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Techno-Economic Analysis of Atmospheric Water Harvesting Across Climates

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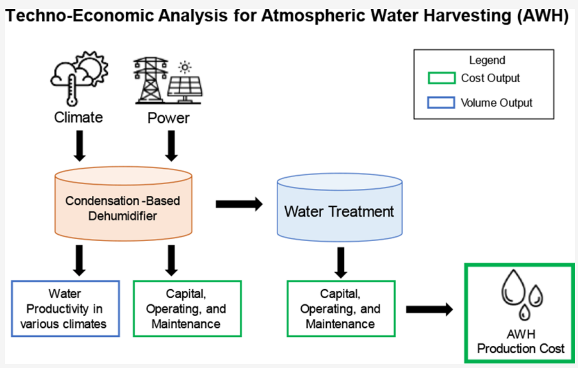
ABSTRACT: Drinking water scarcity is a global challenge as groundwater and surface water availability diminishes. The atmosphere is an alternative freshwater reservoir that has universal availability and could be harvested as drinking water. In order to effectively perform atmospheric water harvesting (AWH), we need to (1) understand how different climate regions (e.g., arid, temperate, and tropical) drive the amount of water that can be harvested and (2) determine the cost to purchase, operate, and power AWH. This research pairs thermodynamics with techno-economic analysis to calculate the water productivity and cost breakdown of a representative condensation-based AWH unit with water treatment. We calculate the monthly and annual levelized cost of water from AWH as a function of climate and power source (grid electricity vs renewable energy from solar photovoltaics (PV)). In our modeled unit, AWH can provide 1744–2710 L/month in a tropical climate, 394–1983 L/month in a temperate climate, and 37–1470 L/month in an arid climate. The levelized cost of water of AWH powered by the electrical grid is \$0.06/L in a tropical climate, \$0.09/L in a temperate climate, and \$0.17/L in an arid climate. If off-grid solar PV was purchased at the time of purchasing the AWH unit to power the AWH, the costs increase to \$0.40/L in an arid climate, \$0.17/L in a temperate climate, and \$0.10/L in a tropical climate. However, if using existing solar PV there are potential cost reductions of 4.25–5-fold between purchasing and using existing solar PV, and 2–3-fold between using the electrical grid and existing solar PV, with the highest cost reductions occurring in the tropical climate. Using existing solar PV, the levelized cost of AWH is \$0.09/L in an arid climate, \$0.04/L in a temperate climate, and \$0.02/L in a tropical climate.



KEYWORDS: *dehumidification, condenser, refrigerant, point of use, fit for purpose*

1. INTRODUCTION

As the world's population and demand for freshwater increase, new water resources are needed. According to the United Nations Children's Fund, 2 billion people lack access to safely managed drinking water at home.[1] This is especially true for remote areas that lack access to water and electricity. Traditional liquid water sources such as rivers, lakes, and groundwater may be inaccessible due to municipal or natural disasters, contamination, or drought. For example, in 2022 in the community of Las Vegas, New Mexico, U.S.A., 13000 residents had less than a month's supply of drinking water left after postwildfire monsoons and flooding sent carbon-rich dirt and debris into the local Gallinas River watershed and contaminated the water supply.[2] Meanwhile, in 2022 in the community of Jackson, Mississippi, U.S.A., more than 150000 residents did not have potable water after a loss of pressure in the water service lines raised concerns about pathogens in the water.[3]

The atmosphere is an alternative freshwater reservoir that contains 12900 km^3 of water, 6-fold more than the global volume of rivers, and is universally available, regardless of location or time.[4,5] Atmospheric water harvesting (AWH) has been proposed as a possible alternative technology and resource that could serve water off both the water and electrical grids.[6−18] Three types of technologies have been studied for AWH: (1) fog nets, (2) desiccant-based technologies, and (3) condensation-based technologies. The mesh fog nets are used to collect water droplets as fog passes over them and are therefore only viable in areas where water vapor is present as fog (i.e., relative humidity (RH) > 95%).[19,20] Desiccant-based technologies are used to extract water from low to high humidity areas by absorption or adsorption, which is then followed by heating the desiccants to release water.[21−23] These technologies are versatile in many climates, but have not been scaled to produce large volumes of

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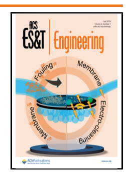

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water. Lastly, condensation-based technologies use a cold surface to cool ambient air below the dew point temperature (T_{DP}) to condense or harvest water.[24] These systems are well studied by the American Society for Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE),[25] and several commercial systems are currently available.[26] Condensation-based systems are frequently marketed as dehumidifiers and atmospheric water generators (AWGs) and have achieved the highest technology readiness level (TRL) of all AWH mechanisms and will therefore be the focus of this study.

AWGs that are marketed for drinking water consumption consist of a condensation-based dehumidifier coupled with a point-of-use (POU) water treatment system to treat harvested water to Environmental Protection Agency (EPA) or World Health Organization (WHO) drinking water standards[27] (Figure 2). For example, Aquaboy AWGs utilize a high efficiency particulate air (HEPA) filter to prohibit micro-particles and dust from entering, an ultraviolet (UV) sterilizer to eliminate bacteria and microorganisms, a carbon filter to remove organic chemicals, and an additional disinfection phase to purify the water before entering the final tank.[28] Similar POU treatment units can be found on other AWGs such as WaterGen.[29]

Most commercial-scale condensation-based dehumidifiers are benchmarked for capacity (i.e., amount of water removed per day) at a single climate scenario by the Association of Home Appliance Manufacturers (AHAM) at 80 °F/26.7 °C/ 60% RH.[24,30] For example, the Dri-Eaz LGR 7000XLi portable commercial-scale dehumidifier, used for drying large areas such as offices and warehouses, has a water removal capacity of 61.5 L/day at the AHAM test conditions. Similarly, portable home-scale dehumidifiers are benchmarked by the Energy Star program for the amount of water removed per day at the test condition of 65 °F/18.3 °C/60% RH. The Frigidaire FFAD5033W1 dehumidifier, used in home basements or closets, has a water removal capacity of 50 pints/day, or 23.7 L/day, at Energy Star test conditions. However, the true quantity of water harvested varies as a function of climate conditions such as RH, specific humidity (SH, [g water vapor/ kg air]), dry-bulb temperature (T_{DB}), and T_{DP}, and other unit parameters (e.g., air flow rate).[22−24]

Condensation-based dehumidifiers operate using constant power [Watts], but water productivity or the quantity of water harvested per unit of time [L/h or L/day] varies with climate. Therefore, the energy required to harvest water (kWh/L) also varies with climate. In previous work we have shown that the operating cost for grid-tied AWH can be calculated using the energy consumption.[24] There is a need to further analyze how climate impacts AWH production cost, which includes the capital cost and operating and maintenance (O&M) costs for both water harvesting and water treatment.

Techno-economic analysis (TEA) is a tool that can be used during the development phase of a system or product to evaluate if a proposed technology is truly competitive from an economic point of view. Researchers have used TEA as a prospective tool for topics such as hydrogen production, concentrated solar power, electrochemical oxidation, and several other technical concepts to foresee competitiveness.[31−34] Prior TEAs of AWH have studied energy consumption and levelized cost, with an emphasis on desiccant-based systems.[21,35] Solar desiccant-based AWH in an arid climate requires an energy input of 116−1021 kWh/m^3 depending on atmospheric conditions and process configuration. The levelized cost of water for sorbent-based systems is \$6.5−11/m^3, depending on system configuration, energy recovery, and sorbent material.[21,35] The levelized cost of water for AWH by active cooling in a humid climate can be >\$20/m^3 and up to \$50/m^3 in a dry climate.[35] Water harvesting in semiarid regions by membranes can cost \$0.033−0.325/L.[36] To build on these studies, there is a need to understand the specific impact of different climate regions and power supplies together, as well as unit capital cost. The variability of the climate over a meteorological year influences the volume of water harvested over time. TEA can reveal the complex interaction between the cost and performance drivers of harvesting water in various climates powered by renewable energy or the electrical grid. TEA can provide a framework to identify both the levelized cost of water from AWH (i.e., the average net present cost of water produced from AWH over its typical meteorological year) and the month-by-month costs of operating and maintaining AWH. An AWH device with fixed power draw will therefore have variable specific energy consumption (kWh/L) as a function of climate. Therefore, the operating cost and annual cost of AWH will depend collectively on the volume of water harvested, specific energy consumption, and the source of power (i.e., grid-tied or off-grid).

The objective of this paper is to perform TEA of condensation-based AWH in arid, temperate, and tropical regions powered by renewable energy (e.g., existing solar photovoltaics (PV) vs newly purchased solar PV systems) and the electrical grid. The process flow diagram in Figure 1 shows the TEA development. We aim to answer three research questions: (1) What is the water harvesting productivity of a representative AWH unit as a function of climate? (2) What is the O&M cost of AWH (including water treatment) as a function of climate and power sources? (3) What is the levelized cost of AWH as a function of climate and power sources?

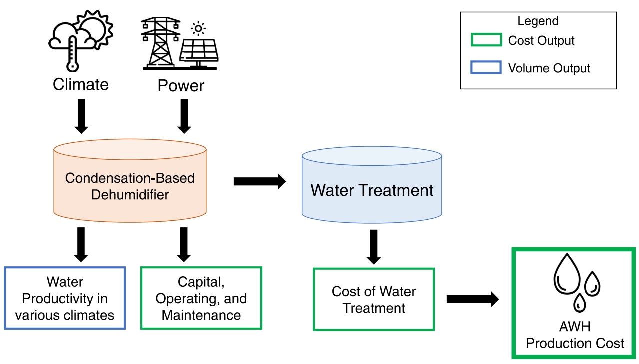

Figure 1. Process flow diagram for techno-economic analysis of atmospheric water harvesting (AWH).

The levelized cost of water produced from AWH [\$/L] is compared to the unit cost of purchasing bottled water (\$1.22/ gal or \$0.32/L). Transported water and bottled water are often used during emergency relief scenarios to provide a stopgap solution when municipally treated water is unavailable. Rural and remote communities as well as military operations may rely upon transported or bottled water as their primary water source. AWH may fit a similar niche role at a similar or lower cost point. AWH is not meant to be competitive with reverse osmosis or pumping from groundwater wells, which have

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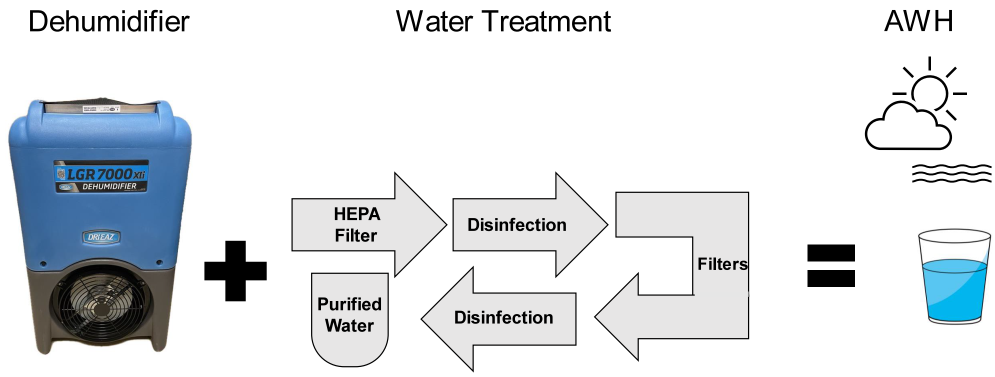

Figure 2. The atmospheric water harvesting (AWH) unit is a coupled condensation-based dehumidifier with water treatment. The dehumidifier unit modeled in this study is the DriEaz LGR 7000XLi.

significantly lower specific energy consumption but require plumbing or fixed infrastructure.[24,35] Instead, it can serve as a solution for emergency or decentralized drinking water needs and as an alternative to bottled or transported waters.

2. METHODS

2.1. AWH Unit. For this study, a specific condensation-based dehumidifier (Dri-Eaz LGR 7000XLi) and a water treatment point of use (POU) system (AquaBoy Pro II Ez-Filter) were selected for analysis. A rationale for why this dehumidifier was chosen is provided in SI, Section S1 and Figure S1. Throughout the rest of this paper we will refer to the "AWH unit" as a coupled condensation-based dehumidifier with water treatment (Figure 2).

2.1.1. Dehumidifier Unit. The Dri-Eaz LGR 7000XLi dehumidifier (from here on referred to as "dehumidifier unit") has three manufacturer-reported capacities of (1) 111 L/d at 32.2 °C/90% RH ("Saturation"), (2) 61.5 L/d at 26.7 °C/60% RH (AHAM), and (3) 8 L/d at 26.7 °C/20% RH ("Low Grain"). The unit has an air flow rate of 552 m^3/h and uses 0.95 kW of power. The system has a lifetime expectancy of 10 years.[37]

2.1.2. Water Treatment Unit. Although dehumidifiers do not have existing water treatment inside the unit, a POU water treatment system can be installed externally to harvest potable water. The POU unit used in this TEA was the AquaBoy Pro II Ez-Filter with a cost of $215.[28] This POU water treatment system uses a high efficiency particulate air (HEPA) filter to prohibit microparticles and dust from entering, an ultraviolet (UV) sterilizer to eliminate bacteria and microorganisms, a carbon filter to remove organic chemicals, and an additional disinfection phase to purify the water before entering the final tank. This system is already in use in commercial Aquaboy atmospheric water generator (AWGs), and similar units can be found on other commercial AWGs such as WaterGen.[29] With a POU system, the atmospheric water harvested from the dehumidifier can be treated to meet the U.S. Environmental Protection Agency (EPA) water quality standards.[27]

2.2. Climate Regions. We consider three representative climate conditions in this study: arid, temperate, and tropical. The three climate zones were established using the Köppen Climate Classification system (Figure S2).[38,39] A dry or arid zone is determined by the amount of annual precipitation in the warmest 6 months of the year. Phoenix, Arizona, U.S.A., falls within this classification and was used to represent an overall arid climate. A temperate climate zone is classified as an area with hot summers and cool winters, but no dry seasons. Dallas, Texas, U.S.A., falls within this classification and was used to represent a neutral climate. A tropical zone has an average temperature of 17.8 °C or higher with significant precipitation throughout the year. Miami, Florida, U.S.A., is representative of a tropical climate and can be used as a baseline to understand the general water productivity and costs of AWH in a place with high temperatures and high humidity especially during the summer months.

Climate data was obtained for a typical meteorological year (TMY) through the National Solar Radiation Database (NSRDB).[40] TMY databases contain one year of hourly data that best represents median weather conditions over a multiyear period. The data are considered "typical" because the entirety of the original solar radiation and meteorological data is condensed into one year's worth of the most usual conditions.[41] For an arid climate scenario, data was extracted from the Phoenix Sky Harbor International Airport in Arizona (33°27′00.0″N 111°58′58.8″W). For a temperate climate scenario, data was pulled from the Dallas Fort Worth International Airport in Texas (32°54′00.0″N 97°01′01.2″W). For a tropical climate scenario, data was pulled from the Miami International Airport in Florida (25°49′01.2″N 80°18′00.0″W).

2.3. Rate of Water Harvested. Rate of water harvested [L/h] was calculated by first coupling hourly NSRDB climate data with thermodynamic equations (eqs 1−4).[42] Air temperature, hereby referred to as the dry-bulb temperature (T_{DB}), and dew point temperature (T_{DP}) were obtained from NSRDB TMY for the 3 locations that best represented the 3 climate regions (Phoenix, Arizona = arid; Dallas, Texas = temperate; and Miami, Florida = tropical). Data were filtered to only include hours when T_{DP} was greater than 0 °C, as water cannot be harvested through dew-point condensation methods when T_{DP} is below freezing.[42] This was denoted as *pct_op*, or percent of operable hours per analysis period, and was calculated using eq 1.

$$\text{pct}_{\text{op}}[\%] = \frac{\text{hours in which } T_{DP} > 0\ °\text{C}}{\text{hours in analysis period}} \times 100 \tag{1}$$

Next, the hourly saturated vapor pressure (e_{s_DP}) was calculated by means of the Clausius−Clapeyron equation (eq 2). Here, e_{so} is the saturated vapor pressure 611.25 Pa at temperature (T_0) 273.16 K, $\triangle H_{vap}$ is the heat of vaporization 2.5×10^6 J/kg at T_{DB} = 273.16 K, R_v is the vapor gas constant

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461.945 J/kg/K, and T_{DP} is the hourly dewpoint temperature given by NSRDB.

$$e_{s\_DP}[\mathrm{Pa}] = e_{so} \times \exp\left(\frac{\Delta H_{vap}}{R_v}\left(\frac{1}{T_0} - \frac{1}{T_{DP}}\right)\right) \quad (2)$$

Equation 3 shows the ideal gas law rearranged to solve for the hourly vapor density.

$$\rho_{vap}\left[\frac{\mathrm{kg}}{\mathrm{m}^3}\right] = \frac{e_{s\_DP}}{R_v \times T_{DB}} \quad (3)$$

Equation 4 was used to calculate the hourly ideal volume of water that passes through a condensation-based dehumidifier (V_{ideal}), where air flow rate (Q_{air}) [m^3/h] is provided in the device manufacturer's specifications sheet. The mass flux of water vapor over time (kg/h) is converted to volume over time (L/h) using the density of water (1 kg/L). Unit conversions were applied where appropriate to obtain hourly volume of water harvested [L/h], for every hour of a TMY where $T_{DP} > 0$ °C.

$$V_{ideal}\left[\frac{\mathrm{L}}{\mathrm{h}}\right] = \rho_{vap} \times Q_{air} \quad (4)$$

However, the ideal volume is not representative of the actual volume of water that is harvested using a condensation-based dehumidifier owing to limitations including the cooling capacity of the condenser (8600 BTU/h), air flow rate, available surface area on the condensation coils, and/or heat transfer.[24] Therefore, eq 5 was used to calculate the water recovery efficiency, η, of the dehumidifier unit. The water recovery efficiency is a major factor in the usefulness of the dehumidifier and is the fraction or percentage of the "water harvested rating" divided by the ideal volume of water. The numerator of eq 5 is the "water harvested rating at test condition" which comes from the user manual of the dehumidifier and varies by climate: (1) 111 L/d at 32.2 °C/90% RH ("Saturation"), (2) 61.5 L/d at 26.7 °C/60% RH (AHAM), and (3) 8 L/d at 26.7 °C/20% RH ("Low Grain").

$$\eta = \frac{\text{water harvested rating at test conditions}}{V_{ideal} \text{ at test conditions}} \times 100 \quad (5)$$

The water recovery efficiencies for the saturation, AHAM, and low grain conditions are 27%, 30%, and 12%, respectively (Table S1).[43] These water recovery efficiencies match those of other commercial and portable dehumidifiers.[24] Our model assumes temperate and tropical regions operate at 30% water recovery efficiency year round, because their climate conditions match the saturation and AHAM test conditions. In an arid region, climate conditions in winter months such as January, February, November, and December match the low grain test condition. In these months, our model assumes that the arid region operates at a 12% water recovery efficiency. In the other months of the year (March through October), arid climate conditions vary between the low grain and AHAM test conditions. Due to the lack of information from the manufacturer regarding the true volume of water harvested by the dehumidification unit in these test conditions, our model assumes a 30% water recovery efficiency in March through October to match the AHAM values. Water recovery efficiency (η) is incorporated in eq 6 to calculate the hourly volume of water harvested for all climate scenarios.

$$\text{hourly water harvested}\left[\frac{\mathrm{L}}{\mathrm{h}}\right] = V_{ideal} \times \eta \quad (6)$$

2.4. Alternative Power Scenarios. In addition to different climate conditions, we also consider three power supply scenarios in our model: (1) grid electricity, (2) electricity from owned solar PV systems, and (3) electricity from newly purchased solar PV systems. AWH can be powered or operated using nonrenewable energy for standard grid-tie operation, or renewable energy for true off-grid application. In Power Scenario 1, grid electricity, no capital cost is required, and the user only has to pay operating cost. The Energy Information Administration (EIA) shows the average national electricity price for operating power from the grid is \$0.13 per kWh in the U.S.[44] Studies have found strong evidence that consumers respond more to average electricity prices rather than marginal prices.[45,46] In Power Scenario 2, where a user already owns a solar PV system, electricity is harvested from the panels or battery storage. Both capital and operating costs for electricity are avoided. The preowned solar PV system may be on a rooftop or ground-mounted and associated with existing residential or commercial infrastructure (e.g., warehouses, parking garages, community centers, universities, buildings). We assume that operating costs are avoided, because the responsibility for solar PV upkeep was on the onus of the existing owner. In this scenario, the surplus electricity generated by the solar PV system is directed toward AWH (e.g., if there were solar panels installed on the roofs of parking structures that were being used to offset grid-electricity usage by a commercial entity or university). The AWH unit would be integrated with the PV system to utilize the excess electricity generated by the preowned solar PV.

In Power Scenario 3, the user must pay capital and O&M cost to purchase, operate and maintain the solar PV system. A solar PV system was sized according to the annual energy consumption of the dehumidifier unit of 8361 kWh/year (see SI, Section S2 for calculations). Quotes were obtained from Greenwired Renewable Energy Solutions and Solar Topps to purchase a solar PV system to support this energy need.[47,48] The dehumidifier unit requires a 6.24 kW system to perform at a 100% duty cycle every day for 10 years. The manufacturer estimated annual kWh production range by this PV system in Year 1 is 8414−9348 kWh, in Year 10 is 8226−9140 kWh, and in Year 24 is 7943−8825 kWh. The expected cost to install 16−20 330 W panels, battery storage, inverter, and other components is \$39422−39565 before tax (see SI, Section S3 for cost breakdown and estimated annual kWh production table). The Greenwired quote was for a PV installation in Miami, FL, and the Solar Topps quote was for an installation in Tempe, AZ. Both quotes assumed a constant power draw for the duration of operation of the AWH unit, irrespective of climate. This system size and cost are used for all three climates: arid, temperate, and tropical. Operating and maintenance cost of the solar PV system is \$29.49/$\mathrm{kW_{dc}}$/yr or \$184.02/yr (\$15.33/month) for a 6.24 kW system.[49] This fixed cost was derived from NREL's recent report on U.S. Solar Photovoltaic System and Energy Storage Cost Benchmarks, which outlined the current minimum sustainable price (MSP) benchmark for residential Solar PV at \$29.29/kW/year.[49]

2.5. Techno-Economic Analysis to Determine Water Production Cost. Techno-Economic Analysis was performed for 3 climates (arid, temperate, and tropical) across 3 power supply scenarios: Power Scenario (1) AWH operated using

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grid electricity; Power Scenario (2) AWH operated using owned solar PV systems; and Power Scenario (3) AWH operated using newly purchased solar PV systems.

Equation 7 shows the total cost to purchase the AWH unit, which includes capital cost ($CapCost_{Scenario}$) of purchasing the AWH unit and purchasing the solar PV system (only for Scenario 3), operating cost of the power scenario ($OpCost_{Scenario}$, applicable for Scenarios 1 and 3), and maintaining the AWH unit (*MaintCost*). This equation was applied in two analyses: (1) a month-by-month analysis and (2) a levelized annual cost analysis. The month-by-month analysis determines the monthly cost to operate and maintain the AWH unit (dehumidifier + water treatment) in each climate powering each energy source. It assumes that the user already owns the AWH unit. Therefore, in the month-by-month analysis the capital cost in eq 7 was set to $0, and we only calculated the operating and maintenance costs. Conversely, the levelized annual cost analysis for all three power scenarios estimates the cost of ownership of the AWH unit throughout its 10-year life span and for Power Scenario 3 includes cost of purchase of the solar PV system over its 25-year life span. The equipment may continue to be operational beyond the 10-year AWH unit life span contingent upon certain climates' wear and tear. The analysis does not account for any additional expenses (i.e., operating and maintenance) associated with owning the AWH unit beyond its initial 10-year lifespan.

$$\mathrm{TotalCost}_{\mathrm{scenario}}[\$] = \mathrm{CapCost}_{\mathrm{scenario}} + \mathrm{OpCost}_{\mathrm{scenario}} + \mathrm{MaintCost} \quad (7)$$

Equation 8 determines the operating cost for Power Scenario 1 ($OpCost_{Scenario1}$), calculated by multiplying the power draw of the AWH unit [kWh/month], the percentage of operable hours (*pct_op*), and the electricity price [$/kWh]. There is no OpCost associated with Power Scenario 2. The operational cost for Power Scenario 3 ($OpCost_{Scenario3}$) is set at $184.02/year or $15.33/month, as described in Section 2.4. The operating cost in the month-by-month analysis was in units of [$/month] and in the levelized annual cost analysis was [$/TMY].

$$\mathrm{OpCost}_{\mathrm{scenario1}}[\$] = \mathrm{power\ draw} \times \mathrm{pct\_op} \times \mathrm{electricity\ price} \quad (8)$$

Next, maintenance costs were calculated for years 0–9 for the dehumidifier unit and the POU water treatment system. The maintenance costs of the dehumidifier unit were obtained from communication with A&R Supply, a company that specializes in janitorial equipment.[37] Each year the condensation-based dehumidifier requires quarterly replacement of air filters and regular cleaning of internal components. The filter replacement is on the onus of the unit owner to perform the task. The filter replacement cost for the 10-year lifetime was calculated as follows: In year 0, the unit will come with an existing filter, therefore, only 3 additional filters will be used the first year of ownership. In years 1–9, the cost of replacement filters includes 4 filter changes every 3 months. External sourcing of a maintenance and labor company is needed annually to disassemble the unit and clean coils, pump tray, drain hose, submersible pump, and heat exchanger box. This annual cleaning is required for the dehumidifier to function at optimal levels. According to A&R Supply Co, the labor required for this annual maintenance is $125 and the filter replacements cost $15.33 each (4 filters per year).[37] As for the POU water treatment system, the annual kit from Atmospheric Water Solutions can be purchased for $185/yr to perform four filter cartridge replacements per year.[28] The total cost of maintenance was calculated as the sum of dehumidifier and water filter replacements and labor over a TMY. For the month-by-month analysis, the total cost of year 1 was then divided by 12 to determine the monthly maintenance of the system.

2.5.1. Month-by-Month Analysis. The monthly production cost of water ($WaterProdCost_{monthly}$) is estimated from a month-by-month analysis, following eq 9. The hourly water harvested (L/h), calculated by eq 6, was used to determine the monthly water harvested (L/month) by summing each hour per month. Meanwhile, the monthly cost includes the monthly operating and maintenance costs of the AWH unit, and in Scenario 3 includes the monthly cost of upkeep for solar PV.

$$\mathrm{WaterProdCost}_{\mathrm{monthly}}\left[\frac{\$}{\mathrm{L}}\right] = \frac{\mathrm{OpCost} + \mathrm{MaintCost}}{\mathrm{monthly\ water\ harvested}} \quad (9)$$

2.5.2. Levelized Cost Analysis. For the levelized annual cost analysis, the capital cost of the AWH unit consists of the off-the-shelf whole unit cost of the dehumidifier unit and the POU water treatment system. In Power Scenarios 1 and 2, no capital cost of power was included. In Power Scenario 3, the capital cost of purchasing a complete solar PV system was included. As noted in Section 2.1.1, the assumed lifespan of the entire AWH unit was set at 10 years. However, it is important to acknowledge that Solar PV panels typically have longer lifespans, estimated to be 25 years for a residential unit and 30 years for a commercial unit.[47,49] This discrepancy can lead to an overestimation of the levelized cost if only considering the AWH unit's lifetime, neglecting the longer lifespan of the Solar PV. Consequently, in the levelized annual cost analysis we set the lifetime of AWH to 10 years, and the lifetime of Solar PV in Power Scenario 3 to 25 years, to accommodate for the varying lifetimes.

After the capital cost and annual O&M costs were estimated, discounting was done to generate the present value of costs (PVC) [$/L] of AWH in varying climate conditions (arid, temperate, and tropical) for the 3 power scenarios. The discounting process is a way to convert units of value across time horizons, translating future dollars into today's dollars.[50] The present value of the total cost ($PVC_{TotalCost}$) is calculated by eq 10, where T is the lifetime of the system (10 years for AWH or 25 years for Solar PV), t is the time period index (0–9 years for AWH or 0–24 years for Solar PV), $TotalCost_t$ is the cost value in period t, r is the discount rate, and $1/(1 + r)$ is the discount factor. In this study the discount rate, r, was assumed to be 4%/year to correspond to the planning period of 10 years and to adjust for inflation.[51−54] In summary, eq 10 applies a discount factor to future values to convert them into present values over a specific lifetime.

$$\mathrm{PVC}_{\mathrm{TotalCost}}\left[\frac{\$}{\mathrm{lifetime}}\right] = \sum_{t=0}^{T} \frac{\mathrm{TotalCost}_t}{(1+r)^t} \quad (10)$$

$$\text{Power Scenarios 1 and 2 Levelized Annual Cost}\left[\frac{\$}{\mathrm{yr}}\right] = \left(\frac{\mathrm{PVC}_{\mathrm{AWH\ unit}}}{10\ \mathrm{yr}}\right) \quad (11)$$

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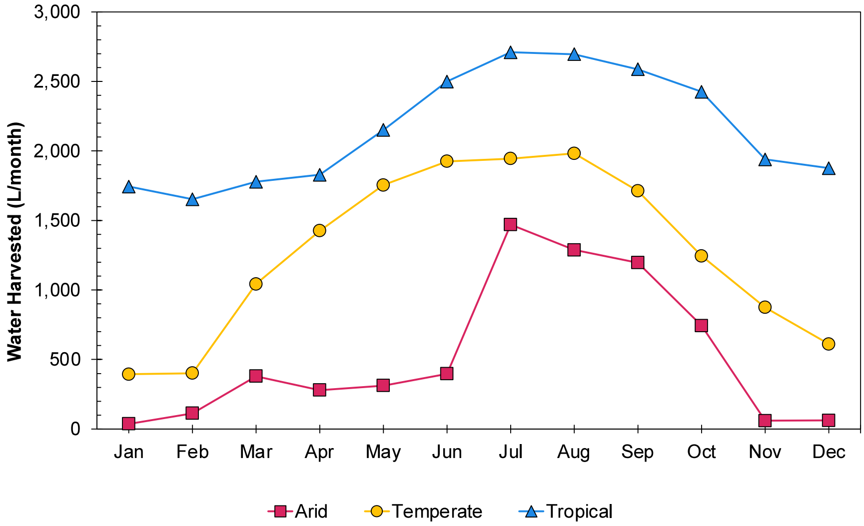

Figure 3. Monthly volume of water harvested by the modeled atmospheric water harvesting (AWH) unit as a function of climate.

$$\text{Power Scenario 3 Levelized Annual Cost}\left[\frac{\$}{\text{yr}}\right] = \left(\frac{\text{PVC}_{\text{AWH unit}}}{10\text{ yr}}\right) + \left(\frac{\text{PVC}_{\text{PV unit}}}{25\text{ yr}}\right) \quad (12)$$

The $PVC_{TotalCost}$ from eq 10 was divided by the respective lifetimes of the AWH unit and PV unit and added together to get the levelized annual cost for Scenarios 1−3 (eqs 11 and 12). The Levelized Annual $Cost_{per\ Scenario}$ [$/year] was then divided by the annual water harvested from the month-by-month [L/TMY], to get the Levelized Cost of Water [$/L] (eq 13).

$$\text{Levelized Cost of Water}\left[\frac{\$}{\text{L}}\right] = \frac{\text{Levelized Annual Cost}}{\text{annual water harvested}} \quad (13)$$

2.5.3. Uncertainty Analysis. Two uncertainty analyses were performed to assess the sensitivity of the TEA on levelized water production cost [$/L]: (1) impact of differences in discount rate and (2) impact of capital cost on Solar PV installation (Scenario 3).

We performed a bounding analysis on discount rate using 3%/yr and 7%/yr rates to represent the consumption rate of interest and rate of return to private capital. This analysis was implemented using eq 10 and modifying the discount rate, *r*, to 3%/yr and 7%/yr. According to the Office of Management and Budget, discount rates of 3% and 7% are typically applied in cost-benefit estimations where a 3% rate is a more precise indicator when the cost or benefit influences consumption, while the 7% rate is more precise when the cost or benefit impacts capital.[51]

Uncertainty ranges between −10% and +15% were applied for the capital cost of Solar PV in Scenario 3. This range was recommended by the Association for the Advancement of Cost Engineering for Class 1 projects, which are characterized as projects with a 50−100% completion.[55] The ± percentage signifies the percentage fluctuation of actual costs from the estimated cost after the application of contingency. The analysis was performed by reducing the capital cost of Solar PV by −10% and increasing the capital cost of Solar PV by +15%.

3. RESULTS AND DISCUSSION

3.1. Impact of Climate on Water Harvested.

Figure 3 shows the monthly water harvested [L/month] of the modeled AWH unit over a TMY, broken down by 3 climates. In an arid climate, the water harvested ranges from 37 to 1470 L per month; in the temperate climate, the water harvested ranges from 394 to 1983 L per month; and in the tropical climate, the water harvested ranges from 1744 to 2710 L per month. In February, for example, a cold winter month, water harvested in an arid and temperate climate is 93% and 76% less than in a tropical climate, respectively. The difference in water harvested between the 3 climates varies much less in the summer months. In July, for example, a warm summer month, water harvested for an arid and temperate climate is only 46% and 28% less than for the tropical region, respectively. Over all climates, the level of water harvested is highest in July and August. The difference in water harvested across seasons in a single climate can vary as little as 1.6-fold between winter and summer in a tropical climate and as much as 39-fold in arid climates.

There are two factors that influence the volume of water harvested: (1) dew point temperature and (2) percent of operable hours in a month with dew point temperature above 0 °C. Water harvested increases from 397 to 1470 L/month (3.7-fold) between June and July in an arid climate (Figure 3). This corresponds with an increase in average dew point temperature from 3.45 to 15.19 °C. Additionally, the unit is operable for 59% of hours (or 18 days) in June, while it is operable for 94% of hours (or 29 days) in July (Table S2). Meanwhile, in a temperate climate, the dew point temperature remains above 0 °C for all hours between April through September. In a tropical climate, the dew point always remains above 0 °C. Water harvested is then dependent on only the change in dew point temperature. In April vs July in a temperate climate, water harvested varies from 1426 to 1945 L/month (1.4-fold increase) while dew point increases from 13.42 and 18.85 °C. Similarly, in a tropical climate, water harvested varies from 1828 to 2710 L/month (1.5-fold increase) between April and July, while dew point increases from 18.15 to 24.31 °C.

A consensus from the United States Centers for Disease Control (CDC) and the Federal Emergency Management

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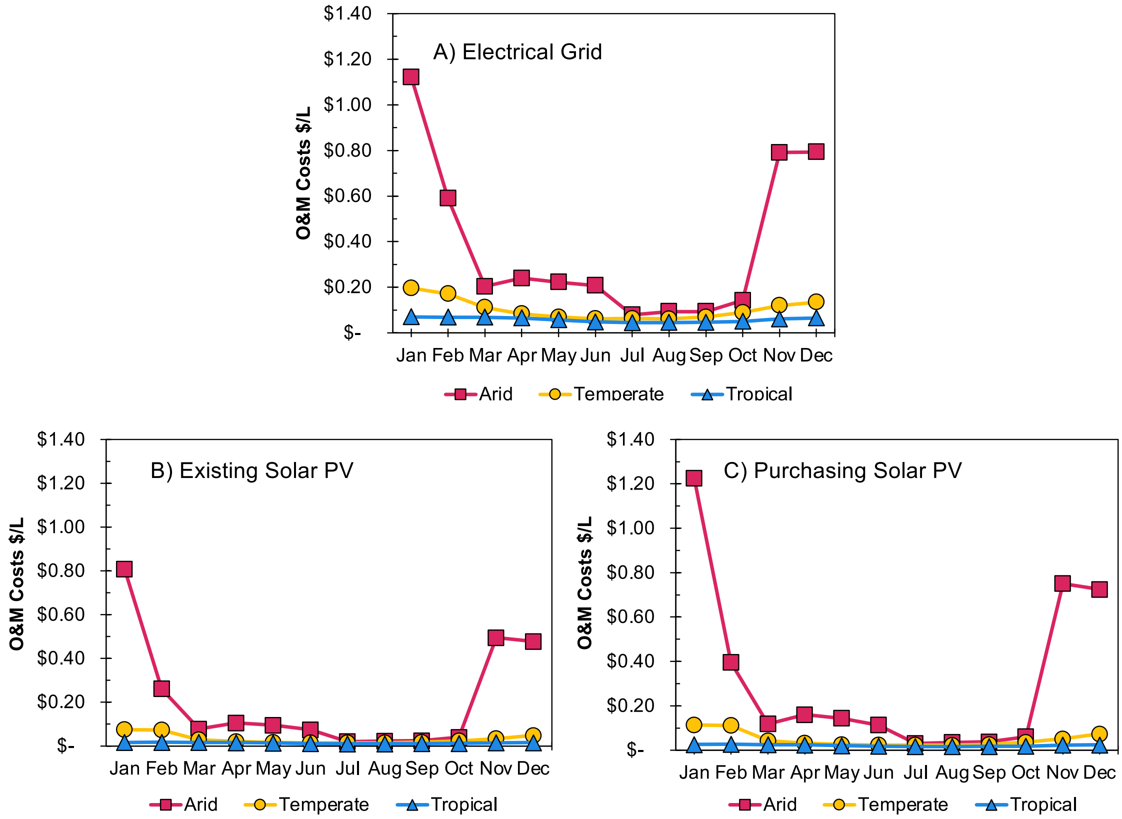

Figure 4. (A–C) Monthly operation and maintenance (O&M) costs of the modeled atmospheric water harvesting (AWH) unit as a function of climate and power supply. (A) AWH unit is operated using electricity purchased from the grid at \$0.13/kWh. (B) AWH unit is operated using existing solar PV (no operation cost). (C) AWH unit is operated using purchased solar (includes operation cost).

Agency (FEMA) states that, during an emergency state, one adult utilizes about 1 gallon of water per day, the equivalent of 113.7 L per month (30 gal/month).[56] Figure 3 shows that in all climates and in all months (except January, November, and December in an arid climate) this emergency need can be achieved. The modeled AWH unit can provide water for more than 20 people in July, a common hurricane season for a tropical region. In a temperate region, in July, the AWH unit can provide up to 17 people with water, which could be used for scenarios like the 2022 Jackson, Mississippi water crisis. Furthermore, in an arid region in July, the AWH unit can provide approximately 13 people with water which can be used after postwildfire surface water contamination like the 2022 Las Vegas, New Mexico water crisis.

3.2. Water Harvesting Cost.

3.2.1. Monthly Cost to Operate and Maintain AWH. Knowing a system's monthly operating and maintenance costs is crucial to managing cash flow and budget. In the month-by-month cost analysis, we assume that the customer already owns the unit. We focus on comparing the operating and maintenance costs of the AWH unit (dehumidifier + water treatment) as a function of the power scenario. Thus, the capital cost was set to \$0.

Figure 4A–C shows the cost per liter to harvest water from the atmosphere for each month in an arid, temperate, and tropical region powered by the electrical grid and solar PV. Renewables were used to compare the cost of operating AWH in a truly off-grid manner versus relying on the electrical grid for power. For the electrical grid (Figure 4A), the cost of AWH in a tropical region ranges between \$0.05/L and \$0.07/L. June through October were all the least expensive months each at \$0.05/L, and January through April were each the most expensive months at \$0.07/L. For a temperate region, June through August were the least expensive months at \$0.06/L, whereas January was the most expensive month at \$0.20/L. For an arid region, cost ranges between \$0.08/L and \$1.12/L, where July is the least expensive and January is the most expensive.

Monthly cost is inversely related to water harvested, exhibiting economies of scale. A higher water harvested amount is representative of a lower cost. Since water harvested is influenced by dew point temperature and percent operable hours, the higher the dew point temperature, the less it will cost to operate and maintain AWH. The lowest cost across each climate commonly occurs in July. Water harvesting in July for tropical, temperate, and arid climates was 2710, 1945, and 1470 L/month, respectively. The cost to operate and maintain AWH during the month of July in tropical, temperate, and arid climates using the electrical grid is \$0.05/L, \$0.06/L, and \$0.08/L respectively.

Cost can be significantly reduced on a month-by-month basis if using existing solar PV (Scenario 2) rather than connecting to the electrical grid (Scenario 1), because only the cost of the AWH needs to be considered. The monthly cost in a temperate region in January, the month with the lowest average dew point temperature of 2.85 °C and highest cost, was \$0.20/L using the electrical grid. If AWH were powered by existing solar PV, the cost becomes \$0.08/L. This is due to the operating cost of using solar PV being \$0 per year, and only AWH unit maintenance cost is considered. However, Figure 4C shows the cost difference for Scenario 3, purchasing solar.

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As discussed in Section 2.4, O&M costs were included for this scenario and were estimated at \$15.33/month for a total of \$184/year. In January, the estimated cost to own and operate an AWH unit in an arid climate is \$1.22/L which is comparable to the electrical grid.

The O&M cost of AWH can be cost competitive with purchasing bottled water. In temperate and tropical regions, it is optimal to harvest water year-round since the cost will always be lower than bottled water (\$0.32/L or \$1.22/gal), regardless of which power supply is used (Figure 4A−C). In an arid climate, there are at least 8 months (March to October) in which AWH costs less than bottled water. In the case of a municipal disaster similar to Jackson, Mississippi (temperate) or Las Vegas, New Mexico (arid), where the municipal water supply was disturbed or contaminated,[2,3] there may still be power from the electrical grid. If AWH was used in July for a tropical climate using the electrical grid, where the water harvested quantity is 2710 L/month, the monthly cost to operate and maintain water at \$0.05/L is equal to \$136/month. The cost of the same volume of bottled water would be \$867/month. When compared to bottled water, AWH has the potential to cost 6 times less. Similarly, in July in a temperate climate where water harvested is 1945 L/month, the monthly operating cost is \$0.06/L equating to \$117/month. In comparison, the cost to purchase the same volume of bottled water, not including additional cost of transportation and distribution, would be \$622/month. In a temperate climate, AWH has the potential to cost almost 5 times less than bottled water. Finally, if the water harvested in an arid climate is 1,470 L in July at \$0.08/L, this would equate to \$118/month. Compared to the bottled water cost in July of \$470, AWH could cost almost 4 times less. These monthly costs for AWH could be reduced to \$0.02/L in arid and temperate climates or \$0.01/L in tropical climates if using owned solar power.

3.2.2. Levelized Cost. Figure 5A−C displays all expenses that were calculated in the TEA levelized annual cost analysis including capital and O&M costs. It shows the cost breakdown of operating AWH in an arid, temperate, and tropical climate under three power scenarios: (1) using the electrical grid, (2) using owned solar PV, and (3) purchasing solar PV. The capital cost for the modeled LGR 7000XLi dehumidifier is \$2800. The capital cost of the POU water treatment system is \$215. In total, the capital cost for the AWH unit for Power Scenarios 1 and 2 is \$3015. Power Scenario 3 includes the capital cost of purchasing a 100% duty cycle off-grid solar PV system for \$39565 before tax (see SI, Section S3 for a cost breakdown from Greenwired Renewable Energy Solutions).[48] The capital cost for the AWH unit and purchasing off-grid solar power in Scenario 3 is \$42580.

The maintenance costs for the AWH unit are the same for all scenarios, regardless of the power source. This is because the same AWH unit is being used, and maintenance for the unit does not change for the different power supplies. Maintenance costs for the existing solar PV power supply are outside of the scope of this analysis. The maintenance cost for purchasing Solar PV is incorporated in the operating cost analysis ($OpCost_{Scenario3}$). The maintenance cost for the levelized annual cost analysis is split between years 0 and 1−9 for a 10-year lifetime. In year 0, we assume the unit already comes with one filter from the purchase of the dehumidifier. The maintenance cost is \$171/yr, accounting for 3 filters and labor work for cleaning coils, sump pump, and heat exchanger. Years 1−9 account for 4 filter replacements for the dehumidifier, an annual filter kit for maintenance on the POU unit (\$185/yr), and labor work for the regular cleaning of internal components. The maintenance cost for years 1−9 is \$371/yr.

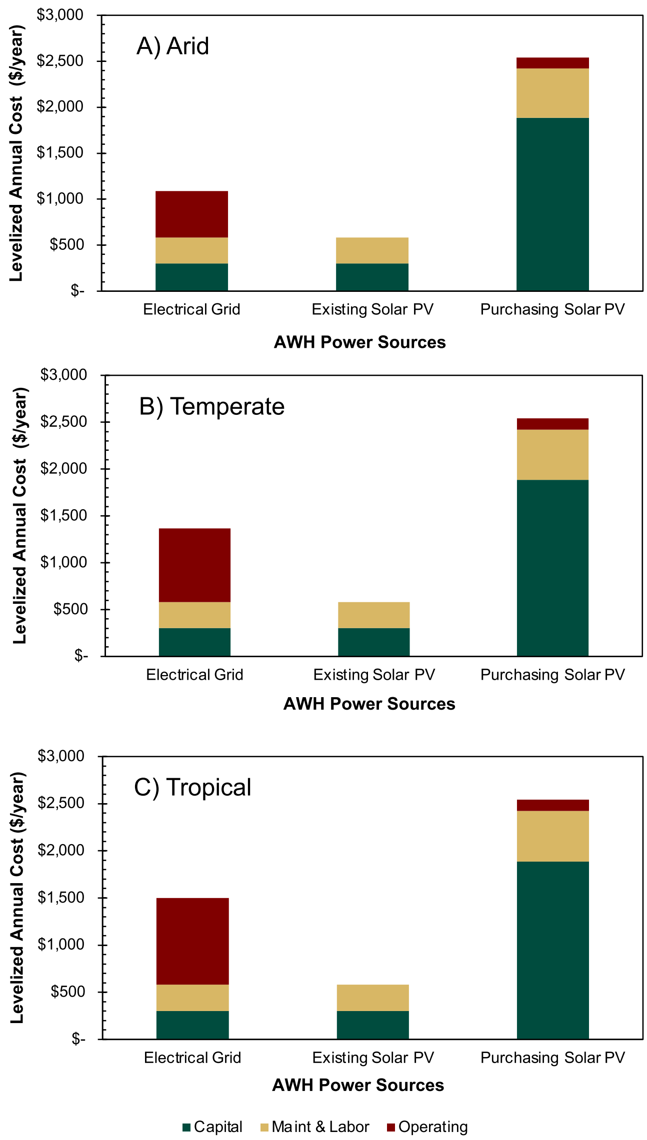

Figure 5. (A−C) Levelized annual cost of atmospheric water harvesting (AWH) across (A) arid, (B) temperate, and (C) tropical climates.

The operating cost for each power source is the driver of the differences in the leveled annual cost. The operating cost for the electrical grid (Scenario 1) is \$0.13/kWh, the operating cost for existing Solar PV (Scenario 2) is \$0/kWh, while the operating cost for purchasing Solar PV is \$184.02/year (Scenario 3). Figure 5A−C shows the levelized annual cost (capital, maintenance, labor, and operating) calculated by using eqs 11 and 12. The cost of AWH when powered by the electrical grid in the tropical climate is \$1498/year; in a temperate climate, the cost is \$1365/year; and in an arid climate, the cost is \$1088/year. The total cost is lower in an arid climate compared with temperate and tropical climates due to the number of operable hours, where $T_{DP} > 0$ °C. In an arid climate, an AWH unit will only operate for 55% of the year (4834 h), while in a temperate climate the unit operates for 85% of the year (7478 h) and in a tropical climate for 100% of

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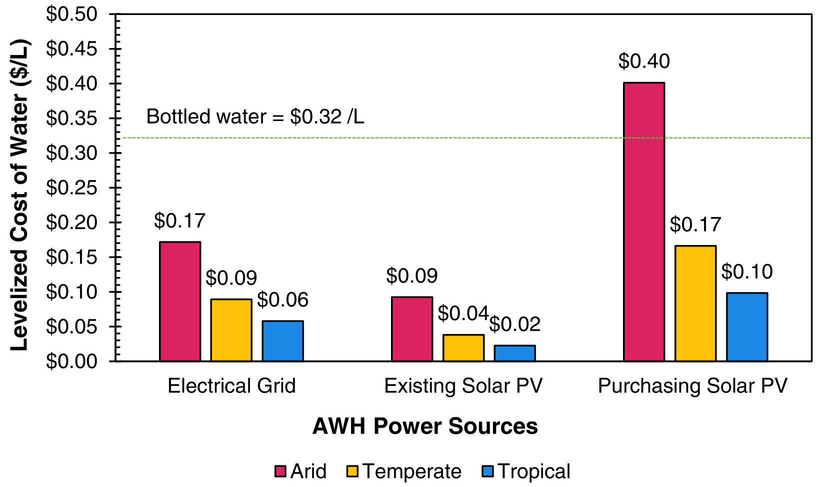

Figure 6. Levelized cost of water from the modeled atmospheric water harvesting (AWH) unit in an arid, temperate, and tropical climate powered by the electrical grid, existing owned solar PV, and purchasing new solar PV. Levelized costs for AWH are compared to the cost of purchasing bottled water at $0.32/L.

Table 1. Uncertainty Analysis for Levelized Cost of Water by AWH

		levelized cost of water for AWH ($/L)				
power supply	climate	base scenario (discount rate 4%/yr)	discount rate 3%/yr	discount rate 7%/yr	solar capital cost 10% lower	solar capital cost 15% higher
electrical grid	arid	$0.17	$0.18	$0.16		
	temperate	$0.09	$0.09	$0.08		
	tropical	$0.06	$0.06	$0.05		
existing solar PV	arid	$0.09	$0.09	$0.09		
	temperate	$0.04	$0.04	$0.04		
	tropical	$0.02	$0.02	$0.01		
purchasing solar PV	arid	$0.40	$0.41	$0.38	$0.39	$0.45
	temperate	$0.17	$0.17	$0.16	$0.16	$0.19
	tropical	$0.10	$0.10	$0.09	$0.10	$0.11

the year (8760 h). Meanwhile, the levelized annual cost of water for the solar-powered AWH scenarios does not vary by climate because the capital cost of AWH unit and solar panels, maintenance and labor for the AWH unit, and operating cost of Solar PV, are all fixed. The estimated levelized annual cost of AWH across all climates is $582/year when powered using existing solar PV, and $2541/year when purchasing new solar PV.

The monthly volumes of water harvested shown in Figure 3 were summed to calculate the annual water harvested over a TMY. The modeled AWH unit can produce 25890 L/TMY in a tropical climate, 15316 L/TMY in a temperate climate, and 6341 L/TMY in an arid climate. By dividing the Levelized Annual $\text{Cost}_{\text{per Scenario}}$ [$/year], shown in Figure 5A–C with the annual water harvested from the month-by-month [L/TMY], we found the levelized cost of water for AWH (LCOW_{AWH}) [$/L]. This is a parameter that expresses the cost of water harvested per liter and can be compared to the cost of other forms of water supply and treatment.

Figure 6 shows the LCOW_{AWH} for Scenario 1, power consumption by the electrical grid, to be $0.17/L in an arid climate, $0.09/L in a temperate climate, and $0.06/L in a tropical climate. If off-grid solar PV was purchased at the time of purchasing the AWH unit and used to power AWH (Scenario 3), LCOW_{AWH} increases to $0.40/L in an arid climate, $0.17/L in a temperate climate, and $0.10/L in a tropical climate. However, if using existing solar PV (Scenario 2), there are potential cost reductions of 4.25–5-fold between purchasing and using existing solar PV, and 2–3-fold between using the electrical grid and existing solar PV, with the highest cost reductions occurring in the tropical climate. Using existing solar PV in Scenario 2, the LCOW_{AWH} is $0.09/L in an arid climate, $0.04/L in a temperate climate, and $0.02/L in a tropical climate. AWH can be a cost-effective competitor to bottled water in all modeled scenarios except in an arid climate powered by newly purchased solar PV. It is important to note that the $0.32/L levelized cost of bottled water is only the cost for purchase and not transportation and distribution. It is therefore a conservative estimate and the lower boundary of the true cost of relying on bottled water, furthermore, indicating that AWH may be more appealing than bottled water.

3.2.3. Uncertainty Analysis for Levelized Cost of Water by AWH. Table 1 shows results of the two uncertainty analyses (the discount rate and capital cost of solar PV). Changing the discount rate from the base scenario of 4%/year to either 3%/year or 7%/year did not have a significant impact on LCOW_{AWH}. The change in LCOW_{AWH} only varied by ± $0.00–0.02/L for all climate and power scenarios. A sensitivity analysis was also performed on the capital cost of purchasing solar PV in Power Scenario 3, as this could vary as a function of the market and inflation or recession. Decreasing capital cost of solar from $39564.90 by 10% only decreased LCOW_{AWH} by $0.00–0.01/L for all climates. Increasing the capital cost of

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solar by 15% increased the cost in an arid climate by \$0.05/L, in a temperate climate by \$0.02/L, and in a tropical climate by \$0.01/L. The highest variability in $LCOW_{AWH}$ is seen for the arid climate because it produces the least amount of water.

3.2.4. Additional Potential Cost Reduction. Additional cost reductions can occur through innovative approaches to the AWH. A piece-by-piece analysis of the dehumidifier unit found the heat exchanger (condenser + evaporator) to be the driving cost of the unit (Table S3). Innovation in heat exchanger technology could reduce the capital cost further. Additionally, there is potential to increase cooling capacity, in turn increasing the water harvested, especially in the temperate and tropical climates, which would result in a lower cost. A recent study states entropy generation due to heat transfer in dew plates may significantly impact the overall system efficiency and optimal recovery ratio.[57] In an arid climate, the major limitation was the water vapor being too far from saturation and $T_{DP} < 0$ °C for 45% of the year. Unfortunately, condensation-based dehumidifiers do not work well in cold and arid regions. However, a desiccant-based approach could be utilized for AWH at extreme temperatures (−20 °C) and low humidity areas (<20%).[7,26,58] By using a desiccant, the efficiency may increase, resulting in a higher water harvested rating and lower cost.[35]

4. CONCLUSION AND FUTURE OUTLOOK

TEA was applied to the modeled AWH unit, consisting of a condensation-based dehumidifier and POU water treatment across three climates and three power scenarios. We find that there is significant seasonal variability in the volume of water harvested across all climates: 37 to 1470 L/month in an arid climate; 394 to 1983 L/month in a temperate climate; and 1744 to 2710 L/month in a tropical climate. Higher water volume harvested resulted in lower levelized cost of water: cost of AWH powered by the electrical grid was \$0.17/L in an arid climate, \$0.09/L in a temperate climate, and \$0.06/L in a tropical climate. The levelized cost was further subsidized if the AWH unit was operated using existing owned solar PV: \$0.09/L in an arid climate, \$0.04/L in a temperate climate, and \$0.02/L in a tropical climate.

There are many challenges and barriers to widespread application of AWH, including uncertainty about cost, implementation, water quality, and consumer perception of alternative water supplies. This research provides a first step toward addressing the knowledge gap on cost and shows locations and power scenarios in which AWH can be reasonably and economically implemented. An AWH unit such as that modeled in this analysis can provide a sustainable alternative to bottled water during times of municipal or natural disaster in all modeled scenarios, except in an arid climate where solar PV is purchased at the time of AWH unit purchase. In events such as postwildfire flooding in Las Vegas, NM and municipal water infrastructure damage in Jackson, MS, electrical power may be readily available to support the AWH unit. A unit could be placed directly outside homes, in a school courtyard, or at a community center to provide a centralized location to access safe drinking water.

There are unique scenarios, such as after hurricane events, where both water and electricity infrastructures are damaged for many months (e.g., Puerto Rico after Hurricane Maria in 2017). In events such as this, an AWH unit could be supported by alternative renewable energy sources such as solar power. However, the scale in terms of size and weight of solar PV infrastructure (20 panels, battery, inverter, and additional supplies) that is required to operate a single compressor dehumidifier may be challenging to transport and install after a disaster. Instead, off-grid AWH systems may be better supported at industrial warehouses or agricultural sites that already have large PV arrays installed and may be able to use AWH water for fit-for-purpose use at their facility.

This analysis calculates $LCOW_{AWH}$ as the levelized annual cost per volume of water harvested in a TMY on a per climate basis. There are several critical assumptions that govern the final $LCOW_{AWH}$ values: (1) The unit is attempting to operate and harvest water every hour for which climate is optimal over a TMY; (2) levelized annual cost of the AWH unit is calculated over an anticipated 10 year lifetime, and levelized annual cost of an optional purchased PV unit is calculated over an anticipated 25 year lifetime; (3) any additional expenses associated with owning and operating the AWH unit beyond the additional 10 years are not included. In the purchase solar PV scenario, the owner would need to continue to pay off the PV unit, and could purchase a new AWH unit to operate during the PV's remaining lifespan. Future research in AWH may be directed toward cost calculation and optimization for short-term use scenarios, e.g., AWH operation only during summer months or AWH operation only for a year as a stopgap solution, while potable water supply is temporarily unavailable. Future research can also consider unique renewable energy cost scenarios, such as a power purchase agreement between a third-party developer and the AWH unit owner.[59]

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsestengg.4c00098.

> Description of atmospheric water harvesting unit; Capital cost and water harvesting capacity of condensation-based atmospheric water harvesting units; Koppen climate types in the United States and study zones for this research; Water harvesting efficiency ratings for AWH unit studied; Annual energy consumption calculation for the AWH unit studied; Quotes for purchasing solar PV; Percent of operable hours to perform AWH by month during 2020 TMY; AWH unit piece-by-piece cost analysis (PDF)

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CRediT: **Natalie Gayoso** data curation, formal analysis, methodology, visualization, writing-original draft, writing-review & editing; **Emily Moylan** data curation, formal analysis, methodology, visualization; **Wenny Noha** conceptualization, funding acquisition, project administration, resources; **Jingjing Wang** conceptualization, methodology, supervision, validation, visualization, writing-review & editing; **Anjali Mulchandani** conceptualization, funding acquisition, methodology, project administration, supervision, validation, visualization, writing-review & editing.

Notes

The authors declare no competing financial interest.

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