NM WRRI Student Water Research Grant Progress Report

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Project Title: Techno-Economic Analysis of Atmospheric Water Harvesting Across Climates

Research Problem and Research Objectives:

Drinking water scarcity is a global challenge as ground water and surface water availability diminishes. The atmosphere is an alternative freshwater reservoir that has universal availability and an abundance of water within the air. This makes the atmosphere a great source to capture 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 being produced, and 2) determine the cost to purchase, operate, and power AWH. This research pairs thermodynamics with Techno-Economic Analysis, a method of analyzing the economic performance and feasibility of a technology, to highlight the cost breakdown and water productivity of AWH across climates.

Research Methodology:

1.1 AWH Unit

For this study, a specific condensation-based dehumidifier (Dri-Eaz LGR 700XLi) and a water treatment point of use (POU) system was selected for analysis. A rationale for why this dehumidifier and water treatment process was chosen is provided in Appendix A (Figure A1). Throughout the rest of this paper, we will refer to “AWH unit” as a coupled condensation-based dehumidifier with water treatment (**Figure 1**).

1.1.1 Dri-Eaz LGR 7000XLi

This unit has three manufacturer reported capacities of 29.4 gal/day at 90°F/ 32.2°C / 90% RH (Saturation), 16.3 gal/day at 80ºF/ 26.7°C/ 60% RH (AHAM), and 2.1 gal/day at 80F/ 26.7°C/ 20% RH (Low Grain). The unit has an air flow rate of 325 ft^3/min (552 m^3/h) using 0.95 kW of power. Additionally, the system has a lifetime expectancy of 10 years.[1]

1.1.2 Water Treatment

Although dehumidifiers do not have existing water treatment inside the unit, a point of use (POU) water treatment system can be installed externally to harvest potable water. The POU water treatment system that are associated with water harvesters contain the following filtration components: 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.[2,3] 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.

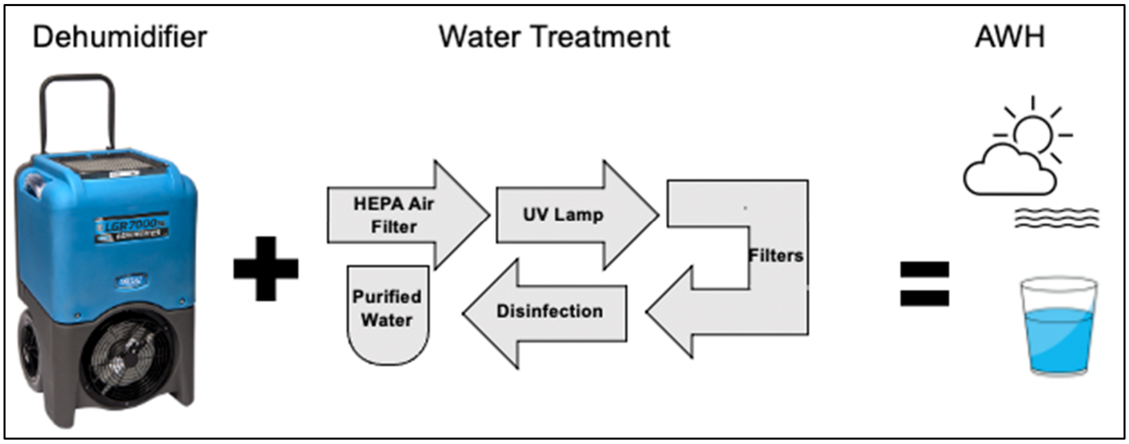

Figure 1. Condensation-based dehumidifier plus a water treatment system equals the AWH process or "AWH unit" researched in this paper

The AWH unit was modeled under three different climate conditions (arid, temperate, and tropical) and a TEA was conducted to determine a) the water harvested of the AWH unit and b) the cost of production across these different conditions. Additionally, the effects of renewable energy (new solar PV installation and existing soar PV) versus the electrical grid on production costs were examined.

1.2 Climate Regions

We determined monthly water production of the AWH as a function of three climate conditions. The three climate zones (arid, temperate, and tropical) were established using the Köppen Climate Classification system.[4] A dry or arid zone is determined by the amount of annual precipitation in the warmest 6 months of the year. Phoenix, Arizona, USA falls within this classification and was used to represent an overall arid climate globally. A temperate climate zone is classified as an area with hot summers and cool winters but no dry seasons. Dallas, Texas, USA falls within this classification and was used to represent a neutral climate worldwide. A tropical zone has an average temperature of 17.8°C or higher with significant precipitation throughout the year. Miami, Florida, USA is representative of a tropical climate and can be used as a baseline to understand the general 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).[5] 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.[6] 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, Florida international airport (25°49'01.2"N 80°18'00.0"W).

1.3 Water Harvested and Efficiency

Water harvested (gal/h) was calculated by first coupling hourly NSRDB climate data with thermodynamic equations (Equations 1.1-1.4).[7] Air temperature, hereby referred to as 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. 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.[7] This was denoted as "percent of operable hours" (Equation 1.1).

$$\%\, of\ operable\ hours\ per\ analysis\ period = \frac{hours\ in\ which\ T_{DP} > 0°C}{hours\ in\ analysis\ period} \times 100 \tag{1.1}$$

Next, the hourly saturated vapor pressure (e_{s_DP}) was calculated by means of the Clausius-Clapeyron equation (Equation 1.2). 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 $T_{DB}= 0$, R_v is the vapor gas constant 461.945 J/kg/K, and T_{DP} is the hourly dewpoint temperature given by NSRDB.

$$e_{s\_DP} = e_{so} \times \exp\left(\frac{\triangle H_{vap}}{R_v}\left(\frac{1}{T_0} - \frac{1}{T_{DP}}\right)\right) \tag{1.2}$$

Equation 1.3 shows the ideal gas law rearranged to solve for hourly vapor density, where T_{DB} is the dry-bulb temperature given by the NSRDB.

$$\rho_{vap} = \frac{e_{s\_DP}}{R_v \times T_{DB}} \tag{1.3}$$

Equation 1.4 was used to calculate the hourly ideal volume of water that passes through a condensation-based dehumidifier, where air flow rate has units [ft^3/min] or [m^3/h] and is provided in the device manufacturer's specifications sheet. Unit conversions were applied where appropriate to obtain hourly water harvested with units, gal/h, for every hour of a TMY where $T_{DP} > 0^oC$.

$$Ideal\ volume = \rho_{vap} \times\ air\ flow\ rate \tag{1.4}$$

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.[8] Therefore, Equation 1.5 was used to calculate the water recovery efficiency, η, of the Dri-Eaz LGR 7000XLi. Water recovery efficiency of a dehumidifier indicates how well its input water vapor is converted to useful output water production.

The numerator of Equation 1.5 is the "water harvested rating" which comes from each climate and water productivity condition from the user manual of the Dri-Eaz LGR 7000XLi: 90°F/ 32.2°C/ 90% RH (Saturation), 80°F/ 26.7°C/ 60% RH (AHAM), and 80°F/ 26.7°C/ 20% RH (Low Grain). 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 ideal volume of water.

$$\eta = \frac{Water\ harvested\ rating}{Ideal\ volume} \times 100 \tag{1.5}$$

The water recovery efficiencies for the saturation, AHAM, and low grain conditions are 27%, 30%, and 12%, respectively (see Appendix A, Table A1 for additional calculations).[9] Based off the manufacturer water harvested ratings at these three conditions, it was assumed temperate and tropical regions operate at 30% efficiency year round. Meanwhile the winter months in the arid climate such as January, February, November, and December operate at 12% efficiency. This is due to the low dry-bulb temperatures that make it harder for the AWH unit to condense water at these already cold and dry conditions. However, the other months in the year (March through October) in the arid climate were assumed to operate at 30% efficiency. Equation 3.6 shows the hourly water harvested.

$$Water\ harvested = Ideal\ Volume\ \times\ \eta \tag{1.6}$$

1.4 Techno-Economic Analysis to Determine Water Production Cost

Equation 1.7 shows the total cost to purchase, operate and maintain the AWH system.

$$TotalCost = OpCost + MaintCost + CapCost \tag{1.7}$$

The equation was applied in two analyses: a month-by-month analysis and a lifetime analysis. The month-by-month analysis determines the monthly cost to operate and maintain AWH in each climate powered by solar PV and the electrical grid. This analysis assumes the user already owns the system. Therefore, capital cost in Equation 1.7 was set to \$0, and we only calculated the operating and maintenance costs. The lifetime analysis estimates the cost of ownership throughout the AWH unit's 10-year life span.

AWH can be powered or operated using renewable energy for true off-grid application, or non-renewable energy for standard grid-tie operation. The power sources that were used for this analysis to calculate "OpCost" were solar PV energy and the electrical grid. According to the Department of Energy (DOE) SunShot Initiative, the average residential electricity price of solar PV in the U.S. is \$0.06/kWh.[10] Additionally, the Energy Information Administration (EIA) shows the average residential electricity price in the U.S. is \$0.13 per kWh.[10] Therefore, the average operating cost of renewable and non-renewable power sources that were used for this study are \$0.06/kWh for Solar PV and \$0.13/kWh for the electrical grid. The solar panel installation cost or capital costs are included in section 1.4.2.

In Equation 1.8, the electricity price (\$/kWh), the power draw (kWh/month), and the percentage of operable hours per analysis period were multiplied to calculate the operating costs for each power source at difference time scales. The month-by-month analysis was in units of \$/month and the lifetime was \$/TMY.

$$OpCost = ElectricityPrice\ \times\ PowerDraw\ \times\ \%\ of\ operable\ hrs\ per\ analysis\ period \tag{1.8}$$

Next, maintenance costs were calculated for years 0-9. The maintenance costs of the Dri-Eaz LGR 7000XLi were obtained from communication with A&R Supply, a company that specializes in janitorial equipment.[1] 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 year 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 clean internal components including the coils, submersible pump, and heat exchanger box. This annual cleaning is required for the dehumidifier to function at optimal levels. The cleaning service was calculated for 3 hours of labor every year for the lifetime of ownership. According to the U.S. Bureau of Labor Statistics the average hourly wage for maintenance and repair workers in 2022 is \$21.60.[11] An additional \$50-100 can be added for the maintenance company fees,[1] resulting in an annual cost of labor of \$100-\$200/ year. 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. The lifetime cost of maintenance was calculated as the sum of filter replacement and labor from years 0-9.

1.4.1 Month-by-Month Analysis

The month-by-month analysis uses the hourly water harvested (gal/h) calculated in section 1.3 Equation 1.6 to determine the monthly water harvested (gal/month) by summing each hour per month and using it as the denominator in Equation 1.9. Meanwhile the numerator, “total cost”, includes the monthly operating and maintenance costs of the AWH unit.

$$AWH\_ProdCost = \frac{TotalCost}{Monthly\ water\ harvested} \tag{1.9}$$

1.4.2 Lifetime Analysis

The lifetime analysis was important for understanding the cost over the 10-year lifespan of the unit. For the lifetime analysis, the capital cost of the AWH unit consists of the off-the-shelf whole unit cost of the Dri-Eaz LGR 7000XLi dehumidifier, the POU water treatment system, and the solar panel system cost. Further explanation as to why the Dri-Eaz LGR 7000XLi was selected over other dehumidifiers is located in Appendix A Section 1. Additionally, the specific POU system used in this TEA is explained further in Appendix A Section 1. The capital cost of solar panels will be explained below.

The Dri-Eaz LGR 7000XLi has an annual kWh usage of 8340 kWh/yr (see Appendix A Section 3 for calculations). According to a homeowner solar PV report,[12] this energy usage would require a 6kW to 8 kW system depending on the location. A 6kW system includes 20-25 panels while an 8kW system includes 26-33 panels. The average cost after the 30% federal solar tax credit is \$11,928 for the 6kW system, and \$15,904 for the 8kW system.[12] A 6kW system can be used in the arid climate scenario given the direct normal irradiance (DNI) is more than 45% higher than the temperate and tropical climate. The DNI monthly average in Phoenix is 7.35 kWh/m^2/day, whereas the monthly DNI in Dallas is 4.95 kWh/m^2/day and 5.04 kWh/m^2/day in Miami. The 8kW works best in the temperate and tropical climate since they don’t receive as high of a DNI than the arid climate.[5] To summarize, the lifetime analysis modeled a 6kW solar PV system for the arid region while the temperate and tropical regions modeled a 8kW system.

After the operating, maintenance, and capital costs were accounted for, discounting was done to generate cost (\$/gal) of AWH in varying climate conditions (arid, temperate, and tropical) using two power sources (solar PV and the electrical grid). The discounting process is a way to convert units of value across time horizons, translating future dollars into today's dollars.[13] The discounting process, $PVC_{TotalCost}$, is calculated by Equation 1.10, where T is the planning horizon, t is the time period index, $TotalCost_t$ is the future value in period t (from Equation 1.7), 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% to adjust for inflation.[14–17] Equation 1.10 applies a discount factor to future values to convert them into present values over a specific lifetime.

$$PVC_{TotalCost} = \sum_{t=0}^{T} \frac{TotalCost_t}{(1+r)^t} \tag{1.10}$$

The lifetime analysis then sums the monthly water harvested to determine the annual water harvested (gal/TMY). The annual water harvested is multiplied by the lifetime of the system, which is 10 years, to get the "Lifetime water harvested" (gal/lifetime). Finally, the AWH harvested cost can be calculated using Equation 1.11.

$$AWH\_ProdCost = \frac{PVC_{TotalCost}}{Lifetime\ water\ harvested} \tag{1.11}$$

Results:

2.1 Impact of Climate on Water Harvested

Figure 2 shows the monthly water harvested (gal/month) of the modeled AWH unit over a TMY, broken down by 3 climates. In an arid climate, the water harvested ranges from 10 to 388 gallons per month, in the temperate climate 104 to 523 gallons per month, and in the tropical climate 436 to 715 gallons 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 the tropical region, respectively. Over all climates, water harvested is highest in July and August. The difference in water harvested 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 water harvested: 1) dew point temperature, and 2) percent of operable hours in a month with dew point temperature above 0ºC. Water harvested increases from 105 to 388 gal/month (3.7-fold) between June and July in an arid climate (**Figure 2**). This corresponds with an increase in average dew point temperature from 3.45ºC to 15.19ºC. 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 1**). Meanwhile, in a temperate climate, dew point temperature remains above 0ºC for all hours between April through September. In a tropical climate, dew point always remains above 0ºC. 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 376 gal/month to 513 gal/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 482 to 715 gal/month (1.5-fold increase) between April and July, while dew point increases from 18.15 to 24.31°C.

A consensus from the CDC and FEMA states that during an emergency state, one adult utilizes about 30 gallons per month.[18] **Figure 2** 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 over 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 can provide approximately 13 people with water which can be used after post-wildfire surface water contamination like the 2022 Las Vegas, New Mexico water crisis.

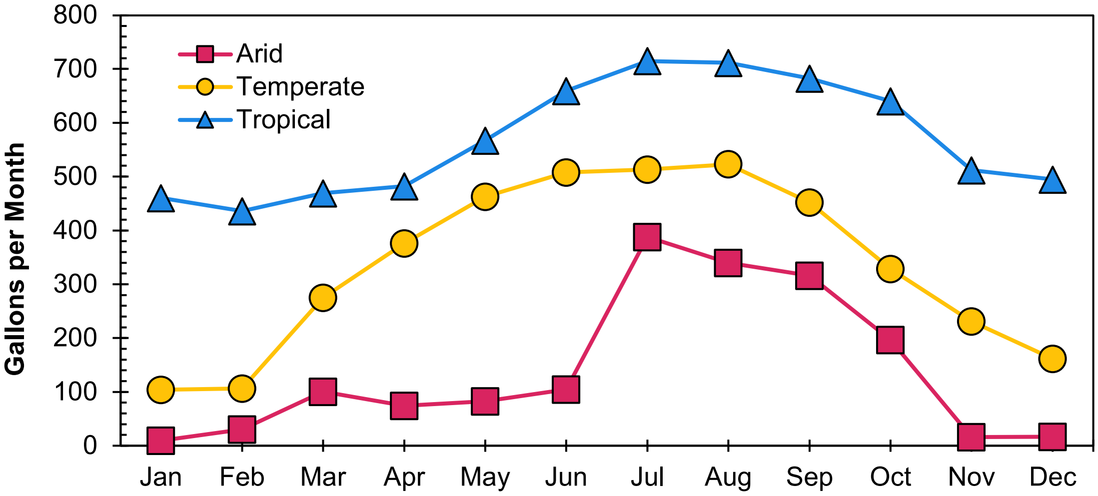

Figure 2. Water harvested as a function of climate for the 2020 TMY

Table 1. Percentage of operable hours to harvest water by month during 2020 TMY

	Arid	Temperate	Tropical
Jan	13%	52%	100%
Feb	45%	47%	100%
Mar	52%	94%	100%
Apr	42%	100%	100%
May	43%	100%	100%
Jun	59%	100%	100%
Jul	94%	100%	100%
Aug	98%	100%	100%
Sep	92%	100%	100%
Oct	82%	88%	100%
Nov	20%	84%	100%
Dec	21%	57%	100%

2.2 Water Harvesting Cost

2.2.1 Month-by-Month Analysis

Knowing a system's monthly operating and maintenance costs are crucial to managing cash flow and budget. In the month-by-month cost analysis, we assume the customer already owns the unit and we focus on comparing the operating and maintenance cost on a monthly basis without the upfront AWH unit cost. Thus, capital cost was set to $0.

Figure 3A-B shows the cost per gallon 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 because we want to operate AWH in a truly off-grid manner and not rely upon the electrical grid for power.

For the electrical grid (**Figure 3A**), the cost of AWH in a tropical region ranges between $0.15-0.23/gal where the summer months (July-September) were all the least expensive months and January was the most expensive. For a temperate region, June and August were the least expensive months at $0.20 /gal, whereas January was the most expensive month at $0.60 /gal. For an arid region, cost ranges between $0.26-2.66 /gal where July is the least expensive and January is the most expensive.

Monthly cost is inversely related to water harvested. 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 in each climate occurs in July. Water harvesting in July for tropical, temperate, and arid climates was 715 gal/month, 513 gal/month, and 388 gal/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 $0.15, $0.21, and $0.26 respectively.

Cost can be significantly reduced at a month-by-month basis if using solar PV rather than connecting to the electrical grid. The monthly cost in a temperate region in January, the month with lowest average dew point temperature of 2.85°C and highest cost, was $0.60 using the electrical grid and when using solar PV the cost becomes $0.35. The cost reduction in each climate is proportional to the reduction in residential cost ($/kWh) from electrical to solar.

If a person owns the AWH unit, it is optimal to harvest water year-round in temperate and tropical regions since the cost will always be lower than bottled water ($1.22/gal) regardless of which power supply is used. In an arid climate there are at least 8 months (March to October) in which AWH costs less than bottled water. If using solar PV, AWH can be harvested for 9 months (February to October) for less than $1.22 /gal. In the case of a municipal disaster similar to Jackson Mississippi (temperate) or Las Vegas New Mexico (arid), where water has been cut off in summer of 2022, 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 rate is 715 gal/month, the monthly cost to operate and maintain water at $0.15/gallon is equal to $107/month. The cost of the same volume of bottled water would be $872/month. When compared to bottled water, AWH has the potential to cost 8 times less. Similarly, in July in a temperate climate where water harvested is 513 gallons/month, the monthly operating cost is $0.21 equating to $108/month. In comparison, the cost to deploy the same volume of bottled water would be $626/month. In a temperate climate, AWH has the potential to cost almost 6 times less than bottled water. Finally, if the water harvested in an arid climate is 388 gallons in July at $0.26 /gal, this would equate to $101/month. Compared to the bottled water cost in July of $473, AWH could cost almost 5 times less. These monthly costs for AWH could be reduced by half if using solar power.

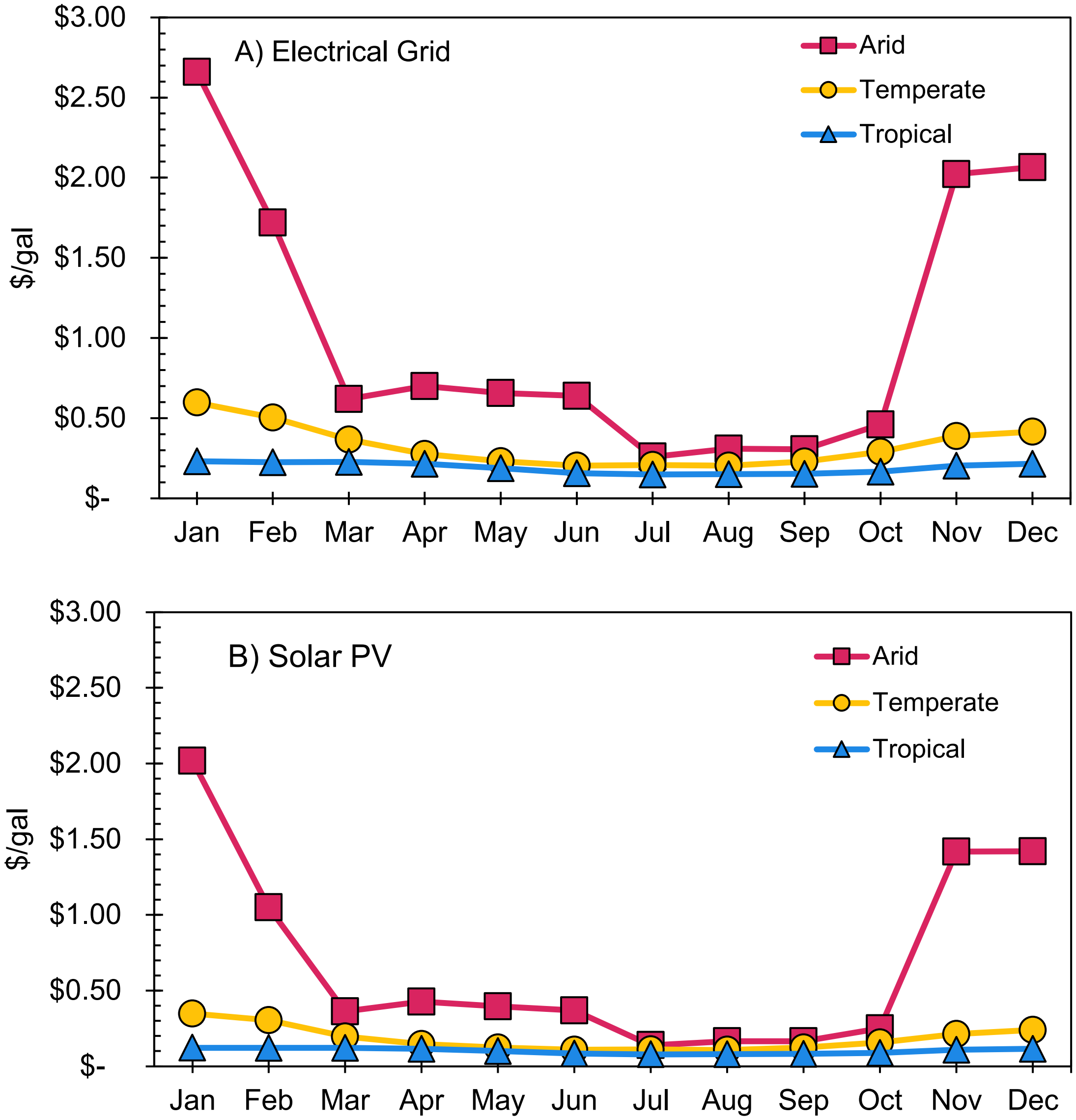

Figure 3 A-B. Cost of AWH powered by A) electrical grid and B) solar PV

4.2.2 Lifetime Analysis

Figure 4 displays all expenses that were calculated in the TEA lifetime analysis including capital, maintenance, and operating costs. It shows the cost breakdown of operating AWH using solar PV and the electrical grid for a temperate climate. The maintenance costs are the same regardless of the power source. This is because the same system is being used, and maintenance for the unit doesn't change for the different power supplies. The capital cost for the modeled LGR 7000XLi dehumidifier is $2800. The capital cost of the water treatment POU system costs $225. And the capital cost for the 6kW solar PV system is $11,928 and $15,904 for the 8kW system. The total capital cost for the AWH unit using the electrical grid is $3025. The capital cost for the AWH unit using solar energy is $18,434 in temperate and tropical regions and is $14,953 in an arid climate. The maintenance cost for the lifetime analysis is split between year 0 and years 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 $157/yr, accounting for 3 filters and 3 hours of labor work for cleaning coils, sump, pump, and heat exchanger. Years 1-9 account for 4 filter replacements and 3 hours of labor work for the regular cleaning of internal components. The maintenance cost for years 1-9 is $171/yr. This maintenance cost includes an additional $50 maintenance company fee.

The operating cost for each power source is the driver of the differences in lifetime cost. The cost of power is $0.06/kWh for solar PV and $0.13/kWh for the electrical grid. In the temperate climate powered by the electrical grid, the total cost over the 10-year lifetime of the AWH unit is $12,281 (calculated using Equation 1.10). In the temperate climate using existing solar PV, the lifetime operating cost is $8,065, and the cost is $23,969 for purchasing solar PV. The additional figures for arid and tropical are located in Appendix B Figure B1 and B2.

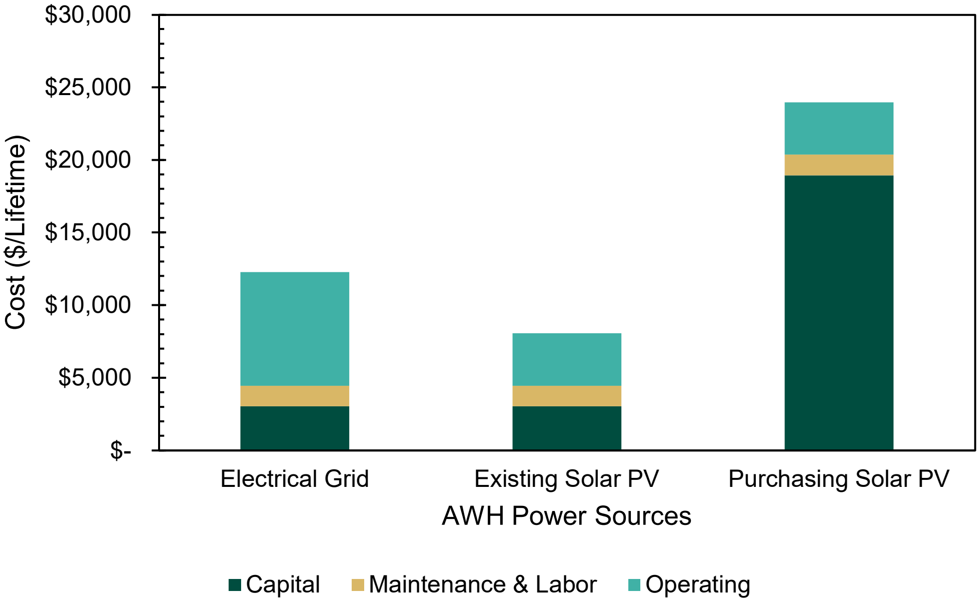

Figure 4. Total lifetime cost in a temperate climate

Using the results from **Figure 4** and the total gallons/lifetime explained in section 3.4.2, the lifetime average production cost ($/gal) for each climate condition and power source was found and is shown in **Figure 5**. If we take a look at the estimated cost of ownership in a temperate climate using the electrical grid, it is $12,281 (**Figure 5**). Over the 10-year lifetime, this unit produces 40,413 gallons/lifetime (see Appendix B Table B1 for the lifetime water harvested values for each climate). By dividing the total lifetime cost by the lifetime water harvested, we find that the cost of water production per gallon in a temperate climate is $0.30/gal over the AWH unit's 10-year lifetime (this is also explained in Equation 3.11). By applying a similar analysis, we found the total cost per gallon over the lifetime using existing solar PV was $0.20 /gal and $0.59 /gal for purchasing new solar PV in a temperate climate.

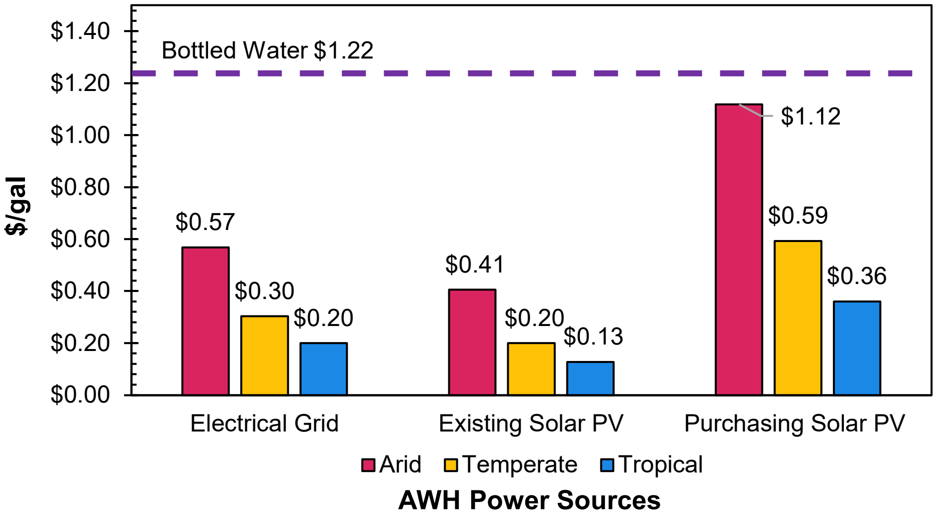

Figure 5. Lifetime average production cost for each climate and power source

Additional cost reductions can occur through an innovative AWH approach. A piece-by-piece analysis of the Dri-Eaz LGR 7000XLi found the heat exchanger to be the driving cost of the unit (Appendix B Table B2). Therefore, 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, resulting in a lower cost. As for the arid climate, the major limitation was the water vapor being too far from saturation. Unfortunately, condensation-based dehumidifiers do not work well cold and arid regions. However, desiccants do work well in extreme temperatures (-20°C) and low humidity areas (<20%).[19] By using a desiccant, the efficiency may increase resulting in a higher water harvested rating and lower cost. Also, a recent study states entropy generation due to heat transfer in dew plates may significantly impact the overall system efficiency and optimal recovery ratio.[20]

3.1 Conclusion

TEA was applied to a condensation-based dehumidifier and a POU water treatment system or "AWH unit" to determine the economic feasibility of AWH. The modeled unit had a manufacturer reported water harvested rating of 29.4 gal/day at 90°F/ 32.2°C / 90% RH (Saturation), 16.3 gal/day at 80°F/ 26.7°C/ 60% RH (AHAM), and 2.1 gal/day at 80F/ 26.7°C/ 20% RH (Low Grain). A TEA model was paired with a climate model to successfully measure 1) the water harvested of the AWH unit as a function of climate and 2) the cost of AWH production powered by renewable and grid tied power.

This work aimed to answer 3 knowledge gaps:

1) How much water can be harvested by an AWH unit as a function of climate?

Results show AWH can be used during municipal disasters, natural disasters, or in rural communities across arid, temperate, and tropical regions. However, the arid climate is limited to 8 months (March to October) in which AWH costs less than bottled water. In our modeled unit, AWH can provide 436-715 gal/month in a tropical climate, 104-523 gal/month in a temperate climate, and 10-388 gal/month in an arid climate. Through climate modeling and TEA, we have established the optimal time frame to harvest water is in July for all three climate regions. Additionally, this is also the time frame in which the cost to harvest water using the Dri-Eaz LGR 7000XLi is the lowest.

The CDC and FEMA estimate that during a disaster, an individual requires 30 gallons/day of drinking water. Typically, summer months are a time prone to hurricanes, heavy rain (flooding), and post-wildfire surface water contamination. During this time, the modeled AWH unit can supply anywhere from 13 to 20+ people with clean drinking water during the month of July.

2) How much will AWH cost to operate as a function of climate?

In the case of a municipal disaster similar to Jackson Mississippi (temperate) or Las Vegas New Mexico (arid), there is still power from the electrical grid. If AWH was deployed using the grid in a temperate region during July, the cost to produce water and provide operation and maintenance to the AWH unit would be \$0.21/gallon which is equal to \$108/month. The cost of the same volume of bottled water would be \$626/month for the month of July. When compared to bottled water, AWH has the potential to cost almost 6 times less. Furthermore, monthly costs for AWH could be reduced by half if using existing solar power.

3) What would be the lifetime cost of owning and operating AWH as a function of climate?

The lifetime cost of ownership for each power source and climate were given in the lifetime-analysis plot (**Figure 4**). In turn, the total cost per gallon over the lifetime of the AWH unit was shown in **Figure 5**. Results found AWH powered by renewable energy (aside from purchasing new solar PV in an arid climate) or the electrical grid would cost less than bottled water. AWH powered by the electrical grid ranges from \$0.20 /gal to \$0.57 /gal, where arid is the highest and tropical the lowest. And AWH powered by existing solar PV ranges from \$0.13 /gal to \$0.41 /gal, where arid is the highest and tropical the lowest. There are advantages to connecting to an existing solar farm since this ultimately reduces the cost to operate AWH anywhere from 18-35%.

However, in the case of a natural disaster, where power is out, users will need to resort to a fully off-grid option. The lifetime analysis for purchasing new solar PV was included within the TEA to provide a practical example of what the capital costs would look like to purchase a new solar PV system for a home or small facility. Although, the upfront cost can be 6 times more than existing solar PV, after the system has been paid for, the monthly cost can be lowered 2-fold. Our work shows that AWH is a feasible technology to use in any climate region to provide water off the municipal and electrical grid.

Who will benefit from these research results?

The findings of this research study will inform the New Mexico Water Resources Research Institute (NMWRRI) and other researchers of cost data on atmospheric water harvesting technologies. The public, especially the New Mexico residents and the Navajo Nation communities, will also benefit from this research because it will give awareness of possible interaction with a new water reservoir and clean drinking water. This research will serve as a basis for future studies to understand the synergies of this water harvesting technology with communities.

How have you spent your grant funds?

Budget		
Transaction Description	**Budget**	**Actual Expenditures**
Salaries	$6,000.00	$6,619.00
Other Staff Benefits	$480.00	$5.27
Lab Supplies	$400.00	$0.00
Travel	$620.00	$875.00
Total	$7,500.00	$7,499.27
Total Budget Remaining		**$0.73**

Presentations made related to the project:

- Center for Water and the Environment Mini Conference, May 2021
- Research Group Meetings, 2021-2022
- PepsiCo Industry Collaborator Monthly Meetings, 2021-2022
- 66th Annual NMWRRI Conference Poster Presentation, October 2021
- NM Water Workshop Oral Presentation, April 2022
- 18th Annual RMSAWWA/RMWEA Student Conference Poster Presentation, May 2022 – **1st Place Award**
- AWWA ACE'22 Fresh Ideas Poster Presentation, June 2022– **2nd Place Award**

Publications or reports:
Gayoso, N., Mulchandani, A., Moylan, E. Techno-Economic Analysis of Atmospheric Water Harvesting Across Climates. *In prep*

List of other students or faculty members who have assisted you with your project:
Advisor: Dr. Anjali Mulchandani, Ph.D.
Committee Members: Dr. Kerry Howe Ph.D., Dr. Jingjing Wang Ph.D., Dr. Mark Stone Ph.D.
CWE Laboratory Manager: Katelin Fisher
Student Research Assistants: Emily Gracie Moylan, Eliana Kai Juarez, Aidan Nico Rodriguez

Special recognition awards or notable achievements:

- Civil, Construction, & Environmental Engineering (CCEE) student receives NMWRRI grant: eNews Article June 2021
- UNM Student Awarded Research Grant to Study the Cost of Atmospheric Water Capture Technologies eNews Article July 2021
- Graduate student wins award at national water conference eNews Article July 2022

Degree of completion and future career plans:
I completed my Master's of Science in Civil Engineering in December 2022. I am currently working as an Environmental Engineer at CDM Smith performing projects on water and wastewater. These projects benefit not only New Mexico communities but communities internationally.

Appendix A

A1. AWH Unit

AWGs are priced up to 4 times higher than dehumidifiers of similar capacities (30 gal/day) for over $12,000 (**Figure A*1***).[2] This is due to lower production volume, niche marketing, and novelty of the concept. Although dehumidifiers do not have existing water treatment inside the unit, a POU water treatment system can be installed externally to produce potable water and together this is still 4 times less than leading AWG. Therefore, this makes dehumidifiers a great alternative for conducting TEA instead of an AWG.

To narrow down a specific condensation-based dehumidifier, a range of dehumidifiers ranging from a residential scale (~5 gal/day) to industrial scale (100 gal/day) were examined (**Figure A1**) to understand the size and capacity of the technology.[19,21–24] There was an inconsistent trend between device capacity, capital cost of purchase, and specific energy consumption. For this reason, this TEA was performed for a single dehumidifier (Dri-Eaz LGR 7000XLi) and post-harvesting water treatment costs that are representative of similar units of its capacity.

The POU water treatment system that are associated with water harvesters contain the following filtration components: 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.[2,3] 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. The POU system used in this TEA was the Viqua VT4 Ultraviolet (UV) Sterilizer with a cost of $225.[3]

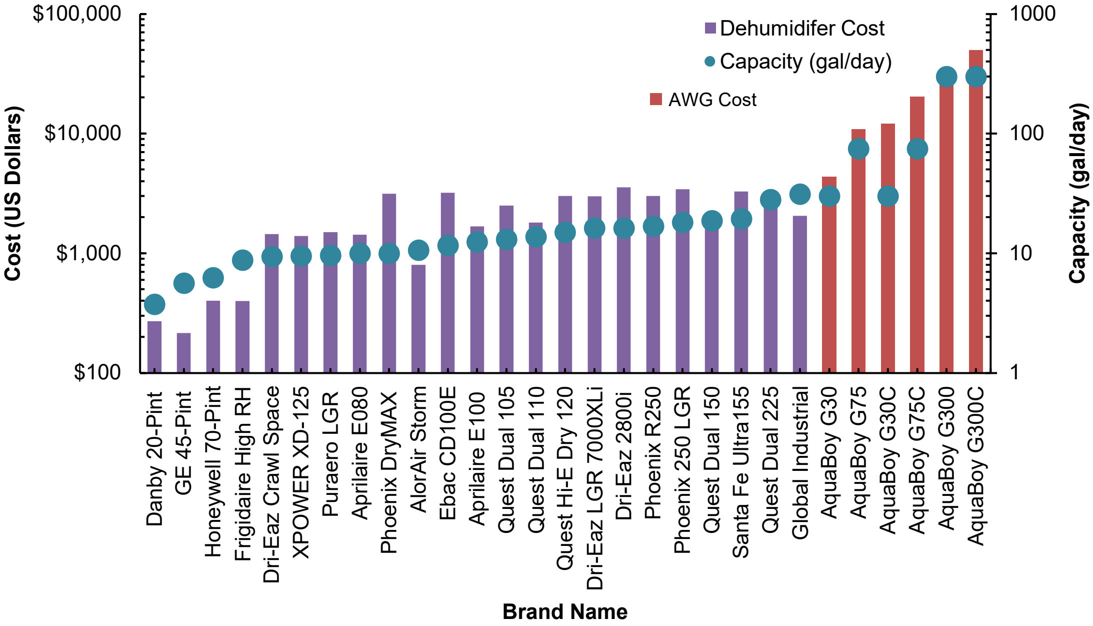

Figure A1. Cost and capacity of condensation-based dehumidifiers and AWG

A2. Water Harvested and Efficiency

Table A1. Water Efficiency Ratings

Parameter	Units	Saturation 90 F / 90 RH	AHAM 80 F / 60 RH	Low Grain 80 F / 20 RH
Rated water production	L/d	111	61.5	8
Air flow rate	m3/h	552.2	552.2	552.2
Dry bulb temp (T_DB)	F	90	80	80
Relative humidity (RH)	%	90	60	20
Dry bulb temp	C	32.2	26.7	26.7
Dry bulb temp	K	305.4	299.8	299.8
Saturated Vapor Pressure (es_DB)	Pa	4944.2	3560.3	3560.3
Initial partial pressure (es_DP)	Pa	4449.8	2136.2	712.1
Vapor Density (ρ_vap)	g/m3	0.03	0.02	0.01
Hourly Water Production	kg/h	17.42	8.52	2.84
Hourly Water Production	gal/h	4.60	2.25	0.75
Water Production	gal/day	110	54	18
Water harvested (rating)	gal/day	29.33	16.25	2.11
Energy consumed for condensation	kW	3211.81	1779.51	231.48
Water efficiency	**%**	**27**	**30**	**12**

A3. Techno-Economic Analysis to Determine Water Production Cost

Energy requirements from specifications sheet of Dri-Eaz LGR 7000XLi:
$Amps = 8.3\ A$
$Volts = 115\ V$
Conversions:
$Watts = A\ \times V = 954.5\ W = 0.9545\ kWh$

$$\mathbf{0.9545\ \frac{kW}{h} = 8361.4\ \frac{kW}{yr}}$$

Appendix B

B1. Lifetime Analysis

Table B1. Lifetime water harvested in each climate

Climate	Gallons/lifetime
Arid	16,731
Temperate	40,413
Tropical	68,312

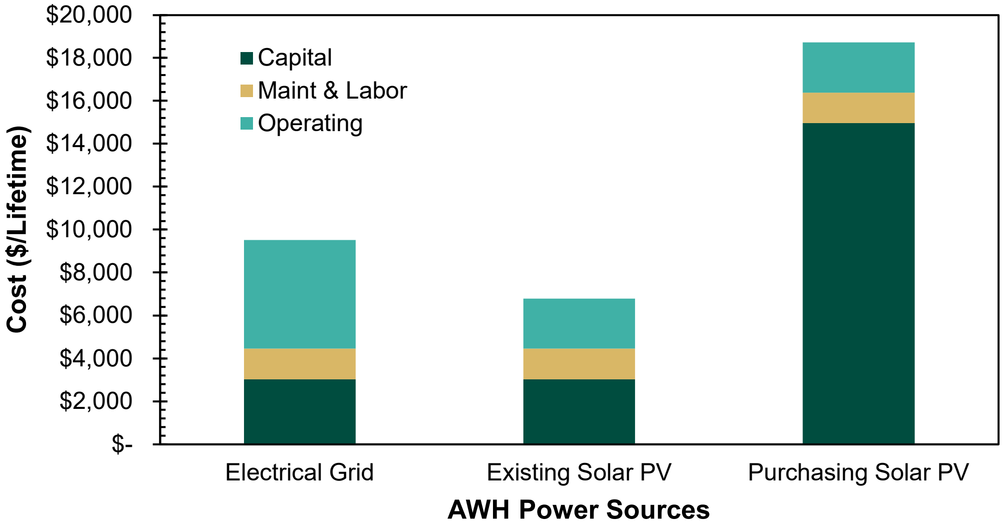

Figure B1. Total lifetime cost in an arid climate

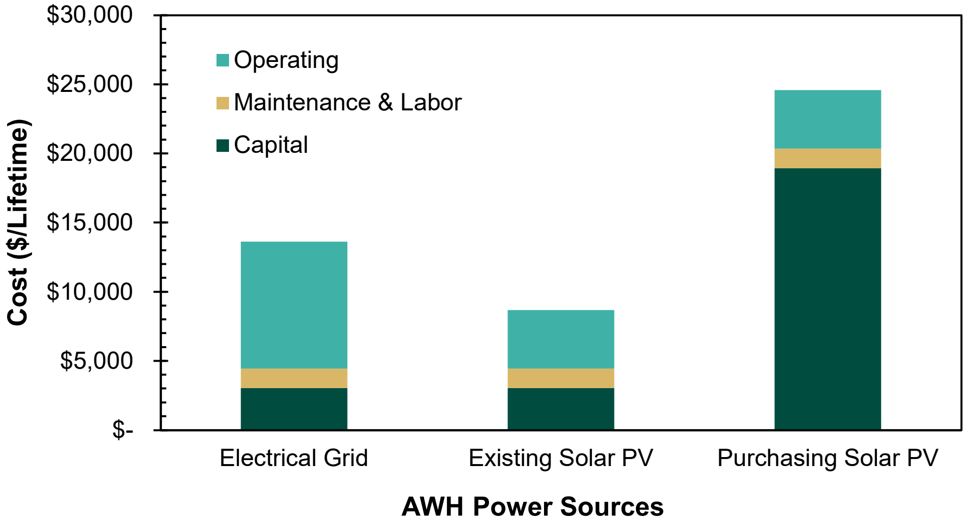

Figure B2. Total lifetime cost in a tropical climate

Table B2. Dri-Eaz LGR 700XLi piece-by-piece analysis

Item	Source 1: Jondon[21]	Source 2: Home Depot[25]	Source 3: Amazon[26]	Source 4: Repair Clinic[27]	Average
Submersible Pump	$143.43	$93.68	$179.55		$138.89
Back Panel	$158.79			$259.47	$209.13
Blower Assy	$172.02	$173.43	$207.93	$383.25	$234.16
Axle Assy	$196				$196
Condenser	$209.17	$283.25	$221.00		$237.81
Compressor	$219	$271.92		$371.09	$287.34
Evaporator	$239.72	$283.25	$239.72	$234.11	$249.20
Electrical Box Assy	$334.75	$267.80	$334.75		$312.43
Control Panel Assy	$603.70	$299.00	$332.00		$411.57
Refrigerant R410A	$703.32				
Heat Exchanger	$1,095	$151.00	$1,399.16	$903.99	$716.66
Total Cost					$3,696.50

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