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Hybrid Condensation-Desiccant Atmospheric Water Generation: A Scientific Analysis of the Aeronero Bubble System for Sustainable Decentralized Water Production

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ABSTRACT
Atmospheric Water Generation (AWG) presents a decentralized technology solution to global water scarcity by producing potable water from atmospheric humidity. This paper delivers a comprehensive scientific, thermodynamic, and material-level assessment of Aeronero's Bubble AWG, designed to generate 15–20 L/day using proprietary ConDessa™ hybrid condensation–desiccant technology. The Bubble system integrates hydrophilic condenser fin geometry, thermoelectric cooling, desiccant-based adsorption, and solar- compatible regeneration for high water yields across 25–95% relative humidity (RH), exceeding standalone condensation systems. Output water meets or surpasses WHO standards. Aeronero's intellectual property portfolio includes 13+ patents, notably IN2025050296 (Publication 2025/181834), in partnership with IIT Madras, forming the basis for hybridization. Incorporating adsorption isotherm theory, Clausius-Clapeyron dew point analysis, hybrid thermodynamic modeling, and performance evaluation, studies show that Bubble achieves 30–45% higher water yield per kWh compared to conventional AWGs. Hybrid AWG demonstrates scalable, resilient solutions for decentralized water access.

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Introduction

Freshwater scarcity impacts billions due to climate change, dwindling groundwater, contamination, and population growth. Conventional approaches — groundwater extraction, RO desalination, bottled water — face sustainability challenges: finite resource depletion, waste, infrastructure needs, and negative ecological impact. AWG circumvents these issues, harvesting water directly from atmospheric moisture, an unlimited source estimated at 13,000 trillion liters globally at any instant.

AWG

- Relies solely on ambient air, no surface water required.
- Produces no plastic or brine waste.
- Provides portable, on-site generation.
- Reduces transport emissions and costs.
- Yields ultra-pure water meeting WHO standards.

Comparatively, RO desalination and bottled water have high energy demands (RO: 3–5 kWh/m³, bottled: substantial indirect), plastic waste, and substantial CO_2 emissions. AWG achieves 0.3–1 kWh/L, and with solar, approaches near-zero operational energy. Its decentralized nature enables cost-effective, scalable deployment for off-grid, water-stressed communities.

Aeronero Technologies' Bubble AWG, powered by proprietary ConDessa™ hybrid technology, achieves robust performance from 50% RH, yielding 15–20 L/day under typical deployment conditions. The underpinning technology is protected by over 13 patents, including IN2025050296 for a roof-integrated, solar desiccant AWG system.

Theory and Background

Psychrometric Basis of Condensation

AWGs cool air below the dew point, using these formulas:

Actual Vapor Pressure

$$e_a = \frac{RH}{100} \times e_s$$

Where $ea$is actual vapor pressure (hPa), $RH$is relative humidity (%), and $es$is saturation vapor pressure (hPa).

Saturation Vapor Pressure

$$e_s = 6.1094 \times \exp\left(\frac{17.625 \times T}{T + 243.04}\right)$$

Where $es$is saturation vapor pressure (hPa) and $T$is temperature (°C).

Dew Point Temperature

$$T_{dew} = \frac{243.04 \times \ln(e_a/6.1094)}{17.625 - \ln(e_a/6.1094)}$$

Where $Tdew$is dew point temperature (°C) and $ea$is actual vapor pressure (hPa).

Condensation alone is energy-intensive below 50–60% RH due to low moisture density**.**

Table 1. Representative desiccant properties used in the Bubble AWG.

Desiccant	Water Uptake (g/g)	Effective / Operating RH Range	Regeneration Temperature	Additional Notes
Silica gel	0.25 – 0.35	Mid-range RH	60 – 80 °C	High cycle stability
Zeolite 13X / SAPO-34	0.20 – 0.30	Strong affinity at low RH	80 – 100 °C	Robust but higher regeneration energy
MOF-303	0.30 – 0.40	Stepwise uptake above ~10–20% RH	Low-grade heat	Suitable for cyclic operation
LiCl-based polymers	0.30 – 0.50	Higher uptake at elevated RH	60 – 90 °C	Used to boost performance in humid conditions

Scientific Principles of Desiccant Technology

Desiccants capture water vapor by adsorption (surface binding) or absorption (bulk binding), crucial for harvesting in low-humidity environments. The Bubble AWG utilizes silica gel, zeolites (13X, SAPO-34), metal-organic frameworks (MOF-303), and LiCl-based polymers, selected for high water uptake, regeneration efficiency, and durability, functioning across 10–100% RH.
Adsorption isotherms describe water uptake (q, g/g) as RH changes:

- SAPO-34: Type I, excels at low RH.
- LiCl polymers: Type III, best at high RH.
- MOF-303: Type V, rapid uptake at specific RH (>10%).

Thermodynamics: Adsorption is exothermic (isosteric heat ~40–60 kJ/mol), while desorption is endothermic, requiring 60–100°C depending on the desiccant type.

Condensation Technology

AWG condensation cools air to its dew point (Td), then condenses vapor by removing:

- Sensible heat (cools to Td)
- Latent heat (Lv, ~2.26 MJ/kg at 25°C)

Bubble uses thermoelectric (TEC) Peltier cooling (75 W, COP 0.8–1.2), condensing up to 0.4 L/h/module. At 30% RH and 25°C, dew point is ~7°C, Under the same ambient condition, pre-concentrating moisture with the desiccant bed can effectively raise the local dew point seen by the condenser by several degrees Celsius, thereby reducing the required temperature lift across the thermoelectric modules.

This hybridization is consistent with the observed reduction in specific energy consumption into the 0.35–0.43 kWh/L range when solar-assisted regeneration is utilized. demanding much cooling energy. Hybrid design pre-concentrates air using desiccants, raising dew point and lowering energy needs, enabling efficient yields at lower RH.

Integration of Desiccant and Condensation Processes

ConDessa™ technology integrates desiccant adsorption with thermoelectric condensation to produce water efficiently across 10–100% RH.
Modes:

- Sequential: Air passes through the desiccant, then heat-induced desorption directs vapor to condenser, elevated RH reduces cooling energy.
- Cyclic: Adsorption maximized at night (higher RH), desorption and condensation during the day (higher temperature, solar-thermal).

Specific Water Production (SWP)

$$SWP = q_{fin} - q_{init}$$

Where $qfin$and $qinit$are final and initial water contents (g/g).

Specific Energy Consumption (SEC)

$$SEC = \frac{Q + c_p(T_{des} - T_{amb})(1 + q_{init})}{q_{fin} - q_{init}}$$

- cp: Desiccant specific heat (kJ/kg·K)
- $Tdes$: Desorption temperature (°C)
- $Tamb$: Ambient temperature (°C)

For Bubble AWG, SEC ranges 1.57–3.5 MJ/L depending on humidity and energy source. Field tests confirm yields of 8–12 L/day in diverse climates.

ConDessa™ Hybrid Technology & Patent Landscape

The patented ConDessa™ system integrates hydrophilic condenser plates, thermoelectric modules (Peltier, 75 W, COP 0.8–1.2), silica gel/MOF desiccant beds, and solar regeneration (200 W equivalent). IoT sensors (RH, temperature, water output) enable live monitoring and optimization.
Key features:

- Hydrophilic aluminum condenser (contact angle <30°)
- Desiccant beds with 0.2–0.5 g/g water uptake
- Solar or waste heat regeneration (60–85°C)
- Internet-connected ESP32 microcontroller
- Modular, scalable design; 50 cm x 30 cm x 40 cm device

System Architecture of the Aeronero Bubble

Parameter	Value
Daily Output	15–20 L/day
Power Consumption	450 W
Filtration	UF, RO, UV-C, Carbon, Ozone
pH Output	7.0–8.5
RH Range	25–95%
Dimensions	400 × 490 × 530 mm
Weight	25 kg

Materials and Methods

Experimental Setup

The Bubble AWG units were evaluated in field deployments across multiple climatic zones, with each site operating continuously for several weeks to months under real-world conditions.

Ambient dry-bulb temperature, relative humidity, electrical energy consumption, and water production were recorded via integrated IoT sensors and data logging, and daily averages were computed after removal of obvious sensor faults and power-interruption periods.

The reported performance ranges therefore reflect aggregated multi-site behavior rather than a single controlled laboratory test

Operational Stages

- Air Intake & Pre-Filtration
  Filtered ambient air (HEPA, 0.3-micron) via centrifugal fan (12 W, 80 CFM). Energy use: 0.0288 kWh/L.
- Desiccant Moisture Adsorption
  Hygroscopic materials (MOF, silica gel), regenerable by 200 W solar/waste heat. Energy use: 0.08 kWh/L (approaching 0 kWh/L with solar).
- Thermoelectric Condensation
  Peltier modules, cooling to 5–10°C. Energy use: 0.31 kWh/L.
- Condensate Collection & Carbon Filtration
  Passive gravity filtration. Negligible energy.
- Multi-Stage Purification
  UF, RO, UV-C, ozone purification, 0.0065 kWh/L.
- Alkaline Mineralization
  Mineral cartridge raises pH/TDS. Passive.
- IoT Monitoring
  Sensors and microcontroller, 0.0048 kWh/L.

Total Energy Efficiency

- Grid-powered: 0.43 kWh/L
- Solar-assisted: ~0.35 kWh/L

Results and Performance Evaluation

- 22 million liters potable water produced across 253 units
- 87+ million liters groundwater saved
- 11 million direct/indirect beneficiaries
- 30–45% higher output per kWh compared to standalone condensation-based AWGs of similar capacity operating under comparable ambient temperature and relative humidity conditions.
- WHO-compliant water quality: pH 7.0–8.5, zero microbial contamination

Discussion

ConDessa™ hybrid AWG demonstrates:

- Enhanced performance at low RH
- Lower energy use with solar heat compatibility
- Modular scalability for diverse climates
- High water purity

Hybrid AWGs are well suited for decentralized, climate-resilient water supply [1-7].

Conclusion

Aeronero Bubble AWG advances decentralized water generation with patented hybrid condensation–desiccant technology, delivering reliable, efficient, and pure drinking water. ConDessa™ sets new standards in atmospheric water harvesting.

Nomenclature

Symbol	Description
es	Saturation vapor pressure (hPa)
e	Actual vapor pressure (hPa)
RH	Relative humidity (%)
Td	Dew point temperature (°C)
AWG	Atmospheric Water Generator
MOF	Metal-Organic Framework
TEC	Thermoelectric Cooler
SWP	Specific Water Production (L/KG/day)
SEC	Specific Energy Consumption (MJ/L)
q	Water uptake per kg desiccant
Qst	Isosteric heat of adsorption

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