Härvist Atmospheric Water Generator System for the Ag Hub Sustainability Center

by

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A thesis submitted to the graduate program in Industrial Design, G. D. Hines College of Architecture & Design in partial fulfillment of the requirements for the degree of

Master of Science in Industrial Design

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University of Houston

May 2020

Acknowledgments

I want to acknowledge God in all I do because it's only through Him that any of this is possible. My wife Jennifer, who supported and encouraged me in this project.

I want to thank my committee chair, George Chow, who, with patience and understanding, guided me through a complex process of not only academic growth, but character as well. Dr. Gordon Vos who provided deep design insight and Dr. Bruce Race who took the time to share his extensive understanding of sustainable systems in urban environments.

I want to thank Dr. Kwon and her faculty at the University of Houston who encouraged my love for design. Also, my graduate peers who were my hands and feet for much of the design process. This could not have been done without their input.

Lastly, God has given me an amazing family, mother, brother, who supported through words of affirmation and hugs.

Thank you all.

"For every drop of water you waste, you must know that somewhere on earth someone is desperately looking for a drop of water!"
- Mehmet Murat ildan

Abstract

Think of a world where you walk 50 miles, every day, to the nearest source of water that is either compromised or quickly dissipating. This is not a future forecast or a waiting dystopia. According to the World Health Organization, this describes the life of over 2.1 billion people today and is projected to grow to 3.9 billion by 2050 [1]. Usable water is quickly becoming the single greatest fading resource on our planet. Ismail Serageldin said that *"the wars of the twenty-first century will be fought over water."* Currently, the battlefront for this complex problem is being solved in several ways. While there are many ways to produce water, the atmosphere is an abundant source of it. With over 37.5 million-billion gallons of water vapor, the Earth's atmosphere has the capacity to cover the entire surface of the planet with one inch of rain if condensed [2].

The purpose of this study is to analyze and design an atmospheric water generator (AWG) for a specific site in Houston, Texas. In this region, humidity averages around 74% annually, with plenty of rainfall year around [28]. While these factors are not the only contributors to water yield, it allows for experimentation in hybrid water yielding methods. By employing fog collection, dew point condensation, and rainwater harvesting, enough water can be provided as needed. The site under analysis is the Ag Hub Sustainability Center, which is a community centered, eco-education facility. However, the Ag Hub is forecasted to operate under a water deficit. A design process was carried out to conceptualize the Härvist device, a novel, hybrid AWG capable of efficient water yield.

This study concludes by analyzing the efficiencies of Härvist, its return on investment, documentation to install and maintain, and its ability to help provide the water supply the Ag Hub needs. By applying a hybrid water production strategy, Härvist can not only help the Ag Hub become “net-zero” in water usage but take a step forward in water production for other similar sites.

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I. Introduction

1.1 Background

The Ag Hub Sustainability Center is a proposed site in Houston Texas that is designed to be a center education site for sustainability in the city and community [3]. The Ag Hub will showcase sustainable technologies and is designed to be a space for eco-tourism. It plans to execute on this mission by providing its surrounding community, of Sunnyside Houston, educational opportunities and open the door to sustainable living. Designed to sit on a 240-acre, decommissioned landfill, remediation of this area is important to all stakeholders. The Ag Hub will have an area for an aquaponics greenhouse creating a micro-economy of urban farming, classrooms for learning, a sizable solar array for decentralized power generation, and water reclamation ponds. This power array is a large-scale solar array of 70 MW which, in addition to other infrastructure, is intended for the benefit and empowerment of the historically disadvantaged Sunnyside community.

Figure 1.1 Renders of the Ag Hub showing growth pond and aquaponics wall
https://www.designerdox.com/urban-farm

While there are many methods of water harvesting like rainwater harvesting, water management systems, seawater desalination, and atmospheric water harvesting; few technologies are sustainable for the environment. A core concept of biomimetic design is to seek out how nature designs solutions for problems and "*nature always looks to create conditions conducive to life"* [32]. Therefore, the methods explored in this study are water yielding methods that attempt to work together to be as efficient as possible and ecofriendly. Rainwater harvesting is a common sustainable water yielding practice that is an established, cost effective method for water yield. In Houston, Texas, where the site is located, there is an annual rainfall of almost 50 inches, making the area excellent for consistent rainwater harvesting [32]. Fog harvesting and dew collection are two methods of atmospheric water harvesting and are both classified as AWG's. While these two methods sound similar, they differ in extraction method. Dew is created in two steps, nucleation where a phase change occurs between water molecules and an object, and growth into a full water droplet by the addition of water vapor in the atmosphere [6]. Fog harvesters are, normally, a bio-inspired technology that collect only in times of heavy fog. Fog harvesters accomplish this by exposing a mesh membrane, as a condensing surface to the atmosphere for dew formation. Fog harvesters have existed for centuries and were used by ancient civilizations to create water. Today, they are predominantly used in South America but can yield water in similar climates across the globe. Dew collectors are smaller devices that accomplish water yield through technology assisted systems that manipulate a surface and the atmosphere around it. Dew collectors can be placed anywhere and require only a cooled condensing surface to be functional. Rainwater harvesting, fog collection, and dew condensation, can be utilized in conjunction to help unlock water that was previously unusable.

The significance of this study extends in layers. Although, none of these technologies are new, the hybridization form and designed service system is novel. At a local level, the Ag Hub has a true need. A physical space whose main mission is to advance sustainable methods should be able to reach net zero in water consumption. Globally, the water scarcity issue is growing exponentially. Families who suffer on a daily basis for lack of water which hinder their quality of life. While this study cannot solve the entirety of the issue at hand, it can help by taking the research in this topic one step further to a solution.

1.2 Product Management Overview

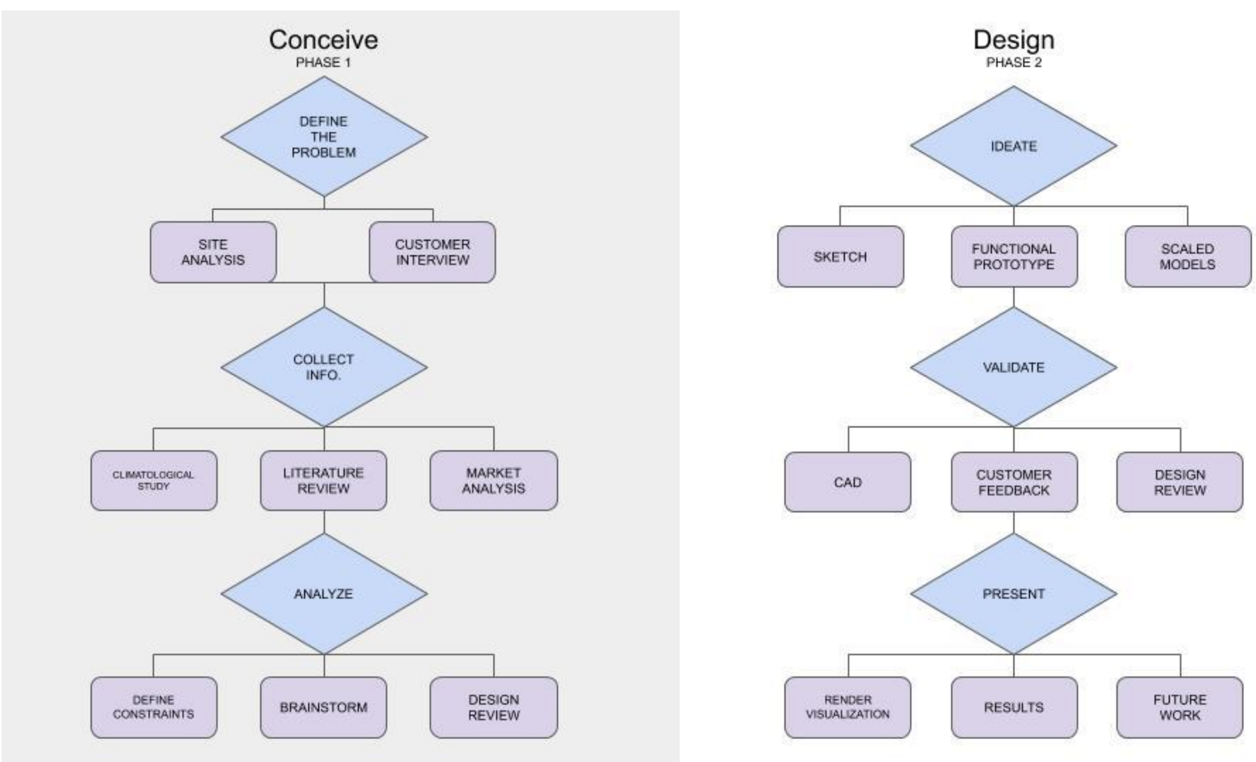


Figure 1.2 Flowchart illustrating the product management roadmap [Martinez 2020]

With the guidance of a committee, faculty, and several designers, a product management roadmap was formulated to set milestones, reach those goals, and stay accountable towards deliverables. Because this project had a client, establishing a strategy is vital. Creation of this execution plan is a mix of the design thinking process and project management strategies. The first phase was an exploration and exercise in empathy and understanding the needs of the stakeholder and available resources. This allowed us to uncover a specific problem with a feasible scope of work that would add value both to the client and the general body of knowledge. A research process took place by diving deeper into scientific journals, market outlook, new technologies, observing nature, etc. to gain a real understanding of all the variables. Once a hypothesis was formulated for the problem, phase 2 of the design process was executed. By brainstorming, ideating, prototyping, experimenting, etc. a solution slowly emerged. This solution was refined, presented, and iterated on until a formidable solution appeared. Product management in design is necessary and a key differentiating factor between art design and commercial design/industrial design.

II. Literature Review:

2.1 Biomimetic Precedence

The Syntrichia Caninervis is a desert moss that has no roots and survives in the harshest deserts in the world due to its moisture trapping antennae called awns at the tips of its leaves [17]. The plant captures water at four different scales. First, nano grooves that catalyze water vapor into liquid, slightly larger microgrooves whose shape and size are optimized to catch pre-condensed water droplets, third the antennae are conically shaped so they funnel droplets that have reached a sufficient size. And lastly, the network of awns are orientated to suppress splash and absorb as much water as possible.

Figure 2.1 Syntrichia Caninervis condensation desert moss
https://www.usu.edu/today/story/this-desert-moss-has-developed-the-ultimate-water-collection-toolkit

This thesis researched a water acquisition system used at a campground [18]. The student specifically looked at mycorrhiza, a fungus, that attaches to plants as a symbiotic relationship. It has an extensive surface area and the ability to alter pressures through osmotic gradients. The osmotic gradients cause areas of high-low pressures to help direct water where it needs to go. A branched system with volumes decreasing in size will increase the amount of water absorbed. Design principles learned from this plant were: 1) increased surface areas aid absorption of water and 2) water flows passively from areas of high fluid pressure to low fluid pressure. Secondly, the student looked at xerophytes which are plants that thrive in low water environments. On these plants, a thick, waxy cuticle and small, low-density stomata reduce evaporation. However, the shedding of this foliage saves water in times of drought. Design principles learned here were to reduce the amount of water loss by slowing down evaporation.

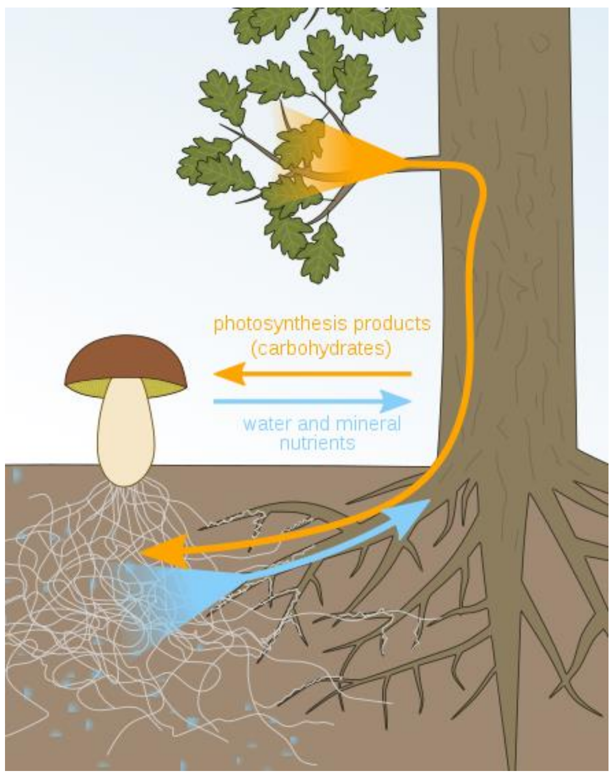


Figure 2.2 Shows how the fungi manipulates water to gain nutrients
https://www.wikiwand.com/en/Mycorrhiza

Another example of an effective "water gathering" plant is the Bromeliad plant which is an expert in the storage of water. This plant does not get moisture from roots and leaves like normal plants do, instead it has a reservoir tank at its center where it stores up water for itself.

Figure 2.3 Bromeliad plant water "tank"
https://www.garden.eco/how-to-water-a-bromeliad

A study that reviewed the Namib beetle's ability to hydrate itself discovered water yielding concepts [34]. The beetle's back is bumpy and has intervals of hydrophilic and hydrophobic areas, creating an extremely effective condensing surface. The research found that mesh membranes and surfaces that created bumpy patterns and mixed hydrophilic with hydrophobic surfaces were 50% more effective at condensing water than smooth surfaces.

Figure 2.4 Namib beetle hydrating
https://www.naturalhistorymag.com/biomechanics/171934/like-water-off-a-beetle-s-back

An excerpt from Marc Chamberland's book investigates bees and their architecture [7]. He stated that the hex is a geometry that is the most efficient use of space. He continues stating *"the optimal way to cover a large region with shapes of the same area, while minimizing boundaries, use the hexagonal structure."* It is established here that bee's build their hives efficiently by using the hexagonal shape. A design principle discovered here is the effective use of polygons to cover areas.

Figure 2.5 Beehive hexagon pattern
https://www.honeycolony.com/article/against-flow-hive/

2.2 Market Solution: Fog Harvesters

Fog harvesters are not new technology. They have been in use for many years by many cultures around the world. The most common type of fog harvester is composed of a mesh membrane, that serves as the condensing surface, the structure, to hoist the mesh into ambient air, and a collection mechanism, that connects to a reservoir. They are currently the most passive, sustainable way to produce water from the atmosphere. As they require no power to operate and use purely the energy and temperature changes throughout the day to condense water onto the mesh. FogQuest is a non-profit with fog harvesters deployed around the world [25]. Their large fog harvester measures 40 m^2, costs $1500 and produces on average 200 L/d. While this is a proven solution, design opportunities exist in installation, size, cost, and reliability. Since the mesh is installed as a wall, high wind easily damages the mesh, as it is the weakest part of the structure.

Figure 2.6 FogQuest AWG's installed in Morocco
https://phys.org/news/2015-06-moroccan-villagers-harvest-fog.html

The evolution of the FogQuest is the Warka Water Tower which was designed by an architect [26]. This fog harvester makes advancement in assembly, as you only need common available tools to install, form and function. Taking inspiration from the warka tree, the Warka Water Tower provides a communal space and shade for the user. The tower is conical and measures 30 ft tall and has a 13 ft diameter. It costs roughly the same, $1500, and produces 20 gallons/day or 80 L/day. Design opportunities still exist in cost and size of the structure as it requires a minimum of 100 square meters of space for each tower and a community to construct it.

Figure 2.7 A community surrounds a warka water tower
http://www.warkawater.org/

Table 2.1 Outlining fog harvesters in the market [Martinez 2020]

AWG	Cost	Production	Dimensions	Surface Area	Liters/ft^2/day	Liters/$
FogQuest	$1,500	200 L/day	12 ft x 36 ft	430.56 ft^2	0.464	.134 L/$
Warka Water Tower	$1,500	80 L/day	30 ft tall x 13 ft wide	1485 ft^2	0.054	.053 L/$

2.3 Market Solutions: Dew Collectors

A Thermoelectric cooler (TEC) is an established technology that cools a surface low enough to function as a dew collector. While other dew collecting technologies exist, like heat exchangers and/or HVAC systems (radiator-condensers), they are less sustainable because of the maintenance, cost, and materials involved. TEC's provide a solution that, although lacking in water yield, makes up in power consumption and reliability. Currently TEC's have risen in popularity to solve cooling problems. Small room dehumidifiers have become viable, competitively priced products, as the TEC allows them to be completely silent, low energy consumers. These small units are able to produce from 250 mL- 450 mL in a moderately humid day. However, one company, Zero Mass has designed a panel array, SOURCE, that is able to create drinking water using this technology at scale [27]. With their patented method of insulation, their panel is completely powered by a PV cell, producing around 1.65 gallons/day per panel or 6.25 L/d. At a cost of $2,000 per panel, usually sold in pairs, SOURCE can create drinkable water from the atmosphere at a residential home. Opportunities here are in overall cost and installation. Much of the cost comes from the water filtration and smart controller installed on-board. These functions are value adding and can be considered for the development of a solution for the Ag Hub.

Figure 2.8 TEC stack
https://www.adafruit.com/product/1335

Figure 2.9 SOURCE AWG panel
https://www.zeromasswater.com/rexi/source/

Table 2.2 Outlining dew collectors in the market [Martinez 2020]

AWG	Cost	Production	Dimensions	Surface Area	Production/ SA	Production/Cost
TEC Dehumidifier	$47	0.45 L/day	6.67 ft x 2.1 ft	8.3 ft^2	.054 L/ft^2	.00957 L/$
SOURCE Panel	$2,000	6.25 L/day	4 ft x 8 ft	32 ft^2	.195 L/ft^2	.003125 L/$

2.4 Design Principles: Dew Formation Geometry

In dew formation, geometry can increase your yield passively. A study on architectural forms showed that a *"good condenser design will reduce the heat exchange of the condenser surface with airflow with either free convection or forced induction."* [10] Meaning, one can boost production, using form to force air through a system. Specifically, in this study, the researchers examined how cones reduced the convection along the surface by blocking the heavier cold air at the bottom. In addition, the optimum angle for the condensing surface is 30 degrees which allows the minimum wind disruption, permits cold air to sink, and uses gravitational force to pull water down. When compared to a planar condenser, the inclined condenser yielded 22% more production. This is a key insight in form design of the condensing surfaces used in the water collector.

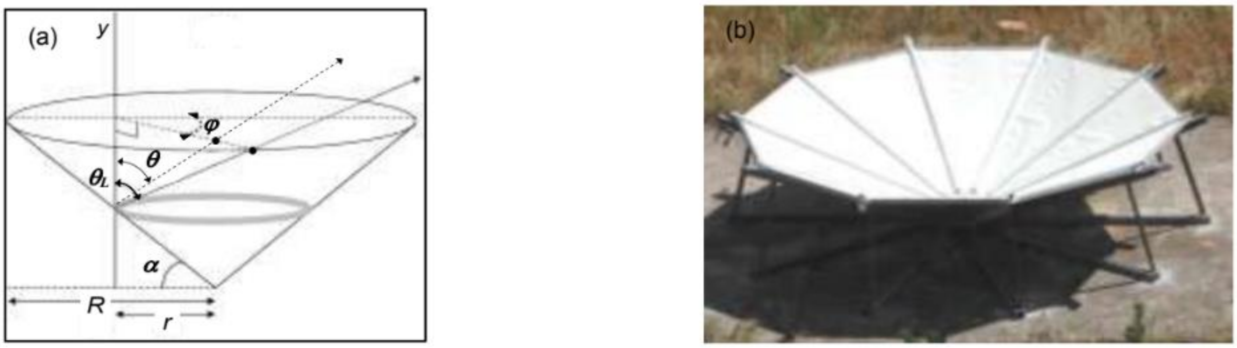


Figure 2.10 Optimal angle for condensation [10]

2.5 Fog Collection: Mesh Membrane

This study focuses on the effects that wind has on a structure used for water generation [15]. The study found that, generally, the weakest component is the mesh membrane in which condensation occurs. Stress concentration occurs where the mesh interfaces with the main structure. Therefore, the attachment method of mesh to the structure is critical to reducing stress in the overall system. The mesh failure can be considered as a mechanical fuse since it is cheap to repair but, this damage can be avoidable for the system by using a new form to decrease the stress on the mesh. According to a group of scientists, traditional fog collectors, at 48 m^2, collect between 150 L to 750 L of water a day depending on the site [21]. This is in line with modern fog collectors which require large amounts of surface area to capture the ambient fog.

The correct selection of mesh is critical for fog collection. A study on different meshes conducted long term measurements of three types of mesh for collecting fog [23]. The three meshes examined were: a double layer 35% shade Raschel mesh, stainless steel mesh coated with the MIT-14 hydrophobic formulation, and FogHa-Tin. The findings were that Raschel collected more water at lower wind speeds and less during fast wind than the FogHa. The MIT-14 stainless steel mesh collected more overall but had a higher cost. Therefore, one type of material is not more effective than the other, it depends completely on different constraints like environment and climatology. Although the MIT-14 mesh is more efficient at water collection, its high cost and mass per square meter might make it unsustainable for certain projects. Another direction could be coating polypropylene nets with hydrophobic formulas. For the Ag Hub, the Raschel collection mesh is most suitable due to its characteristics, properties, and cost effectiveness.

Figure 2.11 Mesh comparison study from left to right: Raschel, MIT-14, FogHa [12]

2.6 Dew Condenser: Thermoelectric Cooler

The Peltier effect was discovered by a French physicist named Jean-Charles Peltier in 1834. Peltier modules or Thermoelectric coolers (TEC's) are a solid state, semiconductor electrical component that functions like a heat pump. TEC's carry heat from one surface to another by using low voltage DC power.

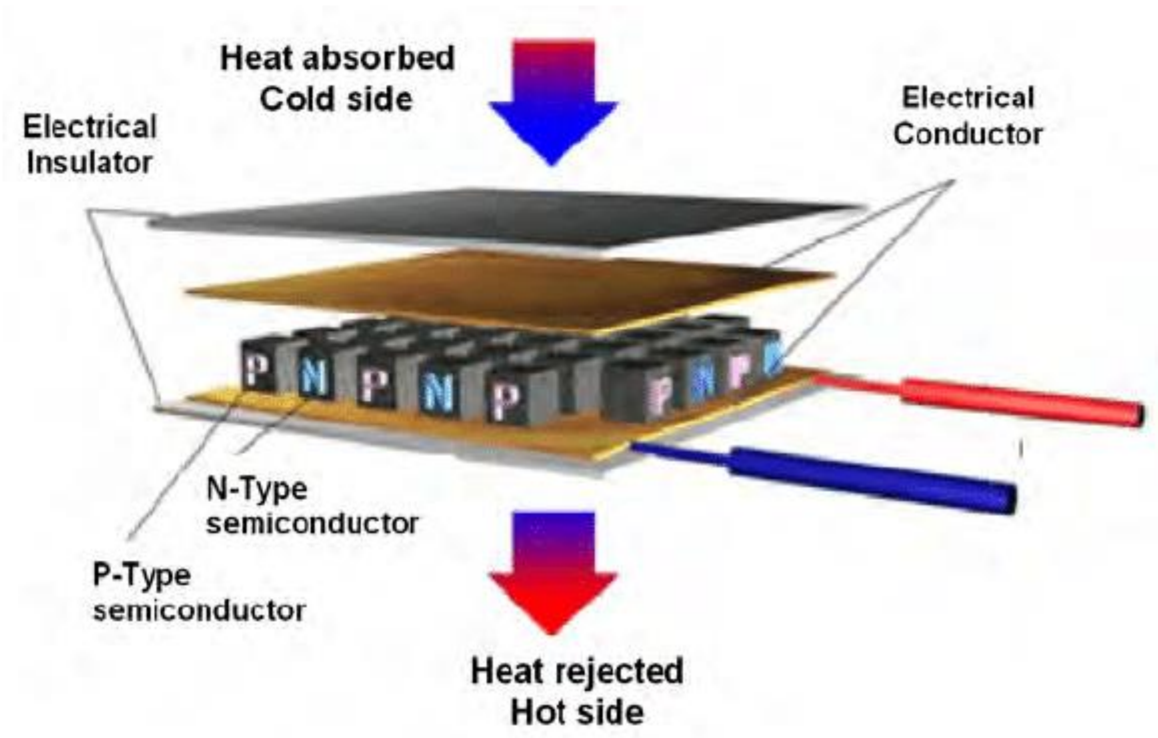


Figure 2.12 TEC exploded view [11]

This module eliminates the need for a compressor and condenser, normally found in refrigerators, which diminishes the power consumption. TEC's tend to be small in size allowing them to fit in small spaces. They are solid state, so they have zero moving parts which allows for increased reliability. The data sheet on a TEC confirms a working life span of over 200,000 hours [8]. Lastly, TEC's are much quieter than their competitors which operate loud compressors. Since TEC's transfer heat from one side of the module to the other, it creates a cold side where dew point temperature can be reached, and condensation can form. But are TEC's better than the competitors? A study examining TEC's had researchers use a thermoelectric cooler, powered by a 12V DC power supply, gather water yield data and conduct experiments to see if efficiency is increased by manipulating air flow while comparing it to conventional commercial products [11]. In their design they used a Peltier module as opposed to a compressor, which commercial units use, to create the cooling effect. The researchers noted that without a renewable power supply, it is not possible for the system to be environmentally superior to its competitors. They employed the use of computational fluid dynamics to optimize the design process of the flow of air through the unit. The simulation showed a change in temperature between the hot side and cool side of the system and they found that by reducing the volume around the radiator, they were able to increase the velocity of moving air in the hot side of the system. Through prototyping, the researchers established that by increasing airflow capacity, water productivity increased gradually but by increasing power consumption from 65 watts to 125 watts, the water production increased significantly. 125 watts is able to be supplied by 1 or 2 panel PV cells as the power supply. The researchers concluded that the prototype produced 0.61 L/hr which yields 14.6 L/day. Compared to the commercially available machine that produced 27.5 L/day but consumes about 4x as much energy. A couple of key takeaways in this study are that with a renewable source of power, any condensation technology will not be sustainable. The Ag Hub is supplied by a 70 MW solar array that can be a power source for the harvesting module. The studies simulation showed that reducing the volume where the units are can increase airflow through the TEC's, increasing their water yields. This gives even further constraints on form design to increase efficiency passively.

An additional study built an AWG with an external fan to force convection. This allowed air to be forced across various aluminum heat sinks that contained TEC's. To create an effective condensing unit, a TEC can be mounted to a cold sink to increase the condensing surface. Much like these researchers did in this design study [20]. This cold sink would have a temperature controller connected to it, maintaining the cold sink at dew point temperature. The researchers first determined their water demand. Second, to calculate how much time it would take for a module to reach that need, the dew point of their site was determined. Together with the given Peltier coefficient of their condenser unit and the current delivered, the generation of water can be derived and tested against.

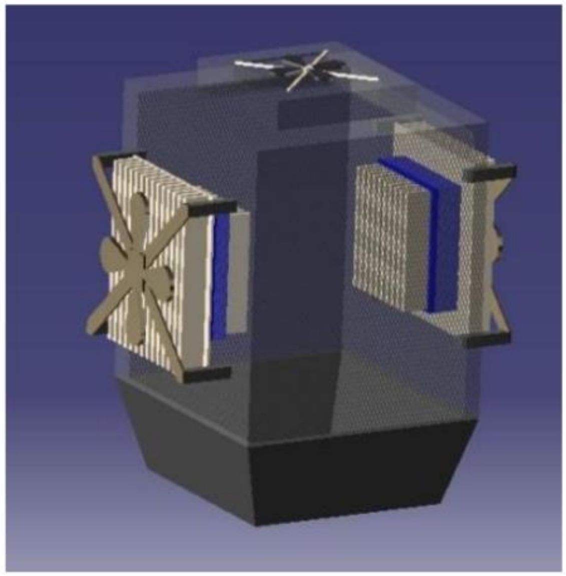


Figure 2.13 Designed condenser unit for multiple TEC units [11]

Another study that used TEC's was able to produce 25 grams/h or 0.025 L/h with a surface area of 0.216 m^2 and 58.2 watt input power [12]. From the data collected, the best yields were on days that relative humidity was high and the ambient air was hot. Therefore, creating a temperature difference in humid days will yield big amounts of water. Also, one finding was that the condensing surface must be as frictionless as possible so that water droplets can fall easily. Increasing the wetting property of the condensation surface is an effective way to increase the amount of water produced. For the harvesting module, the climate will play a huge role in the water yield of a TEC. The site location should have a high constant relative humidity to allow the condensing unit to be cost effective. But how impactful is the climate on water yield?

2.7 Dew Condenser: Condensation surface

The contact angle is a traditional parameter used for measuring hydrophobicity on a solid surface [16]. However, a high contact angle can exist in conjunction with high adhesion to the surface which is called the "rose petal" effect. Therefore, several additional parameters like the ability for water to bounce off a surface, tilt angle needed to initiate flow, and the normal shear adhesion need to be considered. Thus, creating a surface with the ability to allow air cushions to be between the water droplet and the surface.

Another study compared theoretical data with actual data of water yielded from an experimental condensing surface [22]. The experimental condensing surface was composed of a special foil and polyethylene material with infrared emitting properties which allows it to efficiently reflect the visible sunlight. During their study, they found that nearly all dew events occurred when wind velocity was less than 1 m/s. Therefore, blocking random wind from the condensing surface is key to water yield. The data collected in this study shows that a compromise between wind protection and drop recovery by gravity is found for an angle in the order of 30 degrees. At this angle, only 50% of the gravitational force used to gather water droplets is lost. Using these principles, water yield can increase 20% relative to a flat condensing surface.

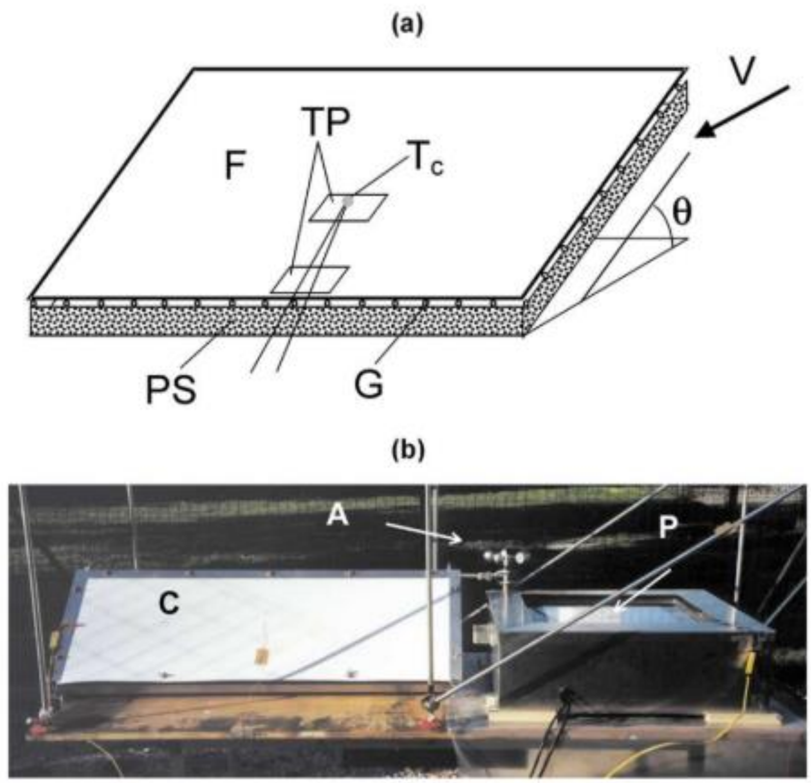


Figure 2.14 Diagram showing the increase in efficiency between an angles surface and a flat one [22]

2.8 Climate and the Economic Viability

Although atmospheric water harvesting has been used throughout history, economic viability and data are difficult to come by. A few researchers conducted a bottom-up economic analysis of an AWG system [13]. They did confirm that there is a limited amount of performance data and models available for AWG's in the water solutions portfolio. They also used historical meteorological daily temperature data and humidity observations from different cities to simulate AWG production. According to this study, an AWG system production widely ranges depending on these variables: humidity, temperature, and technology used in the system. Therefore, an AWG in the correct region can produce a positive return on investment since its variables are highly dependent on geographical conditions in an exponential way. The economic performance of an AWG depends on several factors: water produced, energy consumed, price of competing water sources, and the maintenance of the machine. The AWG system used for this research cost $1665 initially to build and $200 per year for maintenance. Future work stated in this paper is the impact an AWG would have in removing plastic bottle waste, reducing the carbon footprint. This also means there must be a climate analysis on the local site and a discussion on the economic feasibility of the water harvesting system.

Furthermore, a supplementary study calculated water yield of an AWG that used a compressor, in the coastal region of India and mapped out it's pattern over different climatic conditions [14]. Once the data was collected, they were able to obtain meteorological data from the past years and estimate the potential of an AWG system in that region. During their study, the researchers found that, on average, the coastal region had a humidity level of 70%. However, in several cities, there were abrupt changes in humidity in the winter months. Much like the local site in Houston Texas. Even with these variations, their AWG was able to supply drinking water for 35 people every day, 70 L/day with their best months being July, August, and September. Further findings revealed that condensate extraction was dependent on-air inlet humidity ratio and temperature. Their hourly condensate yield clearly follows the trend of relative humidity.

Lastly an analysis of the economic impact of an AWG done aimed at a specific geographical location in the region of Matehuala [24]. To initiate the study, an analysis of the climatological variables like, temperature, humidity, and radiation in the defined region. This allowed them to establish a zone of opportunity for the AWG within a psychrometric chart. Furthermore, a mathematical model was created, using a water dehumidifier, to obtain water guided by the conditions and constraints established. Because water vapor must be brought to a dew point to extract air moisture, the psychrometric chart shows that, in this region, getting to that temperature isn't difficult. The study also formulated, through mathematics, how much energy it would take to bring the temperature to the dew point and compared that to how much energy is available from the sun to conclude that there is more than enough energy available to create condensation with the given variables. Finally, with an average relative humidity of 60%, this region was able to produce 3.6 L/day in the lowest month of January and 18 L/day in the greatest month in August whose production cost was $0.038 L/day. The "Eiffel" fog collector device deployed was able to obtain 2,650 L/day during peak fog season [35]. During the second phase, it was revealed that a capital investment of $35,000 could be paid back in 8 years.

III. Methodology

3.1 Site Analysis

Nestled on the northern side of Third Ward Houston is the proposed Ag Hub site. This is a historic African American site that has been disadvantaged. Having community-focused features, this project is aimed to remediate the area on several fronts for the long-term. Features like education classrooms, aquaponics greenhouse, 70 MW solar power array, and on-site battery storage, will allow the Ag Hub to be a focal point for sustainable education, not only locally, but worldwide.

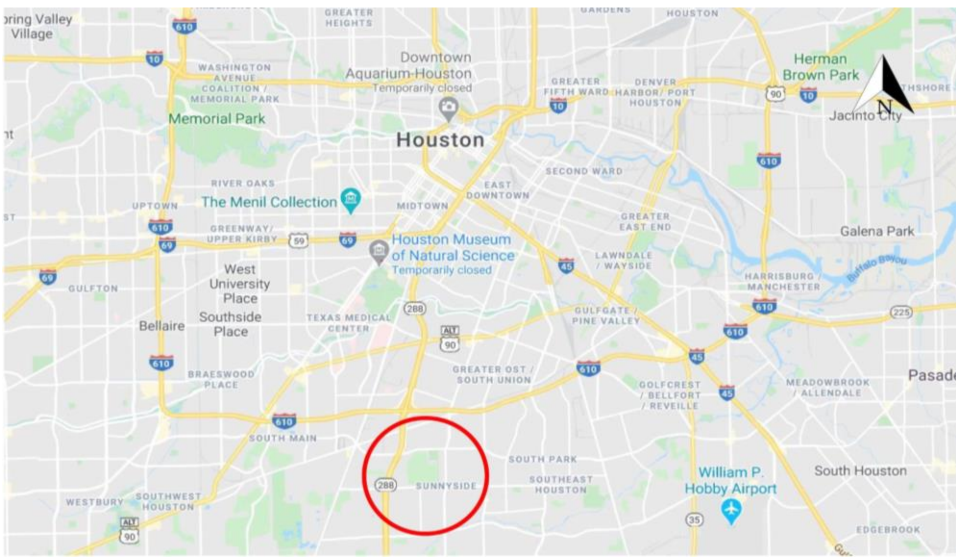


Figure 3.1 Shows the location of the Ag Hub site in Houston [Google Maps]

Figure 3.2 Site plan for the Sunnyside Ag Hub community project [3]

One of the main goals for the Ag Hub is to be “net zero” on all levels. Meaning it equally produces what it consumes. However, due to the growth remediation ponds, the Ag Hub is projected to operate under a water deficit. Upon analysis of the water usage of the Ag Hub, the greenhouse requires between 50-60 gallons per month, however the growth ponds will require 9,000 gallons per month due to evaporation as seen in Figure 3.3. This adds up to 108,000 gallons per year that the Ag Hub needs to supply water for.

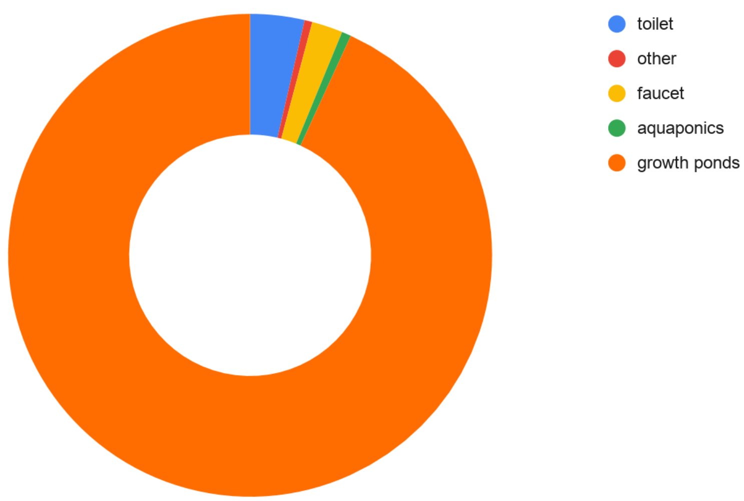


Figure 3.3 Maps out the water usage of the Ag Hub [Martinez 2020]

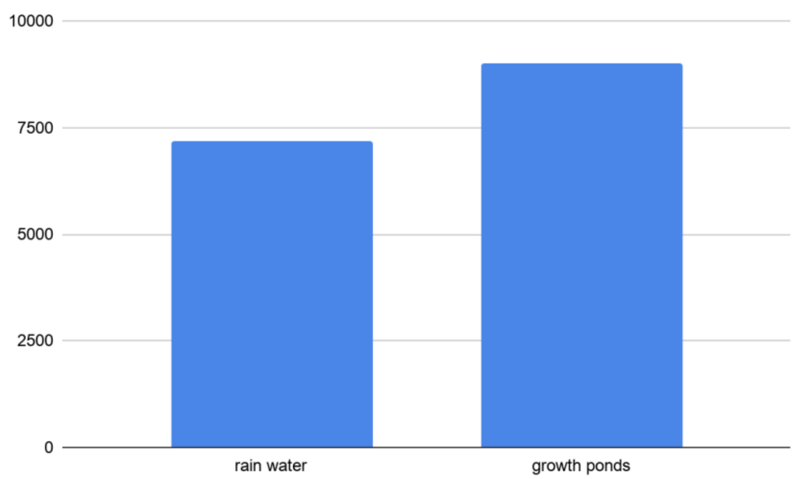


Figure 3.4 Shows the projected supply of rainwater vs. the usage of the growth ponds [Martinez 2020]

What strategies does the Ag Hub have to supply this water? The Ag Hub has developed alternative water strategies, seen in Table 3.1, including trucking in water, collecting runoff from solar panels, building pipeline infrastructure for a water city line, and using the roof for a rainwater harvesting.

Table 3.1 Shows the solutions for water for the Ag Hub [3]

Alternative 1 - Truck in water from outside source				
Price	**Environmental**	**L & M**	**Reliability**	**Health**
Initial Cost: $4300 (for 2700 gal)	Emissions from delivery truck	No maintenance	will provide adequate amount of water for greenhouse and growth ponds	Little to none
Recurring Cost $13000 per month (for 50-60 gal for greenhouse + 2700 for evaporation loss)	Responsible for fraction of negative impacts associated with water treatment plant	High longevity since paying for service	Depends on trust in chosen company to provide their product	Possibly some associated with increased air pollution, but increase is not substantial compared to existing emissions
Alternative 2 - Collect runoff from Community Solar Panels				
Price	**Environmental**	**L & M**	**Reliability**	**Health**
initial cost: $840, Gutters-$340, PVC-$100, 9000 Gallon container-$7000	Minimal	Somewhat unclear since collection and transport system is not standardized	Lot of parts which could affect reliability	Possible impacts from metals in runoff, although this is unlikely given the type of solar panels in use
Recurring Cost: little maintenance or keep up	UT study showed runoff can contain harmful elements	reasonable to assume small amount of recurring maintenance		

Alternative 3 - Use of City Water from Additional Pipeline				
Price	**Environmental**	**L & M**	**Reliability**	**Health**
Initial water cost: $30 (for 2700 gal), Monthly water cost: $90 (for 54 gal in greenhouse + 2700 gal for evaporation loss)	Construction of new pipeline could have potentially detrimental effects on surrounding area, but would most likely only be temporary	Possible maintenance would be required, most likely done by a professional	very reliable overall	city water may have chlorine/chloramine which could be detrimental to the aquaponics system. Water would have to be tested before introducing it to the system
Capital cost: $25000-$75000 (to install pipe 500 ft from Community Center to Greenhouse		Long lifetime considering city water pipelines aren't replaced often	would adequately supply the amount of water needed in the greenhouse and growth ponds	Once system is steady, user would not have to test often since most water is reused
Alternative 4 - Rainwater Storage Container Attached to Greenhouse				
Price	**Environmental**	**L & M**	**Reliability**	**Health**
Initial Cost: $9600	Little to no environmental impacts	Do not expect any required routine maintenance, although some might need to be done by professional	Relies on the amount of rainfall in the region. May 2018-May 2019, the closest rain gauge recorded 50 inches of rain	Negligible. May need to test water before introducing it to the aquaponics system, in case contains contaminants from roof
Includes 3000 gallon storage tank ($9000) 98' of gutters ($600) and labor. Relatively low recurring cost.		system expected to last significant amount of time, and part can be replaced if necessary	Using the surface area of rood corresponds to 90,000 gal water per year. Large container size supports system in any droughts	

Due to capital cost vs water yield, the rainwater harvesting system is the most cost effective water yielding method. The rain harvesting system will collect 86,169 gallons per year, which was calculated by multiplying the total roof surface area, average annual rainfall, and a harvesting constant. The area allocated for rain harvesting is completely exhausted. This amount creates a water deficit of 21,831 gallons per year. Which, divided by the number of days in a year, comes out to ***60.64 gallons/day or 229.55 L/d. Can a novel AWG be developed to supply the water required?***

3.2 Reflections and Analysis

Through the literature review, it was discovered that nature has many ways to create water for itself. From the desert moss, it was identified that conical geometries and water production at different scales is effective. Observing the fungi, a form can manipulate pressure by decreasing volume from high to low creating low-pressure environments that water wants to flow to. By using surface manipulation, form geometry, and evaporation shielding, nature is able to produce water from the atmosphere. Also learning how previous teams used TEC's to produce water and their lessons learned of force induction, air capacity, and ventilation, these design principles can be implemented into a solution. Exploring the market landscape, the novel Ag Hub solution should offer a triple improvement on structure, harvesting performance, and economic viability. From these insights we see that form does not precede design, but it is discovered during the process of solving the problem. Other design features that could be explored can include ease of assembly, low environmental impact, clean, durable, and low to minimum tech.

Finally, the researchers who were able to analyze their climate and provide theoretical data over their region were able to justify the validity of an AWG and showcase the potential water that could be generated in those regions. Allowing the data to be transposed into economic viability. This type of data and analysis is important for setting the foundation for future AWG's and technology that is to come as it maps out opportunity zones and communicates the importance and the profitability that AWG's can be in specific regions.

3.3 Climatological Study

A fundamental stage of this study is an analysis of the climatological magnitudes and average behaviors of key variables. Data over temperature, humidity, and precipitation were taken from a site analysis. With this, an opportunity zone can be established to deploy the Ag Hub AWG and several theoretical forecasts can be made on its production over the year.

3.4 Concept Development

Since the strategy is to hybridize existing water yielding technologies into a single form, an initial concept was developed by taking constraints defined by our site analysis and piecing together available materials to further conceptualize a solution. Afterwards, sketches assisted in exploration of different forms and orientation layout of each technology. While considering the design concepts learned during the literature review on form geometry, inspiration boards, and a visual brand language of the Ag Hub to further strengthen the form. Following the product management roadmap, further refinements were made during scale modeling like modularity, function, and assembly. Translating several forms into CAD models, one was selected for refinement. This CAD model was placed in context with the Ag Hub to validate the design form. The hope is to propose the AWG to the Ag Hub, as the client, for manufacturing and installation.

3.5 Design Solution

Once a form was selected, development of certain features had to be designed. Efficiency solutions like a smart controller, explained in a further section, were implemented to monitor, record, and optimize the AWG. Features, like modularity, can be implemented and easy installation of an array on the specified site can be thought out as this will affect how the water is delivered. A manufacturing and assembly process is defined for the solution. Human factors like maintenance and repairability were described as they are important aspects for the user. Lastly, analysis of the power consumption was established to discuss the economic viability of the novel AWG.

IV. Climatological Study

The ability to capture water from the atmosphere is determined by a collection of variables like temperature, humidity, precipitation, and dew point temperature. Dew occurs when the temperature of a surface falls below the dew temperature. Dew temperature is determined by relative humidity in the area and the ambient temperature of the region. Humidity is a term that describes the total water vapor saturation of a specific region. A region with humidity above 50% has potential for atmospheric water generation despite technological shortcomings of extraction. Therefore, the goal for creating condensation is understanding the change in temperature between the dew point and ambient temperature. By considering annual averages, maximums, and minimums of these variables, a theoretical baseline can be established for the use of an AWG in this region. This study was administered in Houston, Texas, located 29.76° N, 95.37° W. As discussed in the site analysis, The Ag Hub is planned to be located in the Sunnyside community located in south Houston, not far from the weather data centers where this data is acquired. Climatological data was obtained from WeatherSpark U.S. Climate Data and Weather Atlas [28] [29] [30].

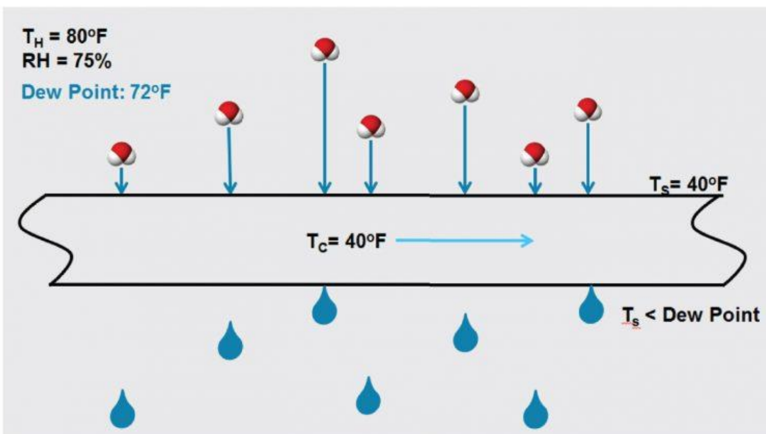


Figure 4.1 An illustration of how dew condensation is created
https://insulation.org/io/articles/condensation-control-why-the-proper-insulation-choices-will-keep-you-out-of-the-rain/

Figure 4.2 shows the annual average temperature max temperature of 93°F in August and an average low temperature of 44°F in January. In Figure 4.3, humidity is observed to be stable year around, having an average of 68% but seeing maximums of 90% in February and minimum of 44% in December. Dew point temperature can be calculated using the approximation formula which is effective for climates with a humidity above 50%. The average annual dew point temperature in graph 4.4 is 54° F with the maximum of 79°F seen from June to August.

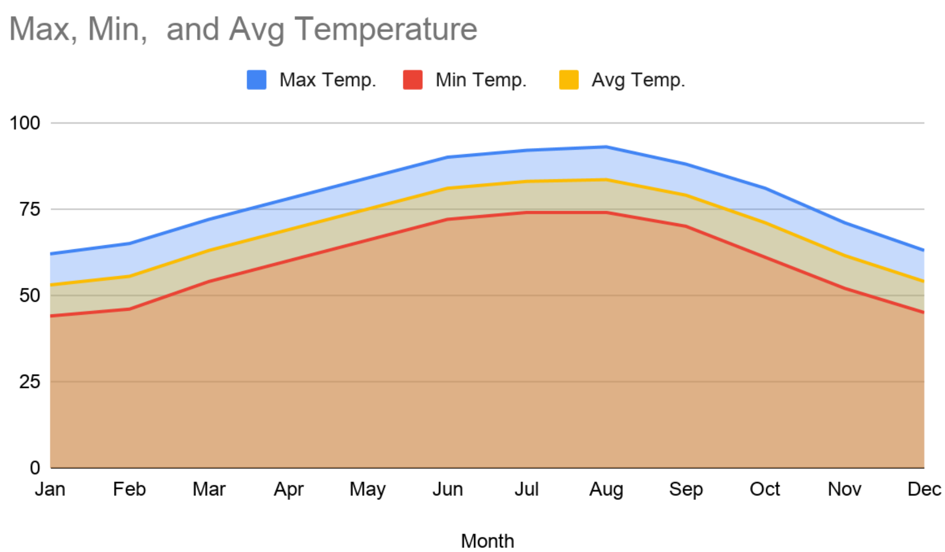


Figure 4.2 Describes temperature characteristics of the site [Martinez 2020]

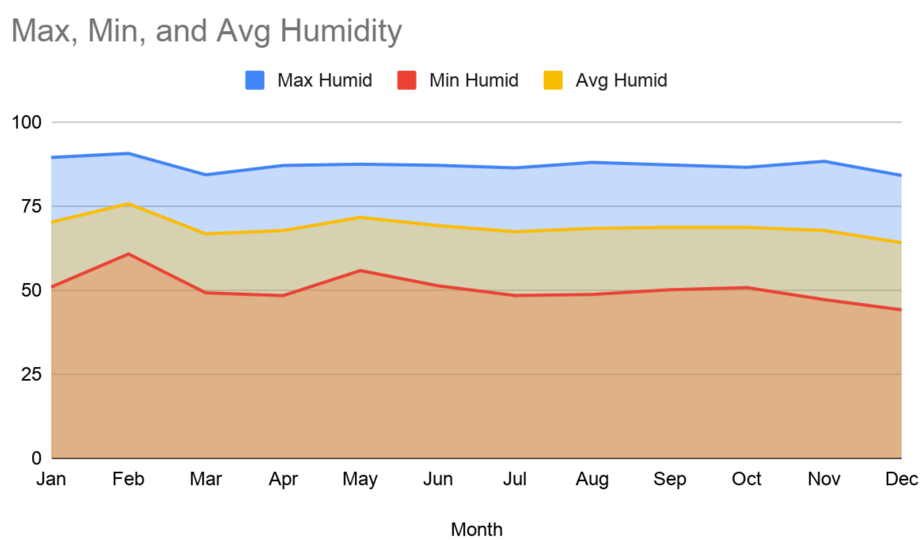


Figure 4.3 Describes humidity characteristics of the site [Martinez 2020]

$$T_{\mathrm{dp}} \approx T - \frac{100 - \mathrm{RH}}{5};$$

$$\mathrm{RH} \approx 100 - 5(T - T_{\mathrm{dp}});$$

Figure 4.4 Simplified formula calculates the dew point temperature and is accurate after 50% RH https://en.wikipedia.org/wiki/Dew_point

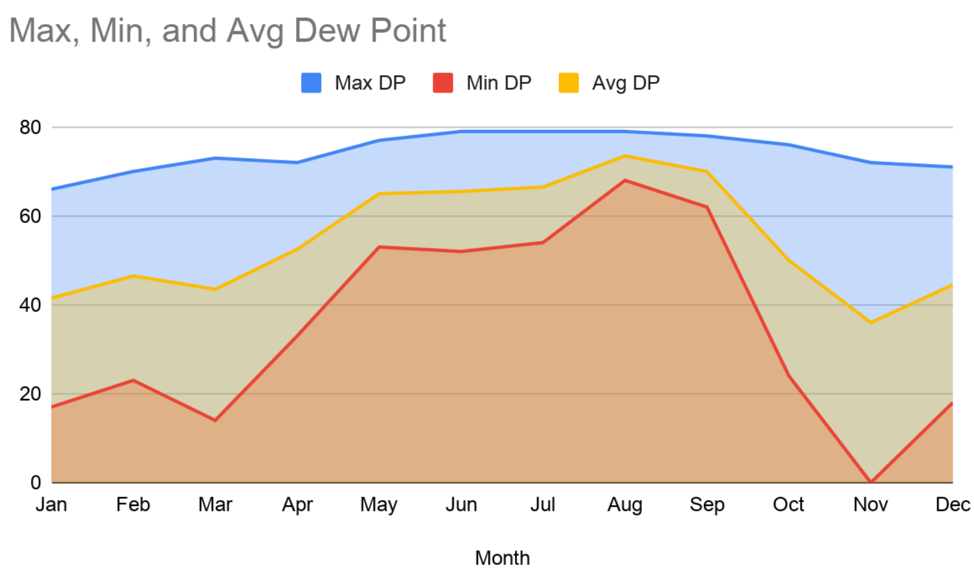


Figure 4.5 Describes the dew point temperature characteristics of the site [Martinez 2020]

Overlaying these graphs, shown in Figure 4.6, it is observed that humidity tends to inversely follow the temperature trend while the dew point temperature duplicates the trend with segments of volatility near the start and end of the year. That relationship is magnified when viewed on a day by day basis in Figure 4.8. On a summer day in May, a high temperature of 90°F registers at noon, while the lowest temperatures occur between 2 - 6 AM. The humidity sharply drops during the afternoon, driving a large difference between dew point temperature and ambient temperature of 20°F. While in March that relationship is minimized, seeing a maximum difference of only 10°F. Annually, the difference in temperature is 13.625°F in this region which means an exposed surface at ambient temperature must traverse this threshold to reach that dew point, creating condensation.

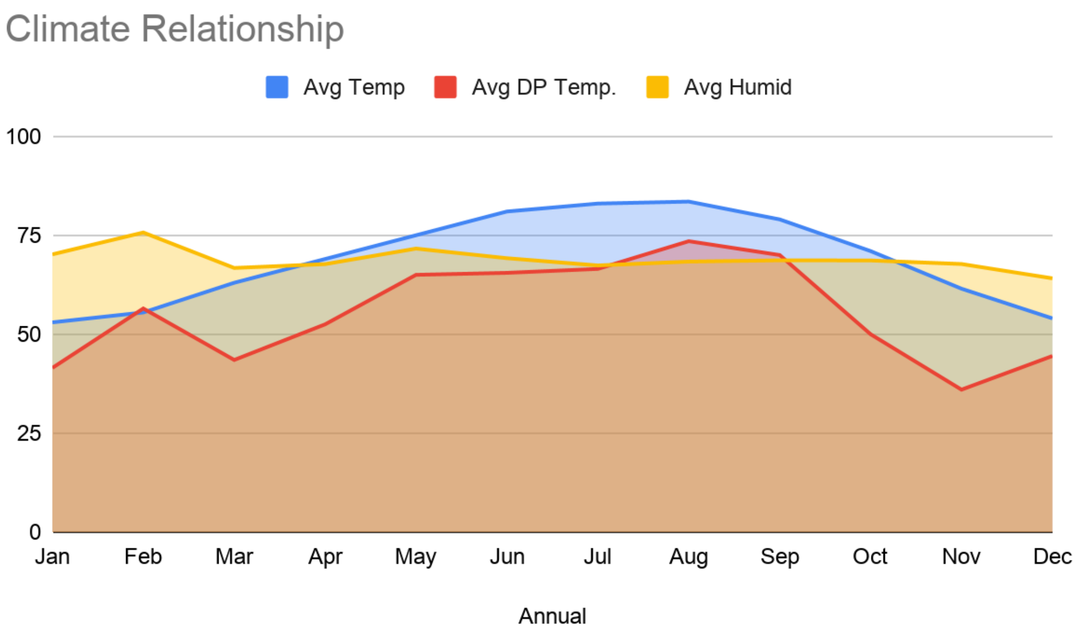


Figure 4.6 Overlays all relevant climate data to visualize relationship [Martinez 2020]

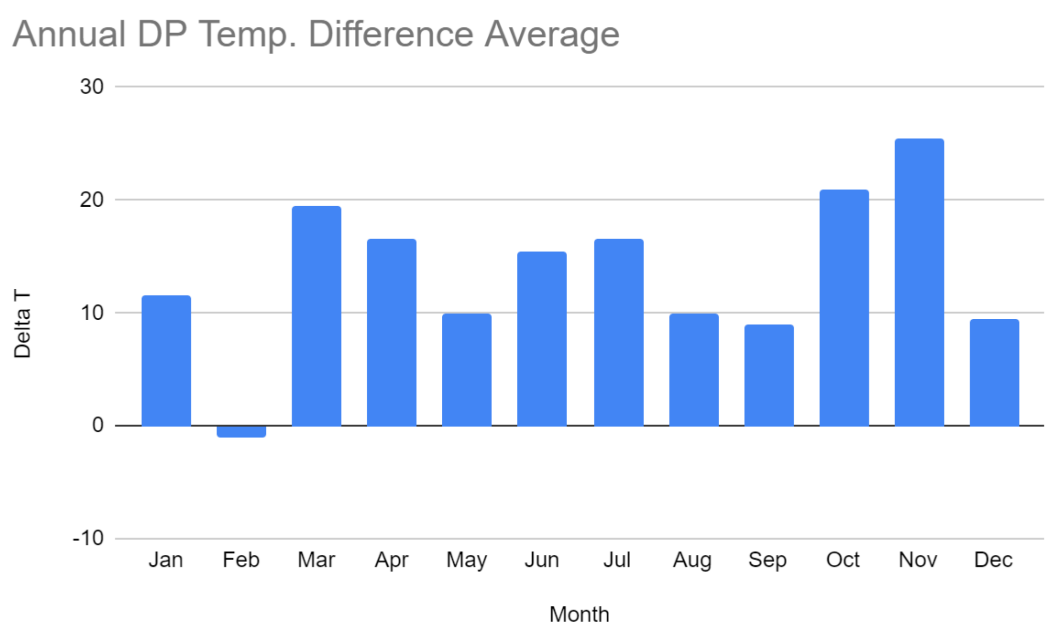


Figure 4.7 Monthly average change in temperature [Martinez 2020}

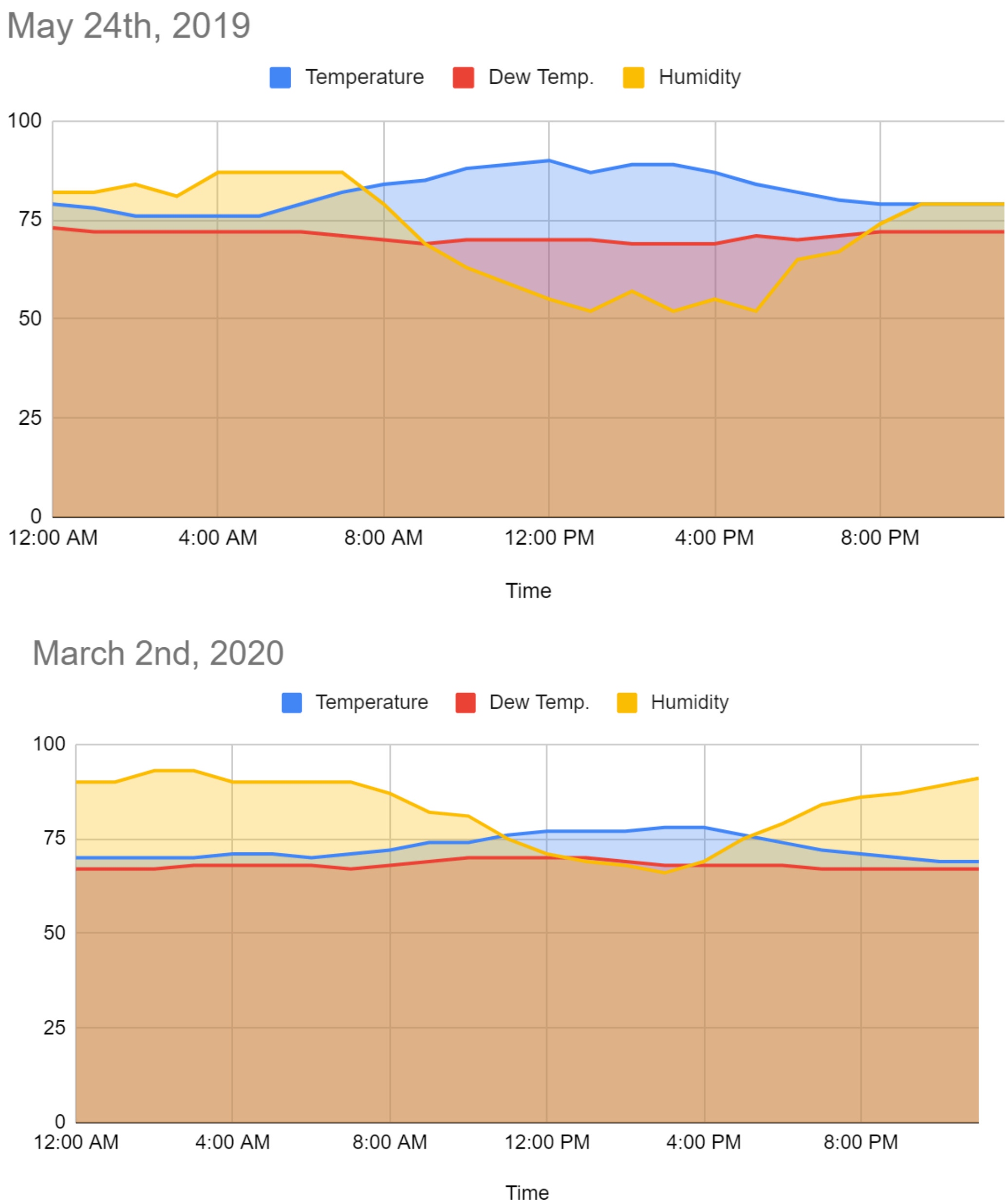


Figure 4.8 Shows climate data taken from two different days [Martinez 2020]

Precipitation in this area is abundant enough to be a substantial source of water. Seeing an annual rainfall of 50 inches. As seen in Figure 4.10, July is a maximum for rainfall while a minimum of 2 inches is seen in March. However, the monthly average of days that rain is 8.8 days out of the month.

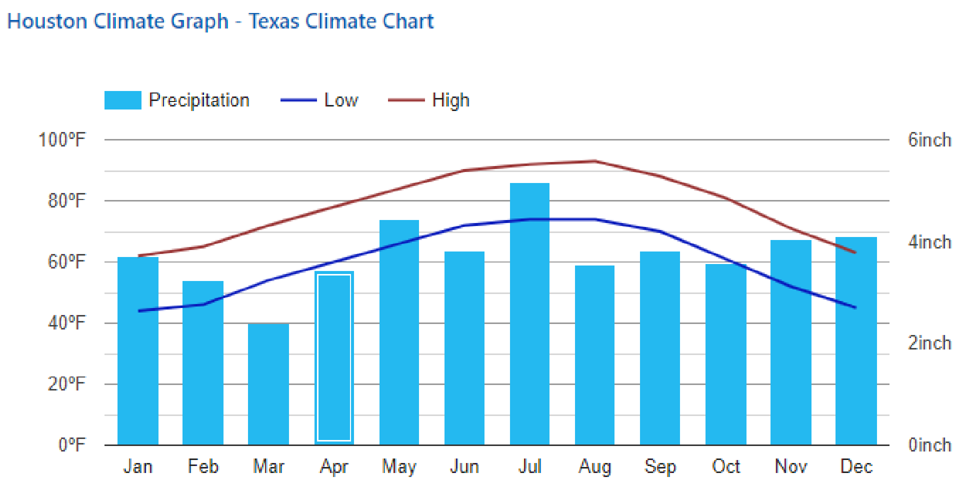


Figure 4.9 Shows precipitation by month
https://www.usclimatedata.com/climate/houston/texas/united-states/ustx0617

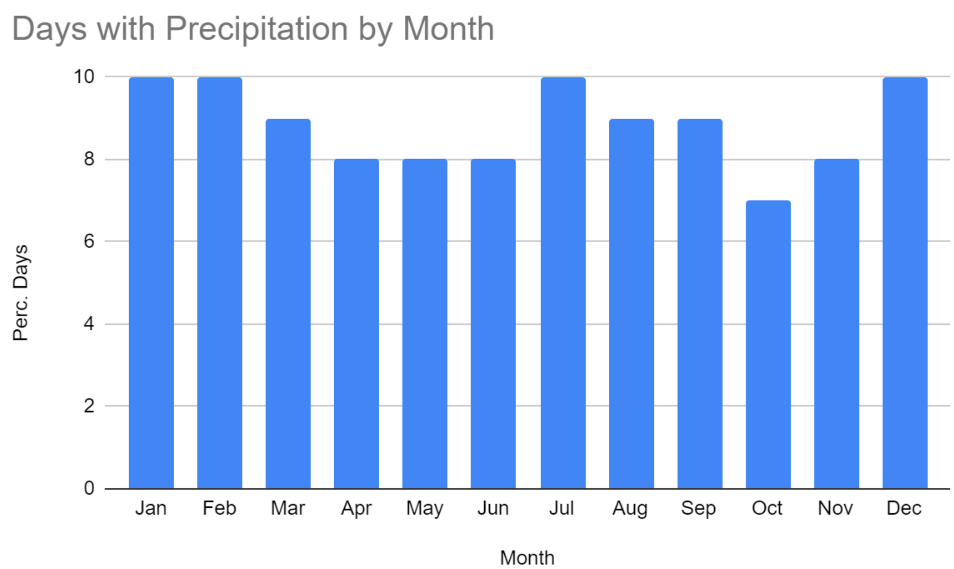


Figure 4.10 Monthly average of days with precipitation [Martinez 2020]

The water that can be generated using the Ag Hub roof area was calculated using the formula shown in Figure 4.11, taking into account the total roof square footage of 2779.07 ft^2, the average rainfall in this region of 50 in and a runoff coefficient of 0.585, it is determined that 81,287.79 gallons can be produced annually calculated in Table 4.1.

$$\text{Harvested water (gal)} = \text{catchment area (ft}^2\text{)} \times \text{rainfall depth (in.)} \times \text{0.623 conversion factor}$$

Figure 4.11 Equation used to calculate rain harvesting
https://rainwaterharvesting.tamu.edu/catchment-area/

Table 4.1 Shows variable input for rain harvesting formula and the product

Total Roof ft^2	Convert to gallons	Average Annual Rain Fall in inches	Projected Rain Harvesting gallons/yr
2779.07	0.623	49.77	86169.82

These relationships correspond with sub-tropical climates whose dew point temperature reveals much potential for water extraction. After this climatological analysis, it is established that in this region an AWG can produce maximum water during the summer season. As a result of a small change in temperature between ambient temperature and the dew point. Also, a considerable amount of rain during the July month will allow rainwater harvesting to be maximized. Which is needed as the summer sun will evaporate the water from the growth ponds at an increased rate. That same sun will help power each AWG unit to run at maximum power. The AWG will be able to condensate nearly without assistance during the month of February as the dew point is closer than any other month. However, in March the dew point falls steeply and is also the month where minimum rainfall occurs so this could be a minimum month for water production. Overall, This region contains more than the minimum resources required for an AWG to produce water nearly year round.

V. Concept Development

5.1 Design Constraints

The investigation of the AWG market, the study conducted on the regional climate and site analysis supplied the design process with constraints used to give shape to the novel AWG. These functions must be created for the device to operate as defined by external requirements. These constraints were organized into the four pillars of sustainability: Technical, Environmental, Economic, and Social as shown on Table 5.1. These constraints must be met for the AWG to be considered successful.

Table 5.1 Outlines constraints for the AWG design [Martinez 2020]

Technical Requirements	
The device will condense water from the atmosphere	The atmosphere contains 3400 trillion gallons of water vapor
The device will be able to harvest rainwater	On-site rain harvesting is maxed out
The device will be to track and control condensation surfaces	If the air is cooled below the dew point then water will condense
The device will be have its own reservoir	More storage is needed for the Ag Hub site
Environmental Requirements	
The device will be able to produce water in humidity between 50%-100%	Controller sensors accuracy is rated for this humidity range
The device will use renewable energy source	To promote sustainability
Economic Requirements	
The device will cost less than $1500	Market competition

Social Requirements	
The device must be easy to assemble by one person	The ability to assemble to device with common tools will promote it's repairability
The device must be easy to maintain by one person	The condenser module will need maintenance
the device must be easy to clean by one person	Because surfaces will have constant contact with water, cleanliness is a factor

Having a deeper understanding of the different water harvesting technologies, the general system of the AWG will follow a diagram shown in Figure 5.2. This broad setup will allow air induction to supply air to the dew collector while capturing fog, if present. The rainwater harvester will share the inlet for the water reservoir to maximize water production for the Ag Hub AWG.

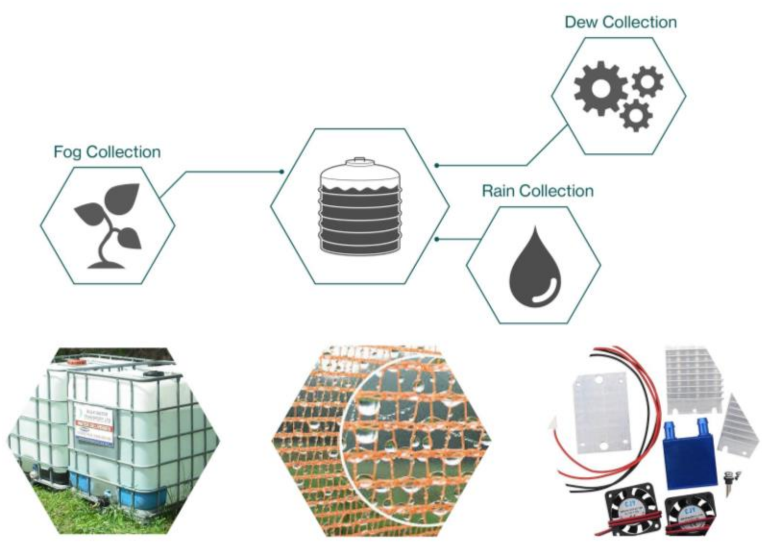


Figure 5.1 Atmospheric water harvesting strategies [Martinez 2020]

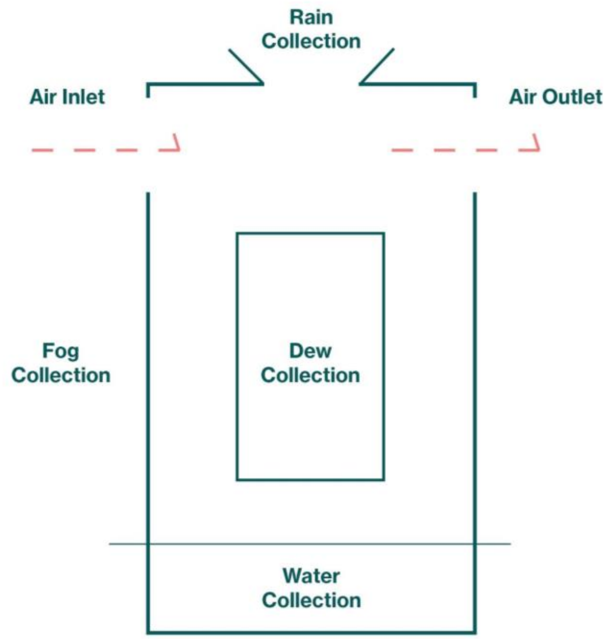


Figure 5.2 Diagrammatic layout of harvesting strategies [Martinez 2020]

The Ag Hub is specifically designed with a visual brand language (VBL). This VBL was observed and given attributes that are transferable to the form of the AWG. These can represent values, characteristics or even values shared by the designers and the physical building. This will ensure that the AWG fits its environment, allowing it to be aesthetically appropriate and functional for the users.

Figure 5.3 Attributes analysis of the Ag Hub for design inspiration [Martinez 2020]

5.2 Sketch Phase

Through the initial phase of defining constraints and establishing design criteria, it was established that the Ag Hub AWG should follow the VBL while accomplishing the overall system requirements. Concepts were initially generated by using a morphological matrix seen in Figure 5.4.

Figure 5.4 Morphological matrix of biomimetic inspired forms [Martinez 2020]

From there, refinement was made by exploring overall form and function. As seen in sketch Figure 5.6, internals like fan orientation, funnels and reservoir position were examined. Furthermore, the adjacent sketch shows diverse geometric explored. Between cones, ellipses, polygons, and cubes, the overall form was designed with established design principles and constraints from the literature review and research. Lessons like, reduction of volume near the condenser for air induction, angling the mesh to gain wind protection while still taking advantage of gravity, and protecting the reservoir from evaporation like the Bromeliad plant is able to do. It was understood early on that the form needs a cold air inlet and a hot air outlet. The following Sketch shows how air flow could work within the constraints given.

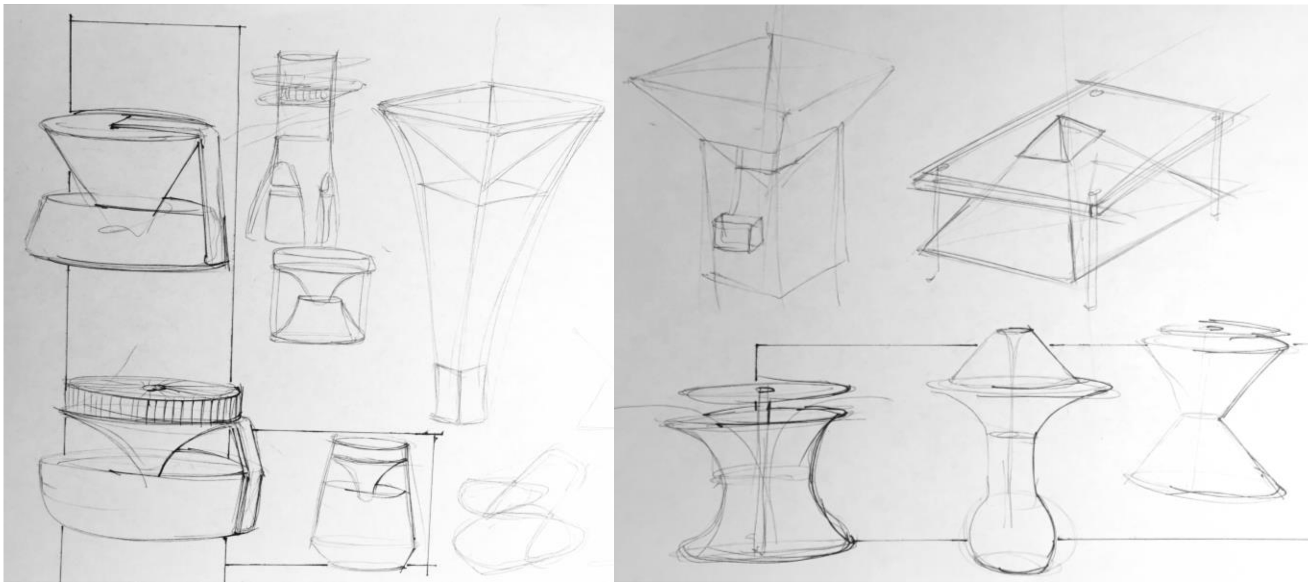


Figure 5.5 Preliminary ideation sketches of overall form [Martinez 2020]

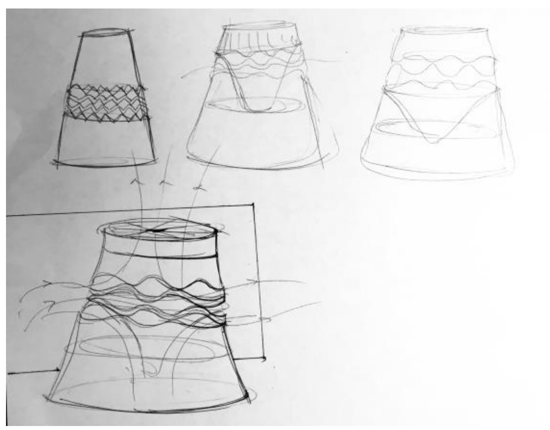


Figure 5.6 Process sketch of air flow movement through internals [Martinez 2020]

From sketching, the volumetric of the rain funnel, fog collector, dew condenser, and reservoir were identified. With this, several forms became likely after refinement and were selected for physical prototyping and CAD. Sketch Figure 5.7 is a polygon concept that emphasized modularity and tested out what a custom reservoir would look like. The next concepts took an hourglass form that helped with the air induction and funneling of water into a reservoir. Lastly, shown in sketch Figure 5.8, exploring installation and stability in minimalist ways, while housing all the necessary components to produce water.

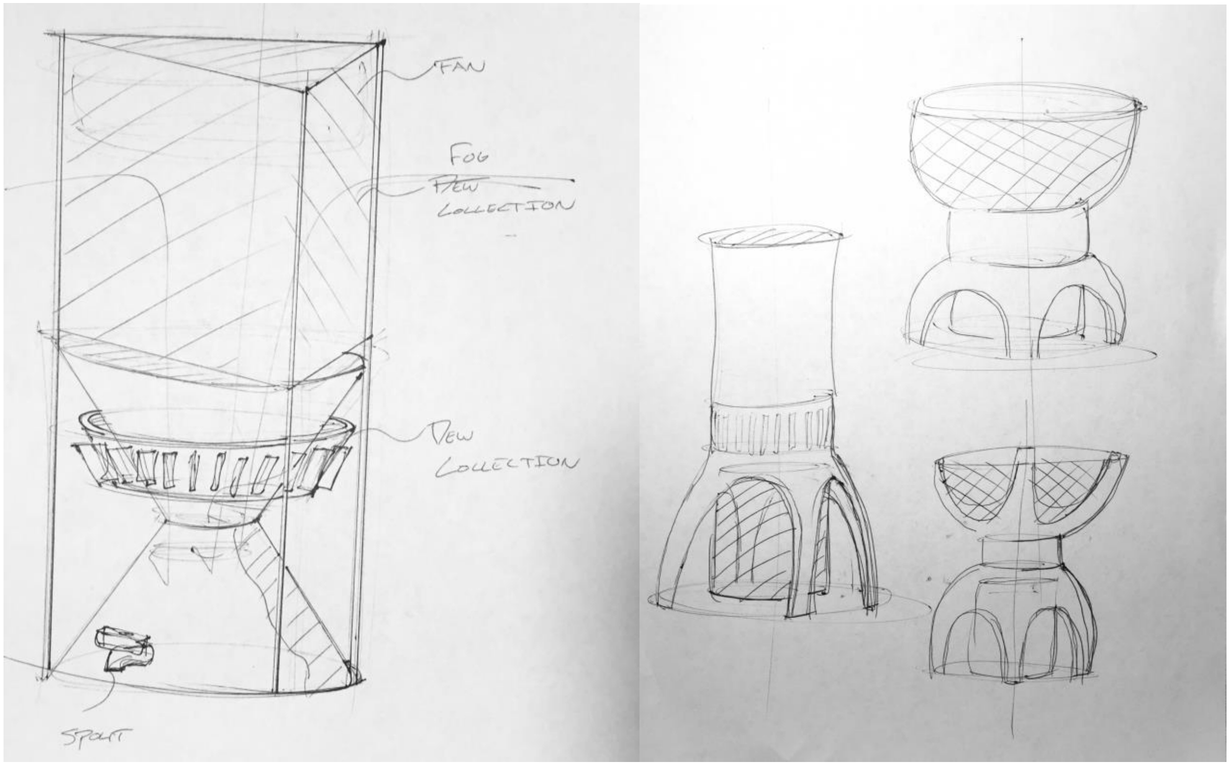


Figure 5.7 Concept development sketches of polygons and cones [Martinez 2020]

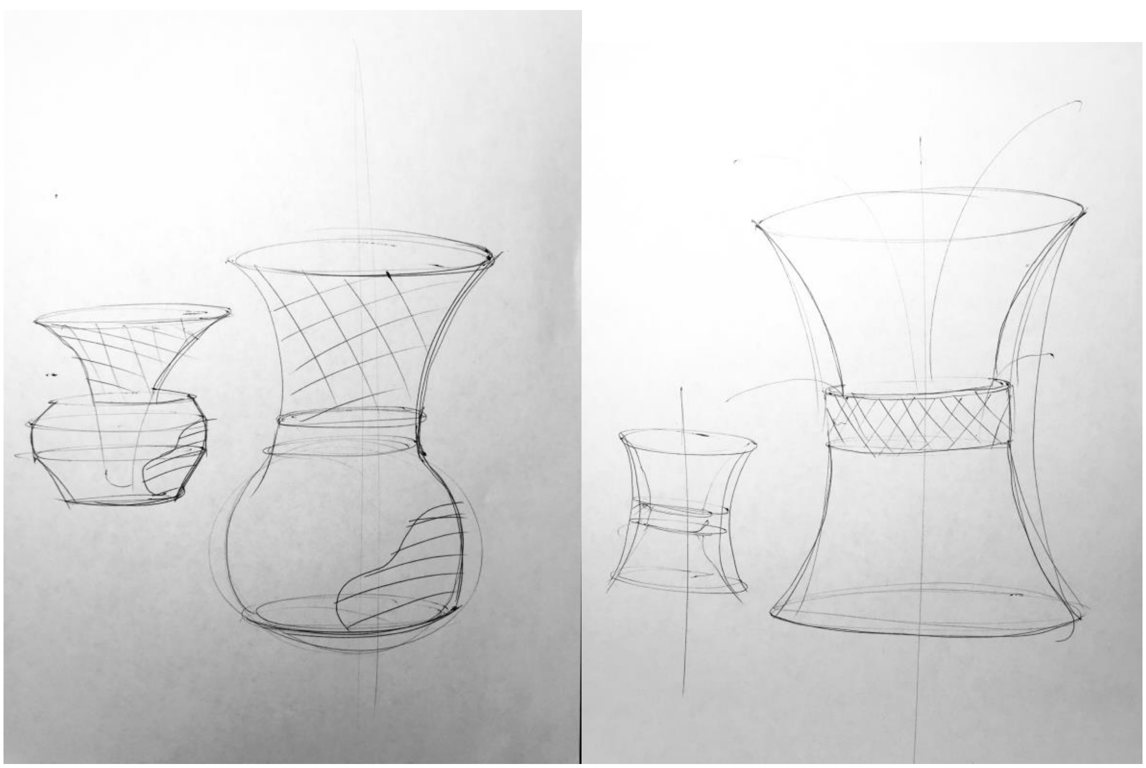


Figure 5.8 Final sketches of minimalist forms for the AWG [Martinez 2020]

5.3 Proof of Concept

Considering the water harvesting methods available, a qualitative study was done for each functionality to test the viability. Specifically looking into locally available meshes, TEC dew condenser build, and rainwater harvesting, each method was measured at a smaller scale and analyzed for implementation and further concept development of the Ag Hub AWG. The TEC unit was tested by building a small unit with a TEC module configuration as seen in the figure below.

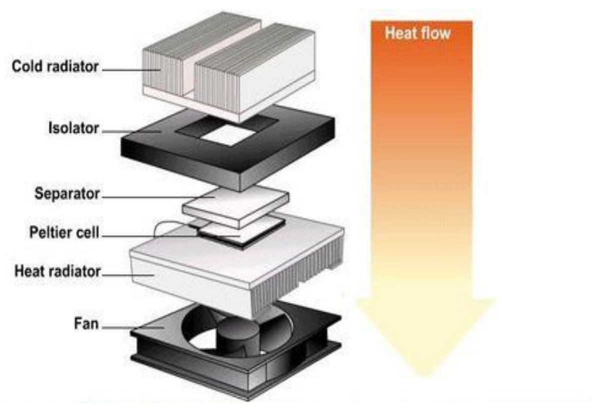


Figure 5.9 TEC stack exploded view
https://www.geeker.co.nz/accessories/other/thermoelectric-cooler-peltier-60w-tec-12706-clone.html

The TEC module consists of a condensing surface, or a cool sink, The thermoelectric unit, insulation, heat sink, and fan. Air passes through the condensing surface as the TEC works to cool it below the dew point, which results in water. The fan then draws the heat from the TEC through the heatsink and the insulation is to protect the cold side from thermal leakage. The proof of concept unit was able to produce condensation. The TEC unit cooled the condensing surface well below the dew temperature as seen in Figure 11

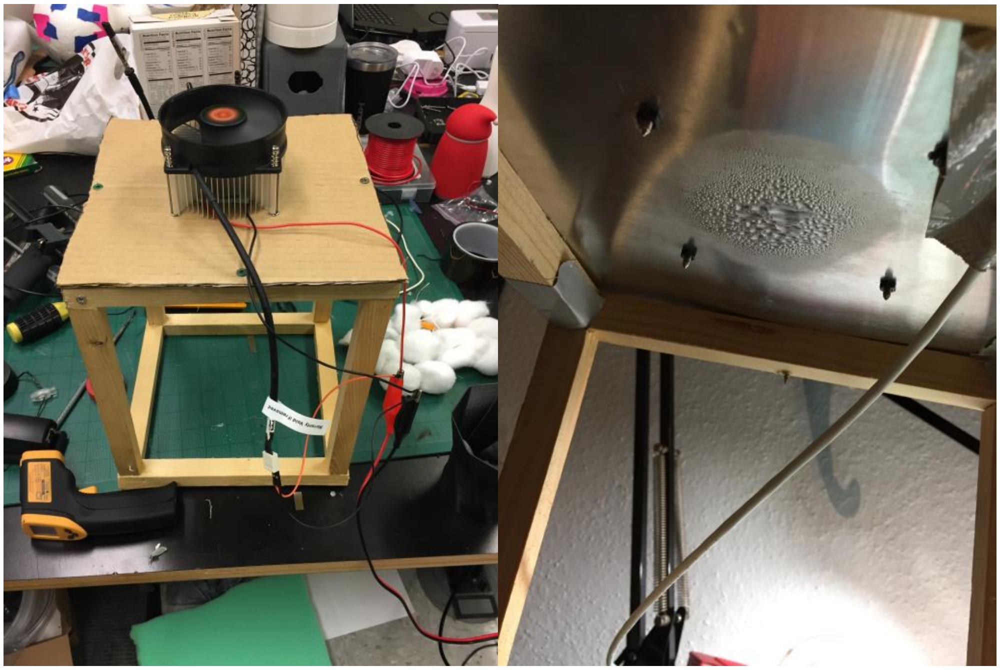


Figure 5.10 Condenser unit consists of a condensing surface, TEC module, and mounting bracket [Martinez 2020]

Figure 5.11 Condensing surface temperature change test [Martinez 2020]

Table 5.2 Production table for the condenser unit with 4 TEC stacks [Martinez 2020]

AWG	Cost	Production	Dimensions	Surface Area	Liters/ft^2/day	Liters/$	Power
Condenser Unit	$139.80	1.6 L/day	26.68 ft x 8.4 ft	9.32 ft^2	0.17 L/ft^2	.011 L/$	60 watts

The experiment consisted of running a TEC stack with the smart controller unit. The experiment was run with relative humidity above 50% for the sensors to be accurate. As seen in Table 5.2, a single TEC stack can yield 0.4 L/d under nominal conditions. This is scaled up for the Ag Hub AWG solution and extrapolated for a theoretical yield.

Figure 5.12 TEC stack setup [Martinez 2020]

The fog collection mesh was locally sourced for experimentation. Black mosquito netting was selected, according to recommendations from the literature review. Although, Raschel mesh would be a better mesh for the Ag Hub application. A comparable study can give us insight into the final design. The mosquito netting, however, was unable to yield usable water. Condensation would form according to the timeline predicated by the climatological study but would quickly evaporate with the rising sun. The mosquito netting was effective at creating condensation but ineffective at collecting the water and directing it to the reservoir.

The rainwater harvesting system yielded the most water as predicted. The amount of water collected is shown in Table 5.3 by using the reservoir tank that was mounted on the fog harvesting mechanism. This structured combination inspired the Ag Hub AWG form further.

Figure 5.13 Fog netting test and condensation formation [Martinez 2020]

Figure 5.14 Rainwater harvesting reservoir [Martinez 2020]

The formula used to project rainwater harvesting for the Ag Hub was applied here. Using the funnel as the receiving surface area, the other variables stay the same. The proof of concept rainwater harvester was able to get about 700 mL of water tested over a single week.

Table 5.3 Rainwater harvesting projection [Martinez 2020]

Funnel ft^2	Convert to gallons	Average Annual Rainfall	Projected Rain Harvesting g/y
5.37	0.623	49.77	166.51

Figure 5.15 Collected water [Martinez 2020]

5.4 Scaled Physical Models

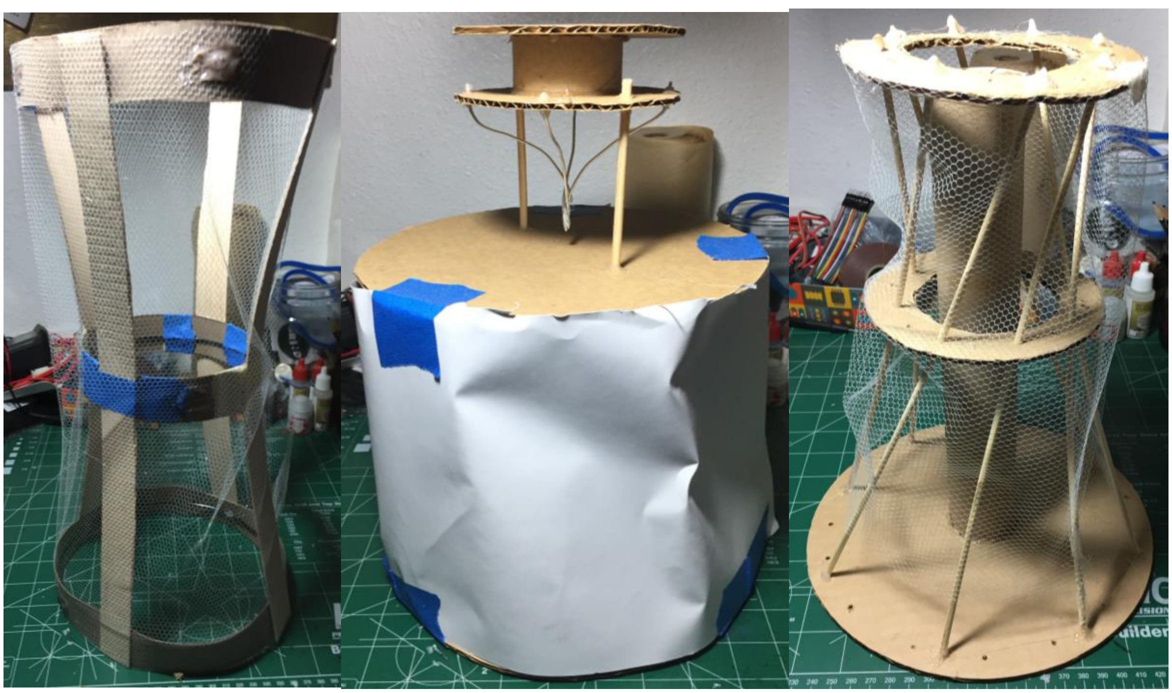


Figure 5.16 Scaled, physical prototype for form exploration [Martinez 2020]

By making these physical models, the understanding of how air moves through the system was further understood. The hourglass shape at the top of Figure 5.16 had the correct characteristics needed to comply with the constraints and requirements given.

5.5 CAD Models & Renders

In this portion of the design process, the possible forms discovered during the sketching, prototyping, and testing phase were developed to better visualize the final product. The first concept, starting from the left of Figure 5.17, shows an AWG that resembles the VBL of the Ag Hub most closely with shade louvers to help protect the meshes from evaporation and a box shape that represents the cargo freight boxes that the Ag Hub would be constructed from. Next, shown in figure 5.20, is a concept with a custom reservoir tank that makes use of the mesh as a funnel for the rain-water harvester. To increase reliability and ease of assembly, an external structural system was explored in the last model of Figure 5.17, while still using the mesh as a funnel with the reservoir tank installed.

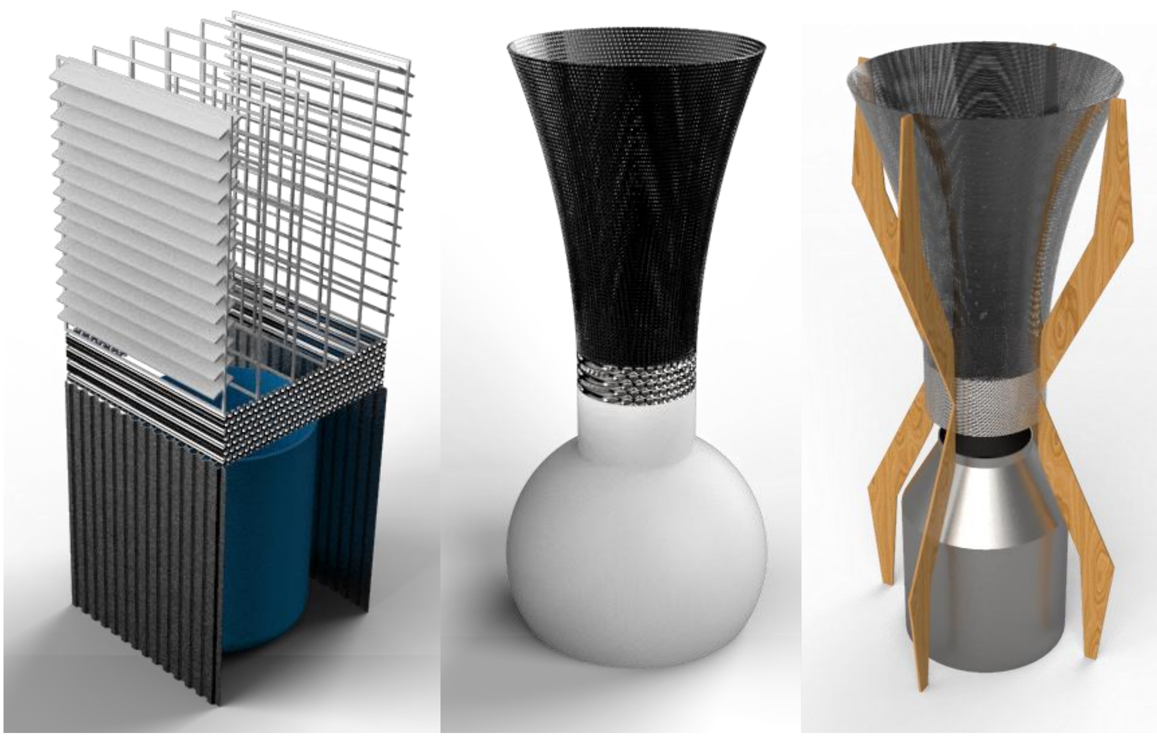


Figure 5.17 Initial CAD and volumetric exploration [Martinez 2020]

Emerging from this development is a 3 module AWG, shown in Figure 5.18, taking on the geometric hex shape. While still using the mesh as a funnel the angle of the mesh faces were set so that condensation is more resilient to wind. Although 30° is ideal for maximum water yielding efficiency, the structures face had to be less of an angle so that there was a realistic balance between dew collection and space taken by the device. The angled faces also allow a decrease of volume near the condensation unit, providing air flow before ending at the reservoir. At this point, the decision was made to add the smart controller which helps increase the efficiency of the AWG through temperature sensors and relays. However, during feedback, the AWG had to be less industrial and further refined to be aesthetically fitting to the client.

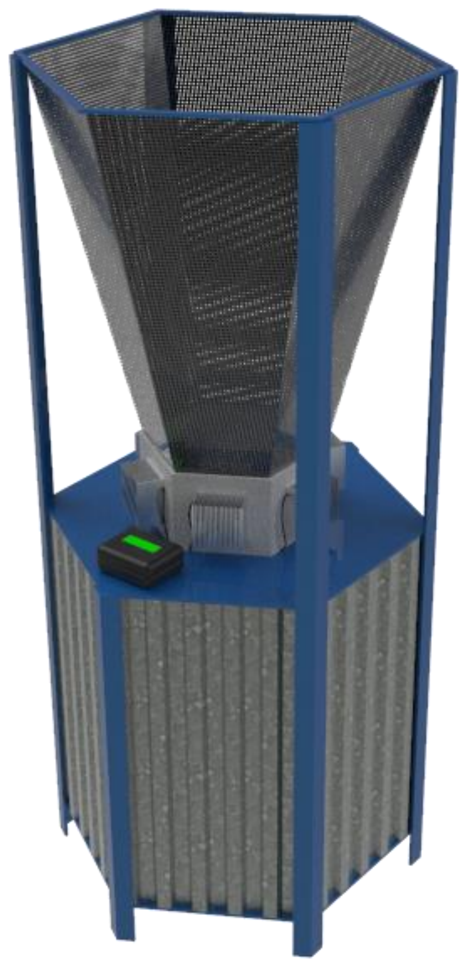


Figure 5.18 Further refinement of CAD and volumetric exploration [Martinez 2020]

The final form of Härvist is shown in Figure 5.19. The name Härvist was chosen because of the device's ability to reap water from different methods. Härvist is a hybrid system, taking the best of the technologies and implementing it into a holistic form so that they work together in the most efficient way possible. Both the user and the design constraints were considered and solved for. Using CAD volumetrics, Härvist stands 7 feet tall with a 30-inch diameter base. It was also identified that a 30 gallon barrel drum could fit in the bottom module. A minimum of 4 TEC modules can fit in the middle module, with space to add more if required, and finally a filtration at the top of the mesh to help filter out big debris. This final concept would be the proposed solution for the Ag Hub together with the assembly and installation process to solve their problem.

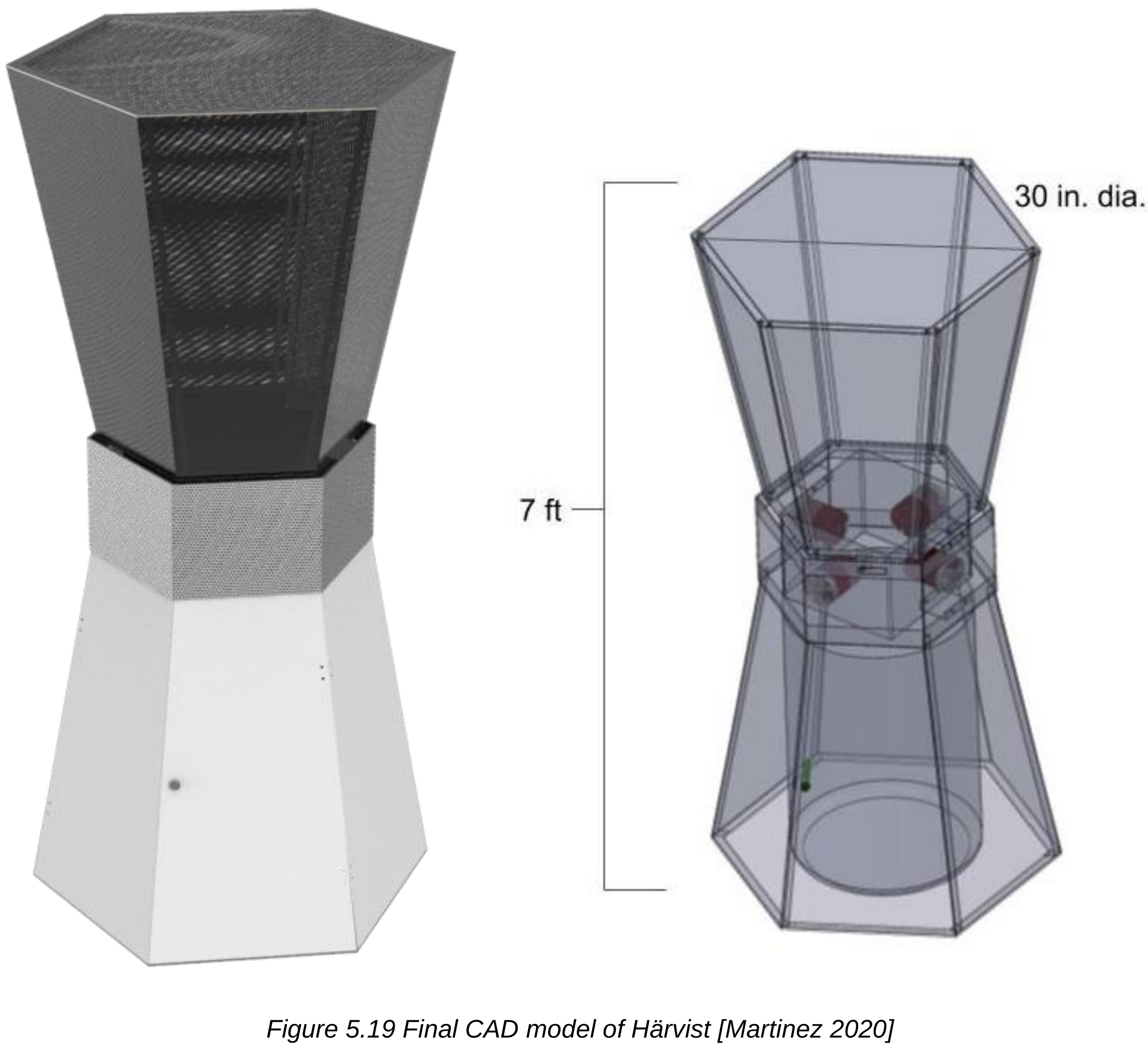


Figure 5.19 Final CAD model of Härvist [Martinez 2020]

Figure 5.20 shows the location of the growth remediation ponds on the Ag Hub site and where Härvist would be most effective and visually impacting.

Figure 5.20 In context renders of Härvist and Ag Hub [Martinez 2020]

VI. Design Solution

6.1 Smart Controller

Part of the success of SOURCE by Zero Mass, is the ability for the hydration panel to have a smart controller. This controller allows them to track production over time, gauge energy, and have simple logic over the condenser unit. The smart controller was designed by starting with the components diagrammed in Figure 6.1. The logic flow chart was then compiled in Figure 6.2 so that the condensation surface was always kept at the dew point at all times without having the TEC's on continuously, consuming energy. This will avoid redundant energy waste by managing the TEC stacks and fan, turning them on only when required. This logic begins by taking in data through the use of sensors. This data is then calculated to get the dew point temperature. The dew point is then compared to the surface temperature, turning on the condenser unit to maintain condensation.

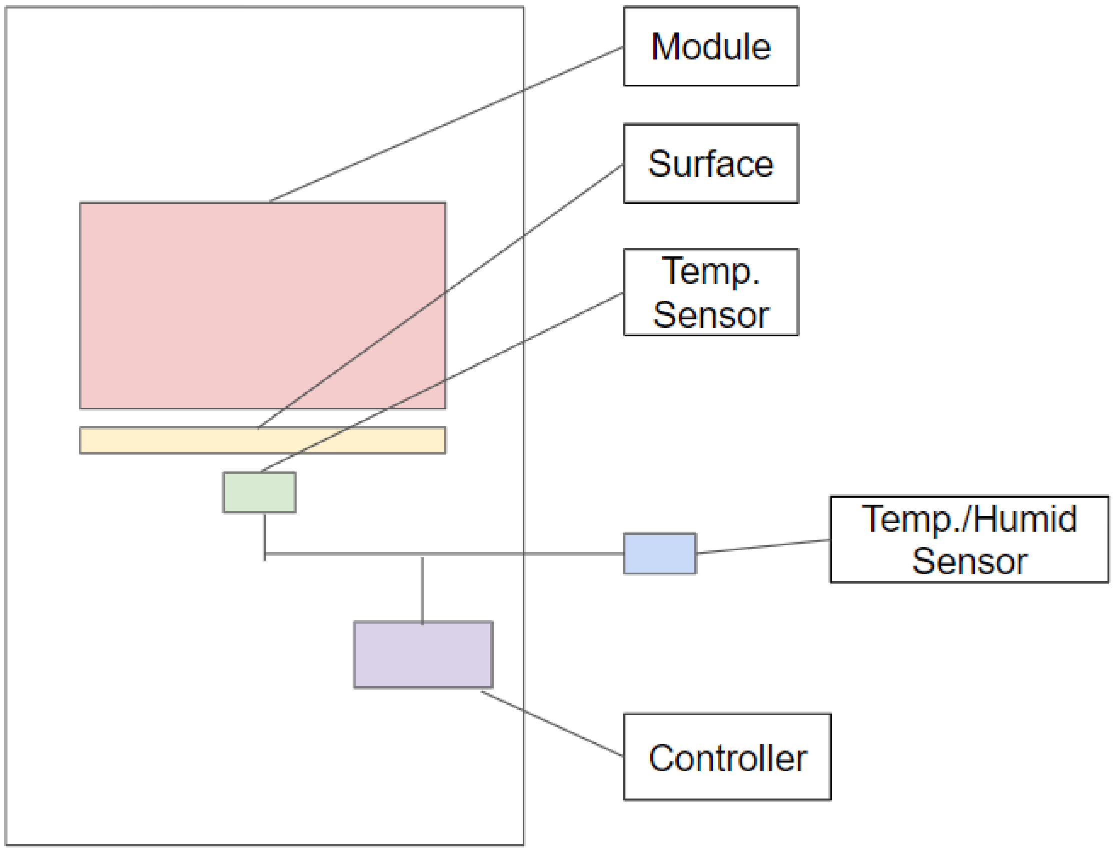


Figure 6.1 Smart controller diagram [Martinez 2020]

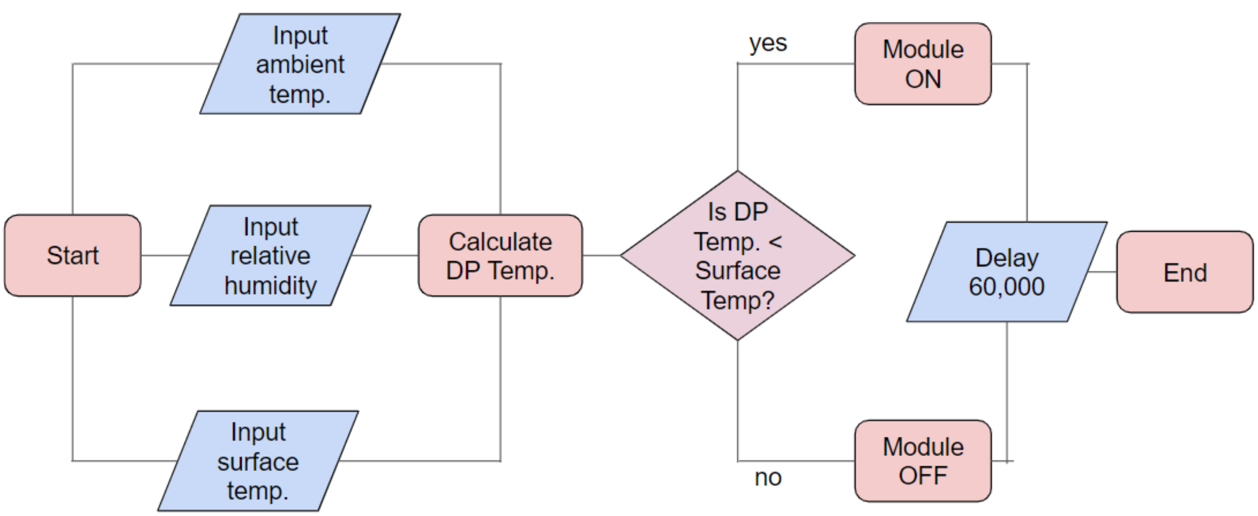


Figure 6.2 Logic flowchart for code [Martinez 2020]

The smart controller was assembled by setting up off-the-shelf electrical components that are cost effective and make up for their investment through energy efficiency of the overall system. These components are available at scale and can be pre-assembled and delivered as a controller for Härvist or any other passive AWG that requires some sort of tracking or simple logic. Table 6.1 shows the bill of materials for the components required for the controller and Figure 6.3 shows how the components were wired up.

Table 6.1 BOM for circuit [Martinez 2020]

Part	**Description**	**Price**
breadboard	base	$5.54
temp sensor	condensing surface	$4.08
temp. humidity sensor	ambient temp	$6.59
fan	12v	$6.99
relay	5v-12v	$5.59
arduino clone	uno	$10.95
wires	12 gauge	$4.50
junction box	waterproof	$5.95
Total		**$50.19**

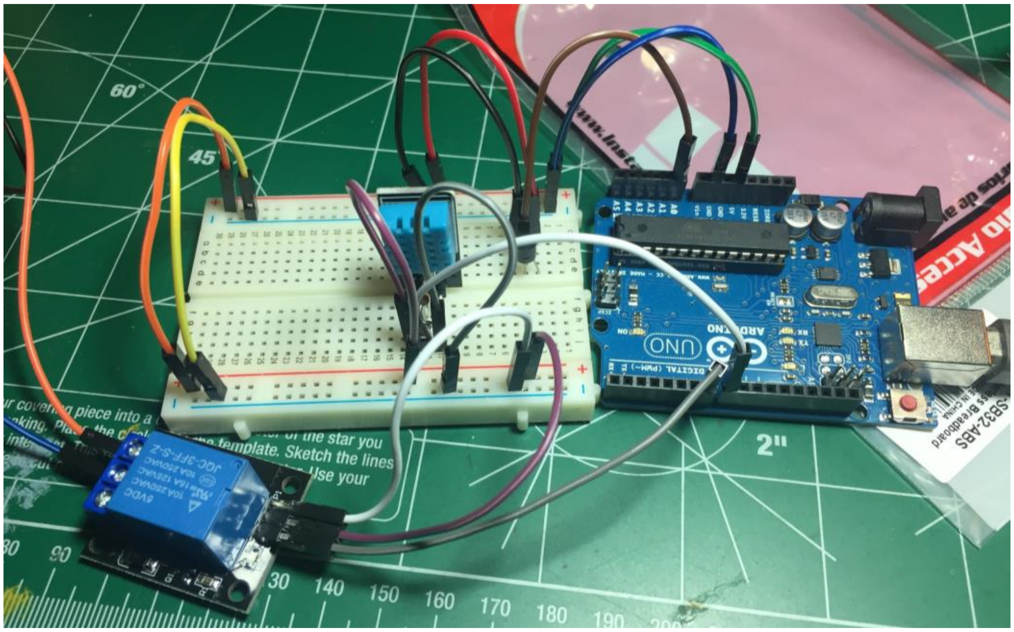


Figure 6.3 Circuit setup [Martinez 2020]

The last part of the controller is the code that dictates the logic in the Arduino. The code below can be copied and edited depending what's necessary for your application. Below the code is an example of the output of the serial monitor or what would be displayed in the included screen.

```
//CONFIG==============================================================
int sensorPinA = 0;
int tempReading;

int relayPin = 7;
#include "DHT.h"
#define DHTPIN 8
#define DHTTYPE DHT11

//===================================================================

DHT dht(DHTPIN, DHTTYPE);
void setup()
{
  Serial.begin(9600); // startup sequence
  pinMode (relayPin, OUTPUT);
  Serial.print("Hello\n");
  delay(2000);
  Serial.print("Starting Up\n");
  delay(2000);
  dht.begin();
}

void loop()  // loop program

{
  delay(5000);  // run program every 10 sec
```

```
  readMyDHT();
}
void readMyDHT()
{
  int readingA = analogRead(sensorPinA); // getting data from sensors
  float voltageA = readingA * 5.0;
  voltageA /= 1024.0;
  float StemperatureC = (voltageA - 0.5) * 100 ;
  float StemperatureF = (StemperatureC * 9.0 / 5.0) + 32.0;
  float humidity = dht.readHumidity();
  float tempF_DHT11 = dht.readTemperature(true);
  if (isnan(humidity) || isnan(tempF_DHT11)){
    Serial.println("Failed to read from DHT sensor!");
    return;
  }  // checking to see if the sensor is working
  float heatiindex_f = dht.computeHeatIndex(tempF_DHT11, humidity);
  // serial monitor print out
  Serial.print("Humidity: ");
  Serial.print(humidity);
  Serial.print(" %\n");
  Serial.print("Temperature: ");
  Serial.print(tempF_DHT11);
  Serial.print(" *F\n");
  Serial.print("Heat Index: ");
  Serial.print(heatiindex_f);
  Serial.print(" *F\n");
  Serial.print("DewPoint: ");
  Serial.print(theDewPoint(tempF_DHT11, humidity));
  Serial.println(" *F\n");
  Serial.print(voltageA);
  Serial.println(" Surface volts\n");
  Serial.print("Surface Temperature: ");
  Serial.print(StemperatureF);
  Serial.println(" *F\n");
  // logic for comparing data
   {
  if(StemperatureF > theDewPoint(tempF_DHT11, humidity)){
    powerOnRelay();
  } else if (StemperatureF <= theDewPoint(tempF_DHT11, humidity)) {
    powerOffRelay();
  }
 }
 //relay logic and dew point calculation
}

void powerOnRelay() {
  digitalWrite(relayPin, HIGH);
  Serial.print("TEC Module On\n");
  Serial.print("====================\n");
}

void powerOffRelay() {
  digitalWrite(relayPin, LOW);
  Serial.print("TEC Module Off\n");
  Serial.print("====================\n");
}
double theDewPoint(double farenTemp, double humidity)
{
  double tempDP = (farenTemp - (0.36 * (100-humidity)));
  return (tempDP);
}
```

Figure 6.4 Code for smart controller [Martinez 2020]

```
====================
Humidity: 89.00 %
Temperature: 78.80 *F
Heat Index: 82.40 *F
DewPoint: 74.84 *F

0.75 Surface volts

Surface Temperature: 77.35 *F

TEC Module On
====================
Humidity: 89.00 %
Temperature: 78.80 *F
Heat Index: 82.40 *F
DewPoint: 74.84 *F

0.74 Surface volts

Surface Temperature: 74.71 *F

TEC Module Off
====================
```

Figure 6.5 Serial monitor output [Martinez 2020]

6.2 Modularity

The Härvist form is also conducive to modularity. This modularity is inherent in the overall geometric form of the hex polygon. As discussed in the biomimicry concepts, bees have mastered the art of maximizing their space by using the hexagon. Shown below in Figure 6.6, is one of many configurations of Härvist units that can be assembled depending on the available area.

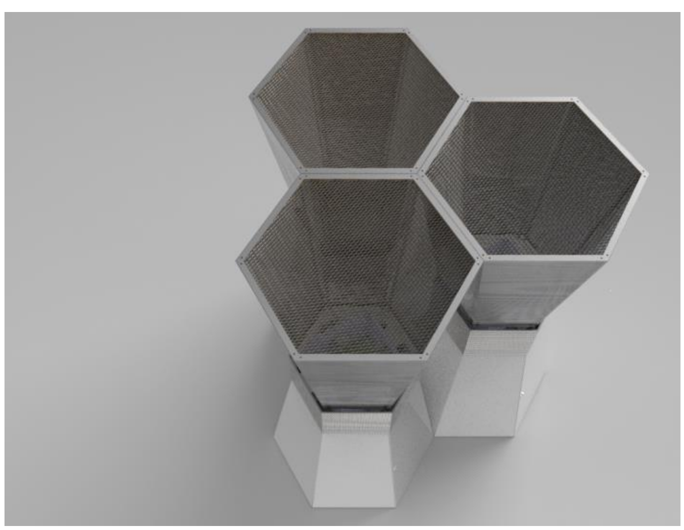


Figure 6.6 One of many modular setups [Martinez 2020]

6.3 Water Delivery

Figure 6.7 Example of plumbing and crushed stone for protected water delivery [Martinez 2020]

Figure 6.8 Rendered example of Härvist on a crushed stone platform with hidden plumbing [Martinez 2020]

The Ag Hub has a designated space for the Härvist units to be placed alongside the growth ponds to minimize water travel from source to demand. PVC plumbing would be required to deliver water to the ponds. To avoid damage to this system, crushed stone can be used to integrate the piping below ground. This will also discourage users from damaging the AWG and also gives the ability to level each unit.

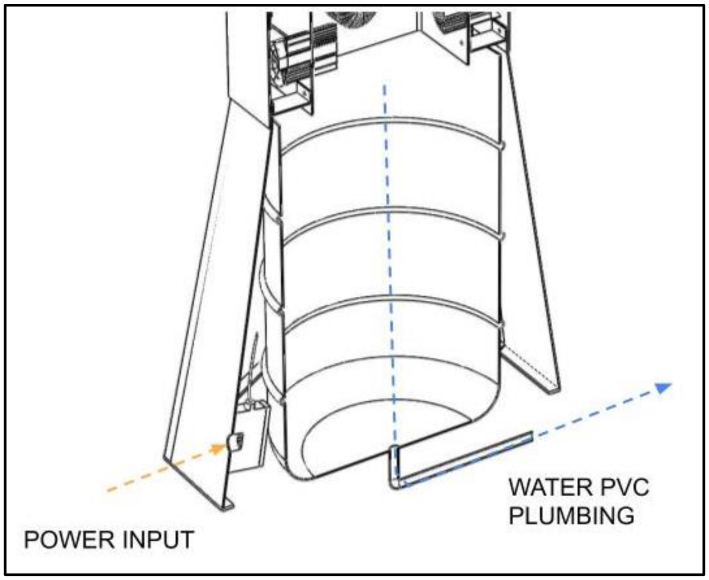


Figure 6.9 Cross sectional view of Härvist power input and PVC plumbing connection [Martinez 2020]

Figure 6.10 shows the bottom module and how Härvist would need both power input and water outlet to be linkable to other units for modularity. This setup is commonly used in other solutions, is reliable, and is constructed from commonly used materials available locally. A further discussion of assembly is laid out in section 6.4.

The Ag Hub will be outfitted with a primary 500-gallon reservoir tank that would supply the whole facility. However, after the analysis of this study, a recommendation increased the reservoir tank to 800 gallons to accommodate extreme drought conditions. The location of the reservoir tank is indicated in Figure 6.10. Therefore, Härvist would need a PVC pipeline infrastructure to direct water into the primary reservoir tank. Contingent upon elevation change, an additional pump might be necessary near the primary reservoir tank to assist in water induction into the tank. The price for the pump is outside of the scope of this project, as it was accounted for in the Ag Hub infrastructure price.

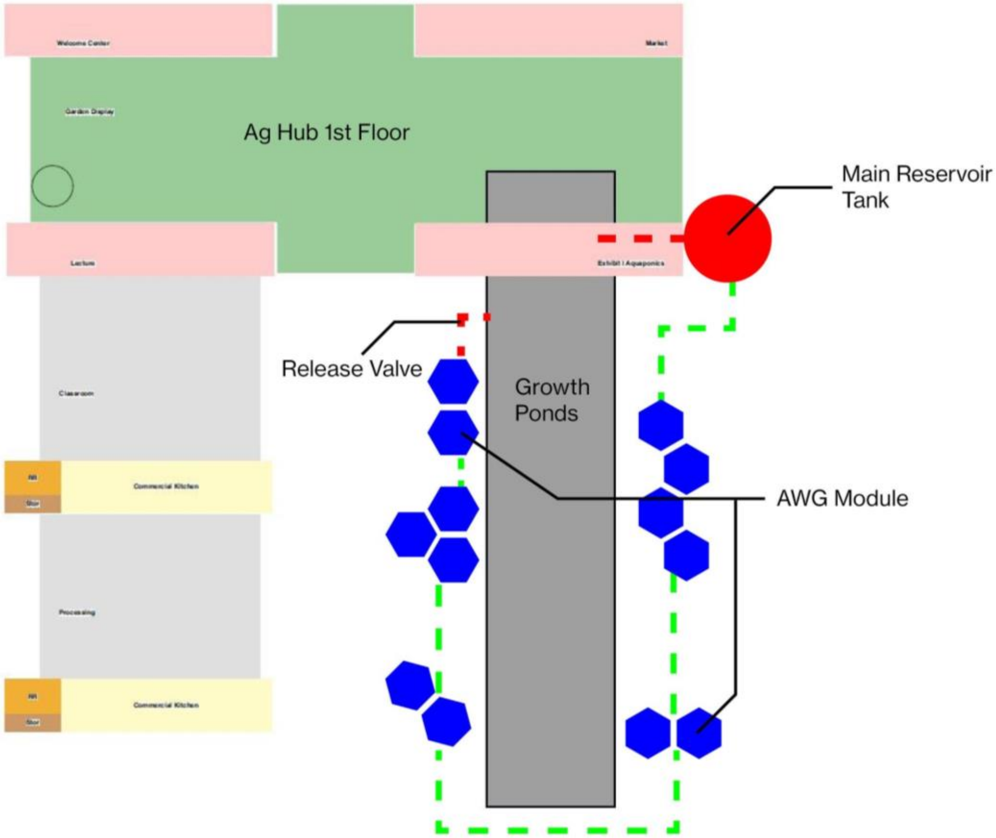


Figure 6.10 Site plan and pipeline layout for water [Martinez 2020]

6.4 Assembly

Härvist is divided up into three modules shown in Figure 6.11. The top module consists of the fog netting, funnel, and primary filter. The mid module is the condenser unit plus the smart controller wiring harness. The bottom module is the reservoir tank, smart controller housing, and base structure. Each module is assembled separately by mechanical fasteners and common tools.

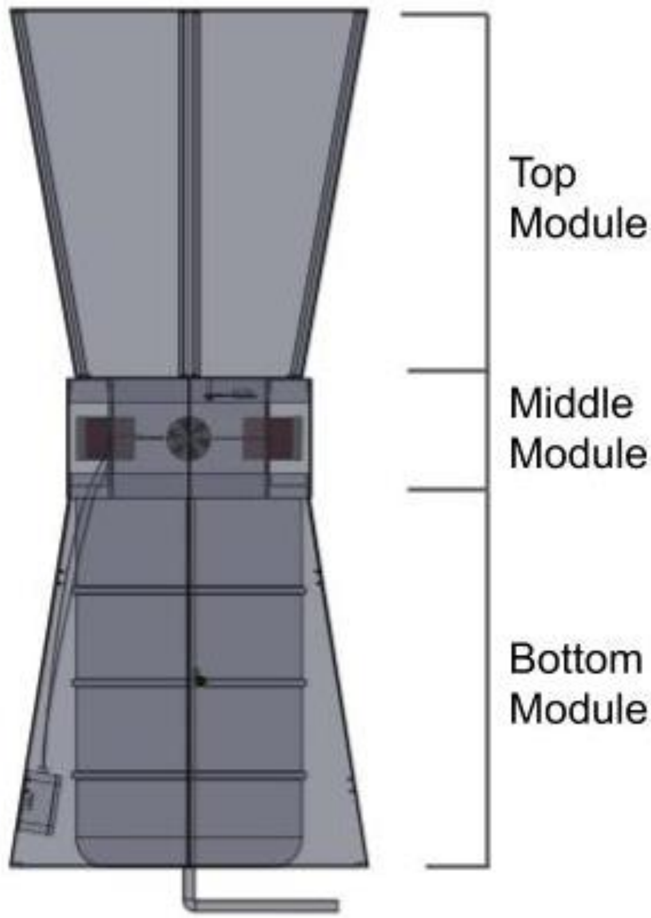
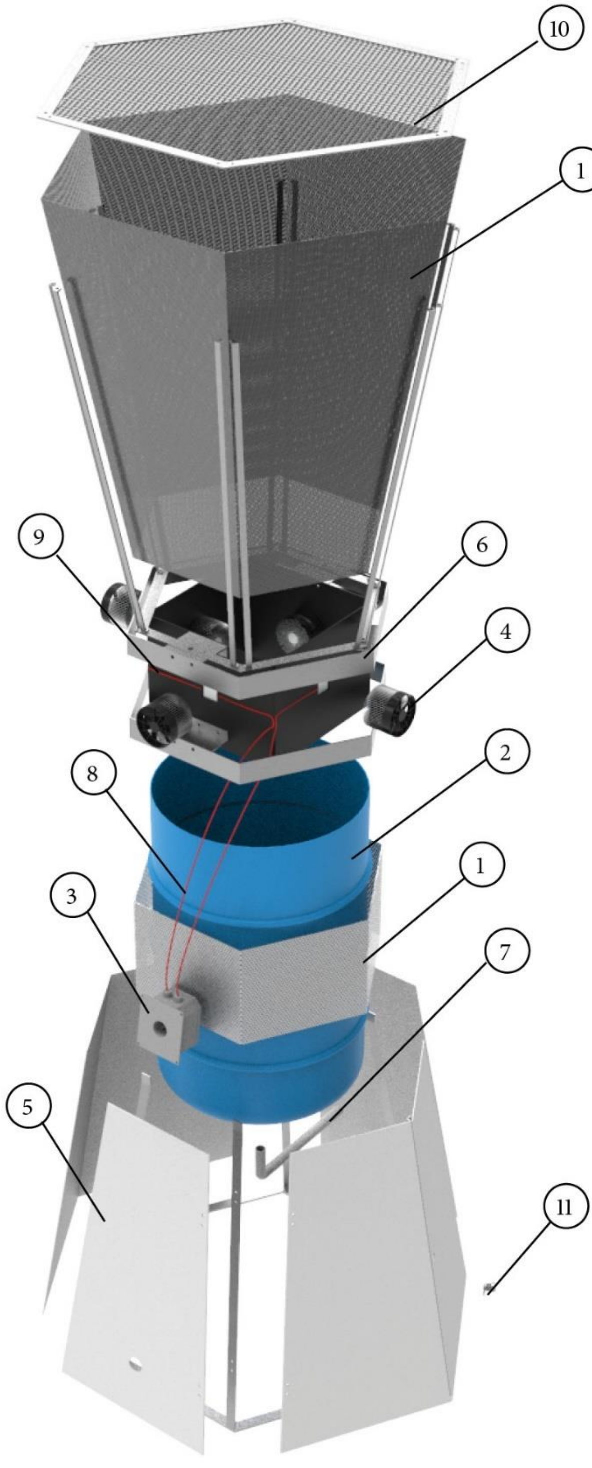


Figure 6.11 Orthographic view of AWG and module diagram [Martinez 2020]

Figure 6.12 is a general price breakdown for Härvist. These prices were gained by acquiring quotes from local sources and required to be able to give a cost comparison against the market competitors.



Bill of Materials

Item	Material	Units	Total
1	Mesh membrane	1	$34.32
2	Gallon drum	1	$46.00
3	Smart controller	1	$50.19
4	TEC stacks	4	$139.80
5	Aluminum	6	$133.92
6	Flat bar	17	$103.32
7	PVC pipe	1	$8.00
8	Wire harness	1	$8.00
9	HDPE sheet	1	$15.92
10	Wire mesh	2	$12.80
11	Hardware	1	$12.00

Grandtotal = $564.27

Figure 6.12 Härvist exploded BOM diagram [Martinez 2020]

The top module has an upper and lower hex, connected by angled brackets fixed by mechanical fasteners for the funnel and the main filter. The mesh membrane is then wrapped, double plied, around this structure.

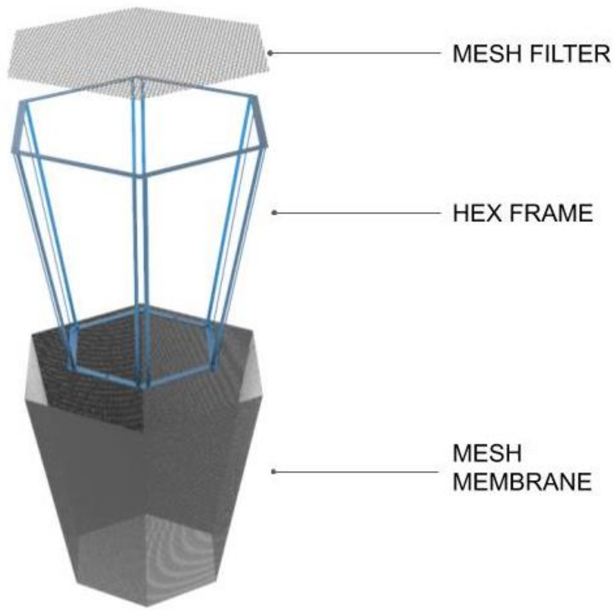


Figure 6.13 Exploded view of top module [Martinez 2020]

By using a slotted bracket in the middle module and a pin on the top module, the harvester has a quick release where the user can lock in the top module and release it quickly for maintenance and repair. By using a recessed slider, the user, with a screwdriver, can reach into the Härvist opening and release the quick-release lock. This is for added security and reliability of Härvist.

module.

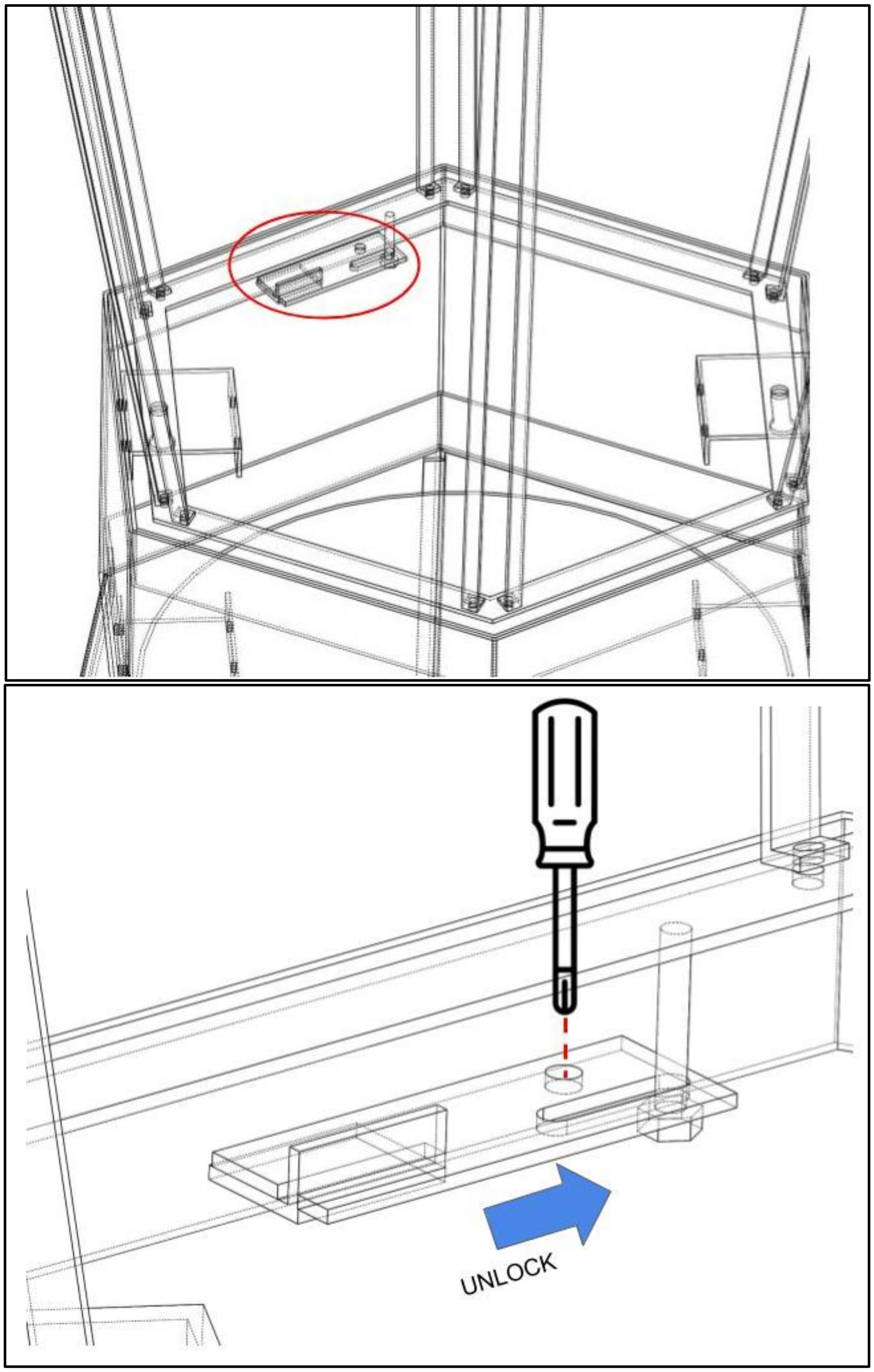


Figure 6.14 How to unlock to top module [Martinez 2020]

The middle module is assembled by bolting on TEC stacks to the condenser unit. Four brackets connect the condenser unit to the metal vent cover and bottom module.

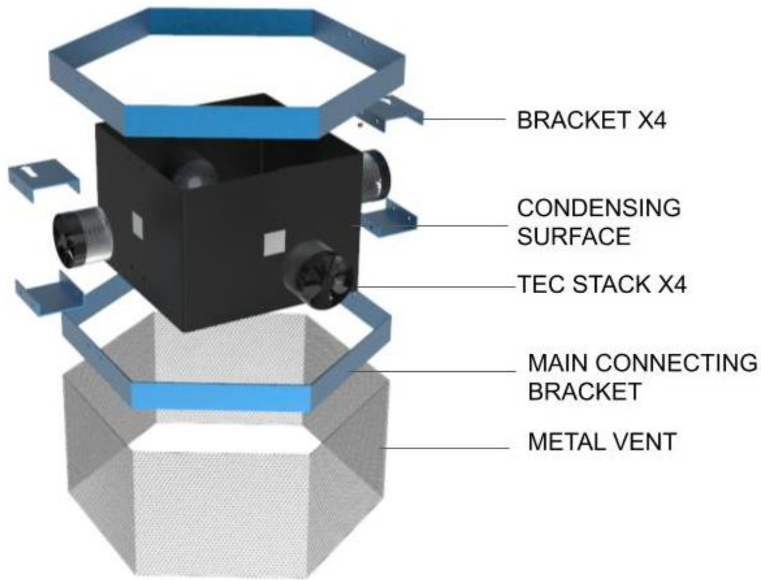


Figure 6.15 Exploded view of middle module [Martinez 2020]

The bottom module is assembled much like the top, with angled brackets connecting an upper and lower hex, but instead of the mesh, sheet metal is fastened for creating a protective covering for the smart controller and the off-the-self, 30-gallon barrel drum that is closed behind a hinged, locking access panel. The bottom module contains the controller with the serial monitor output.

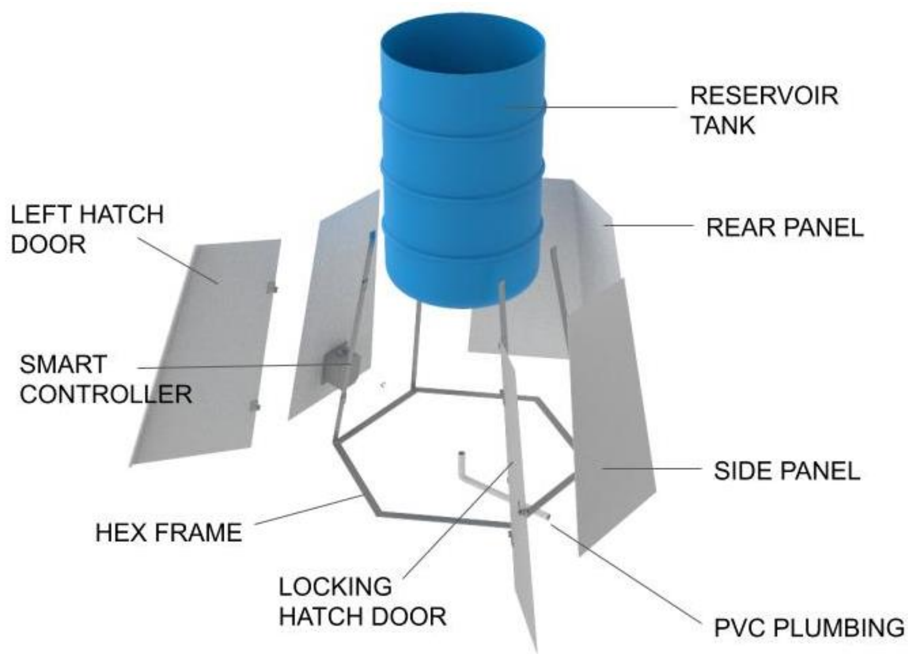


Figure 6.16 Exploded view of bottom module [Martinez 2020]

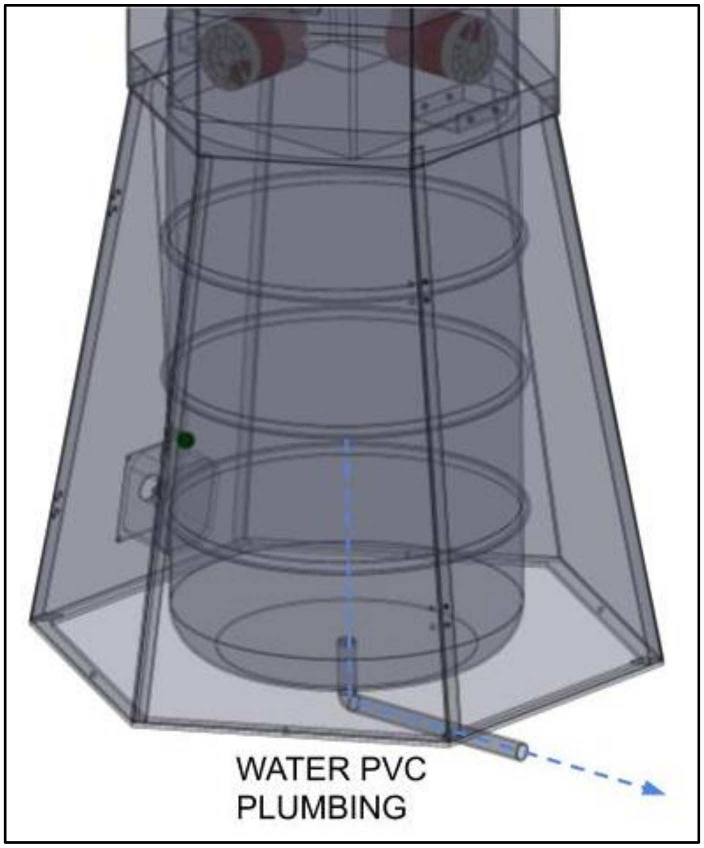


Figure 6.17 PVC plumbing connection to reservoir tank [Martinez 2020]

Once the modules are assembled, the installation process needs to be user friendly to facilitate maintenance and modularity. The PVC plumbing is designed to be placed in the crushed stone plumbing system described in the previous section.

6.5 Installation

Installation of Härvist was designed for a single user. Many AWG's on the market require teams and communities to put them together but Härvist can be delivered, assembled, installed, and repaired by a single person, which is a key differentiating factor of this design.

Figure 6.18 Step 1 installation [Martinez 2020]

The majority of the module will be delivered prefabricated to minimize the user assembly. Step one in the installation process is to place the reservoir inside of the bottom module, in preparation for plumbing and additional module installation.

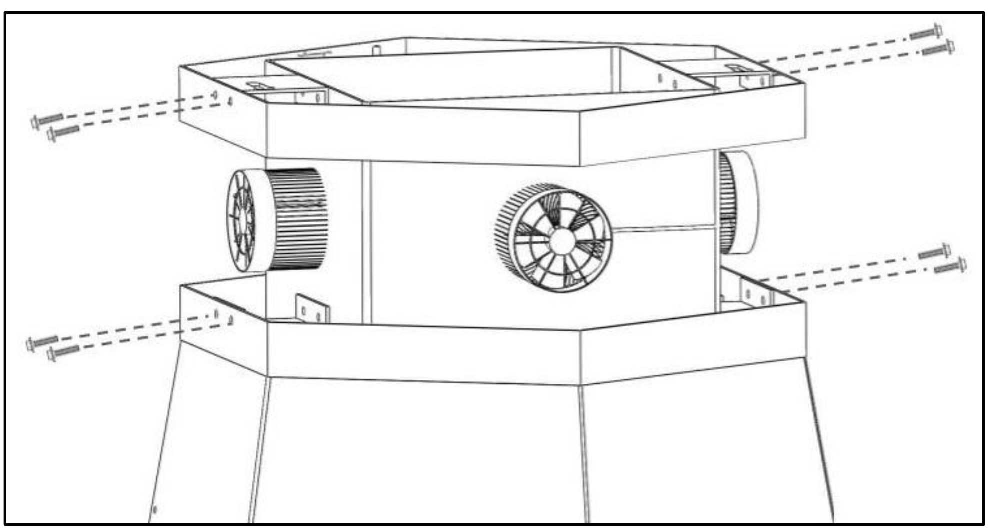


Figure 6.19 Step 2 installation [Martinez 2020]

Once the bottom module is set, step two requires the middle module brackets to be lined up with the condenser unit and eight fasteners are used to fix the middle module to the bottom module.

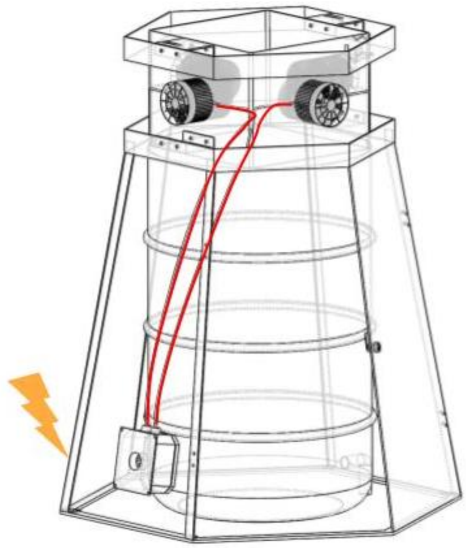


Figure 6.20 Step 3 installation [Martinez 2020]

Step three is connecting the TEC stacks to the smart controller by routing the wiring harness to the smart controller and fastening the supplied MOLEX connectors used in most automotive applications for their reliability and ease of use. This will give the condenser unit power and allow for tandem powering of modular units.

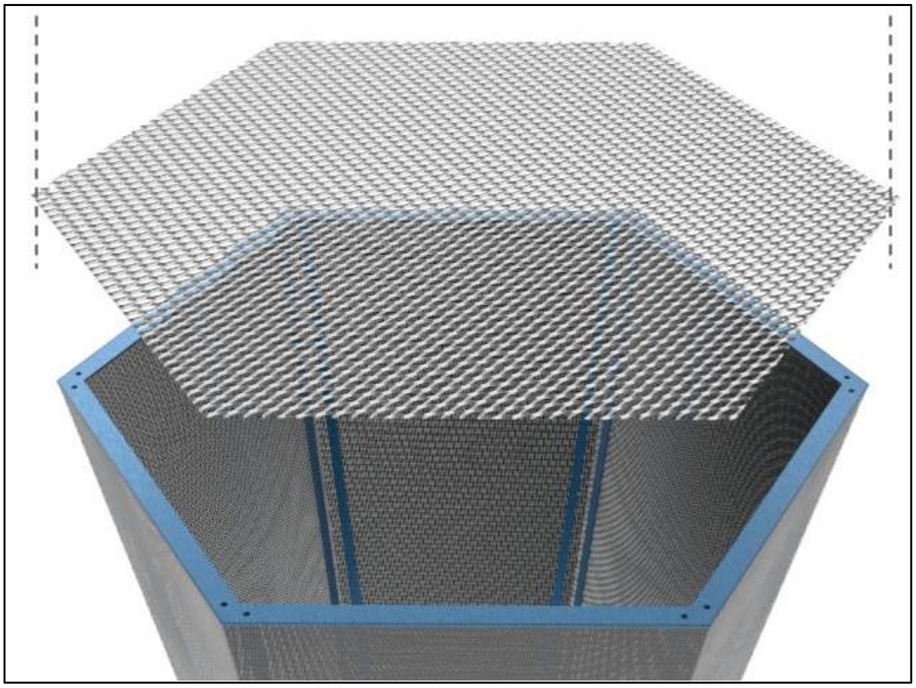


Figure 6.21 Step 4 installation [Martinez 2020]

The main filter is critical to ensure long term device reliability. With incoming water, the device plumbing can get clogged up due to debris. This filter is fastened onto the top hex bracket of the top module prior to installation of the top module to avoid the use of a ladder for installation.

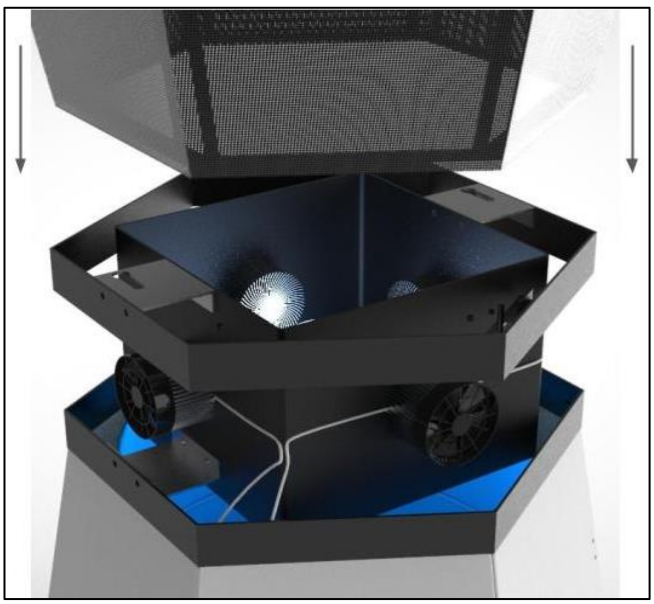


Figure 6.22 Step 5 installation [Martinez 2020]

Once the filter is placed, the top module can be slotted in and locked using the quick release mechanism to ensure security of lower modules.

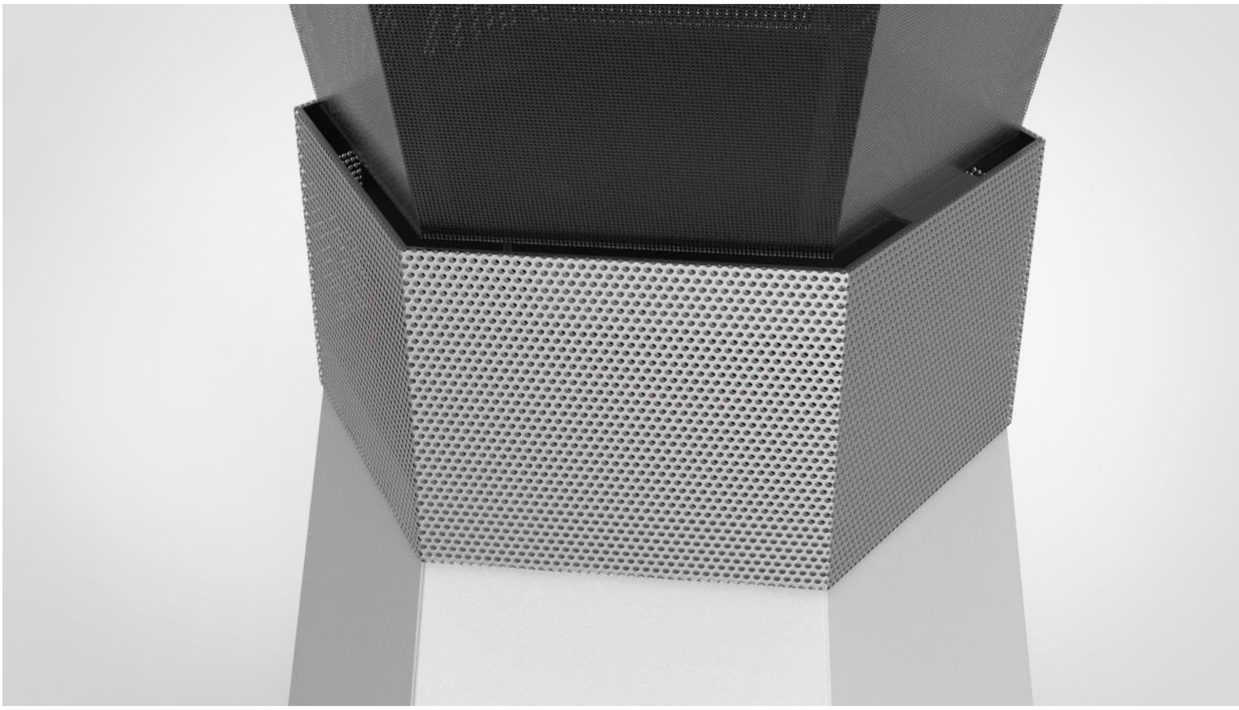


Figure 6.23 Step 6 installation [Martinez 2020]

Lastly, the metal grill is mechanically fastened to the middle module with metal screws, to cover and protect the condenser unit from debris and tampering.

Figure 6.24 Härvist array [Martinez 2020]

6.6 Maintenance & Repair

Periodic maintenance and possible repairs are required for the Härvist unit. Härvist was designed for non-experts to be able to run and trouble shoot as a human factor focus. For periodic maintenance, two areas are high risk, first is the primary filter, second, since Härvist will be wet most of the time, mold can be an issue for condensing surfaces. Filters can be accessed by removing the top module, removing large debris by hand and washing away the smaller debris. Once the top module is removed, shown in the cross-section Figure 6.25, the middle module is easily accessible. Giving way to the condenser unit and TEC stacks for cleaning of condensing surfaces and TEC repair. The TEC's themselves connect to the main wiring harness through MOLEX connectors. Therefore, if a TEC is down, the serial monitor will show no change in temperature, the TEC is identified, disconnected and switched out by removing the fan with a Phillips screwdriver.

The reservoir tank is stored in the bottom module. The bottom module has an access hatch that is fitted with a cam lock for security. This cam lock restricts access to the water reservoir and smart controller for safety and security measure. Therefore, to be able to clean the reservoir, the cam lock needs to be unlocked to open as shown in Figure 6.26.

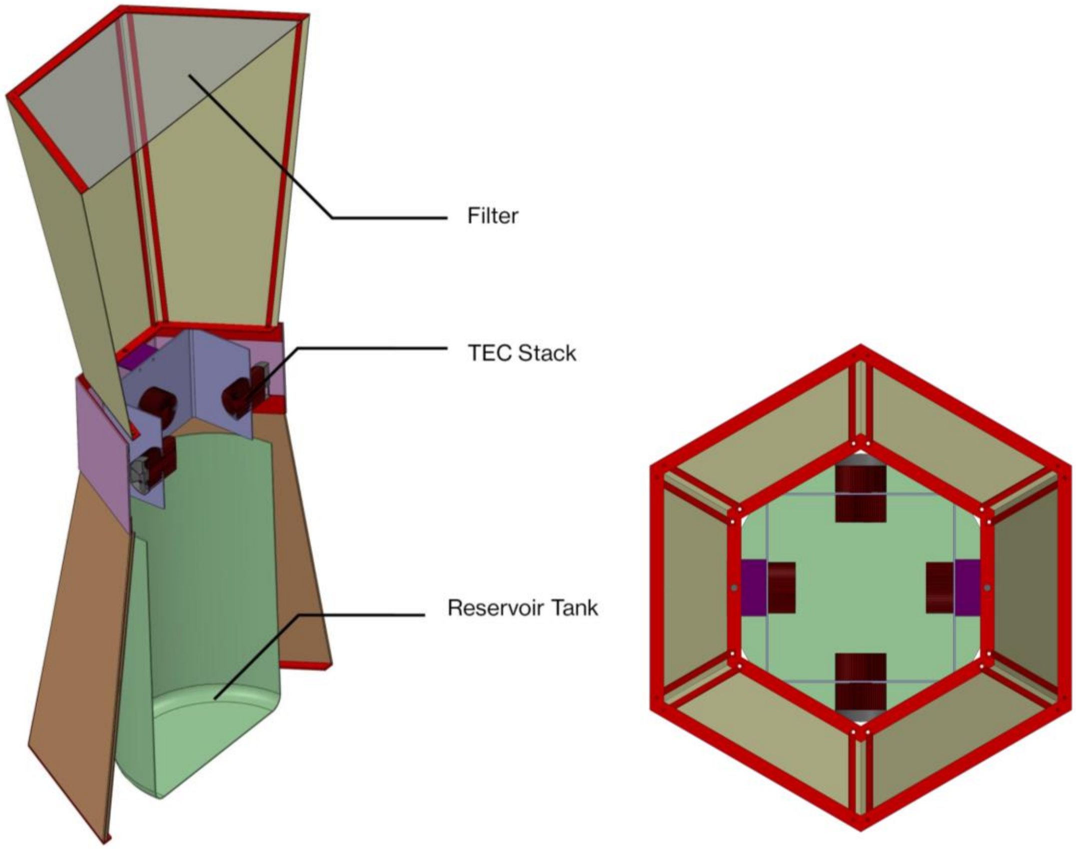


Figure 6.25 Cross-sectional view of Härvist, highlighting high maintenance or repair areas [Martinez 2020]

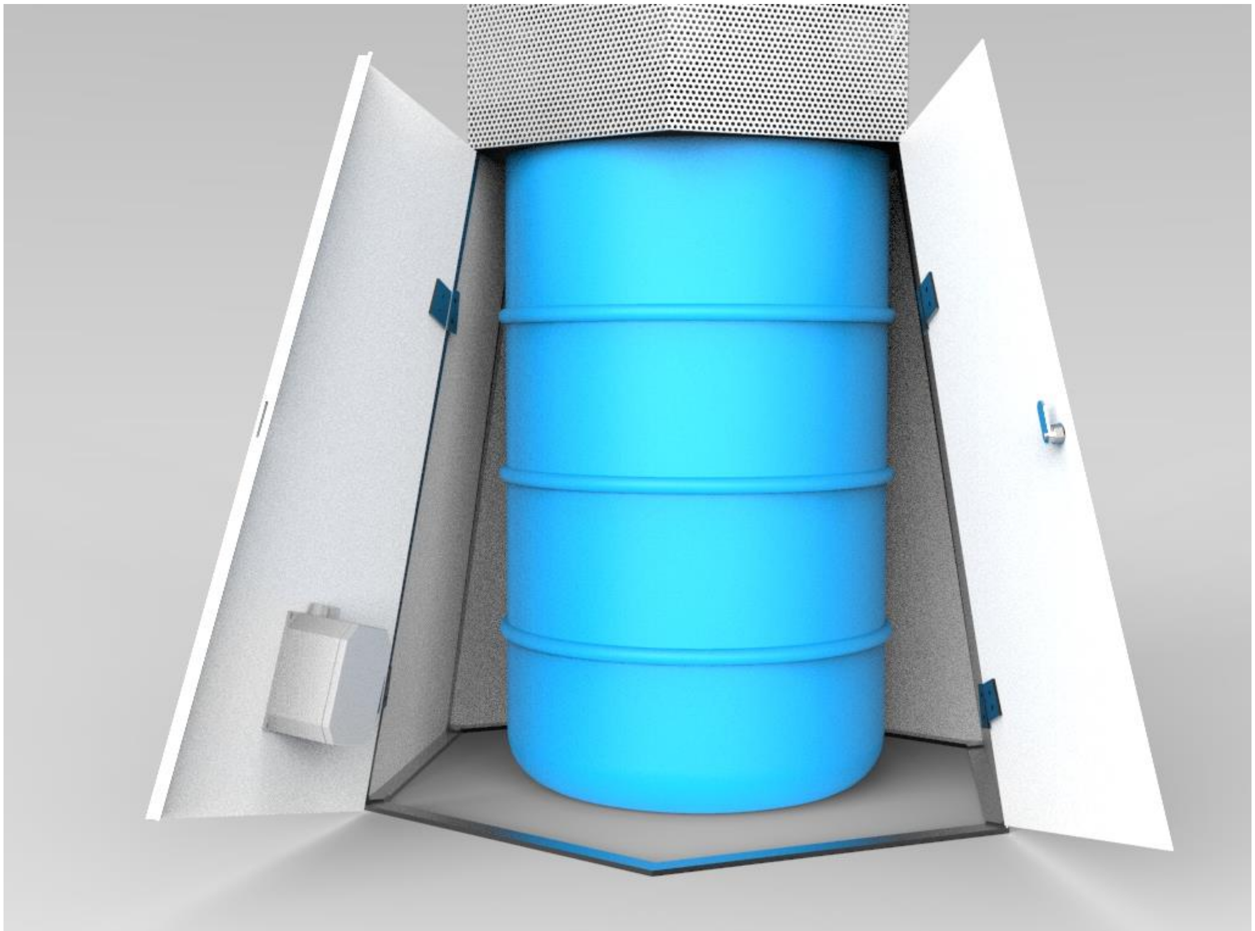


Figure 6.26 Hatch doors for bottom module [Martinez 2020]

As an alternative to the drum reservoir, a bladder can be used to further decrease volume for shipping and delivery. This bladder can be any size needed. The one shown in Figure 6.27 is a 30-gallon bladder and would require a hose line connected to a funnel to capture the water. A Härvist unit can be assembled by constructing a frame with whatever materials are available, installing the middle module and smart controller. This allows for easier shipping if Härvist were to be installed internationally. This strategy can decrease overall cost, allowing access to a greater market. The smart controller is housed in a junction box shown in Figure 6.28 but can alternatively be replaced with an equivalent housing.

Figure 6.27 Bladder reservoir
https://texasboom.com/bladders-tanks/collapsible-potable-water-bladder

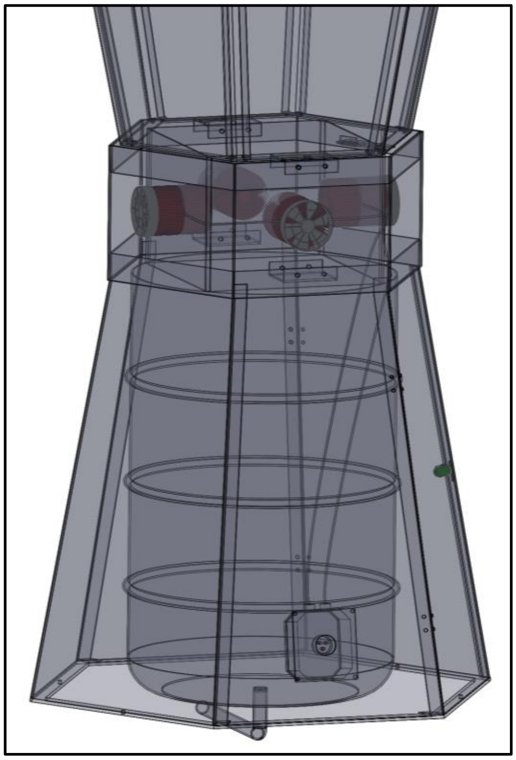


Figure 6.28 Smart controller junction box and power input [Martinez 2020]

VII. Results

7.1 Fog Harvester

Although the proof of concept did not yield measurable water during the time of the study, there is data out there for theoretical analysis of mesh membranes. As outlined in the literature review, the Rashcel mesh can yield 17.25 L/day in this type of climate [36]. This has been tested by research teams in climates above 60% relative humidity and high ambient temperature, observed over time. Table 7.1 outlines the water yield calculation for the Härvist.

Table 7.1 Calculation for mesh membrane water yield [Martinez 2020]

Mesh Membrane	Production Rate	SFA	Yield
Raschel	0.93 L/ft^2/day	18.56	17.25 L/day

7.2 TEC Condenser Module

There is TEC prototype research data available. From market products to experimental proof of concepts, TEC data is more reliable and ubiquitous. This comparison is between the Härvist TEC stack versus prototypes and products found in the literature review. Our specific TEC proof of concept yielded water as expected. The Härvist TEC stacks have the lowest production, relative to surface area, against its competitors as seen in Table 7.2. This can be due to decreased insulation of the condenser unit as a whole. Many of the experimental prototypes in the literature review were built as completely closed systems, therefore they have increased thermodynamic flow.

Table 7.2 Comparison chart for condenser unit [Martinez 2020]

AWG	Cost	Production	Dimensions	Surface Area	Liters/ft^2/day	Liters/$	Power
(39) Prototype		0.6 L/day		2.33 ft^2	0.26 L/ft^2		58.2 watts
(11) Prototype		14.6 L/day		9.32 ft^2	1.57 L/ft^2		125 watts
(42) Prototype	$57	0.21 L/day		1.165 ft^2	0.18 L/ft^2	.0037 L/$	22.2 watts
Aquaboy	$1,849	25 L/day				.014 L/$	500 watts
Härvist	$139.80	1.6 L/day	26.68 ft x 8.4 ft	9.32 ft^2	0.17 L/ft^2	.011 L/$	52.3 watts

7.3 Rainwater Collection

As seen in chapter five, our rainwater collection system also functioned as expected. With Härvist, each module has the probability of generating 1.6 L/d seen in Table 5.2. Out of all the water yielding strategies, rainwater is the most common and sustainable.

7.4 Comparison Analysis

Table 7.3 illustrates the overall performance of Härvist compared to market competitors described in chapter two. Here, it is seen that Härvist has a very efficient use of space relative to other solutions. Fog collectors require massive surface areas, but it is even more efficient in volume relative to the condenser units. This results in an increase in efficiency there, however, cost wise, the Härvist is on par or a little lower in water yield relative to the overall cost of the machine.

Table 7.3 Comparison chart for market competitors [Martinez 2020]

AWG	Cost	Production (L/d)	Surface Area (ft^2)	Liters/ft^2/day	Liters/$
FogQuest	$1,500	200	430.56	0.4645	0.1333
Warka Water Tower	$1,500	80	1485	0.0539	0.0533
TEC Dehumidifier	$47	0.45	8.3	0.0542	0.0096
SOURCE Panel	$2,000	6.25	32	0.1953	0.0031
Härvist	$564.27	16.04	42.713	0.3755	0.0284

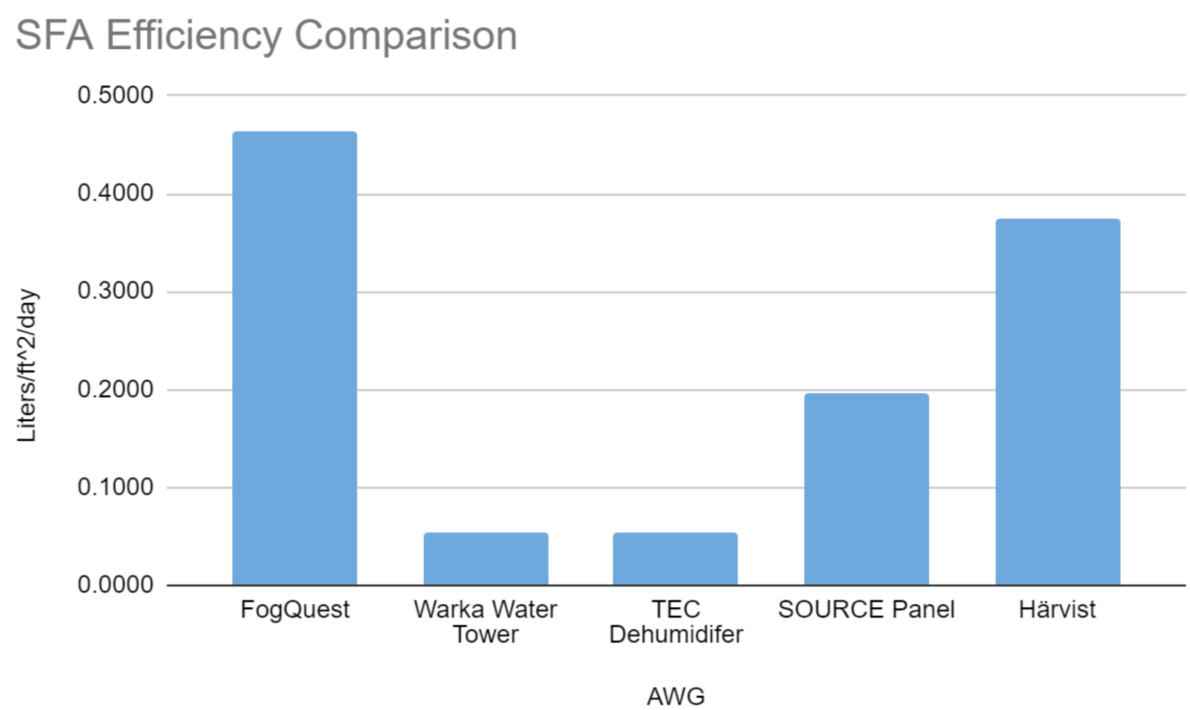


Figure 7.1 Comparison of surface area efficiency [Martinez 2020]

Table 7.4 adds up to a total yield for the Härvist per day. This means that if we were to balance out the Ag Hub deficit of 230 L/day, you would need 12-14 machines. At approximately $560 per unit, the total initial investment for the array would be about $7,800.

Table 7.4 Calculation for total water yield of Härvist

Fog Harvest (L/day)	Dew Collector (L/day)	Rainwater (L/day)	Total Yield (L/day)
11.17	1.864	3.01	16.04

VIII. Conclusion

8.1 Results

Overall, Härvist is able to supply the Ag Hub water deficit, giving it the option to be net-zero. Härvist is able to do this at a fraction of the cost of competitors and is the most adaptable to the site needs. With its ability to be assembled and maintained by a person with no special competency Härvist is the best solution for this problem and many other similar situations. By being modular in multiple levels, Häarvist is able to decrease shipping size and allow the user to deploy only what they need, allowing savings of carbon emissions. Although the results show promise in the hybridization strategy, it can still be improved immediately by decreasing the cost per unit for projects that have less resources by using the modular strategy. Härvist is the first AWG to combine three water yielding methods in a singular, compact thought out form. Through the use of the design process a solution was formulated, taking us one step closer to solving the complex issue of water scarcity.

8.2 Limitations of Study

Some limitations for this study are time and cost. Time when it comes to the rain and fog harvesting as these strategies are usually observed over years to gain data. Studies outlined in the literature review have made the calculations in this study possible. Also, the ability to source the Raschel mesh as there are very few suppliers available in our local area. And lastly, the condenser unit with TEC stacks can be made more efficient by adding insulation, as they did in previous studies.

8.2 Future Work

Many AWG products on the market have on-board filtration, therefore, water filtration for Härvist is a promising opportunity to provide immediate drinking water. Also, the ability to be an Internet of things (IoT) device, allowing Härvist to connect to a local Wi-Fi or Bluetooth device will allow the user to interact with it intuitively. Disassembly for recycling/repurposing is a key pillar of cradle-to-cradle design. Therefore, mapping out a process for the end of use life for Härvist is another way this device can further sustainability.

Disclaimer

Reference to any companies or specific commercial products is for descriptive purposes only and does not in any way constitute endorsement, support, or disdain for their product.

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