cycle for water harvesting through an isothermal regeneration of silica gel on the psychrometric diagram. The comparison between the iso-thermal (grey) regeneration vs the iso-enthalpic (blue) show the increase of achievable maximum dew point and vapor content. The regeneration cycle is obtained combining the thermodynamic properties of humid air and equilibrium water uptakes of the silica gel (material properties in appendix A).

Table 1	
Thermodynamic properties of the	points depicted in the cycle of Fig. 1.

Points	Т	х	RH	h
_	°C	$kg_w kg_{air}^{-1}$	%	kJ kg <sup>-1</sup>
1	55	27.2	27	126.2
2isoH	132	27.2	<1.5	207
2	55	58.5	55	207
3	43.1	58.5	100	194.4
1isoH	34.6	35.8	100	126.2
4	30	27.3	100	100

transformation ( $h_{2iso-T} = 207.6 \text{ kJ/kg}_a$ ), the required desorption temperature would be as high as 132.5 °C to provide the same amount of water as the values approached with 2isoT. An equivalent iso-H would require a higher temperature heat source, lowering efficiency from the exergy point of view, and forcing the use of optical concentrators for a feasible exploitation of solar energy, loosing points of global efficiency. The maximum temperature of the cycle corresponds to the minimum value of water uptake, while at the equilibrium, it is close to of 0.045 kg<sub>w</sub> kg<sub>SiO2</sub>, corresponding to equilibrium condition at point 1. Then, for each kg of dry silica gel particle, the net amount of water pulled out from the air is 0.08 kg, and the minimum energy required for the regeneration 4-1-2isoT is 108 kJ/kga. The total energy required for the regeneration step can be reduced using a regenerative heat recovery system: the preheating step 4-1 is achievable with free energy coming from vapor condensation at higher temperature. This method can potentially save up to 24% of the total energy, increasing consistently the efficiency of the cycle. Therefore, the actual cycle will move along the chart, as the actual water uptake of the material, and operative conditions change. Indeed, since our system is being used in batch mode, the continuous discharge of water reduces the total water uptake, then the line 2–3 will shift down resulting in a reduction of water production and efficiency over time.

## 3. Experimental setup

The silica gel beads have a bulk density of 0.78 g/cm<sup>3</sup> a 99.5% purity and a surface area about 800  $m^2/g$ . They were poured between the fins of a finned coil heat exchanger, filling a 5 mm spacing with a total filling degree of 58% on the total volume of the exchanger. The scheme of the packed ADS-HX and the AWH device, along with its working principle are summarized in Fig. 2. The system works on a batch process, switched through the 4-way valve I, alternating adsorption and desorption stages of the ADS-HX. Water harvesting tests were performed during a day/night cycle, recreating typical environmental condition of a dry climate both in adsorption and desorption. In adsorption mode (ADS) outdoor air  $(25-35 \text{ °C}, 30-50\%, 100 \text{ m}^3 \text{ h}^{-1})$  is directly blown through A, and the outlet stream is rejected to the environment. During the tests several air temperature and humidity sensors monitor the air flows, and a load cell measures continuously the weight of the ADS-HX. By switching the valve I to regeneration mode (REG) the air loop is closed, and the same stream flows between the ADS-HX and the condensation unit. The solar thermal facility installed on the roof of the lab produces hot water (H) at 50–60 °C for the regeneration of the ADS-HX, delivered with the water pump G (42  $W_{max}$ , 60 L min<sup>-1</sup>). The condensation unit consists in an air/air heat recovery system C and an air to water radiator B. In C, the condensation heat is partially recovered to preheat the air before going back to A, reducing the total energy for regeneration.

The condensation heat is rejected through an external dry cooler F at a constant temperature between 25 and 35 °C, regulated with a



Fig. 2. WAT-AIR lab facility to test water harvesting cycle in a controlled environment. (left) Scheme with the different components, where the symbols indicate respectively: A is the ADS-HX, B are the condenser radiators, C is the regenerative air to air HX within the condensation unit, D is the basin for water collection, E is the centrifugal fan for the process air, F is the dry cooler unit, G are water pumps, H indicates the inlet/outlet points of the hot water flow through the ADS-HX (right) Scheme of the ADS-HX configuration, a finned coil packed bed with silica gel particles of 3 mm average diameter.

thermostat to simulate different climatic conditions. Finally, the condensed droplets of water over the radiator B are collected in the basin D and stocked at the end of each test. During regeneration, the valve I prevents any communication with the external environment, and the air flow driven by a fan E (450 Pa, 100 m3h-1, 65 Wel max) to complete all the regeneration steps. All the actuators have been controlled by a microcontroller based on ATMEGA32U4 processor, that defines continuously the power percentage of continuous variable components, and their on/off. Some precautions were needed for the selection of the centrifugal fan E: operational environment with a temperature up to 80 °C, RH>70%, metallic impeller and electronics with a 24 IP protection and a variable speed control with a PWM 0-10 V signal. The heat recovery unit C is a PET (Polyethylene Terephthalate) counterflow air/ air plate heat exchanger with a channel opening of 3 mm, and a total exchange surface of around 18 m<sup>2</sup>. To pursue the goal of a costeffective liter-scale system, the test rig contains around 27 kg of silica gel beads (3 mm average diameter) in the ADS-HX. A complete list of the auxiliary equipment is described in appendix B.

All monitored and logged parameters are listed in the scheme of Fig. 3. The temperature of air  $(T_a)$ , and water  $(T_w)$  were measured using IC temperature sensors (LM35CAZ, ± 0.2 °C, from Texas Instruments). The relative humidity (RH) of air was measured with thermoset polymer capacitive sensors (HIH4000-4, ±3.5%, from Honeywell). An electromagnetic flow meter has been used for the measurement of the hot water flow for the silica regeneration, in the range of 0.5–20 L min<sup>-1</sup> (LFE,  $\pm$  1.5% FS, from SMC), and a hot wire anemometer for the air velocity (Testo416,  $\pm 1.5\% + 0.2$  m/s). At the same time the mass variation of the ADS-HX with silica gel due to the alternating capture and release of water vapor were directly measured through an aluminum alloy IP65 single point load cell  $(2 \pm 0.002 \text{ mV V}^{-1}; \pm 0.023 \text{ of \%F.S.})$ . The detailed uncertainty analysis for each measured parameters is reported in the chapter D of supplementary information. Finally, the water collected from the basin was stored in bottles and separately weighted at the end of each cycle. This final weight was on the average 90% lower than the mass variation of the load cell. The main reason of this difference was the presence of some undetected leaks among the air loop, and the impossibility to collect all the water droplets that remain on the surface of channel and plates of the recovery heat exchanger due to the surface tension of the material.

#### 4. Results and discussion

Testing methodology aims to replicate a day/night cycle in a dry climate environment. Regeneration phase driven at temperatures around 60 °C and powered with solar thermal collectors. In the ADS stage water final uptakes between 0.1 and 0.15 are achievable within 15 h with ambient temperature of 20-25 °C and dew points between 2 and 8 °C. These are considered as environmental condition during the night period of a dry climate. Regeneration was carried out for less than 10 h, just after the adsorption stage, and at different condensing temperature in the range of 25–35 °C. Control of air moisture content for the simulated environment was not necessary during regeneration because the cycle works in a closed loop without any mass exchange, but only thermal exchange through the external radiator. When the cycle is switched between adsorption and regeneration the air valve sketched in Fig. 2 rotates, modifying the air loop from the open to the close configuration and vice-versa. This operation is actuated with a typical rotating damper controller, usually applied for HVAC systems, with a max torque of 6 Nm, and a 3 points control. The continuous monitoring of parameter listed earlier led to the evaluation of some aggregated indicators, to perform comparisons among different operational conditions.

Dew point of the humid air mixture

$$T_{dew} = C \ln\left(P_{sat}\frac{RH}{A}\right) \left[B - \ln\left(P_{sat}\frac{RH}{A}\right)\right]^{-1}$$
(1.1)

where the coefficients A, B, C are 611.85, 17.502, 240.9 respectively. Thermal Efficiency of the cycle is

$$\eta_{th} = \frac{M_w H_{lat}}{Q_{reg}} = \frac{M_w H_{lat}}{\dot{m}_w c_{p_w} (T_{w_{in}} - T_{w_{out}})}$$
(1.2)

Where  $M_w$  is condensed water,  $H_{lat}$  is the condensation heat of water and  $Q_{reg}$  is the heat absorbed by the ADS-HX during the regeneration. If the thermal power terms also consider the source, and the way in which the solar power ( $Q_{sol}$ ) is converted into heat, this efficiency can be defined in terms of primary energy as follows:

$$\eta_{PE} = \frac{M_w H_{lat}}{Q_{sol}} = \eta_{th} * \eta_{sol}$$
(1.3)

This approach is particularly important when the comparison



**Fig. 3.** (top) the scheme of the experimental setup and positioning of sensor for air temperature and humidity, water temperature and flow rate, weight of sorbent. (bottom left) the picture of the final assembly of the test rig. (bottom right) the integration of the atmospheric water harvesting system with two flat solar thermal collectors supplying the thermal energy of the cycle.

across the different devices available in the literature will be performed.

Another interesting parameter is the charging level of the ADS-HX. This indicator is connecting the average water uptake of the material (directly measured with the load cell) and the potential value obtained through the isotherms. This value is the maximum (or the minimum if we are in the regeneration phase) achievable with the configuration when the equilibrium condition with the inlet air will occur:

$$Charge \ level = \frac{W_t}{W_e|_{T_{in}, Pv_{in}}} \tag{1.4}$$

The equilibrium value at the denominator is computed with the fitting equation (1.5), while the instantaneous water uptake at the numerator is estimated as in equation (1.6):

$$\frac{P_{\nu}}{P_{sat}|_{T}} = S_{1}T + S_{2}T^{2} + S_{3}W_{e} + S_{4}W_{e}T + S_{5}W_{e}T^{2} + S_{6}W_{e}^{2} + S_{7}TW_{e}^{2} + S_{8}W_{e}^{3} + S_{9}T^{3}$$
(1.5)

$$W_{istantaneous} = \frac{Weight - M_{dry \ silica} - M_{metallic \ frame}}{M_{dry \ silica}}$$
(1.6)

Where the weight is constantly monitored with the load cell sensor. The dry mass of silica was separately measured before the ADS-HX assembly, after driving a full regeneration  $(T > 90^{\circ})$  in a climatic

chamber. Similarly, the metallic frame was weighted before assembling it. At the beginning of the testing campaign an offset analysis was carried out through a full one-day regeneration of the assembled ADS-HX, to obtain the minimum weight corresponding to a zero-water mass. Further, a full calibration of the load cell was required during the assembling of the experimental setup to correlate the output from the Wheatstone bridge of the load cell with a known tare. In appendix C are reported the calibration procedure and results of the load cell sensor.

The condensing water rate, defines the instantaneous amount of condensed water in the collecting basin, and is estimated starting from the evaluation of the mass variation of the ADS-HX between two consecutive measurements:

$$Water rate = \frac{M_{wt2} - M_{wt1}}{\Delta t}$$
(1.7)

The integral of this parameter over the entire test is the total amount of water produced, that is compared with the amount of water collected during the discharge of the colleting basin, as shown in Table 2.

An inverse indicator, giving information about the energy cost for the process is the Specific Thermal Energy (STE), defining the energy input to the cycle to produce 1 L of liquid water.

$$STE = \frac{1}{n} \sum_{i=1}^{n=30} \left( \frac{\dot{m}_w \, cp_w \, (T_{w_{in}} - T_{w_{out}})}{water \, rate} \right)_i \tag{1.8}$$

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Table 2	
Summary of testing condition and collected water. Graph of each test is reported in appendix A.	

TEST	Fan	T <sub>inADS</sub>	RH <sub>inADS</sub>	T <sub>dewADS</sub>	T <sub>reg prim</sub>	T <sub>reg sec</sub>	T <sub>codenser</sub>	$\Delta m_{ADS}$	$\Delta m_{REG}$	Collected Water
_	%	°C	_	°C	°C	°C	°C	kg	kg	kg
20-21	70%	21.2	0.33	4.11	57.4	56.3	20.8	2.55	2.74	2.5
22-23	30%	22.9	0.29	3.91	57.1	56.2	23.1	2.49	2.00	1.8
24-25	50%	21.3	0.40	7.23	56.1	54.7	20.1	3.33	2.97	2.7
26-27	30%	21.9	0.38	6.90	57.4	56.2	33.0	3.04	3.51	3.2
28-29	50%	22.4	0.40	7.98	55.4	54.1	27.6	2.57	2.76	2.5
30-31	70%	22.4	0.27	2.51	56.1	54.9	29.4	1.86	1.91	1.8
32-33	70%	21.9	0.31	3.98	55.9	54.8	29.6	1.76	1.74	1.6
36-37	30%	22.0	0.37	6.52	56.4	55.3	34.7	2.02	1.90	1.7
38-39	50%	23.8	0.33	6.67	56.4	55.1	35.3	0.94	1.85	1.7

More than 40 tests have been conducted, and we present in the following the performance of the most representative tests for the purpose of showing the effects of the environmental conditions on testing performances.

### 4.1. Charge level dependency

This paragraph investigates the dependency of cycle performances on the charging level of the ADS, analyzing in detail specific results of the adsorption/regeneration test series #20-21. The graph on the left of Fig. 4 shows inlet conditions to the ADS-HX and the mass variation during the 15 h of testing. During the entire adsorption, the fan was operated at 100% regime, corresponding to an air flow rate of  $61.4 \text{ m}^3 \text{ h}^{-1}$ . The average inlet temperature was in the average 21.2 °C with a dew point of 4.1 °C, corresponding to a relative humidity of 33%. At the beginning of the test the load cell measured an adsorbed water mass equal to 0.415 kgw, corresponding to an initial water uptake of 0.017 kg<sub>w</sub> kg $_{SiO2}^{-1}$ . After 15 h of adsorption, the measured water mass was 3.01 kgw, equivalent to a water uptake of 0.111 kg<sub>w</sub> kg $^{-1}_{SiO2}$ , as reported in Fig. 5. The charge level indicator shows that within these operative constraints, the variation was from an initial value of 9.5 to the final 94%, with a curve derivative highly fluctuating as the environmental condition changes over time. The analysis of the outlet dew point from the ADS-HX, shows very high dry conditions for the first hour of adsorption  $(-3.5 \degree C)$ , reaching a final value close to the inlet at the



**Fig. 4.** (left) monitored parameters during the adsorption test #20 are depicted over the entire adsorption operational time of 15 h (right) monitored parameters during the regeneration/condensation of test #21 are depicted over the entire regeneration operational time of 9 h.



**Fig. 5.** Transient behavior of the silica water uptake and level of charge for both adsorption and regeneration tests #20–21.

end of the process (3.6 °C inlet dew point versus 3.3 °C outlet dew point). The switch to the regeneration phase required two preliminary steps before the beginning of water condensation. Firstly, the air valve needs to complete the full rotation to close the air loop, with an elapsed time of 2.5 min. Secondly, the ADS-HX is heated up to the regeneration temperature. The pump G is flowing water between the ADS-HX and the plate exchanger H, reaching a final temperature of 55.4 °C (red line of the graph on the right of Fig. 4). This heating phase takes at least 15 min and a transient is necessary to lift up the temperature of entire sorbent mass (27 kg) from the adsorption value (21 °C) to the regeneration (55 °C). The fan is off during these phases and reactivated only at the end of the preliminary steps, with a partial speed decided a priori, starting eventually the real step of regeneration and condensation of water. For the test #21 fan power level was 70%, corresponding to an air flow rate of 41.5  $m^3$   $h^{-1}$ . Meanwhile, the activation of the other pump *G* and the blower *F* permits to reject outside the heat for the condensation of water in *B* maintaining the temperature close to the external environment, maintained constant with the external thermostat. Once the regeneration starts, the outlet dew point increases immediately from the value of 3.3 up to 38.9 °C. The heat rejection permits to maintain the temperature at the condenser from 28 °C down to 21 °C during the 9 h of regeneration, which reduces the total heat. The mass reduction (Fig. 5) during regeneration is much faster than the increase during adsorption, this permits to obtain a similar water uptake variation from 0.111 to 0.012 kg<sub>w</sub> kg $_{siO2}^{-1}$ , then a total difference of 0.099 kg<sub>w</sub> kg $_{siO2}^{-1}$ . In less than 10 h, this value lowers from 42 to 32 °C, as the water contained in the ADS-HX is less than 0.5 kg. When the outlet dew point and the ambient temperature are equal, water condensation stops and the water harvesting cycle is concluded. The mass difference between the end of ADS and REG corresponds to condensed water, around 2.4 kg with a water uptake variation within the cycle of 0.089 kg<sub>w</sub> kg $_{SiO2}^{-1}$ . The difference between the outlet dew point and

the condensing temperature reduces over time due to the progressive discharge of the material. This means that the potential moisture difference at the condensation step is reducing over time, decreasing the rate of condensation, with drawbacks on energy performances. This is clear from the graph in Fig. 6, where both the water condensation rate in cL min<sup>-1</sup> and the STE in kWh L<sup>-1</sup> are compared.

The maximum value of condensation rate is 1.41 cL min<sup>-1</sup> reducing rapidly to 0.35 cL min<sup>-1</sup> after 5 h of continuous functioning. After 8 h values are quite negligible, and the fluctuation due to the increased uncertainty of direct measured values generate a consistent oscillation of the post computed indicators, reducing its reliability on the description of the phenomenon. The STE has an opposite behavior: the rate of condensation (denominator) is reducing faster than the absorbed thermal power (numerator) by the machine, consequently the relative ratio is increasing over time. The results show values close to 1 kWh L<sup>-1</sup> and quite constant for the first 2 h of functioning, reaching the value of 2.3 kWh L<sup>-1</sup> after 5 h. The consecutive phase is characterized by a faster reduction of the process efficiency, and the rise of the STE is higher than 5 kWh L<sup>-1</sup>.

Most of the inefficiencies of this cycle come from collateral heat absorption not directly connected to the condensation of water and not recovered in the exchanger *C*. Indeed, during the transformation, a portion of heat supplied to air causes a sensible rise of temperature instead of a latent transformation that, at the end of the cycle, goes rejected to the environment through dry cooler unit *F* and *G*, without any positive contribution. This is in Fig. 7, where different steps of the cycle (from 1 to 4) are drawn on the psychrometric chart at different moments of the entire test #21. The graph is a picture of the cycle situation collecting consecutive





measurements for 10 min at different moments from the beginning of the regeneration, at 30 min (red), 90 (blue), 180 (yellow) and 270 (green) respectively. The first aspect is that the real cycle is moving on the (T, x) diagram from the right to the left, due to the lower release of moisture from the sorbent. Water uptake reduction together with a constant regeneration temperature means a continuous reduction of the equilibrium RH.

Second aspect is the variation in the behavior of the cycle. For example, the regeneration step 1–2 of *A* is different from *D* on both quantitative and qualitative aspects: the total enthalpy variation of the transformation is  $h_{1-2\tilde{A}}45$  kJ kg<sup>-1</sup>, of which only 7 kJ kg<sup>-1</sup> correspond to a sensible increase and 38 kJ kg<sup>-1</sup> are the latent part. At point *D*, the weight of sensible part increases because its value is constant at 7 kJ kg<sup>-1</sup>, while the latent one is reduced to 16 kJ kg<sup>-1</sup>. This leads to an increase of the transformation tilt, going away from the isothermal line. Another "shape" modification in the cycle is caused by the ratio between the precooling stage 2–3 and the condensing line 3–4. Because the maximum vapor pressure generated from regeneration is reducing, the distance between 2 and the corresponding dew point increases, consequently the enthalpy difference increases from  $h_{3-2\tilde{A}}14$  to  $h_{3-2D}$ –20 kJ kg<sup>-1</sup>, while condensing line reduces consistently from 16 to 6 kJ kg<sup>-1</sup>.

#### 4.2. Condensing temperature dependency

With similar initial charge level of the ADS-HX, the increase of ambient temperature reduces global performances, both on water production and efficiency. For example, increasing the ambient temperature from 23 to 35 °C (as shown with tests #25 and #37 in Fig. 8) corresponds to a reduction of water production from 3 to 1.9 L, despite the similar initial water content of 0.13  $kg_w/kg_{SiO2}$ . On the contrary there's no effect on the outlet dew point, that had similar maximum value close to 40 °C. This indeed is mainly a function of the two variables, water uptake and equilibrium temperature, that in both cases are close to the regeneration temperatures of 54.7 °C and 56.4 °C for #25 and #37 respectively. Fig. 9 shows the behavior of the 3 performance indicators, STE, thermal efficiency and condensing rate, with a condensing environment of 20, 27 and 35 °C. As seen before, the increase of temperature reduces the rate of production of liquid water, but the benefit of a lower condensing temperature is negligible after around 4–5 h of operation. Indeed, if at 20 °C the water rate is almost double than at 35 °C (1.2 cL min<sup>-1</sup> at 20 °C against 0.55 cL min<sup>-1</sup> at 35 °C), after 5 h the value is similar and equal to 0.42 cL min  $^{-1}$  at 20  $^\circ\text{C}$  and  $0.31 \text{ cL min}^{-1}$  at 35 °C, finally after 10 h it reduces again to 55–70%. The STE has the minimum value of 1.1 kWh  $L^{-1}$  at 20 °C, 1.45 at 27 °C and 1.93 at 35 °C, increasing 4–5 times at the end of each test.



**Fig. 7.** Real cycle of regeneration for water condensation with the intermediate heat recovery. Transformation 1–2 is the regeneration of the sorbent, 2–3 is the heat dissipation towards the dew point, 3–4 is the vapor/liquid phase change among the dew line, 4–1 is the preheating step recovering the heat from the entire condensing line 2-3-4. Cycle A depicts the situation at 30 min since the regeneration start; B at 90 min; C at 190 min; D at 270 min.



**Fig. 8.** Comparison between two different tests. (left) regeneration #25, where the condensing environment was during the 10 h of functioning 23.2 °C in the average. (right) regeneration test #37 with an average condensation temperature of 34.7 °C.

On the contrary, the maximum of the global thermal efficiency was 62, 47 and 34% for each successive test, diminishing after 10 h down to 9–17%. Clearly these evaluations cannot be taken as absolute considerations, but from a qualitative point of view this is useful to identify the criticalities behind this system. Driving a full adsorption is not always the best approach. For the adsorption stage the goal is to reach the highest level of charge, with the constraints of outdoor conditions. Very good examples are tests #26 and #30 where we can see that although the system is still in adsorbing mode, the level of charge is not changing (even reducing in test #30) after many hours. Inlet air conditions are strongly influencing this aspect.

Although a full regeneration maximizes the total amount of water that can be extracted, it is a less efficient utilization of the energy if compared to a partial cycle. This is also important when the heat availability is limited to solar energy, with constraints on the surface availability, and operative time, that reasonably doesn't exceed a duration of 5-8 h.

#### 4.3. Comparison with other AWG devices

Experimental analysis showed performances of the investigated configuration, emphasizing some important parameters: the total amount of heat used for the transformation, and then the efficiency: the total amount of water produced: the water uptake variation. In this paragraph we will compare our setup with other systems in the literature, [29,33,35,36,39,41,48]. In these papers, authors engineered solar driven prototypes, with the goal of producing liquid water out of the humid air using other sorbent materials and composites. The novelty of these systems mainly consists in the use of sorbent with enhanced water uptakes especially for dry climates (T<sub>dew</sub><10 °C). However, when the application at component/prototype level is tested in a real/simulated working environment, a general decline of performance from theory is observed. Indeed, the working environment defines different constraints limiting presumed performance: for example, the use of solar energy, without solar concentrators, limits the maximum working temperature in the range of 50-70 °C, to guarantee optimal solar energy during the day [47]. In addition, condensing at ambient temperature, without refrigeration, implies typical minimum values around 20-35 °C, according to the local climate. These values define roughly boundary limits of an adsorption/desorption cycle operated in a real environment.

Results from reference papers were used as baseline of comparison, applying a common methodology, for the estimation of related performances. Data needed for this comparison, often provided by authors, are the mass of collected/estimated water  $(M_w, \text{ obtained among the day or the experiment)}$  and mass of dry sorbent  $(M_s)$  used in the prototype; specific incident solar radiation (G); surface of solar collector aperture  $(A_C)$ ; operational times for adsorption  $(t_{ADS})$  and regeneration  $(t_{REG})$ . Among different possibilities for the evaluation of prototypes performances, following parameters have been chosen for their relevance:

• the Specific Solar Energy (SSE) defines the total amount of solar radiation, incident over the collector aperture, necessary to produce 1 L of liquid water, and is evaluated as the ratio between

incident total radiation  $(A_C \sum_{i}^{t_{REG}} \Delta t_i G_i)$  and  $M_w$ . The only differ-

ence with the STE is the limit boundary for the analysis (Fig. 10): for the STE is only limited to the device, while for the SSE also



Fig. 9. Effect of condensation temperature (20–35 °C) on STE, thermal efficiency and rate of water generation.



Fig. 10. Sketch of the boundary for the energy analysis of Atmospheric Water Generators.

includes the efficiency of the technology converting solar energy into heat.

- The water uptake variation of the sorbent (Δ<sub>w</sub>), between the adsorption phase and regeneration phase, evaluated as the ratio M<sub>w</sub>/M<sub>s</sub>;
- the global efficiency (η) of the process, defined as the ratio between the energy content of produced water (the latent heat content of condensed water, at the specific condensing tem-

perature 
$$H_w|_{T_{cond}}$$
), as the ratio  $A_C \sum_{i}^{t_{REG}} \Delta t_i G_i * (M_{wi} H_{w_i}|_{T_{cond}})^{-1}$ .

Data from references needed for the evaluation of comparison parameters are collected in Table 3 and Table 4. In this study parameters needed to perform energy analysis are directly sampled: inlet and outlet temperature of water stream ( $T_w$ ) during regeneration; the related mass flow rate ( $\dot{m}_w$ ). The solar energy is then evaluated as the ratio between the heat absorbed by the adsorption heat exchanger  $\sum_{i}^{t_{REG}} (cp_w \dot{m}_w \Delta T_w)_i dt_i$  and the solar thermal collector efficiency  $\eta_{SOL}$ . This value, defined by the power curve equation as given by the standard EN12975, is equal to:

$$\eta_{SOL} = a_0 + a_1 * \frac{T_m - T_{amb}}{G} + a_2 * \frac{(T_m - T_{amb})^2}{G}$$
(1.9)

Where  $T_m$  is the medium temperature of the heat transfer fluid flowing through the flat plate collector; *G* is conventionally a

Table 3

Summary table with the characteristics of the experiments for the reference papers.

normal radiation equal to 1000 W m<sup>-2</sup>;  $a_0(0.82)$ ;  $a_1(3.82)$  and  $a_2(0.01)$ .

Results of this comparison analysis are reported in Table 4 and Fig. 11, where the three plots depict a ranking of the different configurations and experiments. Lower regeneration temperatures led in general to lower SSE. However, the left-hand side of Fig. 11 indicates that MOF-801 represents an outlier from the rest of points. The main reason for the peculiar behavior of this case was an insufficiently high enough temperature for regeneration (without concentration lens) that basically resulted in a failure test. Experiments carried out in this research show lowest values of SSE at the lowest regeneration temperatures. Similar conclusion, but with opposite behavior, comes from right-hand side of the graph. In this case it is interesting to see how, despite improved properties of adsorption material, resulting operation is not necessarily associated with an improved performance of the system. Nevertheless, in the range of dew point equal to 3-10 °C silica gel showed comparable water uptake variation compared to one of the best materials available today, MOF-801. Main merits for this equivalence are the lower regeneration temperatures obtained with an isothermal process. Despite these considerations, we must clarify that silica gel is not suitable for all climates. In very dry environments with dew points lower than 0 °C, silica gel cannot exhibit any sufficient  $\Delta w$  to be applied in a cycle to produce water.

Thermal energy is not the only requirement to perform all the steps of a complete water production cycle (adsorption, regeneration, condensation). Indeed, the three processes may need in general power to drive auxiliary elements (fans, pumps, valves, etc ...), as it is in our case. Further on, some of the experiments analyzed used active refrigeration [29] as a tool to assist the condensation step. This increases the need for electricity, which results in a reduction in efficiency. The evaluation of the total electric energy is evaluated using the average power consumed in each step of the process ( $P_{elSTEP}$ ) and related time ( $t_{STEP}$ ), as in the following equation.

$$E_{el} = P_{elADS} * t_{ADS} + P_{elREG} * t_{ADS} + P_{elCOND} * t_{REG}$$
(2.0)

Where the term  $P_{elADS}$  typically considers power required to drive air fans, moving the air through the sorption material,  $t_{ADS}$  the duration of the adsorption phase;  $P_{elREG}$  the power during regeneration, to heat up the sorbent and to drive all the required auxiliary items. If liquid water is obtained by condensing the air stream

Experiment			Material					
Ref#	Year	Description	Sorbent	Mass	Volume	H <sub>ADS</sub>		
				kg	m <sup>3</sup>	kJ mol <sup>-1</sup>		
#1 [49]	2017	RH controlled environmental chamber with solar simulator	MOF-801	$1.79\times10^{-3}$	$1.03\times10^{-5}$	45		
		Outdoor with solar radiation	MOF-801	$1.34 imes10^{-3}$	$7.75  imes 10^{-6}$	45		
#2 [ <mark>41</mark> ]	2018	Outdoor with solar radiation 0.8–1 kW/m2	MOF-801	$2.98 \times 10^{-3}$	$1.08  imes 10^{-5}$	45		
		Outdoor with solar radiation 0.8–1 kW/m2	MOF-801	$2.98  imes 10^{-3}$	$1.08  imes 10^{-5}$	45		
		Outdoor with concentrated (X1.8) solar radiation	MOF-801	$2.98  imes 10^{-3}$	$1.08  imes 10^{-5}$	45		
#3 [ <mark>29</mark> ]	2019	Indoor water harvesting	MOF-303	4.33E-01	0.21	52		
		Outdoor and solar electricity	MOF-303	4.33E-01	0.21	52		
#4 [ <mark>36</mark> ]	2007	Controlled regeneration environment	MCM-41/CaCl2 30 ÷ 60%	0.1	_	50		
		Outdoor, total passive solar device	MCM-41/CaCl2 53%	0.4	_	50		
#5 [ <mark>35</mark> ]	2017	Outdoor, regeneration driven with air evacuated tube	ACF/CaCl2	2.25	_	_		
		Outdoor, regeneration driven with air evacuated tube	ACF/LiCl	40.8	_	-		
#6 [ <mark>50</mark> ]	2018	Evaluation of weight reduction after sun exposure, from complete saturated state	CuCl2	_	_	-		
			CuSO4	_	_	-		
			MgSO4	_	_	_		
7 [33]	2018	Proof of concept of sunlight regeneration. 0.8 ÷ 1.2 kW/m2	PAM-CNT-CaCl2	35	$7.88 \times 10^{-3}$	-		
8 [39]	2020	Rotating cylinder, 25% surface exposed to simulated sunlight	HCS-LiCl nanoparticle	$2.93  imes 10^{-3}$	6.92E-04	-		
9 [51]	2019	Thermal switching between hydrophilic/hydrophobic	PPy-Cl/poly-NIPAM	_	_	-		

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#### Table 4

Summary of data recovered from literature for the evaluation of performance indicators. The column "How" indicates the approach used to drive regeneration and condensation. For regeneration: A = direct sun exposition; B = concentration of solar radiation; C = simulated solar radiation at 1 kW  $m^{-2}$ ; D = hot air; E = hot water; F = electric resistance heater. For condensation: a = passive heat sink; b = dry cooler; c = passive surface condensation; d = vapor compression unit; e = thermoelectric cooler; f = direct liquid recovery.<sup>19</sup> cycles in 24 h of around 1.5–2 h of adsorption and 1 h of regeneration; <sup>18</sup>8-10 cycles in 24 h of around 1.5–2 h of adsorption and 1 h of regeneration.

#Ref	Adsorpti	on						Reger	neration				Conde	ensation		
	T <sub>amb</sub>	T <sub>ADS</sub>	RH <sub>ADS</sub>	$P_{v}$	T <sub>dew</sub>	$W_{ads}$	Time	How	T <sub>REG</sub>	W <sub>REG</sub>	Time	Δw	How	T <sub>cond</sub>	T <sub>amb</sub>	Mw
#1 [49]	35	35	20	1.2	10	0.25	1.17	F/D	80	0.02	0.5	0.23	e	10	35	$4.12*10^{-4}$
#2 [41]	25	25	65	2	18	0.35	over night	Α	66	0.05	8	0.3	e	23	32	$4.02*10^{-4}$
	20	17	40	0.94	6	0.28	8 ÷ 11	Α	74	0.16	3.67	0.12	a	28 ÷ 33	28 ÷ 33	$3.58*10^{-4}$
#3 [ <mark>29</mark> ]	23	20	50	1.4	12	0.31	8 ÷ 11	Α	74	0.175	4	0.135	a	30 ÷ 35	30 ÷ 35	$4.02*10^{-4}$
	20	17	40	0.94	6	0.28	8 ÷ 11	В	100	0.01	2	0.27	a	28 ÷ 33	28 ÷ 33	$8.05*10^{-4}$
	27	_	32	1.1	9	-	14 <sup>i</sup>	F/D	120	_	9 <sup>i</sup>	0.13 ÷ 0.16	d	0	27	1.3
#4 [ <mark>36</mark> ]	15 ÷ 25	_	10 ÷ 70	0.3 ÷ 1.2	-9÷9	-	12 ÷ 15 <sup>ii</sup>	F/D	120	_	8 ÷ 10 <sup>i</sup>	0.03 ÷ 0.12	d	0	15 ÷ 25	0.55 ÷ 0.75
	10 ÷ 15	_	80 ÷ 90	1 ÷ 1.5	6.7 ÷ 13.4	0.8 ÷ 1.4	24	F/D	80	< 0.1	2.5	_	_	_	_	0.24 ÷ 0.29
#5 [ <mark>35</mark> ]	10 ÷ 15	_	80 ÷ 90	1 ÷ 1.5	6.7 ÷ 13.4	0.87	over night	Á	80	0.26	All day	0.61	с	_	_	0.223
	25	_	70	2.2	19.2	0.53	8	D	85	0.14	5	0.39	b	40	30	0.32
#6 [ <mark>50</mark> ]	30 ÷ 33	_	70 ÷ 85	3 ÷ 3.7	30	0.27	11	D	80	0.02	7.5	0.25	b	40	30	9
	22	_	60	1.6	13.9	_	>24	С	80	_	1.5	0.17	с	22	22	_
#7 [ <mark>33</mark> ]	22	_	60	1.6	13.9	_	>24	С	80	_	1.5	0.21	с	22	22	_
	22	_	60	1.6	13.9	_	>24	С	80	_	1.5	0.16	с	22	22	_
	26	_	60 ÷ 70	2 ÷ 2.4	17.6 ÷ 20	1.06	15	А	75	0.49	2.5	0.57	с	_	28 ÷ 32	20
#8 [ <mark>39</mark> ]	22	22	60	1.4	12	_	3 <sup>3</sup>	С	47 ÷ 50	_	1 <sup>3</sup>	0.1	с	22	22	$1.25*10^{-3}$
#9 51	25 ÷ 27	25	60 ÷ 90	2.1 ÷ 2.7	18 ÷ 22	5	4	А	42 ÷ 65	0.2	3.5	4.8	f	25	25	_



**Fig. 11.** Comparison charts between papers in the literature [29,33,35,36,39,41,48] and this experiment. On the left the SSE is classified over the specific regeneration temperatures of those experiments. In the center the total water uptake variation is compared using as reference the dew point during the respective adsorption phases. On the right-hand side, the global system efficiency is ordered over the extracted liters of water per unit of dry sorbent mass.

from regeneration with a pure passive method (dissipation through metallic heat sink exposed to ambient temperature and natural convection), then the term  $P_{elCOND}$  is null. Instead, when a dry cooler is driving condensation (temperatures higher than external

ambient)  $P_{elCOND}$  is small but not null (auxiliaries of the dry cooler). Instead,  $P_{elCOND}$  is considerably high when active refrigeration is involved (temperatures lower than external ambient). Total electric consumptions are reported in Appendix B.

### 5. Conclusions

In this work, we demonstrate an efficient cycle that is based on the use of very low-grade heat and conventional material such as silica gel, which has water uptake as low as 0.1 kg\_w kg\_{SiO2}^{-1}. Such a technology is applicable in most of the water stressed regions around the world. The prototype produced between 3.3 and 1.7 L dav<sup>-1</sup>, with low initial water content of silica (<0.1 kg<sub>w</sub> kg<sup>-1</sup>si $_{i02}$ ) typical of dry environments), regeneration temperature of 57 °C, over an operational time of 10 h. Compared to existing prototype in the literature, this configuration is one of the most efficient at the liter-scale dimension. Despite this evidence it is clear that silica gel, given its intrinsic properties, is not suitable for all climates. Scaling up this configuration to larger water daily production will rapidly increase to unsustainable volumes and encumbrances of the system. In very dry environments, with dew points lower than 0 °C, silica gel cannot exhibit any sufficient  $\Delta w$  to be applied in a cycle to produce water. For these reasons, further developments will be carried out to apply the method of AWH cycles based on isothermal regeneration on more sophisticated and performing materials such as MOF and polymeric desiccants, containing the regeneration temperatures to the level of low temperature energy sources. In addition, a different design of the adsorption heat exchanger can be done with a different ratio of the sorbent mass devoted to mass exchange, to the metallic mass devoted to heat exchange. In particular, by shifting this ratio towards the thermal exchange. faster cycles can be realized instead of a strict day/night time scale.

## Credit author statements

Vincenzo Gentile: Conceptualization, Methodology, Experiments, Writing and Graphical Editing; Michael Bozlar: Data analysis, Writing and Reviewing; Forrest Meggers: Supervision, Reviewing, Editing; Marco Simonetti: Supervision, Reviewing, Editing

#### **Declaration of competing interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Nomenclature

Variables

Cp	specific heat at constant pressure [k] kg <sup>-1</sup> ]
đ	diameter [m]
h	enthalpy [kJ kg <sup>-1</sup> ]
Ha	adsorption heat [kJ kg <sup>-1</sup> ]
H <sub>lat</sub>	latent heat [m]
L	liter
ṁ	mass flow rate [kg s $^{-1}$ ]
Μ	mass [kg]
Pν	water vapor pressure [Pa]
Р	Power [W]
Q	Air flow rate $[m^3 h^{-1}]$
R	universal constant of gases [J kg <sup>-1</sup> K <sup>-1</sup> ]
RH	relative Humidity [%]
r	radius [m]
ρ	Density [kg m <sup>-3</sup> ]
STE	specific thermal energy [kWh kg <sub>w</sub> <sup>-1</sup> ]
SSE	specific solar energy [kWh kg <sub>w</sub> <sup>-1</sup> ]
Т	temperature [°C]

- t time [min]
- W weight [kg]

*w* water content  $[kg_w kg_{SiO2}^{-1}]$ 

*x* air moisture content; Humidity ratio  $[kg_w kg_a^{-1}]$ 

## Symbols

#	number
Δ	Delta, difference

 $\eta$  efficiency

∑ Sum

## Subscripts

a	air
amb	external environment
b	bed
dew	dew point
e	equilibrium
el	electrical
in	inlet
iso-H	iso-enthalpic
iso-T	iso-Temperature
lat	latent
max	maximum
out	outlet
reg	regeneration
SiO2	silica gel
sat	saturation
sol	solar
th	thermal
tot	total
V	vapor
W	water

## Acronyms

ADS	Adsorption
HX	Heat Exchanger
MOF	Metallic Organic Framework
PV	photovoltaic
REG	Regeneration
AWG	Atmospheric Water Generator
PE	Primary Energy

#### Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2022.124295.

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