MCGILL UNIVERSITY

DEPARTMENT OF MECHANICAL ENGINEERING

ATMOSPHERIC HARVESTING METHODS

MECH 497– VALUE ENGINEERING

TEAM D – TECHNOSPIN

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Executive Summary

The aim of this project is to investigate atmospheric water harvesting methods. This value engineering analysis was performed to address various client's needs.

Objectives

Some methods for atmospheric water harvesting were reviewed. Atmospheric and social conditions for a successful deployment of the technology were considered. The technology was selected using a value engineering methodology. The technology is meant to be used in a remote location to supply water mainly for agricultural activities (feasibility for human consumption is an added advantage).

Methodology

After defining the scope of the problem, a functional analysis in order to assess the client's needs was performed. Next, the creativity phase resulted in the generation of multiple ideas of available methods of atmospheric water harvesting. Then, these ideas were evaluated using the gut feel index and a multi-criteria matrix. We narrowed down the concepts to 4 possible technologies: geothermal cooling, desiccant technology, radiative cooling condenser and traditional fog harvesting mesh nets. Then, the 4 technologies were analyzed in order to select the optimal concept for atmospheric water harvesting in given conditions.

Summary of technologies

The Airdrop geothermal cooling system allows to passively collect atmospheric water by pushing air through underground pipes in order to cool it down and achieve condensation. Then, the solar desiccant collector system uses solar energy and solid desiccants to extract water from atmospheric air. The radiative cooling condenser system is inspired by the principle of dew formation on plants. For this design, the formation of dew is caused by a radiation phenomenon on the surface of the technology. Finally, the traditional fog harvesting mesh nets capture the moisture in the fog as opposed to capturing dew or condensation. This technology extracts the liquid water by intercepting the wind that carries the fog.

The performance and the best implementation of the 4 technologies are summarized in the following Table.

Table 1: *Performance and Conditions required for the 4 Technologies*

	Airdrop Geothermal Cooling	**Solar Desiccant Collector System**	**Radiative Cooling Condenser**	**Fog Collector Nets**
Performance	0.7 L/m^2/day	2.5 L/m^2/day	1.3 L/m^2/day	5.3 to 13.4 L/m^2/day
Conditions	- 25 to 36 °C, - 50 to 80% of relative humidity	- 25 to 36 °C, - 50 to 80% of relative humidity	- Large surface area, - 10 to 25 °C, - 70 to 80% of relative humidity	- Presence of fog, - 10 to 25 °C, - 70 to 85% of relative humidity

Recommendation

The best concept that meets the client's needs is the traditional fog harvesting mesh nets for their great cost-value characteristics. A typical village project will cost approximately $15,000 USD for the total lifecycle of 10 years and will produce 2000L of water per day. This outcome will certainly satisfy the main project requirement of providing water for agricultural activities and will also be able to provide water for human consumption. In arid environments, some of the other options are indicated in Figure 4. Moreover, there may be still other options yet to be discovered, evaluated, and compared later. Therefore, such investigation is an ongoing process.

Introduction

Value Engineering

Value Engineering is a systematic methodology to improve projects, products and processes at the lowest cost possible. Value is achieved with the client's satisfaction while minimizing the cost of resources.

$$Value = \frac{Satisfaction\ of\ Needs}{Cost\ of\ Resources}$$

Water Harvesting

Water harvesting is done by cooling the ambient point below its dew point and collecting the condensate. Moisture harvesting materials enable spontaneous vapor sorption to trap water molecules, which extracts vapor from air. Using this specific method, one can harvest water in low relative humidity in addition to high relative humidity (H. Kim, 2018). The ideal moisture harvesters have the following elements (A. LaPotin, 2019):

- High water uptake
- Low energy demand
- Fast water capture
- High cycling stability
- Low cost

To evaluate water harvesters, we can calculate the specific energy consumption and ratio for water absorption effectiveness. Specific energy consumption per unit mass water production is calculated in the following manner:

$$\frac{Q}{m} = \frac{C_p(T_1 - T_2)}{w_1 - w_2} + h_{fg}$$

The ratio for water absorption effectiveness is calculated in the following manner:

$$R = 1 - \frac{w_2}{w_1}$$

Where $T_1\ and\ T_2, w_1\ and\ w_2$ are the temperature and humidity ratio of the incoming air (1) and condensation (2), respectively. It should be noted that these formulas assume ideal heat and mass exchange. This concludes that optimal water harvesting occurs with low temperatures and high humidity ratio of air (T. Yaodong, R. Wang, Y. Zhang, J. Wang, 2018).

Client and Project Background: Technospin Water Harvesting Project

Technospin is an engineering consulting company that aims to introduce advanced manufacturing technologies and product designs to clients. They look to deploy an appropriate atmospheric water harvesting method in remote locations. These areas currently have an insufficient water supply, which is further deteriorating. They are dependent solely on rain as the water source for their agricultural activities and human consumption. However, there is substantial water that can be harvested from the atmosphere. Atmospheric water can be condensed and collected using various technologies. Technospin's goal is to supply the most suitable existing technology for atmospheric water harvesting to these remote areas.

Team Members

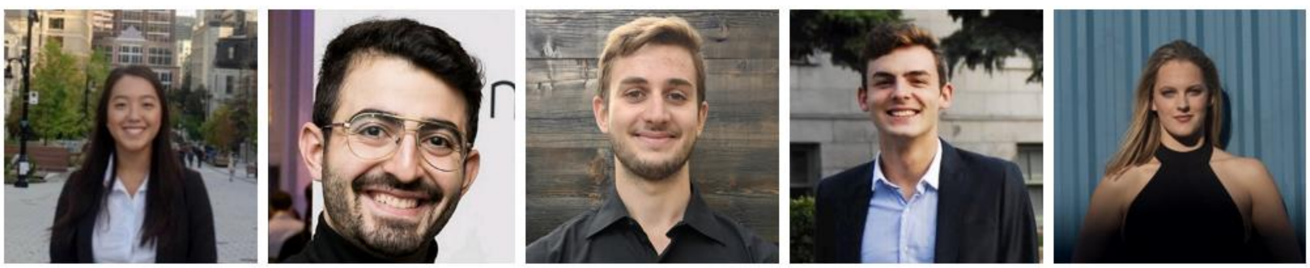

Figure 1: *Team members*

From left to right:

- Jenny Li
- Vassil Kroumov
- Emeric Bernier
- David Masson
- Esmee Smit-Anseeuw

Methodology

In order to select the most suitable solution to meet our project's goals, we needed a clear and organized method to evaluate all the available technologies. We started this process with a functional analysis.

Functional Analysis

Information Phase

The first stage in the functional analysis is the information phase where we defined the goals and objectives of the project, the project's scope, and the users of the technology that we would be implementing. In this stage, team members are encouraged to think and speak freely about ideas. We made a list of all the needs that our final solution would need to satisfy.

List of Needs:

- Harvest water
- Store water
- Work in areas with high temperature
- Work in areas with low humidity levels
- Require non-technical users
- Cost effective
- Low maintenance
- Develop procedure to evaluate with defined parameters
- Delivered
- Manufactured
- Assembled

Function Identification

Next, we made a list of the primary and secondary functions that the technology implementation must satisfy. The primary functions are the main tasks that the technology must perform; whereas the secondary functions are not as critical but will help the technology achieve its purpose more efficiently.

List of Functions:

- **Primary function**
    - Supply water
- **Secondary functions**
    - Harvest atmospheric water
    - Easily implemented

- Easily maintained
- Be versatile to all atmospheric conditions
- Be adaptable
- Resist corrosion

Environmental Analysis

In order to further analyze the functions, an environmental analysis of the quintessential technology was made. This analysis was done to examine how the technology and its functions would affect its surroundings. The analysis involved the following steps:

1. Identification of environmental elements that interact with the process
2. Definition of the element characteristics
3. Defining the relation between each element and the process
4. Identification of links between elements

Note that in this case, the 'product' is the water harvesting process.

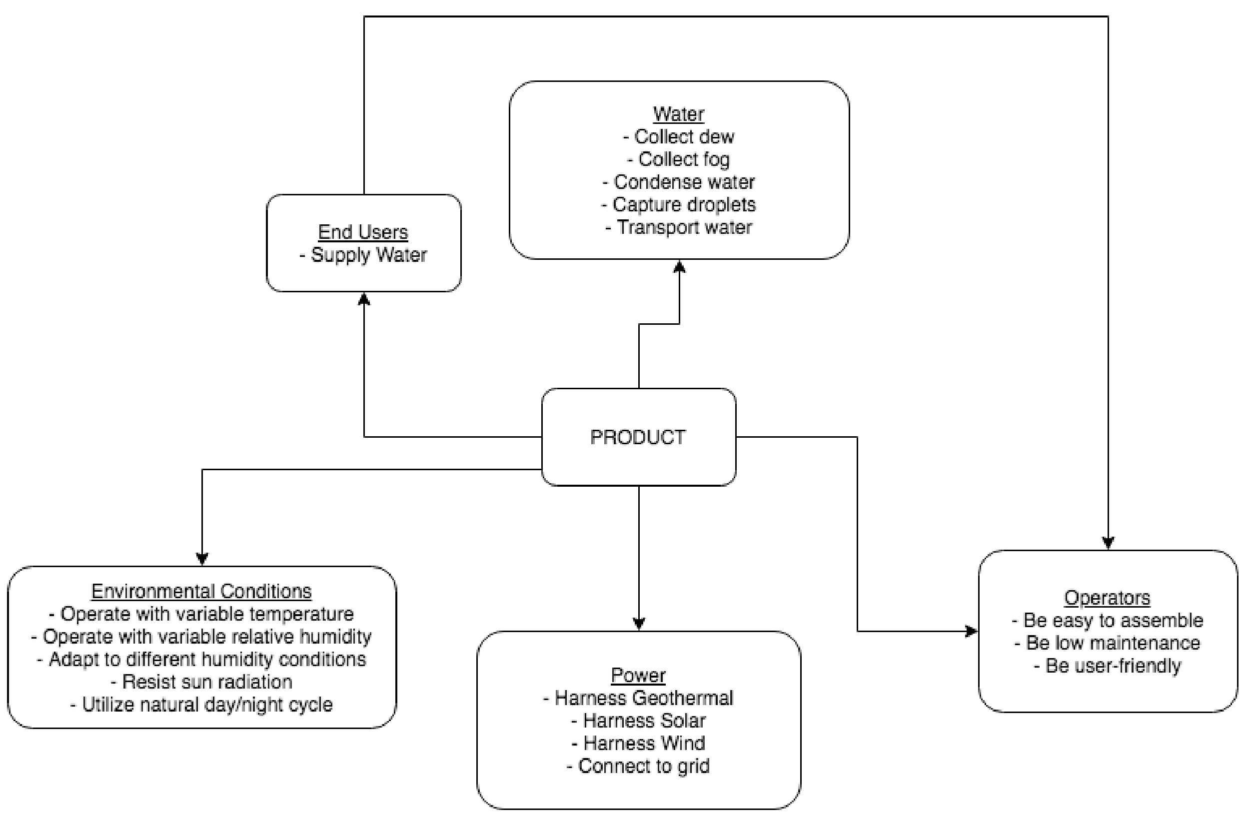

Figure 2: *Environmental Analysis*

Flexibility Table

From there, we created a flexibility chart, which allowed us to analyze the strictness of all the requirements. Creating this chart allowed us to get a better idea of which functions to prioritize. In this chart, we listed the function, the function criteria, the level of acceptability and a flexibility rating going from F3-F0, with F0 being the most rigid.

Table 2: *Flexibility Analysis Table*

Function	**Criteria**	**Level**	**Flexibility**
Supply water	Volumetric flow rate	5L/m^2/day	F0
Transport water	Water losses	< 5%	F0
Collect fog/dew	Volume per area per day	5L/m^2/day	F1
Require minimal operator training	Operator training	<5 hours	F1
Ensure easy maintenance	Maintenance time	<2 hour/week	F1
Ensure easy installation	Installation time	<4 hours	F1
Consist of simple equipment	Geometry of parts	N/A	F2
Consist of minimal components	Number of parts	<10 parts	F2
Deter animals	Infrastructure	N/A	F2
Resist corrosion	Warranty	10 year	F0
Withstand strong winds	Wind speed	Up to 100 km/h	F2
Resist heat damage	Ambient Temperature	Up to 100°C	F2

Functional Diagram

Finally, the functions were organized into a diagram in hierarchical form where the functions become more specific as the tree is branched out. Asking the two questions of "why" and "how" identifies the functions.

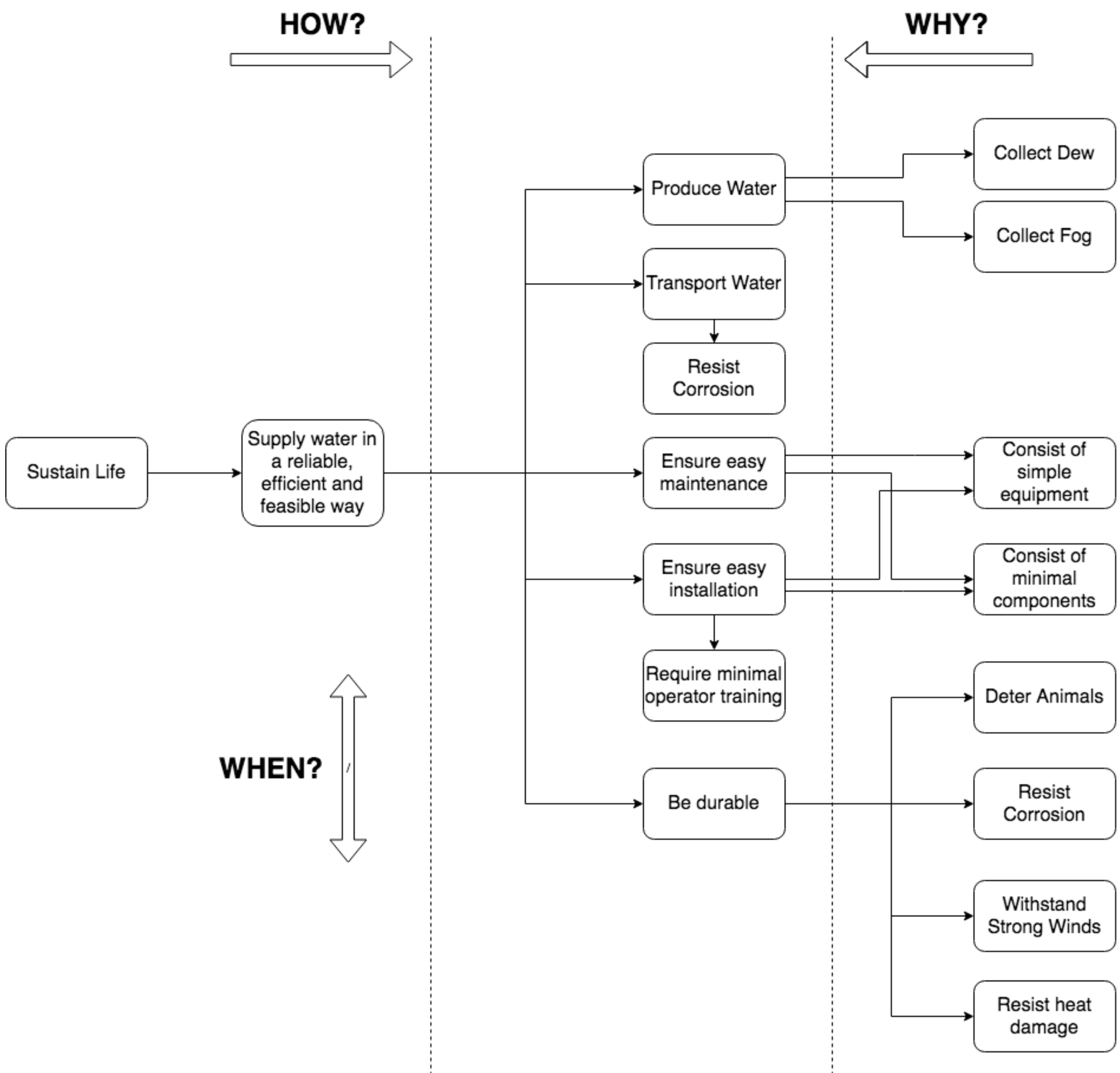

Figure 3: *Functional Diagram*

Creativity Methods

In the creativity stage, the team brainstormed the most amount of ideas as possible. For full efficiency of the session, the facilitator had to encourage the members to contribute ideas without censorship. Every idea had to be discussed among all group members, no matter how unfeasible it may have seemed at first glance. Factors such as the budget, complications, time needed to implement and logistics of implementation were not considered in this phase. Members and the facilitator had positive attitudes, inducing creativity. With the online nature of the course, a white board application was used over zoom to stimulate a creative and informal work zone. With each member having different skillsets and strengths, we were able to fill a list of ideas of all ranges. In addition, parts from different ideas were combined to create hybrid solutions. This is known as a morphological combination. The list of all the feasible technologies that we researched and analyzed in the creativity session are as follows:

- Airdrop geothermal cooling
- AWG passive system with sheet bed desiccant
- AWG passive system with chloride desiccant
- RAWG active system with solid desiccant
- RAWG active system with liquid desiccant
- Radiative cooling condenser
- Classic mesh design for fog-harvesting
- Harp design for fog-harvesting
- Spider-web inspired design for fog-harvesting
- Multi-layer hydrophilic vs hydrophobic design based desert beetle for fog-harvesting
- Use of superhydrophobic surface treatments for fog-harvesting
- Use of electrodes to attract fog droplets to the mesh for fog-harvesting

Evaluation Methods

Gut Feel Index

All ideas generated in the creativity section were then evaluated using the “gut feel” index methodology. This method allowed us to narrow down to our top solutions that we would further analyze. Any idea with a score less than 5 was discarded. We then moved on with the four top solutions that had either a score of 6 or 7.

Table 3: *Gut Feel Index Analysis Table*

Ideas	Gut Feel Index	Comments
Airdrop geothermal cooling	6	Versatile, good for agriculture,
AWG passive system with sheet bed desiccant	2	Not an efficient desiccant
AWG passive system with chloride desiccant	7	Requires low amount of power
RAWG active system with solid desiccant	3	Requires a lot of Power
RAWG active system with liquid desiccant	2	Requires a lot of power and mixing desiccant is complicated
Radiative cooling condenser	7	Implemented in India, low tech
Classic mesh design for fog-harvesting	7	Low-cost, simple, but risk of not working in every location
Harp design for fog-harvesting	4	Only been tested in a research setting, no data available for large scale set up
Spider-web inspired design for fog-harvesting	4	Not yet implemented, no data available if it works
Multi-layer hydrophilic vs hydrophobic design based off dessert beetle for fog-harvesting	4	Not implemented
Use of superhydrophobic surface treatments for fog-harvesting	1	Not durable, added cost without increased value
Use of electrodes to attract fog droplets to the mesh for fog-harvesting	2	Requires additional energy supply without increasing efficiency significantly

The following technologies were found to be feasible according to the gut feel index and will be examined further:

1. Geothermal cooling
2. Desiccant technology
3. Radiative cooling condenser
4. Traditional fog harvesting mesh nets

Multi-Criteria Analysis

The key criteria in the evaluation of the design alternatives were defined based on the customer requirements. The criteria are listed below. An acceptable range for testing each criteria is also indicated.

1. **Performance**: The device must produce the maximum amount of water daily.
2. **Versatility**: The device must have the ability to adapt to many different regions.
3. **Consistency**: The water production should remain the same at different times.
4. **Size**: The device must be as compact as possible.
5. **Ease of Installation:** The device must be easily implemented and require minimal training to install.
6. **Durability:** The device must last as long as possible.

The multi-criteria analysis table allows for the comparison of several concepts leading ultimately to which best meets a set of criteria. In this project, each criteria is given a weight factor from 1 (worst) to 10 (best). Also, each concept is ranked from 1 (worst) to 10 (best) on how they fulfill each criteria relative to one another. The merit of the concept is characterized by the total weight; the greatest the total weight, the greatest merit is attributed to the concept.

Table 4. *Multi-Criteria Analysis Table to Rank the Various Concepts According to Given Evaluation Criteria*

Criteria	Weight	Airdrop Geothermal Cooling	Solar Desiccant Collector System	Radiative Cooling Condenser	Fog Collector Nets
Performance	9	3	6	5	9
Versatility	7	9	6	6	2
Consistency	7	9	4	4	3
Size	4	9	8	1	5
Ease of Installation	3	4	9	2	7
Durability	6	4	7	9	3
TOTAL		225	225	179	175
COST ($/m^3 H_2O)		$ 120.00	$ 45.00	$ 35.00	$ 2.00

In terms of performance, the first concept is clearly the least favorite since it produces the least amount of water per meter square daily. The second and third concepts produce an equivalent amount of water, but the solar desiccant collector system produces slightly more water daily. The fog nets clearly produce the most amount of water when in the appropriate operating conditions.

The airdrop geothermal technology is the most versatile since it does not require large temperature swings nor high air humidity to operate. The solar desiccant and the radiative cooling systems require large temperature swings to operate, and the fog nets require fog to operate.

The airdrop geothermal technology produces water the most consistently since it only requires the ground temperature to be lower than the ambient temperature to operate. The solar desiccant and the radiative cooling systems can only operate during the day, hence their score is lower. Again, the fog nets require fog to produce water, hence its low score.

The first concept is drilled in the ground, hence it does not require a lot of ground space. The solar desiccant system consists of a pyramid that measures approximately 1m^2 on the ground which is relatively small. The fog nets are big structures that measure approximately 40m^2, and the radiative cooling system consists of large aluminum sheets that require a lot of ground space.

The solar desiccant collector system is very easy to install given that it is essentially a pyramid box. The fog nets are a simple square structure that needs to be fixed into the ground. The airdrop geothermal system requires some work to install the various devices, and the radiative cooling system requires a lot of labor to dig holes and install the large sheet metal structure.

The radiative cooling system is the most durable given its robust structure. The solar desiccant system is durable since it is essentially a pyramid with a robust structure. The airdrop geothermal and the fog nets are not durable since they can be easily damaged by animals and the fog nets by wind gusts.

The third concept is very robust meaning it will last a long time. The second concept is also durable given that it is small and made of a robust frame. The first and fourth concepts are not durable since they can be easily damaged by animals and the fourth by wind gusts.

Psychometric Chart

Finally, all the solutions were plotted on a psychometric chart to showcase the regions for best performance. The regions for each technology were determined through literature and research, and are as follows:

- Airdrop geothermal cooling (green): 25°C+, 50%+ humidity
- Radiative cooling (blue): 10-25°C, 70-80% humidity
- Solar desiccant (yellow): 25-35°C, 50-80% humidity
- Fog net collectors (red): 10-25°C, 70%+ humidity (needs a 2.5°C difference between air temperature and dew point)

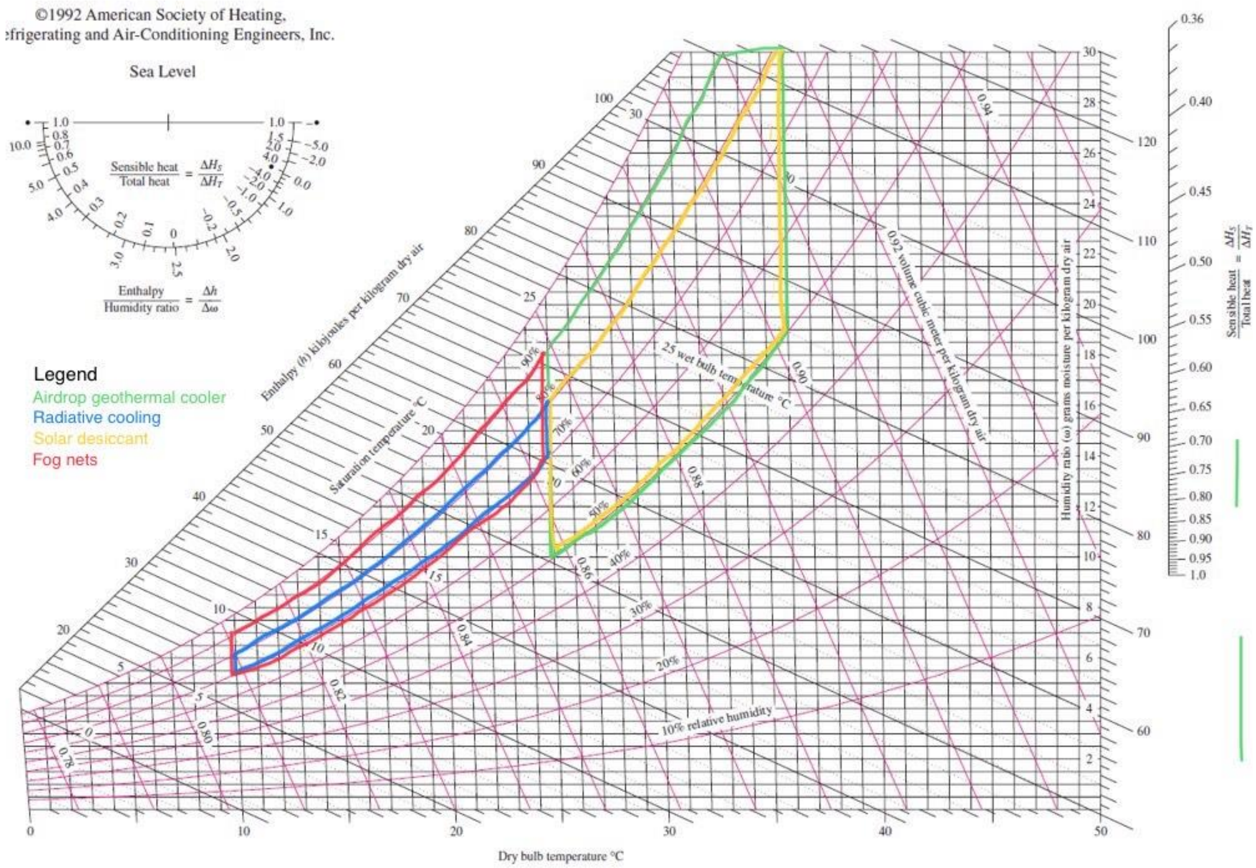

Figure 4: *Psychometric Chart for Performance of the 4 Technologies*

Proposals

Concept 1: Airdrop geothermal cooling

The Airdrop irrigation system allows to passively collect atmospheric water by pushing air through underground pipes in order to cool it down and achieve condensation. Then, the water can be delivered to the roots of the plants.

Figure 1 illustrates the Airdrop process. Indeed, the air is drawn into a turbine and then flows underground. The air is quickly cooled to soil temperature through the piping system in order to create an environment of 100% humidity. The condensed water can then be harvested and stored in an underground tank. The water in the tank is ready to be pumped for irrigation.

***Figure 5**. Airdrop Irrigation System*

The soil temperature at 2m depth is 6 degrees Celsius. By inserting copper wool into the piping as shown in Figure 6, the temperature of the soil is transferred to the piping inner wall and the wool which allows to drastically increase the cooled surface area the air is in contact with. Additionally, copper was chosen for its high thermal conductivity. Moreover, the wool stops the air from passing straight through which creates a turbulent flow and allows the warm air to stay in the piping in order to drop to soil temperature and efficiently produce condensation (Moses A., 2011).

Figure 6. *Innovative condensation process*

Assumptions

- For the system to work efficiently, it requires air to be drawn into the turbine or a sufficient amount of energy in the solar-battery unit
- The ground needs to be cold enough to cool air below dew point

Advantages/Disadvantages:

The Airdrop system has the following advantages (Moses A., 2011):

- The system is able to harvest 11.5 mL of water for every cubic meter of air. In other words, it can create between 0.7 and 1L of liquid water per day.
- Works in the driest deserts such as the Negev in Israel, which has an average relative air humidity of 64 percent.
- The system is compact, meaning it is easy to transport.
- The system can be powered by solar panels.

On the other hand, the system has the following disadvantages:

- There is not a lot of research already done on this design since it is in the prototyping phase.
- The system is mostly used in agriculture, meaning it is not adequate for gathering large quantities of drinkable water yet.
- Underground pipes need to be installed close to the roots of the plants.

Concept 2: Solar Desiccant Collector System

The solar desiccant collector system discussed in the theory uses solar energy and solid desiccants to extract water from atmospheric air. The process consists of a cycle that absorbs water at night and recovers the evaporated water during the day: the moist air is cooled to a temperature lower than the air dew point, and water vapor is absorbed from moist air using a solid desiccant, with subsequent recovery of the extracted water by heating the desiccant and condensing the evaporated water during the day.

The alternative is deemed feasible since an experimental study on the technology has already been conducted in the Egyptian climate (Helmy Gad, 2001). The apparatus of the study is the following:

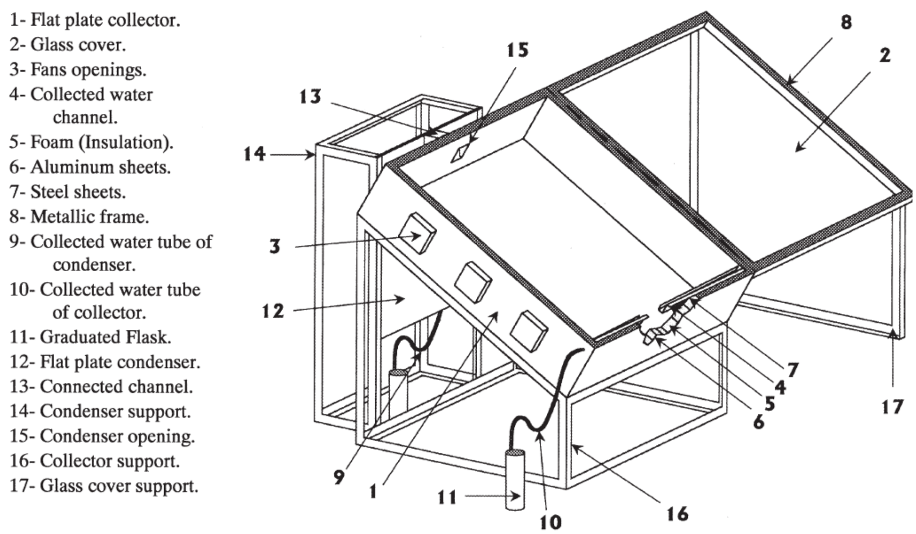

Figure 7. *Experimental apparatus of the solar desiccant collector system for passive AWG*

The apparatus contains three main components: a flat plate collector (glass cover), a bed surface and an air-cooled condenser. The absorption process may be enhanced by increasing the absorption area. Therefore, the bed area in the collector containing the desiccant may be increased by corrugation of the bed surface as follows.

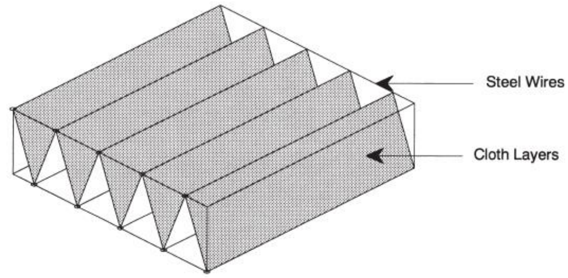

Figure 8. *Corrugated bed surface for the flat plate collector*

The box is insulated by a high-density foam to prevent any loss/leakage, and it is positioned at a certain angle optimized to have the most sun exposure. The glass cover behaves as a heat addition surface on which condensation takes place and the net heat exchange through the glass is positive. An air-cooled condenser consisting of two parallel flat plates is also considered to increase the efficiency of the system.

After the water has evaporated from the desiccant, it is recovered in two ways: through the condenser inlet (15) or through the collected water channel (4) after the water has condensate onto the glass cover. The mass of moisture recovered from the atmosphere depends mostly on the atmospheric conditions (temperature, relative humidity, and vapor pressure), the desiccant properties, the absorption area (A), the absorption time ($\Delta\tau$), and the mass transfer coefficient (β).

$$m \sim \beta A \Delta p \Delta\tau$$

Where Δp corresponds to the difference in pressure between the ambient environment and the desiccant bed: $\Delta p = p_\infty - p_D$. For any given period of time, the mass transfer coefficient, the absorption area, or the vapor pressure difference may be varied to increase the moisture recovery. From the experimental study, the solar driven system can provide approximately 1.5L of fresh water per square meter per day.

The thermal energy requirement to operate a desiccant-based atmospheric water generation system (DAWG) is a function of the regenerator temperature (T_{REG}), the ambient dry bulb temperature (T_∞), the specific heat of the desiccant/water solution (c_p), the dilute desiccant concentration (β_1), the concentrated desiccant concentration (β_2), and the latent load (h_{fg}) (Conser, Fall 2019). It can be written as follows:

$$Q_{DAWG}[kJ/kg_{H2O}] = \frac{\beta_2}{\beta_2 - \beta_1} * c_p * (T_{REG} - T_\infty) + h_{fg}$$

Therefore, to minimize the required thermal energy requirement, a desiccant with a high-water carrying capacity should be selected. In other words, the desiccant should have the lowest possible equilibrium mass fraction. This will allow for the dilute desiccant concentration ($\beta 1$) to be very low when compared to the concentrated desiccant concentration ($\beta 2$). The mass of water generated consists of the difference between the mass of the desiccant before and after it has regenerated.

$$M_{H2O} = M_{wet} - M_{dry}$$

Thus, the desiccant solution concentrations can be expressed in terms of ratios of the mass of desiccant in the solution (M_{des}) over M_{wet} and M_{dry}:

$$\beta_1 = \frac{M_{des}}{M_{wet}}$$

$$\beta_2 = \frac{M_{des}}{M_{dry}}$$

Assumptions

- For the system to work efficiently, it requires some energy input in the form of air flow (fans/blowers).
- To obtain the above-mentioned volumetric production of freshwater per square meter per day, the atmospheric conditions must correspond to the following
    - Large temperature swings (between day and night)
    - Large relative humidity

Advantages/Disadvantages

The passive atmospheric water generation (AWG) just described has the following advantages:

- The system is compact, meaning it is easy to transport and install.
- The maintenance is quick and simple: the glass cover needs to be closed in the morning and opened at night, and the desiccant solid needs to be changed occasionally.
- The system produces a satisfactory amount of freshwater per meter square per day.

- The system uses solar energy to adsorb moisture from the desiccant and produce fresh water.

On the other hand, the system has the following disadvantages:

- Fans are required for atmospheric air to flow through the system which means the system needs to be connected to the electric grid.
- Replacement of desiccant beads is typically recommended every two years.
- Desiccants are particularly effective at attracting water molecules. However, they may also attract unwanted molecules such as pollutants, contaminants, organic vapors or microbes.

Implementation Conditions

The following ideas correspond to methods of implementing the existing solution to make it more efficient or produce a greater quantity of water per meter square per day.

- From the conclusion of (Helmy Gad, 2001), the system experiences a reduction in efficiency of about 5% when the condenser is connected to the collector. Therefore, the condenser section should be removed from the design, thereby making it simpler and cheaper. Water collection is still possible through the water collection channel once the water has evaporated from the desiccant beads and condensed onto the glass cover.
- According to (Conser, Fall 2019), the fan speed and direction has an impact on water absorption by the desiccants. A high-speed fan (16 mph) was compared to a low-speed fan (4 mph) both pointed at the bed (not parallel to it as in the experimental study discussed here). He concluded that higher fan speeds are best suited since the desiccant will be better mixed and subsequently have a higher water absorption rate.
- Given the long sun exposition most of the year in arid areas, solar energy could be stored in a battery and then used at night to power the fans. This would remove the need to be connected to the power grid.
- (Conser, Fall 2019) also discusses the most efficient chloride desiccant by comparing lithium-chloride (LiCl) and calcium-chloride ($CaCl_2$). Given that LiCl has a lower theoretical equilibrium mass fraction at the same ambient conditions, it absorbs almost twice as much moisture in the same time.

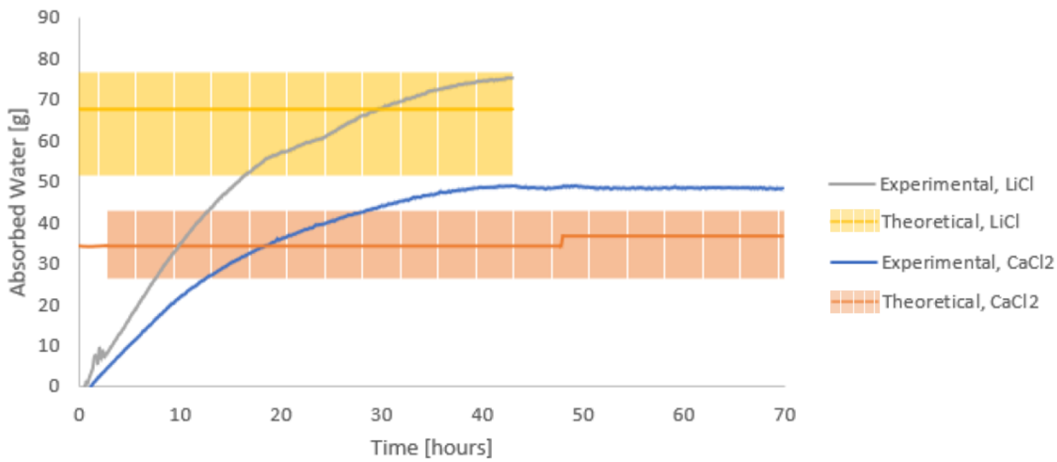

Figure 9. *Mass of water absorbed over time, comparing $CaCl_2$* and LiCl

- According to (Kabeel, 2007), a pyramid shape configuration with four glass surfaces and multi-shelves increases water collection by 90–95% compared to the horizontal and corrugated bed solar desiccant collector system. The approach can increase the production to 2.5L of fresh water per square meter per day in the same conditions.

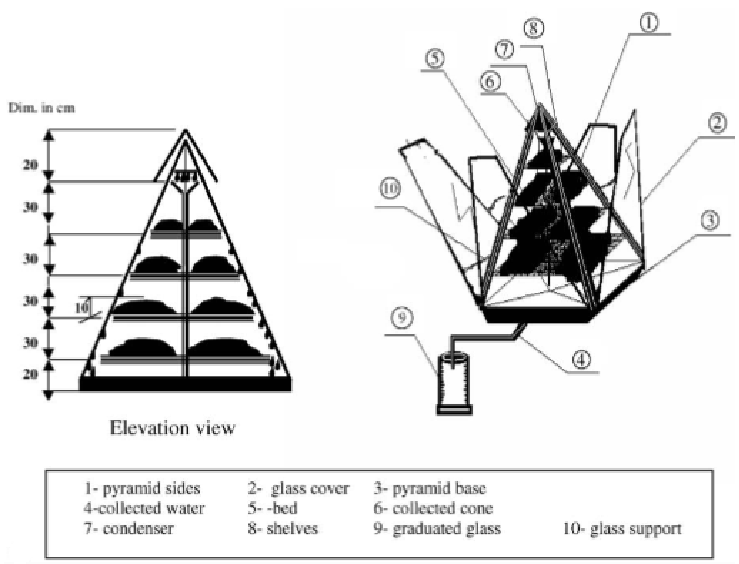

Figure 10. *Pyramid shape configuration for a desiccant collector system*

Concept 3: Radiative Cooling Condenser

Another technology used for water harvesting is a radiative cooling condenser system. In order to understand this solution, it is important to understand the basic principle of dew formation on plants since this technology is inspired by this natural phenomenon. Indeed, dew is formed on plants at night as temperature drops. Partial pressure of water vapor varies directly with temperature therefore water vapor condenses on cool surfaces (i.e. plants) when the ambient temperature is below the dew point.

The radiative cooling condenser is a passive system which means it does not require additional energy to operate. It uses material surfaces at specific angles to collect dew and rainwater. In fact, the formation of dew is caused by a radiation phenomenon on the surface of a material. During the day, the temperature is high and the relative humidity is lower, and therefore the temperature at which the water condenses is lower than the ambient temperature. However, at night, when the ambient temperature drops and the relative humidity is higher, radiative cooling occurs on the surface which creates dew on the surfaces since the condensation temperature is now lower than the ambient temperature (Li et al, 2021). The radiative cooling is provided by radiation from the warm surface to a clear night sky which is a black body whose temperature is only slightly above 0 degree. Recall Romans made ice in the summer with shiny bowls placed on a mountaintop and insulated from the warm ground with straw.

The design can be observed in the following figures, where a cooling material is applied on angled surfaces which than collect the harvested water at the bottom (Alnaser, 2000).

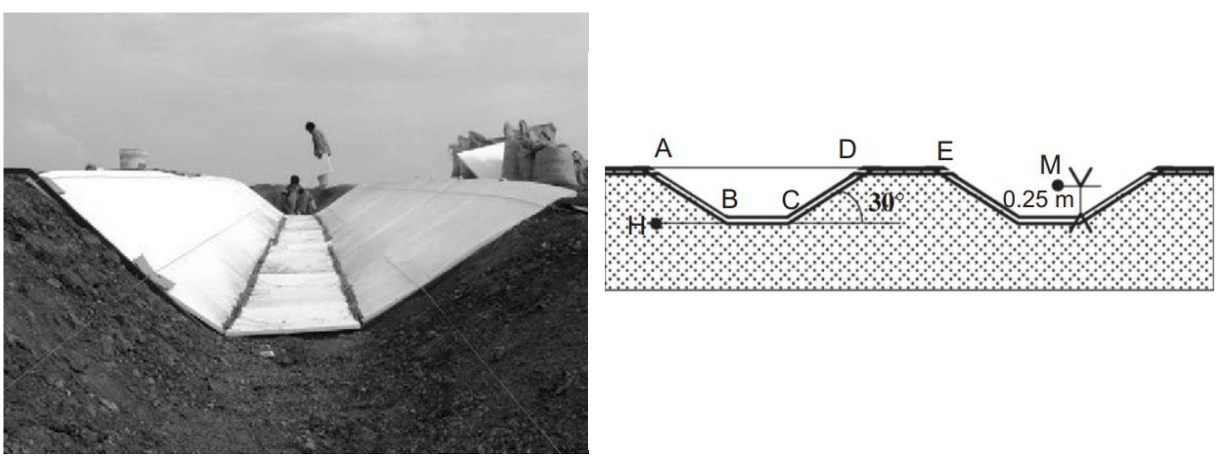

Figure 11. *Radiative Cooling Condenser Design on Ground*

Note: The height A-H is 0.5m, the flat surfaces BC=DE=0.5m and the inclines AB=CD=1m.

In order to optimize the performance of this water harvesting concept, the governing equation of radiative cooling, called the Stefan-Boltzmann law, is analyzed.

$$\boldsymbol{P = \epsilon \cdot \sigma \cdot A \cdot \left(T^4 - T_C^4\right)}$$

where $P =$ Total radiated power $[W]$; $\epsilon =$ Emissivity of the surface

$\sigma =$ Stefann-Boltzmann constant = $5.6703\ x\ 10^{-8}\ \left[\frac{W}{m^2 \cdot K^4}\right]$; $A =$ Radiating Area $[m^2]$

$T =$ Temperature of radiating surface $[K]$; $T_C =$ Temperature of surroundings $[K]$

From this equation, the key element is the power gradient between the sky radiative power (P) and the condenser surface outgaining condenser power.

To produce more dew, the selected surface needs to have a high reflectivity in order that the surface does not trap heat and evaporate the condensed water during the day. The infrared wavelength emitting properties of the selected surface should also be as high as possible in order that the surface cools as fast as possible at night (i.e. high emittance).

Studies were made using different materials on sample sizes of the design installed on metal framing to see which surface would collect the largest amount of water (Sharan, 2011). The potential materials studied were glass, aluminium and polyethylene foils. For the study, the ambient conditions on site such as the air temperature, relative humidity and wind speed were recorded. It was found that aluminum sheets were the most efficient. You may experience this effect on your back while swimming at night in an outdoor pool. It is eerie to feel that cold on your back in relatively warm water.

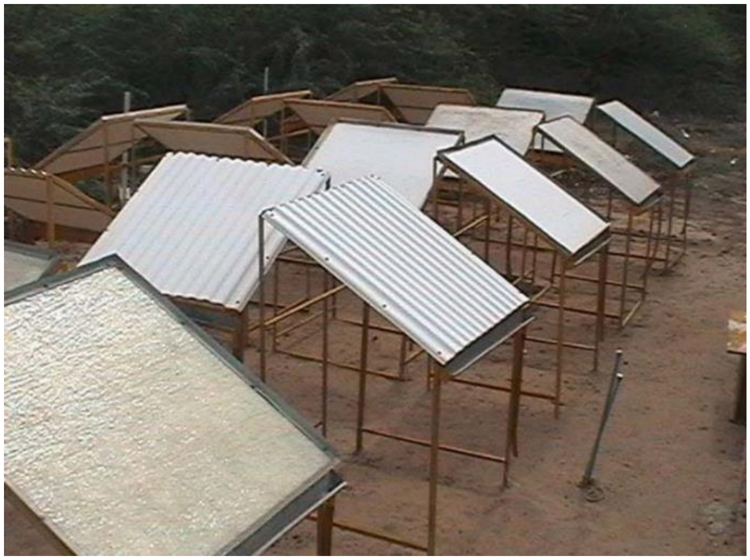

Figure 12. *Different Condenser Surfaces Sample Tests*

It was found that aluminum sheets satisfied these criteria and were the most efficient by collecting 1.3L/m^2/day in the best conditions. These values occur in ranges of dew point temperature from 10 to 25 degree as well as relative humidity from 70% to 80% Therefore, the material used on the ground design is polished aluminum sheets.

Assumptions:

- Large land is available for the installation of the water harvesting plant.
- To obtain the above-mentioned volumetric production of freshwater per square meter per day, the atmospheric conditions must correspond to the following
    - Large temperature swings (between day and night)
    - Large relative humidity
    - Relatively low dew point temperature
    - Mild wind effects

Advantages/Disadvantages:

- The benefits of this solution include that it is not limited in size, which means the plant could be extended if the community needs more water. It is a simple technology for the local community and requires simple maintenance as the sheets should be clean every week. The system can also collect rain water if it ever rains in the region.

- However, in order to collect a significant quantity of water, the plant has to be very large and the communities might not have enough space for it, and it requires a lot of sheet aluminum.

Implementation Conditions:

The following figure displays different steps followed in the construction of a radiative cooling condenser system in a community in need of water.

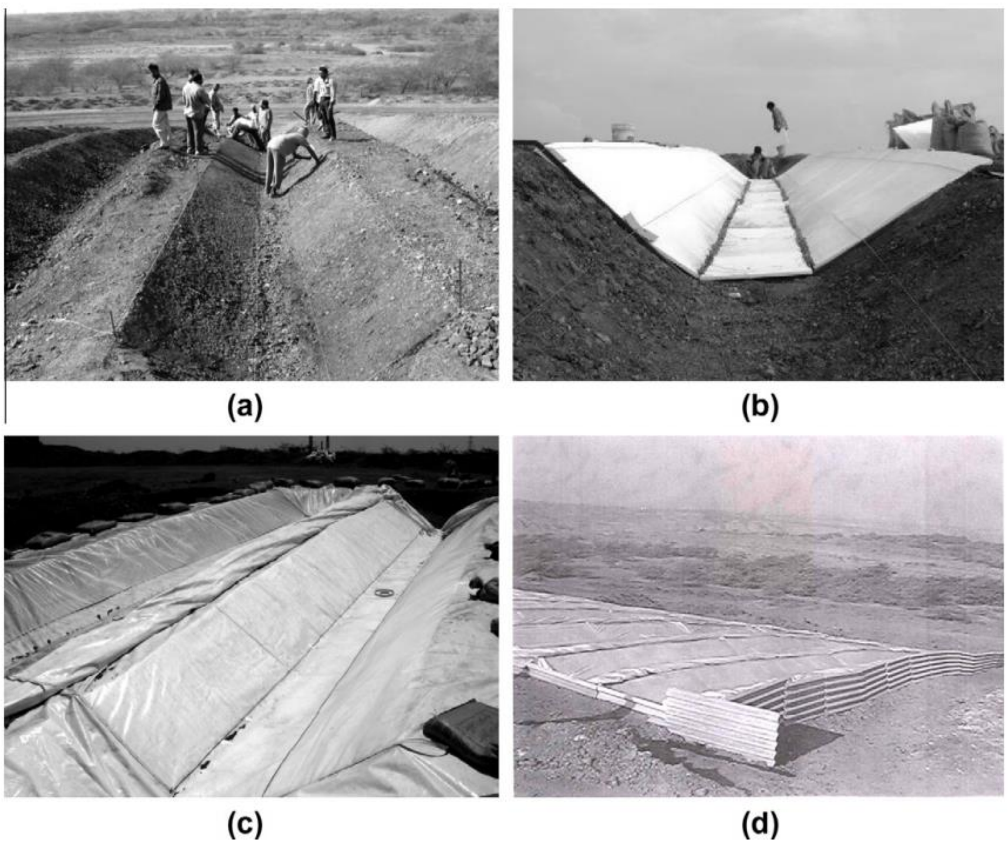

Figure 13. *Implementation Steps and Installation*

Aluminum sheets are used. The first step is shaping the ground to the appropriate dimensions (a). The inclines are at a 30 degrees angle in order to minimize the effects of winds. A foamed polystyrene insulation is then installed on the ground as a medium to separate the ground and the aluminum sheets (b). Then, the aluminum sheets are placed as shown in (c). Finally, the overall installation is shown in (d), where 10 ridges are present which represents 850 m^2.

Concept 4: Fog Collector Nets

Another approach for atmospheric water harvesting is capturing the moisture in fog as opposed to capturing dew or condensation. Fog has 0.05-0.5g of liquid water per cubic meter that is present in tiny droplets about 5-50 μm in size (Domen 2013). This technology extracts the liquid water by intercepting the wind that carries the fog. The most common way to accomplish this is using large, vertical mesh nets called fog collectors. These double-layered mesh nets are held up with tall posts with a trough at the bottom to collect the water. The principle of this design is that as wind blows fog through the nets, water droplets are captured by the mesh just because the nets are so small (the most optimal mesh netting is made filaments the size of three to four human hairs and with holes that are twice as big as the filament). The two layers of mesh then rub against each other causing the droplets to coalesce. Gravity pulls these heavier droplets down the netting and into the gutter at the bottom. The collected water is transported to the desired location through further infrastructure. A simple schematic of this process is shown in Figure 14 and a full-scale installation is pictured in Figure 15.

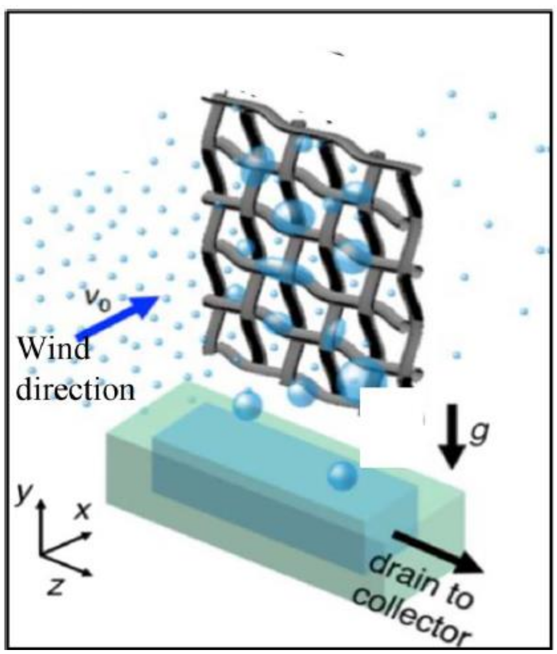

Figure 14. *Basic principle of a fog collector*

For fog collectors to be viable, the location *must* have a prevailing wind and fog or low hanging clouds. Without these two factors, mesh nets will not produce any water. The nets need to be set up perpendicular to the prevailing wind and are spaced around 5m apart so as to not create a large wind obstruction. Areas without fog cannot consider this technology. Coastal and/or mountainous regions, and other foggy areas are the ideal location.

Fog collectors can be made of various materials, have different mesh designs, and are considered either small or large. Small fog collectors, SFC's, are $1m^2$ and mostly used for location feasibility assessments as well as studying new netting designs. Large fog collectors, LFC's, can range in size but are typically $40m^2$ and are used in full-scale installations.

Typical water production rates range from 5.3 to 13.4 L/m^2/day depending on the season, location and design (OAS n.d.). For a large fog collector, this would be around 200 to 500 L/day. However, on days with no fog this could be as low as 0 L/day. Efficiency of a fog collector can improve with larger fog droplets, higher wind speeds, and new mesh design concepts.

Figure 15. *Large fog collectors installed in a foggy, mountainous area*

The most common mesh design uses polyethylene or polypropylene netting, a Raschel weave, and two layers (OAS n.d.). This setup is durable, cheap, and efficient. Other net materials can be considered such as stainless-steel filaments. Steel nets are more efficient and durable but these installations are more expensive. The standard weave design is currently the Raschel weave, shown in Figure 16, as it has been well studied and implemented. It has a couple issues with efficiency, however, such as re-entrainment of deposited droplets and clogging of the mesh with stuck droplets. Other designs have been studied to fix these issues such as a harp design that only uses vertical wires and designs mimicking a spiderweb. One example draws inspiration from the Namib beetle, using a mesh panel instead of a net, with a refined material that has both a hydrophobic component that attracts water droplets, and a hydrophobic material to send them down to the container (Zhu 2016). Despite being promising, these mesh designs have not been implemented at large-scales and cannot be considered a solution at this time.

Figure 16. *Raschel weave netting with droplets*

The expected lifespan of fog collectors is 10 years, but installations can remain functional much longer than this with appropriate maintenance and care. If properly installed, the structural components of the installation, namely the posts/frame and water trough, can be expected to last longer than 10 years. The netting is likely to need replacing at the end of its expected life to continue performing efficiently.

Advantages/Disadvantages:

The main advantage of fog collectors is their inexpensive cost in all aspects of the life cycle. The low cost arises from two basic factors: the simplicity of the materials and the simplicity of the technology. The materials typically consist of plastic netting, metal or wood posts, and metal gutters. These common materials are cheap to manufacture and replace due to their non-technical nature and availability. The material for the posts and gutters can often be sourced locally which also benefits the local economy and minimizes downtime due to broken parts. The netting is mainly manufactured in South America, but it is light, compact and thus relatively inexpensive to ship to other parts of the world. The simplicity of the technology also has a direct impact on the low cost. Both installation and maintenance require minimal training and time due to the straight forward, understandable design. This is ideal for developing areas where highly skilled labour may be scarce. Lastly, fog collectors are a completely passive system meaning they do not require any energy to operate. This eliminates operation costs, apart from maintenance, and also eliminates the need for additional infrastructure to transport power to the collectors.

Another advantage of fog collectors is their ability to collect rainwater. Rain tends to fall at an angle, so the vertical nets are actually capable of capturing more rain than a horizontal basin of the same area (FogQuest n.d.). The captured rainwater then drips down the nets into the gutter and is transported just as the fog-water would be.

The most notable downside of fog collectors is that they do not work everywhere. Fog and wind are a necessity, and it is usually recommended that a pilot project is carried out in the location to assess performance before a full-scale setup is installed. If not, the project has a large potential to fail. Furthermore, the simplicity of the technology, while providing many benefits, has a few inherent disadvantages. The mesh nets are large and to produce a sufficient amount of water, many need to be installed. These full installations can be massive, spanning large horizontal distances. This large profile also makes them susceptible to damage from wind and storms. Things such as animals, plant matter, or debris can get blown into the netting causing it to tear, and in extreme circumstances cause the posts to fall. Small tears in the netting can be repaired, however larger tears require the nets to be replaced. The nets also need to be brushed on a regular basis to remove any smaller debris that has been swept into them.

Implementation Conditions:

As previously mentioned, the success of a fog collector installation is almost entirely dependent on the environmental conditions of the region it is placed in. The following conditions must be met for it to be a viable and efficient project:

1. Fog must occur frequently throughout the year and persist for a relatively long time. Under 100m of visibility is a typical marker for adequate fog levels.
2. Fog must be accompanied by wind that has one prevailing direction throughout the year.
3. For arid lands, high-elevation fogs with relatively high liquid water content should be harvested.

Analyzing the results of a small-scale pilot project is the most foolproof way to determine if a location is suitable for fog harvesting. If a pilot project is not possible, the community should be consulted for their knowledge of local conditions, specifically the frequency, level, and locations of fog and wind throughout the year. Without a thorough assessment of these conditions, the installation of fog collectors has the risk of producing negligible amounts of water.

Development Phase/Cost Analysis

Concept 1: Airdrop Geothermal Cooling

Cost of Hardware

The total hardware cost consists in the cost of purchasing the raw material to build the tank, the casing, the semi-permeable hose and also the finished components, such as the solar panel, the turbine, the pump, and the battery. The total cost is approximately $700.

Cost of Installation

It is considered that two people paid $30/hour can install one device in approximately four hours. Thus, the labor cost is $240.

Total life cycle water production

Given that the Airdrop Irrigation system produces between 0.5 and 0.7L of fresh water per meter square per day, the total life cycle water production is:

$$Total\ Life\ Cycle\ Production = \frac{0.7L}{m^2 \cdot day} \cdot 10950\ \frac{days}{30\ years} \cdot \frac{1m^3}{1000L} = 7.665m^3$$

Total Life Cycle Cost = Hardware cost + Installation cost = $940 per device

Concept 2: Solar Desiccant Collector System

Cost of Operation: Desiccant Beads Change

The desiccant beads should be changed every two years to ensure constant efficiency of the system, hence they will have to be changed 7.5 times in the fifteen-year life cycle of the system. The cost of technical grade lithium chloride is approximately $5.50/kg and the configuration require 2kg which yields a total cost of $82.50 over the 15 years life cycle period. Calcium chloride is not much cheaper (approximately $5/kg), but it is much easier to acquire. In the event lithium chloride cannot be acquired in a given region, calcium chloride could be purchased for a life cycle cost of $75.

Cost of Hardware

The total hardware cost consists in the cost of purchasing the raw material to construct the frame, the shelves, the beds, the container, and the glass panels, and also the finished components, such as the solar panel and the battery. The total cost is approximately $600.

Cost of Installation

It is considered that two people paid $40/hour can construct one device in approximately three hours. Thus, the labor cost is $240. This cost is very conservative since the construction does not require technical labor which may be much cheaper depending on the region where the device is built.

Total life cycle water production

Given that the pyramid configuration produces around 2.5L of fresh water per meter square per day, and that the configuration has approximately a surface area exposed to convection of 1.5 m^2, the total life cycle water production is:

$$Total\ Life\ Cycle\ Production = \frac{2.5L}{m^2 \cdot day} \cdot 5475\ \frac{days}{15\ years} \cdot 1.5m^2 \cdot \frac{1m^3}{1000L} = 20.53m^3$$

Therefore, the minimum theoretical levelized cost of water (LCOW) is $45/$m^3$ for a desiccant-based AWG system in a pyramid configuration.

$$LCOW \frac{= \$600 + \$82.50 + \$240}{20.53\ m^3} \simeq \$45/\mathrm{m}^3$$

Concept 3: Radiative Cooling Condenser

Cost of Operation

Every week, cleaning of the aluminum sheet is expected to be done in order to conserve the quality of the water harvested. Assuming 2 workers paid $15 an hour take 1 hour each to clean the metal sheet of the entire plant (850m^2) over the course of the week, this totals $30 weekly, which is $28 over 15 years for 1m^2. However, this means that it costs $28 per m^2 for the cost of operation.

Cost of Hardware

A sheet of 1m^2 of aluminum sheet costs $170 while the foamed polystyrene insulation costs $40 for 1 m^2. Therefore, the total cost of hardware is $210 per m^2.

Cost of Installation

The entire installation is quite large as it is distributed over 850m^2, its full installation is estimated to last 2 weeks and cost $10 000. This leads to a cost of installation of $12 per m^2.

Total life cycle water production

$$Total\ Life\ Cycle\ Production = \frac{1.3L}{m^2 \cdot day} \cdot 5475\ \frac{days}{15\ years} \cdot 1m^2 \cdot \frac{1m^3}{1000L} = 7.12m^3$$

Therefore, the minimum theoretical levelized cost of water (LCOW) is $35/m^3 for a desiccant-based AWG system in a pyramid configuration.

$$LCOW \frac{= \$28 + \$170 + \$40 + 12\$}{7.12\ m^3} \simeq \$35/\mathrm{m}^3$$

Concept 4: Fog Collector Nets

Cost of Operation

As fog collector nets are a completely passive system, there is no significant operation costs. Simple maintenance must be done to keep the nets clear of debris and fix any minor issues. These maintenance costs are dependent on the region of installation and would be similar for any technology implemented.

Cost of Hardware and Installation

Fog collectors range in price depending on the region of installation and size of the project. Large $40m^2$ fog collectors that produce around 200L per day cost between $1000 to $1500 US each and have a lifespan of 10 years (FogQuest n.d.). For this analysis we will use the more expensive side of this spectrum. For a full installation producing about 2000L per day, the cost would be about $15000 US.

Total life cycle water production

To calculate the total life cycle cost per m^3 of water produced the following calculation was done using the cost, production rate, and lifespan of one large fog collector.

$$LCOW = \frac{\$1500}{LFC\ net} \cdot \frac{LFC\ net}{10\ years} \cdot \frac{year}{365\ days} \cdot \frac{day}{200\ L} \cdot \frac{1000\ L}{m^3} = \$2.05/m^3\ H_2O$$

Summary

The following table summarizes the hardware, installation, and operational costs in terms of $\$/m^3$ of water produced for each of the 4 technologies presented earlier.

Table 5: *Costs Associated with the Implementation of the 4 Technologies*

	Airdrop geothermal cooling	Solar Desiccant Collector System	Radiative cooling condenser	Fog collector nets
Hardware	$ 91.32	$ 29.23	$ 29.49	$ 2.05
Labour and Installation	$ 31.31	$ 11.69	$ 1.69	
Operation	$ -	$ 4.02	$ 3.93	$ -
TOTAL ($/m3 H2O)	**$ 122.64**	**$ 44.93**	**$ 35.11**	**$ 2.05**

Merit Analysis

To evaluate the different technologies, a cost/merit graph was made. Merit is derived from the multi-criteria matrix, and measures how much each solution satisfies the client's needs. The cost analysis was derived from a combination of cost of hardware, operation and labor, then adjusted to account for amount of water it produces each day. The final cost plotted was the minimum theoretical levelized cost of water (LCOW). The cost/merit graph value can be determined by looking at the slope of the line of each technology. The upper and lower limits of the coordinate axes are defined by the maximum merit and cost between the technologies.

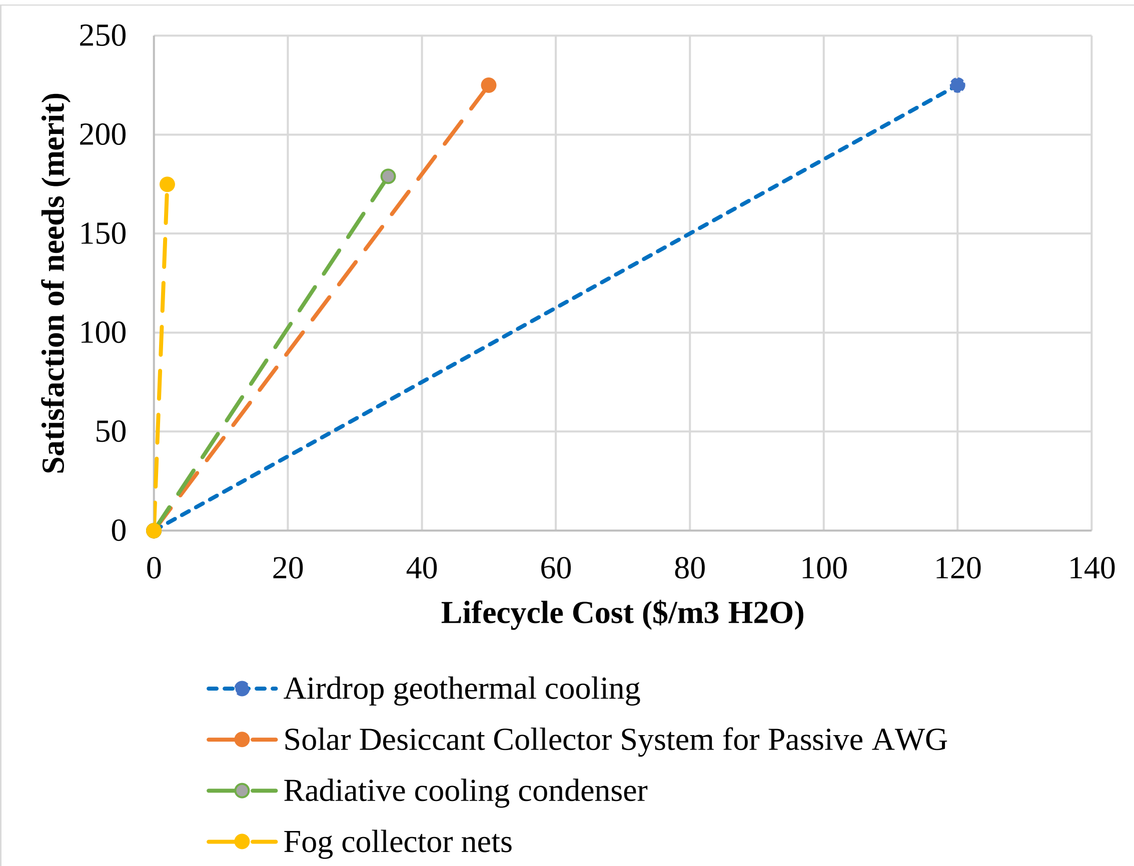

Figure 17: *Satisfaction of Needs over the Lifecycle Cost of the 4 Technologies*

As seen from the graph, the best technology to deploy for our project is the fog collector nets. The solar desiccant and radiative cooling had a similar slope, while the airdrop geothermal cooling technology turned out to be the least suitable. The airdrop geothermal cooling technology also has a different marker to showcase that it is unable to produce water for human consumption unlike the other technologies.

Conclusion/Final Recommendations

Many remote areas in the world have an insufficient water supply for agricultural activities and human consumption. Thankfully, there is substantial water that can be harvested from the atmosphere. The goal of this project was to select the most appropriate existing technology to harvest water for these remote areas. After a thorough value engineering procedure, the analysis was narrowed down to four water harvesting technologies: airdrop geothermal cooling, radiative cooling, solar desiccant and fog net collectors. The four water harvesting technologies were further explored with a literature review, a multi-criteria analysis, a cost analysis and a cost/merit graph.

After our analysis using value engineering methodology, we recommend using the fog collector nets for this project. These nets capture moisture by intercepting the wind that carries the fog and extracting the liquid water. Fog net collectors are low cost and are extremely effective in areas with high fog. The project is also very easy to install and maintain, making it perfect for remote locations where workers are less skilled. A typical village project will cost $15,000 USD in total and will be able to produce 2L of water/day. If implemented, this project will surely provide enough water to sustain agricultural activities and the excess can be used for human consumption. Alternatively, if the area of deployment has little fog, the solar desiccant is recommended for its ease of installation and compact size. It uses solar energy and solid desiccants to extract water from atmospheric air. Finally, in the most ideal situation, with no budget limitations, we recommend a hybrid solution of the fog collector nets and the solar desiccant. That way, water can be harvested in almost any condition.

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