# NAVAL POSTGRADUATE SCHOOL

**MONTEREY, CALIFORNIA**

# THESIS

## ANALYSIS AND OPERATIONAL FEASIBILITY OF POTABLE WATER PRODUCTION

by

Ali Abulfateh

September 2015

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The need for fresh water, a most precious resource on Earth, is increasing as civilizations and technology evolve and populations increase. The feasibility and scalability of alternative water harvesting methods to ensure a continuous supply of water for the future becomes vital.

Alternative methods of water harvesting were analyzed to determine the fundamental physics that provides scalability from one size unit to larger and smaller units. In terms of off-the-shelf water harvesting equipment, each technique is engineered to take advantage of a particular technology. This research compared the technologies of nuclear reverse osmosis for the fresh-water producing plants that serve metro-cities, and the technologies employing condensation and non-nuclear reverse osmosis for the city-sized, village-sized, and individual household-sized units. The feasibility of scaling water-harvesting equipment based on a particular technology is limited by both the economics of competing suppliers as well as the engineering to harvest freshwater. This thesis argues from a systems engineering perspective to investigate the feasibility of water-harvesting systems. A personal portable self-operated water-harvesting system is introduced as a new market niche for individuals without access to water. This micro-sized system can operate day and night using solar and Earth's radiation.

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# ANALYSIS AND OPERATIONAL FEASIBILITY OF POTABLE WATER PRODUCTION

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requirements for the degree of

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# ABSTRACT

The need for fresh water, a most precious resource on Earth, is increasing as civilizations and technology evolve and populations increase. The feasibility and scalability of alternative water harvesting methods to ensure a continuous supply of water for the future becomes vital.

Alternative methods of water harvesting were analyzed to determine the fundamental physics that provides scalability from one size unit to larger and smaller units. In terms of off-the-shelf water harvesting equipment, each technique is engineered to take advantage of a particular technology. This research compared the technologies of nuclear reverse osmosis for the fresh-water producing plants that serve metro-cities, and the technologies employing condensation and non-nuclear reverse osmosis for the city-sized, village-sized, and individual household-sized units. The feasibility of scaling water-harvesting equipment based on a particular technology is limited by both the economics of competing suppliers as well as the engineering to harvest freshwater. This thesis argues from a systems engineering perspective to investigate the feasibility of water-harvesting systems. A personal portable self-operated water-harvesting system is introduced as a new market niche for individuals without access to water. This micro-sized system can operate day and night using solar and Earth’s radiation.

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# EXECUTIVE SUMMARY

This thesis argues from a system engineering approach that scalability and feasibility of water-harvesting systems compete in different distribution domains due to limitations on technology and engineering. As technology advances according to people's needs and requirements, these advances can be utilized in terms of water harvesting across all levels of distribution to individuals and mega-populations. According to Otero (2011), millions of people do not have access to drink and use essential fresh water. The study of scalability in water-harvesting systems provides a means of understanding water production technology and its feasibility to satisfy the different sizes of populations—from mega-cities, to cities, to villages, to individual households, and to individuals.

"Scalability is all about doing what you do with either more people doing the same thing, or being able to do more with one person" (Langford 2012, 367). The process of scaling exposes the essential dimensions and relations between objects, e.g., patterns. It is these patterns that illustrates the sequencing and simultaneity of interactions that we observe as scaling, as exemplified by their relative interactional strengths, in conjunction with their physical and temporal arrangements (Langford 2014, 114).

This thesis analyzes the feasibility of the water harvesting methods based on nuclear reverse osmosis, condensation, and non-nuclear reverse osmosis. The results indicate that the limitations of one technology do not seamlessly match with the need for engineered equipment based on a different technology. These gaps in the quantity of fresh water harvested by commercially available equipment suggest new technologies that may have limited scalability, yet provide a very useful niche to provide access to water in all circumstances.

Each technology offers a benefit not found in other offerings. For example, water harvesting through condensation provides a mobile self-operated system. Extracting water from oceans requires adjacency to oceans.

The feasibility of scaling the water-harvesting system from individual-sized units to city-sized units is the focus of this thesis. Developing measures of effectiveness and

measures of performance can be compared with current engineering efforts and feasibility issues. Scaling factor is associated with water-harvesting systems is non-linear across the scale of large to small systems. In order to ease water crises around the world, water-harvesting systems can provide the essential assistance for poor areas with short or contaminated water resources (*Patriot Daily* 2006).

The scalability of the familiar technologies of condensation, adsorption and other common industrial methods such as reverse osmosis desalination and fresh water treatment are described to compare the feasibility of large-scaled, mid-scaled, and small-scaled water-harvesting systems according to the populations' need. A personal portable self-operated water-harvesting system is introduced as a new market niche for individuals without the reach of water. This system can be used in day and night using proven solar powers.

**List of References:**

Langford, Gary. 2012. *Engineering Systems Integration: Theory, Metrics, and Methods.* CRC Press, Boca Raton, FL.

Langford, Gary. 2014. "Building the Determinants of Cyber Deterrence Effectiveness." Monterey, CA: Naval Postgraduate School, Department of Systems Engineering.

Otero, Maria. 2011. *Global Water Issues: A Compendium of Articles.* Washington, DC: U.S. Department of State.

*Patriot Daily*. 2006. *Creating drinking water from air*. November 6, 2006. http://science.the-environmentalist.org/2008/04/creating-drinking-water-from-air.html

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# I. INTRODUCTION

## A. BACKGROUND

Water is one of the most precious substances on earth. It is considered the only substance on Earth that is naturally present in three different forms—as a gas, as a solid, and as a liquid. Although 70% of the surface of planet Earth is covered with water, only 3% of the world's water is considered "fresh" (U.S. Geological Survey Water Science School 1984), and nearly one billion people suffer short access to safe water. According to the World Health Organization (WHO), two million people die yearly due to shortage in clean water and sanitization (Otero 2011).

Several regions suffer shortages of potable water nowadays due to limited rainfall, lack of surface water flow an insufficiency of lakes or reservoirs, pollution of ground water or pollutants in the rainfall. Studies show that between 36 to 40 states of the United States are predicted to suffer from water shortages in the next ten years as water supplies reduce due to absence of water resources, rising temperatures, growing populations, and inefficient management of water resources (*Patriot Daily* 2006; Cartwright and Shank 2015).

Several companies and individuals (Lewis 2015; Nilsson et al. 1994; Coanda 1968; Engel and Clasby 1993) have developed technologies to capture water vapor in the form of dew or humidity from the air to create drinking water. These water harvesters may reduce the demand on potable water supplies and be an advantageous conservation method to preserve water and lower the overall cost of providing water. Some water harvesters can supply water to villages with limited or contaminated natural supplies (*Patriot Daily* 2006). For instance, EcoloBlue has demonstrated the continuous supply of harvested water in several regions of the United States and 17 other countries (EcoloBlue 2012a).

Water harvesting is not a new technique. In fact, ancient civilizations used several forms of harvesting water to collect dew from atmospheric humidity as exampled in Byzantine and Achille Knapen of India (Nelson 2003) (*Patriot Daily* 2006) (United

Nations Environment Programme Finance Initiative [UNEP FI] and Stockholm International Water Institute [SIWI] 2004) (UNEP FI and SIWI 2004). The water harvesting techniques used by these civilizations were known to generate a fair amount of water depending on the humidity percentages in their regions.

However, other water harvesting developments have been experimented on over the years with variable degrees of achievement in locations around the world. For example, ancient underground passages, known as Foggaras, were found in the Sahara Desert (*Patriot Daily* 2006). These passages were excavated for several miles into mountains sides that linked with surfaced air vents set apart every 75 feet to harvest humidity from air (*Patriot Daily* 2006) (Boualem and Rabah 2012). Another ancient marvel must be credited for its extensive water delivery system, which once supported over 1,000 residents in the ancient Incan city built on a mountain ridge in the Andes of Peru. The aqueducts of Machu Picchu represent a prodigy of hydraulic engineering as shown in Figure 1 (Otero 2011).

Figure 1. The Aqueducts of Machu Picchu, Peru

From Natural Habitat Adventures 2015

Several regions in the world are expected to face water scarcity in the near future as supplies decrease due to an absence or lack of water resources, rising temperatures, increasing populations, and inefficient management of water resources (Otero 2011). This scarcity could threaten the future of the next generations. Numerous businesses and researchers have developed techniques to harvest water vapor in the form of dew from the air to create potable water (*Patriot Daily* 2008). These water harvesters may decrease the potable water demands and be an advantageous preservation method to manage water resources (*Patriot Daily* 2008). Some water producers can provide entire small villages with potable water, especially in areas of absent or contaminated natural supplies of water (*Patriot Daily* 2008).

Water production does not require innovative technologies. For example in India, 18th century scientists built an air well made of a thick-walled 45 foot tower that operated by cooling air that passes through inner rows of slates, leaving moisture on the slates to leak to a basin at the well's bottom (Sharan 2007) (*Patriot Daily* 2008). While the amount of water harvested from such primitive technique was not great, extraction of water from air was demonstrated. Recently, a few companies have developed equipment to absorb and harvest water from the air using the same concept as demonstrated in these earlier systems, but now making use of modern technology to improve effectiveness of extraction.

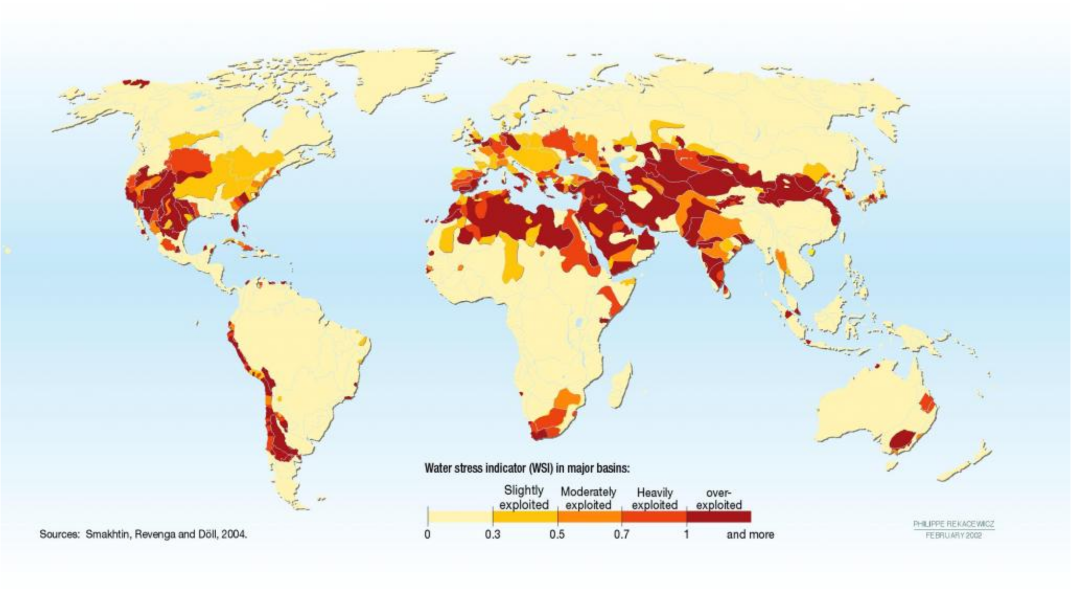
The water harvested from the atmosphere is inherently contaminated with the elements from which the water was extracted. These contaminants include lead, iron, copper, chemicals, and coliform bacteria. Testing of the condensed water is important to ensure potability, as common tests have been conducted to ensure potability as indicated in Appendix Table 10 (Penn State College of Agricultural Sciences 2015).

For condensation techniques, as humidity percentages affect the content of water to be collected in the desired amount of potable water, an analytical study was performed to observe and verify the minimum air humidity level required per day to harvest sufficient drinking water for one person in the region of study. The preferred minimum amount of water to be consumed per person per day is 2–3 liters (WHO 2003), given average climate conditions of the region of study.

Water-harvesting systems (WHSs) would ease water crises around the world on the small scale of distribution which deals with one individual at a time to the scale of the village and city level. WHSs would be useful for deprived villages worldwide to survive as water resources are threatened by contamination or shortages in water availability (*Patriot Daily* 2006) to a city-sized distribution system.

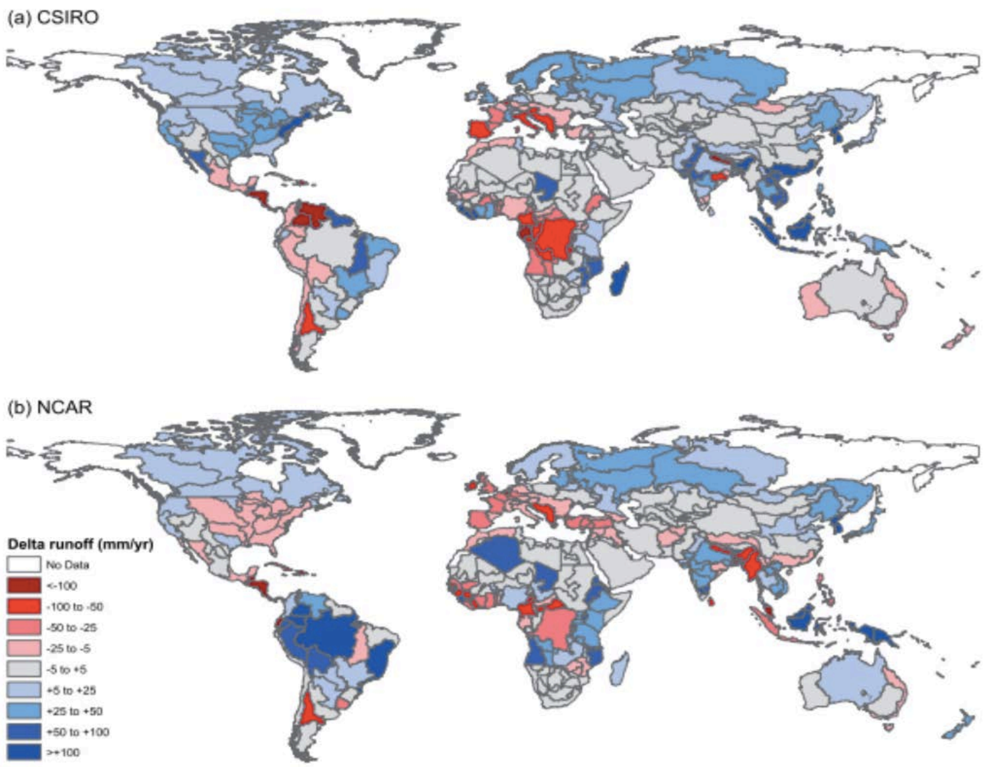
Based on current studies on fresh water availability in the world, it is estimated that by the year 2025, 40% of the population of the world could live in regions with limited fresh water resources. This water shortage is due to lack of fresh water resources and the increasing demand by agriculture, industry, and population (Barbut et al. 2004). Figure 2 demonstrates the Water Stress Indicator (WSI) in major basins in the world. A report on global climate change and water security discussed that “even at estimated modest levels of Environmental Water Requirement (EWR), parts of the world are already or soon will be classified as environmentally water scarce or environmentally water stressed” (Andrew et al. 2013). “The total number of population living in basins where modest EWR levels are already in conflict areas with current water use is over 1.4 billion, and this number of people is expected to grow depending on the regional stability and world peace” (Andrew et al. 2013). Currently, the 2012 annual population growth rate worldwide was determined to be at 1.07% (Emery 2012), while the water stress is increasing, as shown in Figure 3 (Andrew et al. 2013). In this paper by Andrew et al., the need of additional exploration in this field is highly encouraged (Smakhtin, Revenga, and Döll 2004).

Figure 2. Water Stress Indicator (WSI) in Major Basins in the World



From UNEP 2008

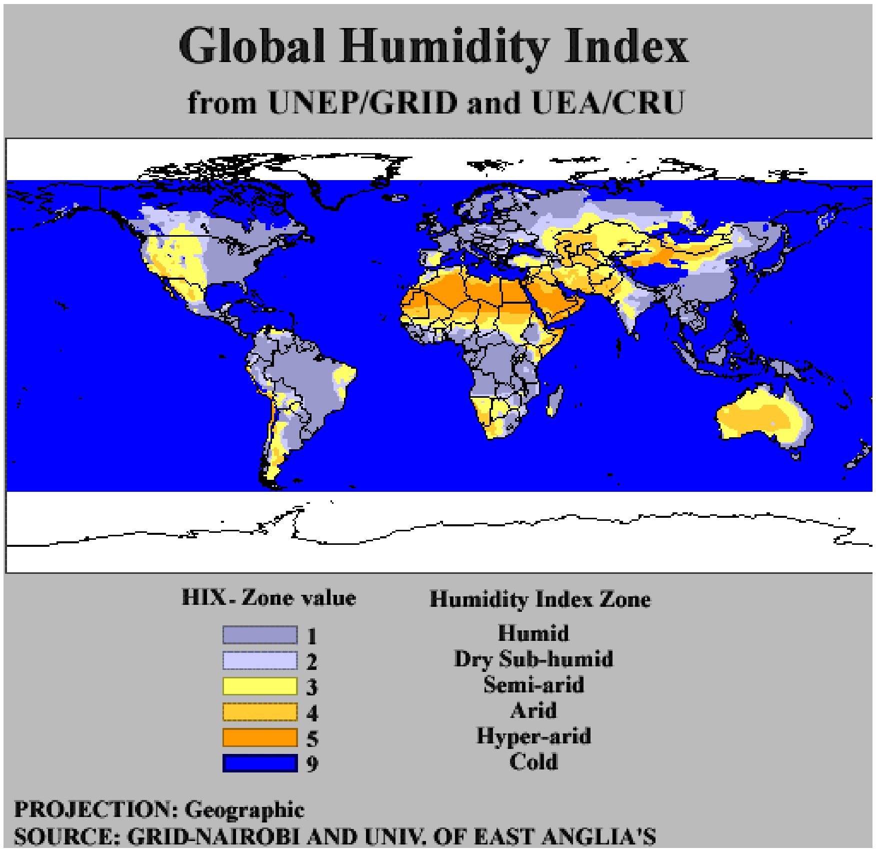
Figure 3. Mean Annual Runoff (in Millimeters) between 1961–1990, Expected Increased to 2050



From Andrew et al. 2013

On the other hand, another method of finding water supplies is using water-laded air, which is readily available to all. While humidity levels in the air vary across the world, harvesting water from air in temperatures between a 2–4°C through 40 degrees °C give a better chance to provide water to remote areas to relieve suffering from scarce water resources. According to the global humidity index, the world has a diverse range of potentially useable air to create water resources. Figure 4 reveals the humidity index of the world along with dry regions, according to the Climate Resource Unit (CRU) of the University of East Anglia of the United Kingdom (Grid-Nairobi And University of East Anglia's Climatic Reseach Unit 1991). This index may give an indication of the concentrated humidity areas across the world and provide a better understanding of where the water harvesting methodology can be most effective.

Figure 4. Global Humidity Index



From Grid-Nairobi and University of East Anglia's Climatic Research Unit 1991

For example, according to the Kingdom of Bahrain weather forecast for the year 2015 (Ministry of Transportation & Telecommunications–Meteorological Directorate 2015), humidity percentages were collected and averaged to find the water content that could be captured from air using the WHS method. According to the weather forecast analysis, the monthly mean relative humidity (RH) was 67% with a mean maximum RH of 84% and mean minimum RH of 44%. These humidity readings support the use of humidity as an available source of water in the region of study (assuming that the RH is above 30%).

## B. PURPOSE

This thesis argues that a traditional systems engineering approach emphasizing functional analysis and its derivative techniques provides insights into the scalability of water extracting system technologies. For this research, technology is characterized as an enabler for scaling, but technology does not scale (Langford 2012, 103). Technology is the scientific, mechanical, electronic, or chemical means of improving people's performances or by providing or enhancing their indigenous functions. These improvements provide for (1) making better decisions, (2) doing more work (faster), and (3) doing work that could not be accomplished before by fewer individuals. Langford (2012) goes on to state that functions do not scale, but access to functions is scalable; whereas processes scale, since unlike functions, processes are not measureable by quantifiable performance, but rather by verification (Langford 2012, 239). "The mechanics of scalability centers on the capability of a physical entity to deal with inputs and outputs, including losses to accommodate the inputs and to achieve those outputs" (Langford 2012, 318). Scaling is a characteristic of use described as a product's or service's capability to cope with and perform under an increased (or decreased) expenditure of energy, matter, material wealth, or information (EMMI) (Langford 2012, 3).

"Scalability is all about doing what you do with either more people doing the same thing, or being able to do more with one person" (Langford 2012, 367). Scalability in the first instance (more people doing the same thing with the same product) implies each person requires a product, that is, scalability by single-user products. Scalability in the second instance (being able to do more with one person) is through efficiency by using a service. Scalability in this second instance implies perhaps a single product that (through services) provides a similar functionality as with multiple products. So, by either increasing the number of users or speeding up a service, scalability is achieved on the upside, and the opposite is true for the scaling to the downside, i.e., fewer inputs or outputs of a product or service.

The process of scaling exposes the essential dimensions and relations between objects, e.g., patterns. It is these patterns that illustrates the sequencing and simultaneity of interactions that we observe as scaling, as exemplified by their relative interactional strengths, in conjunction with their physical and temporal arrangements (Langford 2014, 114).

## C. RESEARCH QUESTION

The fundamental question this thesis investigates is how market segmentation can be a tipoff to the scalability of technology. Using a variety of water-harvesting systems as a market-technology example, scalability from individual users to large aggregation of individuals, e.g., cities are discussed. The value of determining scalability can be considered as a determinant to change technology that would increase or a decrease an outcome without disrupting in the ability to deliver that output. The resultant opportunity from a military perspective is there a threshold of operability that can be identified and exploited; or from a commercial perspective is there a market that has been passed over or is just out of reach of competitive products that a new technology might enable.

## D. METHODOLOGY AND APPROACH

The systems engineering approach to implementing a scalability study on water producing systems reflects the life cycle concept for operations in various geographic locations. An analysis of input and output parameters shows the limits of economic feasibility for various levels of users of water from harvesting systems.

The following steps (as augmented by Langford (2012, 3, 318, and 319) to capture the issues of scaling and scalability) represent the systems engineering methodology (Blanchard and Fabrycky 2011, 56) that this thesis followed:

- Identify and translate the problem or deficiency into a definition of need from a system that will provide a preferred solution.
- Accomplish advanced system planning and architecting in response to the identified need.
- Implement changes in the architecture in the functional domain so that the root level processes can be enacted to result in scaling of meta-activities implemented at the top-levels of the architecture processes (Langford 2012, 318).
- Develop system operational requirements describing the functions that the system must perform to accomplish its intended purpose or mission.
- Conduct exploratory studies leading to the definition of a technical approach for the system design.
- Propose a maintenance concept for the sustaining support of the system throughout its planned life cycle.
- Identify and prioritize technical performance measures (TPMs) and related criteria for the design.
- Accomplish a system-level functional analysis and allocate requirements to various subsystems and components.
- Incorporate a system-level process analyses that maps the scaling catalysts to the functional performance analyses (Langford 2012, 88).
- Perform systems analysis and produce trade-off studies.
- Develop a system specification.
- Conduct a conceptual design review.

The completion of these steps constitutes the system definition process at the conceptual level. This process is applicable to any type or category of system, complex or simple, or large or small (Blanchard & Fabrycky 2011, 56).

To study the scalability of water production, a comparison was performed between alternative means of harvesting water, to contrast feasibility and scalability of their production effectiveness. This comparison is demonstrated in the analysis of alternatives (Chapter I, Section E).

A case study approach was used to advance the idea that scalability can be found in any technology offering, with specific instances of thresholds that delimit the effectiveness of that technology. A case study was developed from the open literature and information on EcoloBlue, located in Concord, CA. Their key products for extracting water from the atmosphere are industrial commercial units for large areas coverage varying from 10,000 liters per day down to 100 liters of water per day. There are also products that satisfy home use, which produces up to 30 liters a day (EcoloBlue 2015b). Scaling of products based on their technologies help segment the commercial marketplace in order to validate the economic feasibility of production and use of the systems so that the users can benefit from the effective management of the costs of water harvesting and distribution.

To validate the feasibility of the water harvesting systems, it is important to study and analyze the constraints and variables needed to generate the output of freshwater. A discussion of the percentages of humidity averaged over a year’s time in a hot humid region, for instance, Bahrain, was used to analyze the EcoloBlue product installation in the Middle East. The analysis was performed using Microsoft Excel Risk Simulator 2014 (Chapter III, Section C). Risk Simulator software is considered an add-on to Microsoft Excel. Basically, the software allows the user to analyze the risks and manage how to overcome the constraints in a mathematical representation of analysis. The analysis demonstrated an alternative of water producers that harvests water in different humidity percentages across the year, and measured the scalability and feasibility of the system over an individual use.

## E. ANALYSIS OF ALTERNATIVES

According to Blanchard and Fabrycky (2011), to compare alternatives to describe scaling laws and technology thresholds, it is important that they be converted to a common measure on the basis of equivalence. Quantitative and qualitative measures should be obtained using suitable models and decisions between alternatives should be considered based on differences (Blanchard & Fabrycky 2011). Several studies have been focusing on alternative methods of water generation systems as water becomes more susceptible and endangered, especially in drought-prone regions with increasing populations. Some countries have the accessibility to oceans or seas that would allow them to desalinize their natural water resources with fairly high costs of operation. Riverside areas and lakeside areas have option of water treatment and utilizing these potable water resources with relatively less costs than dieselization.

According to late studies, desalination processes require high energy that makes it prohibitively expensive on large scale (Schirber 2007). Since the 1950s, researchers have developed membranes that filter out salt (Schirber 2007). Another membrane filtering technique is called reverse osmosis. It uses a fourth of the energy and costs half that of distilling saltwater (Schirber 2007). However, even using reverse osmosis requires a great energy demand to produce the high pressure needed to force water into and through the filter (Schirber 2007). “Current methods require energy of about 14 kilowatt-hours to generate 1,000 gallons of desalinated seawater” (Schirber 2007). A study from a U.S. Geological Survey shows that U.S. consumes on day-to-day basis around 323 billion of surface water and 8.5 billion gallons of ground water. If half this water was desalinized, then U.S. only would require over a 100 additional electric power plants of a Gigawatt capacity each (Schirber 2007).

To settle the study of desalination as an alternative resource of water, and depending on local energy costs, “1,000 gallons of desalinated seawater would cost about $3 or $4” (Schirber 2007). For instance, “San Diego desalination project is expected to produce water at the cost of about $2,000 an acre foot, which is roughly the amount of water a family of five uses in a year” (Rogers 2014). According to Bob Yamada, “water resources manager of San Diego County Water Authority, the monthly average consumer’s bill now is $71 and will increase $5 to $7 due to desalination” (Rogers 2014). Therefore, pumping water from the ground or importing it from other areas would be still cheaper in many places. The scalability in this particular area of study shows that water desalination could be of great use on larger scale of population, as the cost dissipates among the total number of users, including the population and industrial customers.

Another alternative of water resources that is available in fresh water region is the treatment of river and lake water. People tend to settle near rivers and lakes to ensure the water accessibility and agricultural benefits. Such fact has motivated the population increase worldwide to change the demographics of the world. This is supported by the fact that people have inhabited areas near surfaced water to assure continuous water supply for several practices, including household, agricultural, and livestock water supplies (McCool, Clark and Stankey 2008). Most filtration and purification methods of river or lakes water are either expensive (ranging between $50-$500) or recently tested (Costhelper, Inc. 2015). According to a study in Japan, traditional methods, such as sand filtration, are not highly efficient in removing common viruses, bacteria and algae from water (New Logic 2015).

These surface water resources are often feasible to be used for large scale urban systems, while smaller community supplies would rather use wells or spring fed gravity systems. “This difference is because the cost of water treatment and delivery of water is likely to be high, and operation and maintenance less reliable” (Health Library for Disasters 1996).

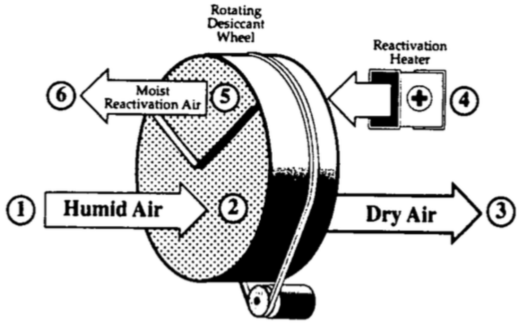
Moreover on alternatives of water resources, new studies on water harvesting technologies have been established to overcome future water challenges. These technologies include the use of desiccants to harvest water. There are two types of desiccants, solid and liquid. Solid desiccants can be in the form of silica gel ($SiO_2$), Calcium Chloride ($CaCl_2$), lithium Chloride (LiCl), Bentonite clay, and Carbon (Oak Ridge National Laboratory 1992). Some are used to absorb humidity from air, while others used to absorb odors and gas. Table 1 shows the differences among the different types of desiccants. The desiccant technology seems promising, but the fact that the absorption occurs between 35–55% of relative humidity limits its use to narrow industrial and personal uses (Oak Ridge National Laboratory 1992).

Table 1. Desiccant Types and Comparison

| Desiccant | State | Absorbs | Operates at RH% | Temperature to release water (F) |
|---|---|---|---|---|
| Silica Gel | Solid | Humidity | >60% | 150-300 depends on dryness needed |
| Calcium Chloride | Solid | Humidity | 35-55% | 150-300 depends on dryness needed |
| Bentonite Clay | Solid | Humidity | Slow rate of absorption between 35- 55% | 150-300 depends on dryness needed |
| Carbon | Solid | Odor/ Gas | >40% | 150-300 depends on dryness needed |
| Liquid desiccant | Liquid | Humidity | 59-62% | 145.4 |

According to Oak Ridge National Laboratory (1992), a research effort was performed on desiccant identifying the desiccant as a solid or liquid material that dries the air contacting the material's surface by absorbing the humidity. Then the desiccant was heated to 'regenerate' or discharge the water absorbed (Oak Ridge National Laboratory 1992). This procedure is a simple description of the desiccant method of operation as shown in Figure 5. There are several ongoing studies concerning the desiccants effectiveness and reliability, but the main problem remains in the unpurified high temperature requirement for water to be discharged from the desiccant particles.

Figure 5. Typical Solid Desiccant System



1. Humid air enters the roating bed of dry desiccant
2. As air passes through the bed, the desiccant attracts moisture from the air.
3. Air leaves the desiccant bed warm and dry. Cooling is accomplished by separate components downstream of the desiccant bed.
4. A small air stream is heated and passed though the desiccant bed to raise its temperature.
6. Heated desiccant gives off its collected moisture to the small warm air stream coming from the heater.
6. The moist reactivation air stream is vented to the weather, carrying excess humidity away from the building being air conditioned.

From (Oak Ridge National Laboratory 1992)

Finally, a comparison between the mentioned alternatives has been conducted in order to scale and identify the most feasible alternative of water production depending on the scalability of its use. This can be demonstrated by comparing and generating a decision making model as described by Blanchard and Fabrycky (2011). The method to be used in order to analyze the alternatives is the systematic elimination method, which is basically a simple approach to choose among alternatives in the face of multiple criteria. A scale shall be introduced in order to evaluate all alternatives and order them accordingly (Blanchard & Fabrycky 2011).

The comparison of alternatives shall be against criterions, which are in this case, the minimum relative humidity, convenience of personal use, and cost. This comparison has been identified by Blanchard and Fabrycky (2011) as alternatives are compared against criteria. This can be done by listing a number of most important criterions, and then eliminate the alternatives that do not meet the minimum standard value, until one alternative survives the examination or until all criteria have been considered (Blanchard & Fabrycky 2011). Table 2 demonstrates the comparison between alternatives and criteria.

Table 2. Blanchard & Fabrycky Method of Comparing Alternatives

| Alternative Water Systems | Criterion 1 Use of RH | Criterion 2 portability | Criterion 3 Cost | Criterion 4 Distribution Size |
|---|---|---|---|---|
| Desalination | Limited to certain areas | Fixed | \$3-\$4 per 1000 Liters | City |
| River & Lake water treatment | Limited to certain areas | Portable | \$50-\$500 for filtration and water treatments | Village |
| Desiccant Technology | from 35% RH | Portable | Inconvenient | Village |
| EcoloBlue (Atmospheric Water Generators) | from 30% RH | Portable | \$0.20 per gallon (3.785 Liters) | Village, City |

According to the comparison of alternatives and criteria to be considered, WHS has the least impact on cost as other technologies are relatively high in cost. In regards to use of relative humidity (RH), the availability of humidity is limited to the demographic location of use of the system, in other words, the use of a portable WHS would be more practical and convenient to use in several high temperature regions that lack water resources such as the Middle East and Africa.

## F. SYSTEM DESCRIPTION

The system to harvest water is principally a device that is engineered to fulfill water requirements as an alternative water solution to minimize the pressure on available natural resources and to enrich the existing resources with further environmentally friendly (Blue) options of water harvesting. Figure 6 shows the first level of the WHS physical decomposition.

Figure 6. Physical Decomposition Level One

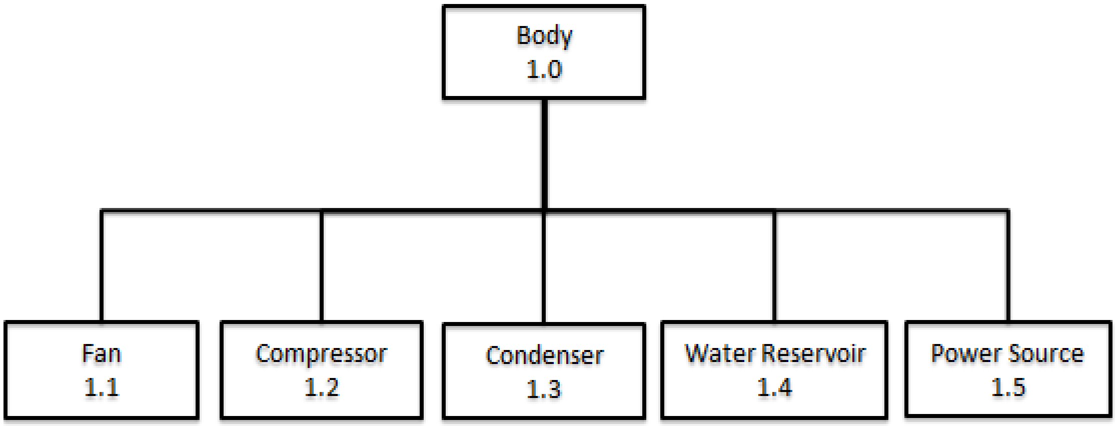


Figure 6 shows the second level of the physical decomposition of the compressor and its major components, which are the pump and the receiver along with their power source. Figure 8 shows the physical decomposition of the condenser and its major components. Condensers usually vary in their components according to the purpose they are used for. In this particular case, the condenser's main components include the fan, motor, capacitor, and condensing coils.

Figure 7. Physical Decomposition Level Two for the Compressor

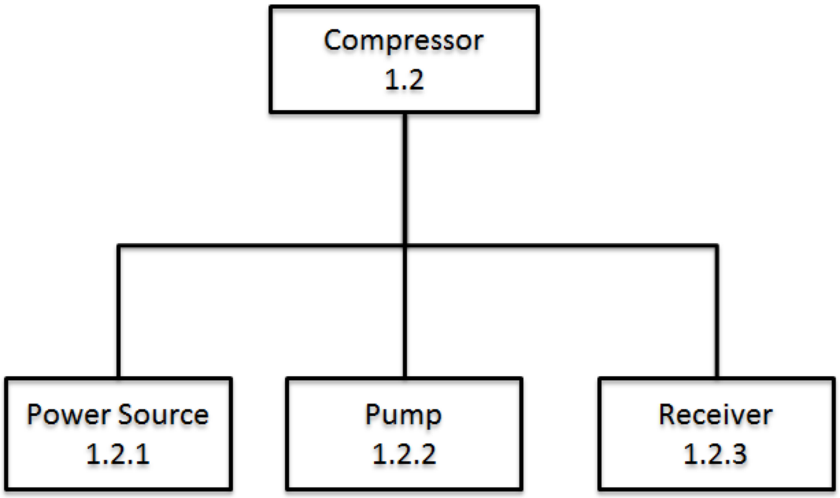


Figure 8. Physical Decomposition Level Two for the Condenser

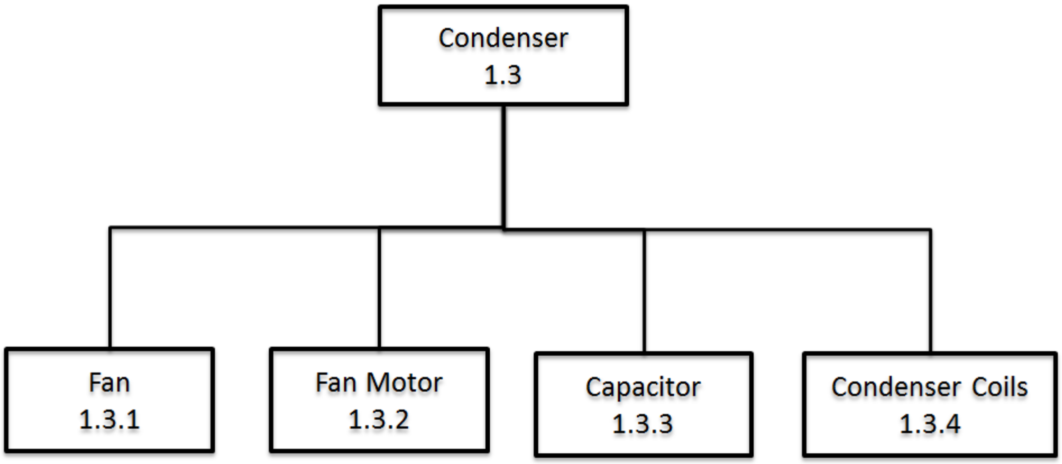
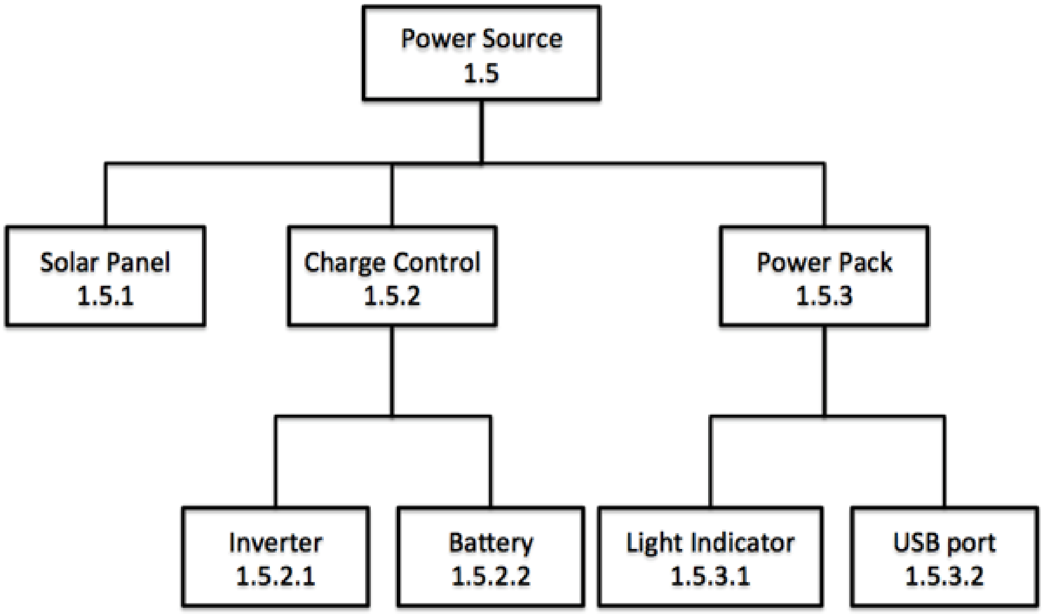


Figure 9 demonstrates the second and third level of the physical decomposition of the power source. For the purpose of this system, the water-harvesting system shall operate by solar power. A solar power source was selected to eliminate ongoing future costs, and it also provides an environmentally friendly energy source to operate a water harvesting system. This system shall be treated as a blue and green project, which means that its generation, operation, and finished product are environmentally friendly assets that demonstrate minimal risk to the environment. Going blue projects are mainly focused on preserving the planet's water resources and finding alternative ways to minimize the pollution of the water concentration on earth (The Going Blue Foundation 2015). Going green, on the other hand, refers to the minimal use of electricity and the use of energy alternatives based on natural resources, such as wind or solar power (U.S. Government 2015). These projects shall preserve the environment for the next generations and maintain the planet's natural resources in an enhanced quality.

Figure 9. Physical Decomposition Level Two for the Power Source



On individual scaling, water-harvesting system can be designed as a humidifier with a humble filtration system to produce potable water at the end of the process. This humidifier filtration system shall generate a substantial amount of water depending on the humidity percentage, coil surface area, and number of coils inside the system. In the case of drinking water systems, this water filtration can be used to remove particulate matter, as well as compounds commonly found in drinking water.

To improve the reliability, dependability and individuality of the water harvesting systems, the system has been envisioned to operate on solar power to generate sufficient energy capable of operating the micro-condensers that will generate water from the atmospheric air, including closed spaces. The system could be used for plantation purposes with minor changes to the overall design of the WHS.

This water-harvesting system may reduce the consumption of electricity and water in countries with limited resources and decrease the burden of water production, which could become very expensive in the future. Currently, Bahrain uses the technology of desalination of seawater, wastewater treatment, and some companies produce bottled water from imported water suppliers all over the world. These technologies obviously require high costs to operate, maintain, and produce sufficient water needs for the country. Hence, it is highly encouraged to study the feasibility of using atmospheric water harvesting and the scalability of its use to overcome any water issues.

## G. CAPABILITIES

From an innovative perspective, the fundamental capability of this system is to provide an alternative source of water as a revolutionary product that may assist in solving the upcoming challenges in water limitations around the world in different scaling measures. Nathan Gillett of the University of East Anglia in the United Kingdom, a co-author of the study, said, “moisture increases by about 6% with every degree Celsius” (1.8 degrees Fahrenheit). “Using the Intergovernmental Panel on Climate Change’s projections for temperature increases, that would mean a 12 to 24 percent increase in humidity by the year 2100” (Borenstein 2007). This supports the idea of using any WHS as the humidity availability would become ample in the future.

## H. OPERATIONAL ANALYSIS

The operational analysis of the device is illustrated in Figure 10 and Figure 11. In Figure 10, the basic system is shown to work through the condenser, as humid air is presented to the system via a fan compressor, the condenser presents the cooling coils to harvest the water content from the humid air. The harvested water then is collected into a water reservoir, and it completes the primary operational purpose of the system. A secondary operational cycle then takes place in collecting the remainder of the generated power into the battery, which feeds any outsourced device through a USB output. The

USB output shall operate once connected to any external device and a light-emitting diode (LED) light shall indicate the status of charging. Figure 11 provides another perspective of the operational analysis. It has a further reutilizing illustration of the power generated in the operational cycle.

Figure 10. Operational Analysis of the Plant-pot System

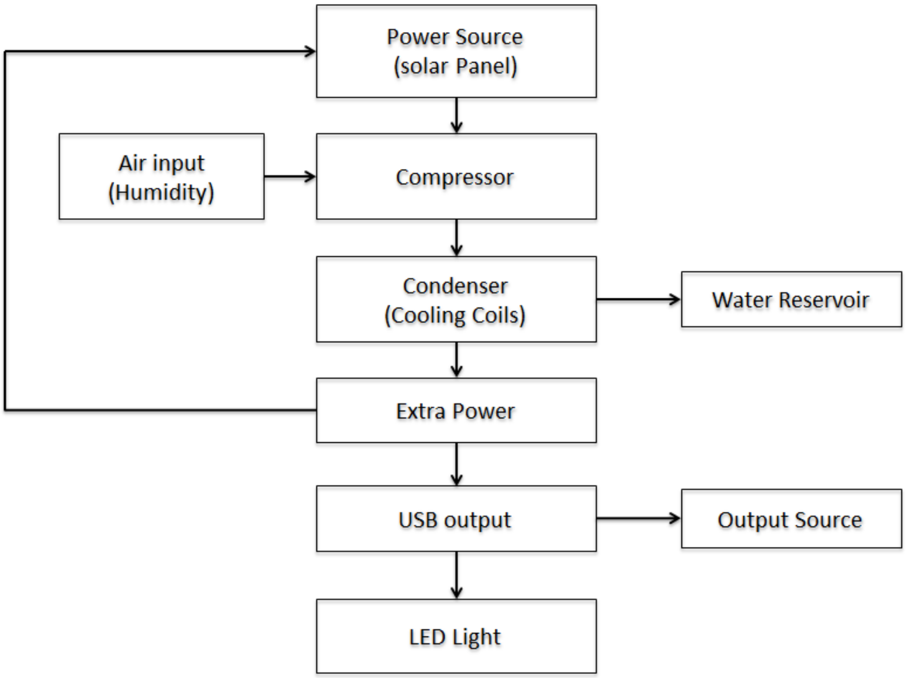
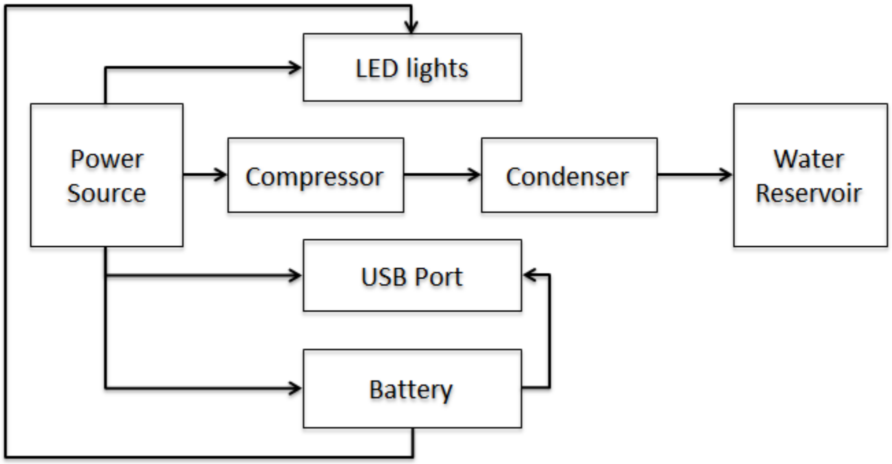


Figure 11. Operational Analysis of the System



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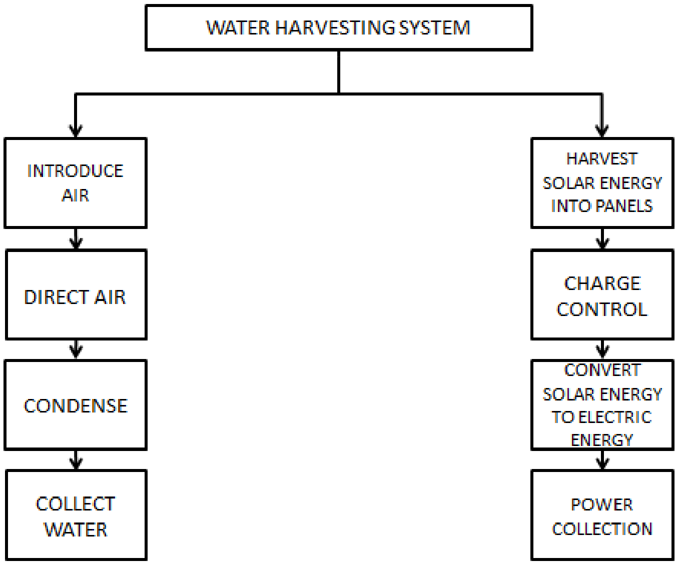
# II. FUNCTIONAL ANALYSIS

## A. FUNCTIONAL HIERARCHY

In systems engineering, logical architecture modeling is commonly used to demonstrate a series of tasks to illustrate functional and behavioral models of how the designed system is projected to operate (SEBoK 2015). Any logical architecture model of a system consists of a collection of technical concepts and principles to support the system’s operation in a logical approach (SEBoK 2015). “It may include a functional architecture view, a behavioral architecture view, and a temporal architecture view” (SEBoK 2015). “A functional hierarchy view is a representation of a static view of functions that would be populated at different levels, as it is not exclusively created by single top-down decomposition, but may branch into other sub-branches across the hierarchy model” (SEBoK 2015).

The functional hierarchy of the water-harvesting system is illustrated in Figure 12. It shows the main functional capabilities of the water harvesting system: harvesting water and producing electricity.

Figure 12. Harvesting System Hierarchy



## B. DESCRIPTION OF FUNCTIONS

A functional description describes the provided functions illustrated in the functional hierarchy. This description allows a thorough understanding of the mechanism of functionality of the system, by which measures of effectiveness are derived.

1.1 Introduce air: The amount of air introduced to the system shall be measured in cubic feet. It is the amount of air input into the system knowing the humidity percentage at that particular moment. This need has to be fulfilled prior to system operation in order to achieve the operation successfully. For instance, the average humidity across the year was measured to be 60.5%, which is sufficient enough to produce water (over 30% RH), as proven later in the analysis.

1.1.1 Direct air into the system by a fan: A fan shall be introduced in the first stage of the system operation, which will act as an accelerator for the air to be introduced to the condenser in the next stage of operation. It shall operate through the system's energy source, which is in this case, the solar power source.

1.1.2 Condense air to collect water moisture over the cooling coils: According to the system's operational theory, the condensation of the air is the key aspect in the process of water generation in this system. The amount of generated water depends on the number of coils condensing the humid air once introduced to it. Hence, the number of coils plays an important role in the amount of water being harvested from the introduced humid air, as revealed in the analysis of the research.

1.1.3 Collect harvested water into a reservoir: In this part, the water dripping from the condensation process shall be measured in liters, as demonstrated in Figure 14, which shows the amount of water collected over a one-year period of time with averaged humidity. The analysis reveals that the amount of water harvested annually is expected to be approximately 730 liters, which is the target of this study to verify the feasibility and effectiveness of the water-harvesting system for individual use.

Figure 13. Average Humidity over a Year Timeline Predictive Curve of Harvested Water by WHS

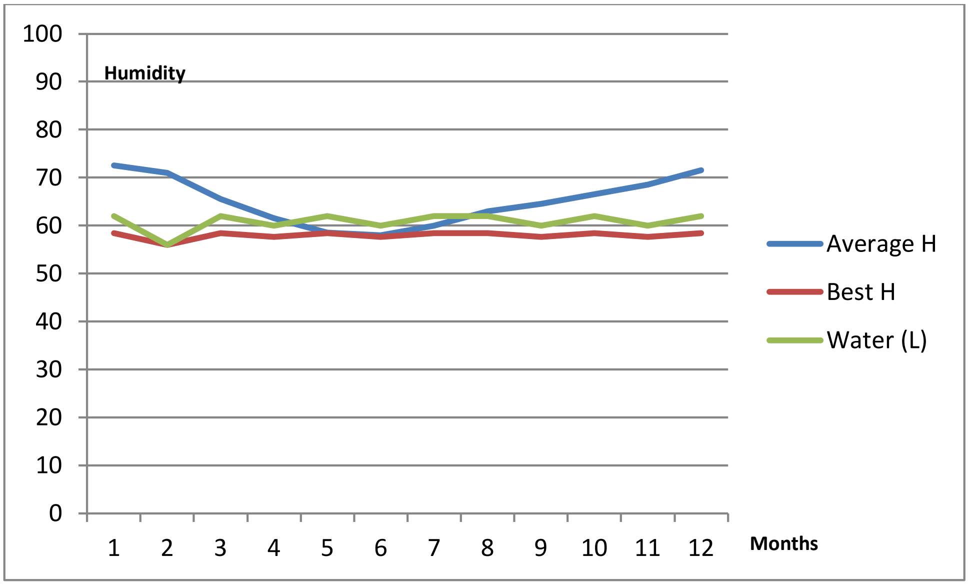


Figure 13 shows the average humidity percentage (Average H) expected over a one-year period of time, where water harvested on a monthly basis varies between 56 and 62 liters. This variation in water collection is dependent on the average humidity percentage expected in the relative month. The best humidity (best H) is the least expected humidity to harvest the water using the WHS. In other words, the water-harvesting system has fulfilled the constraint of the minimum humidity operation requirement and generated the sufficient amount of water needed as a capability.

1.2 Harvest solar energy into the solar panels: In this section, energy collected from any solar source, such as the sun, shall be transformed throughout a charge control, which transforms the solar energy into electric energy and stores it into the power pack.

1.2.1 Charge control to regulate collection of solar energy into their power pack.

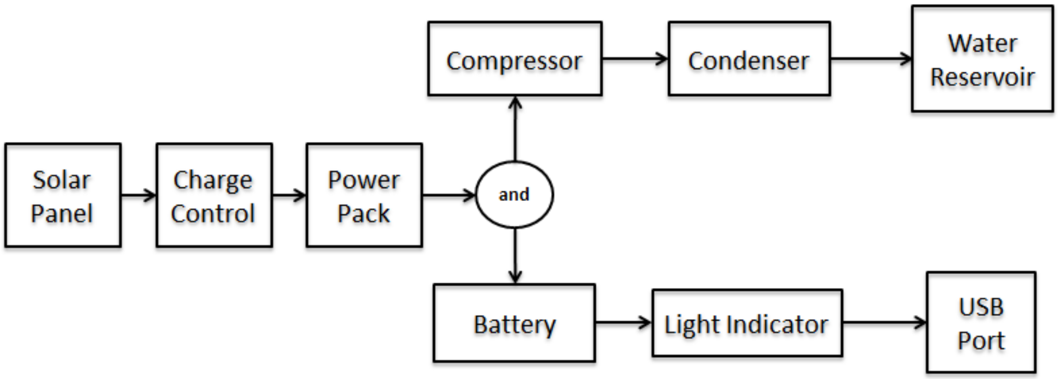
1.2.2 Convert collected solar energy from the power pack into electric energy: This conversion shall be fulfilled using a solar inverter, which converts the photovoltaic solar panel collected current from the solar panels into alternating current (AC), which then can be fed into an electrical network system. The power pack shall act as a storage stage for the energy to be utilized when needed.

1.2.3 Use electric energy through a USB port: The electric energy (AC) shall operate the system and continuously fulfill the minimum requirement of water generation, and then any remaining electric energy collected shall be stored in the battery and used through the USB port, as another useful resource of the WHS.

## C. FUNCTIONAL FLOW BLOCK DIAGRAM

The Functional Flow Block Diagram (FFBD) is a representation of the functions provided by the system. Figure 14 demonstrates the sequence through which the intended system would operate, with the solar panel capturing the required energy to operate the system through a sequence of power generation mechanisms within the charge control as the inverter capsizes the collected energy from the solar panel and stores it into the power pack for direct usage by the compressor, or stores the generated power into an auxiliary battery for other purposes. The compressor is intended to compress the air into the condenser, where the air moisture shall be harvested into a water reservoir as the condensation process takes place. Compression creates heats.

Figure 14. Flow of Energy and Matter through Physical Elements (Physical Architecture of the System) FFBD



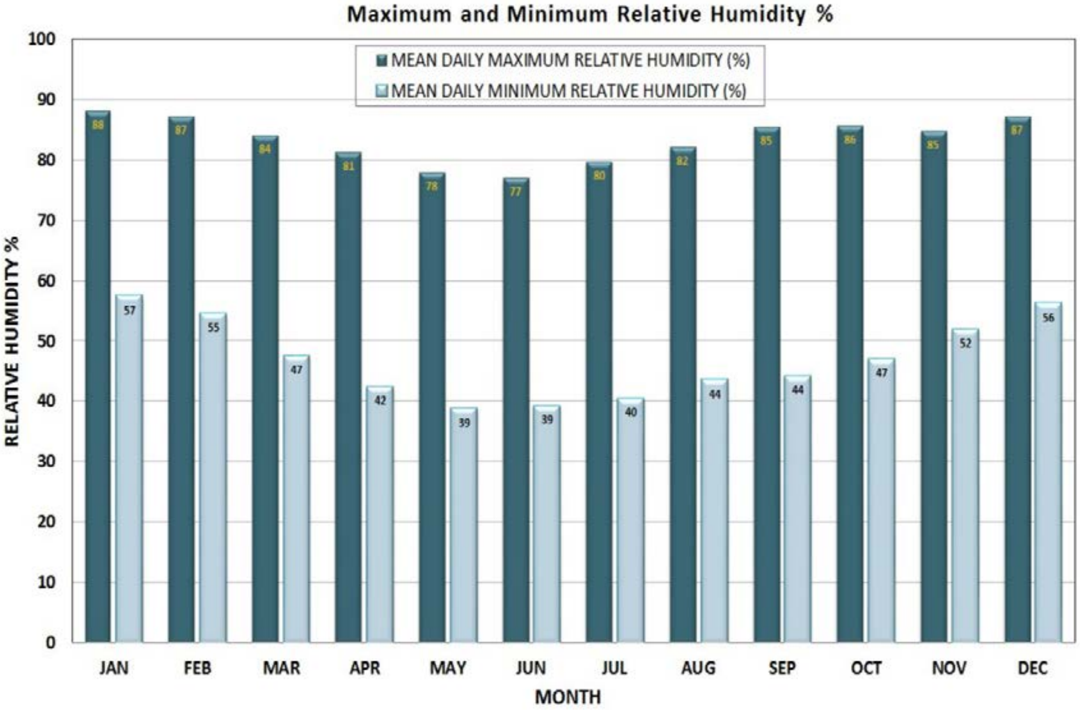
# III. MODELING, SIMULATION, AND TEST RESULTS ANALYSIS

## A. INTRODUCTION

Most systems require modeling and simulation analysis to ensure the successful product consistency, liability, and feasibility. Using a Microsoft Excel Spreadsheet Solver to analyze humidity ranges and solve to the desired study is practical for water harvesting systems. Certain considerations were assumed and gathered in order for complete the analysis. Figure 15 demonstrates the predicted maximum and minimum relative humidity percentages in the year of 2014 for the Kingdom of Bahrain.

According to the analytical research of this thesis, a sufficient amount of water shall be produced at variable humidity percentages collected over a year in Bahrain. The constraint is the minimum amount of water required to be generated, while the variable is the humidity percentage in the area of study. A minimum water amount of 2 liters shall be treated, as constraint and humidity shall play the role of the variable in the analysis of this study. This variable shall assist in the determination of the feasibility and scalability of the water-harvesting system for individuals.

Figure 15. Relative Humidity Percentages for 2014



Ministry of Transportation & Telecommunications–Meteorological Directorate 2015

The humidity ratio is known to be the content of moisture or the mixing ratio. It is also defined as the mass of water vapor per unit mass of dry air (BMCC library 2015). Humidity is the actual quantity of water carried by air in the form of water vapor (BMCC library 2015). “It is expressed as mg/L (milligrams of water per liter of gas)” (BMCC library 2015). “When humidity is compared to the maximum amount of water the gas could hold at the ambient temperature, the relative humidity figure is the result, expressed as a percentage” (BMCC library 2015). Relative humidity is the current humidity relative to the maximum (highest point) for that temperature and is expressed as measured by a percentage value (Labajo Salazar et al. 1991). “The humidity ratio (W) can be calculated if the percentage of moisture by volume (% $M_v$) is known” (Labajo Salazar, de Pablo, and Garcia 1991):

$$\text{Humidity Ratio} = W = 0.622\text{x } \%M_v / (100\text{-}\%M_v) \tag{1}$$

"This equation is valid only for the normal mixture of gases in the atmosphere. When different mixtures of gases are presented, such as that found inside a boiler flue, the factor 0.622 must change" (Labajo Salazar et al. 1991). "This factor is the ratio of the molecular weight of water vapor (18.015) to the average molecular weight of the other gases (28.965 in the case of air)" (Labajo Salazar et al. 1991):

$$18.015/28.965 = 0.622 \tag{2}$$

The percentage of moisture by volume is separate from the molecular weights of all other gases that compose the mixture (Labajo Salazar et al. 1991). The molecular weight refers to the mass of one molecule of a substance in grams per mole.

## B. EXPERIMENTAL RESULTS AND ANALYSIS

From the simulation analysis, the findings validate that the system could operate even with the lowest humidity registered in the region of testing as EcoloBlue have announced earlier; however, it is improved with more condensing coils or an accelerated air flow input.

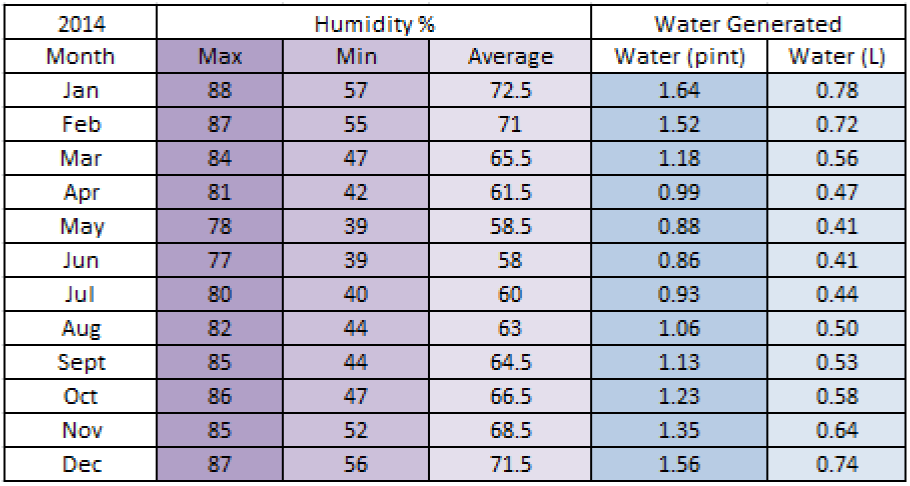
To overcome the constraint of water decrease in the months of May, June, and July, when the minimum humidity appeared, the number of coils increased to 330 to generate a sufficient amount of water to be consumed per day by an average person scaling on a monthly basis. Alternatively, newer technologies of condensers with better performance could be utilized to overcome such constraints.

The optimal number of coils required in the system using the condensation process to generate an adequate water amount of 730 liters to serve an individual on a yearly basis would be 330, even in the lowest humidity seasons.

## C. ANALYSIS OF RESULTS

An indoor potted plant requires less than a person's average drinking water of 2 liters per day, with moderate temperature and humidity. Having that in mind, if the device operates with 150 coils to condense humidity into water, and each coil captures a certain amount of water depending on the surface area of the coils, then the water generated over the year is sufficient within the optimal humidity percentage captured and would not exceed 730 liters of water per person annually at a minimum.

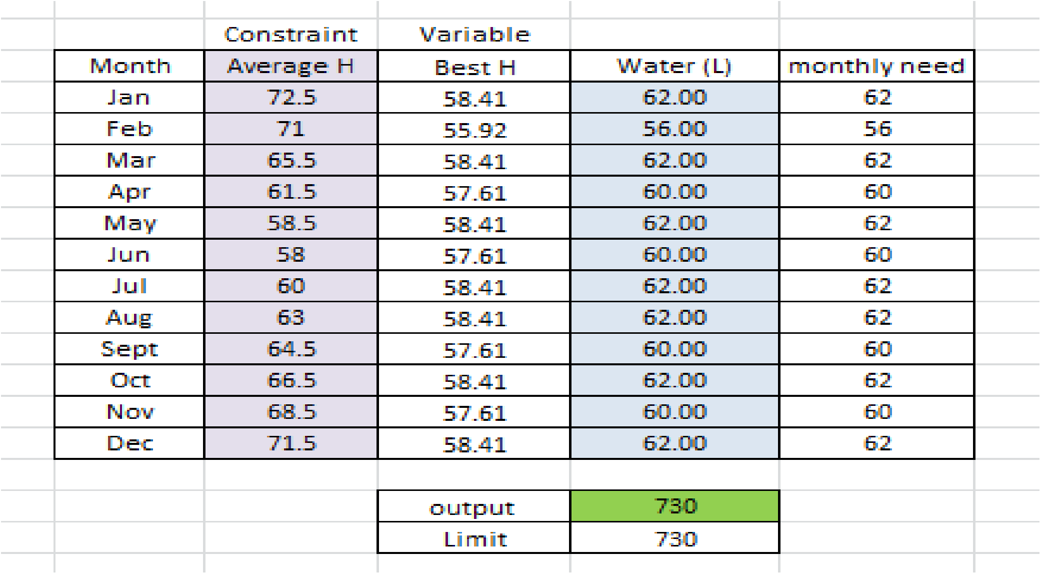
Table 3. Water Generated Amounts in Liters as Formulated by Humidity Ratio Formula



| 2014 | Humidity % | | | Water Generated | |
|---|---|---|---|---|---|
| Month | Max | Min | Average | Water (pint) | Water (L) |
| Jan | 88 | 57 | 72.5 | 1.64 | 0.78 |
| Feb | 87 | 55 | 71 | 1.52 | 0.72 |
| Mar | 84 | 47 | 65.5 | 1.18 | 0.56 |
| Apr | 81 | 42 | 61.5 | 0.99 | 0.47 |
| May | 78 | 39 | 58.5 | 0.88 | 0.41 |
| Jun | 77 | 39 | 58 | 0.86 | 0.41 |
| Jul | 80 | 40 | 60 | 0.93 | 0.44 |
| Aug | 82 | 44 | 63 | 1.06 | 0.50 |
| Sept | 85 | 44 | 64.5 | 1.13 | 0.53 |
| Oct | 86 | 47 | 66.5 | 1.23 | 0.58 |
| Nov | 85 | 52 | 68.5 | 1.35 | 0.64 |
| Dec | 87 | 56 | 71.5 | 1.56 | 0.74 |

Table 3 shows the amount of water generated in liters/pints on monthly basis. The total amount of water generated per year is 6.79 liters, which is considered very low due to the operation of one tube within a condenser in normal weather conditions without a compressor to feed the wet air into the device.

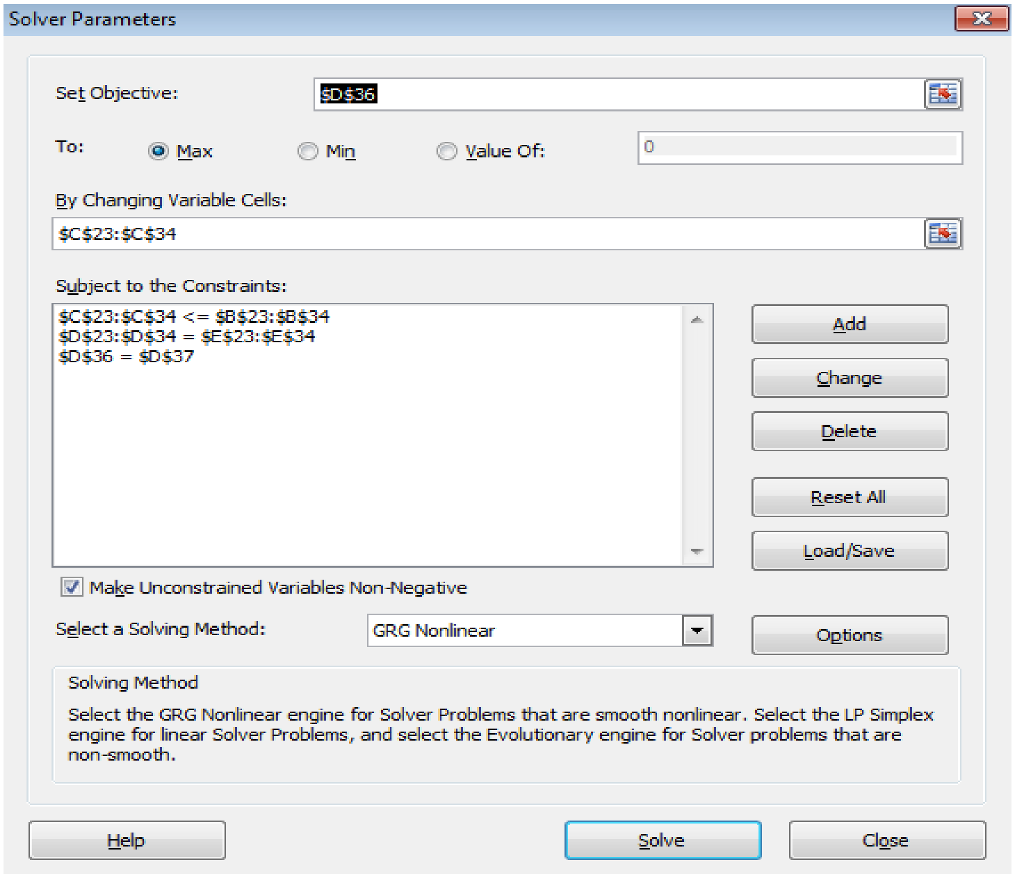
Table 4. Water Generated Using Average Humidity Percentages



| | Constraint | Variable | | |
|---|---|---|---|---|
| Month | Average H | Best H | Water (L) | monthly need |
| Jan | 72.5 | 58.41 | 62.00 | 62 |
| Feb | 71 | 55.92 | 56.00 | 56 |
| Mar | 65.5 | 58.41 | 62.00 | 62 |
| Apr | 61.5 | 57.61 | 60.00 | 60 |
| May | 58.5 | 58.41 | 62.00 | 62 |
| Jun | 58 | 57.61 | 60.00 | 60 |
| Jul | 60 | 58.41 | 62.00 | 62 |
| Aug | 63 | 58.41 | 62.00 | 62 |
| Sept | 64.5 | 57.61 | 60.00 | 60 |
| Oct | 66.5 | 58.41 | 62.00 | 62 |
| Nov | 68.5 | 57.61 | 60.00 | 60 |
| Dec | 71.5 | 58.41 | 62.00 | 62 |
| | | | | |
| | | output | 730 | |
| | | Limit | 730 | |

Table 4 shows the variables and constraints set to generate an output of 730 liters of water needed per person over the year. The best H value, which refers to humidity, is constrained by the average humidity percentages and represents the predicted humidity percentage needed to generate the minimum amount of water needed as constrained by monthly needs using 150 coils. Figure 16 shows the solver used to solve such table. The color coding on the table refers to the constraints, water, and output, which are constant, while the white columns are auto-generated by the solver utility on Microsoft Excel.

Figure 16. Solver Parameters for the Average Humidity Percentages



Set Objective: `$D$36`

To: ● Max ○ Min ○ Value Of: 0

By Changing Variable Cells: `$C$23:$C$34`

Subject to the Constraints:

`$C$23:$C$34 <= $B$23:$B$34`
`$D$23:$D$34 = $E$23:$E$34`
`$D$36 = $D$37`

☑ Make Unconstrained Variables Non-Negative

Select a Solving Method: GRG Nonlinear

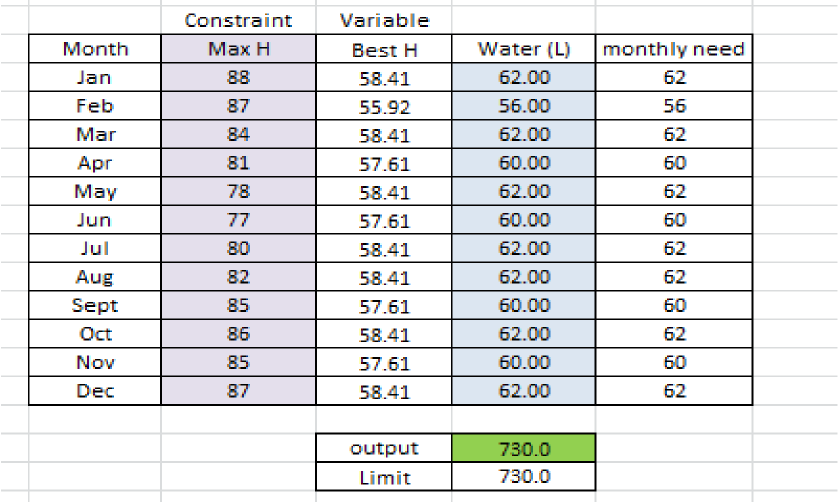
Solving Method

Select the GRG Nonlinear engine for Solver Problems that are smooth nonlinear. Select the LP Simplex engine for linear Solver Problems, and select the Evolutionary engine for Solver problems that are non-smooth.

Note that the constraints set for this problem were set to be a limited amount of water (730 L), limited minimum amount of water per day, and maximum percentage of humidity.

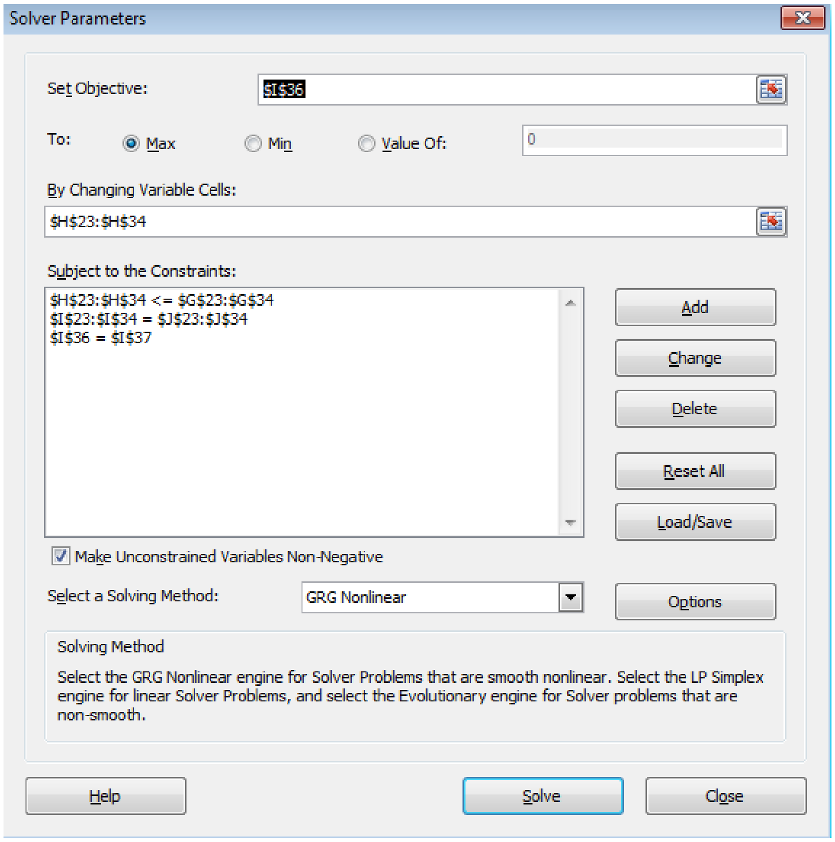
Table 5 shows the variables and constraints set to generate an output of 730 L of water needed per person over the year. The best H in this case is constrained by the maximum humidity percentages registered. The best H represents the predicted humidity percentage needed to generate the minimum amount of water needed as constrained by monthly needs using 150 coils. Figure 17 shows Microsoft Excel Solver model used to solve such table.

Table 5. Water Generated Using Maximum Humidity Percentages



|  | Constraint | Variable |  |  |
|---|---|---|---|---|
| Month | Max H | Best H | Water (L) | monthly need |
| Jan | 88 | 58.41 | 62.00 | 62 |
| Feb | 87 | 55.92 | 56.00 | 56 |
| Mar | 84 | 58.41 | 62.00 | 62 |
| Apr | 81 | 57.61 | 60.00 | 60 |
| May | 78 | 58.41 | 62.00 | 62 |
| Jun | 77 | 57.61 | 60.00 | 60 |
| Jul | 80 | 58.41 | 62.00 | 62 |
| Aug | 82 | 58.41 | 62.00 | 62 |
| Sept | 85 | 57.61 | 60.00 | 60 |
| Oct | 86 | 58.41 | 62.00 | 62 |
| Nov | 85 | 57.61 | 60.00 | 60 |
| Dec | 87 | 58.41 | 62.00 | 62 |
|  |  |  |  |  |
|  |  | output | 730.0 |  |
|  |  | Limit | 730.0 |  |

Figure 17. Solver Parameters for the Maximum Humidity Percentages



Set Objective: $I$36

To: ● Max ○ Min ○ Value Of: 0

By Changing Variable Cells:
$H$23:$H$34

Subject to the Constraints:
$H$23:$H$34 <= $G$23:$G$34
$I$23:$I$34 = $J$23:$J$34
$I$36 = $I$37

☑ Make Unconstrained Variables Non-Negative

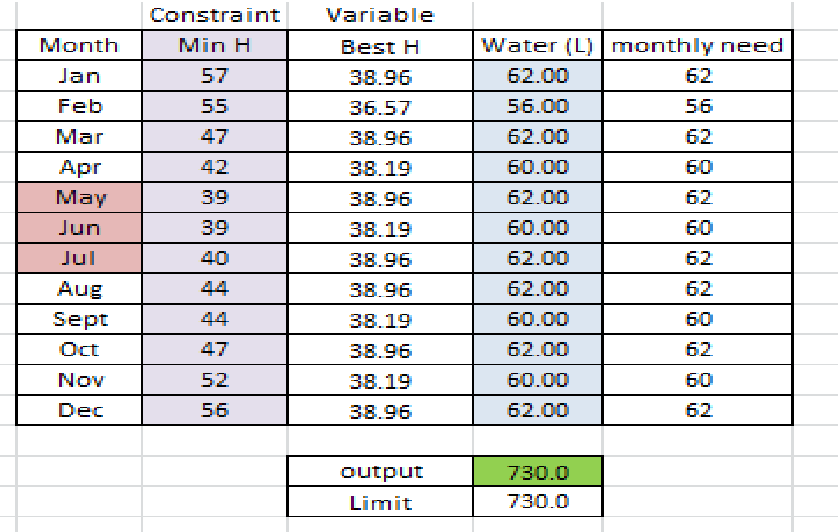
Select a Solving Method: GRG Nonlinear

Solving Method

Select the GRG Nonlinear engine for Solver Problems that are smooth nonlinear. Select the LP Simplex engine for linear Solver Problems, and select the Evolutionary engine for Solver problems that are non-smooth.

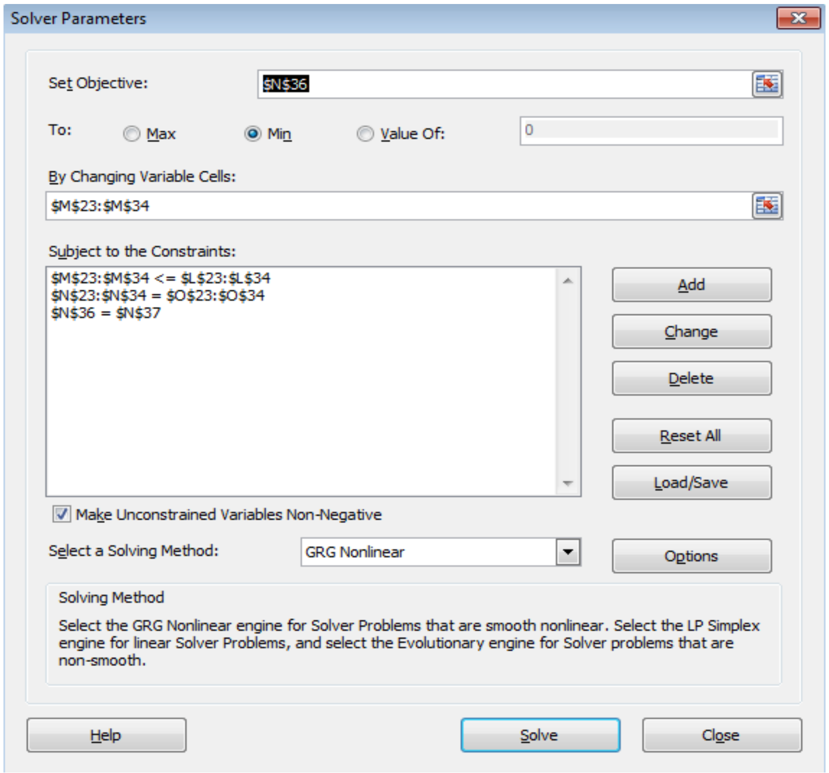
Table 6 and Figure 18 represent the variables and constraints set to generate an output of 730 L of water needed per person over the year with the constraint of minimum humidity percentages registered. The best H represents the predicted humidity percentage needed to generate the maximum amount of water needed as constrained by monthly needs and increasing the number of coils to 330. Figure 18 shows the solver used to solve such table.

Table 6. Water Generated Using Minimum Humidity Percentages



| | Constraint | Variable | | |
|---|---|---|---|---|
| Month | Min H | Best H | Water (L) | monthly need |
| Jan | 57 | 38.96 | 62.00 | 62 |
| Feb | 55 | 36.57 | 56.00 | 56 |
| Mar | 47 | 38.96 | 62.00 | 62 |
| Apr | 42 | 38.19 | 60.00 | 60 |
| May | 39 | 38.96 | 62.00 | 62 |
| Jun | 39 | 38.19 | 60.00 | 60 |
| Jul | 40 | 38.96 | 62.00 | 62 |
| Aug | 44 | 38.96 | 62.00 | 62 |
| Sept | 44 | 38.19 | 60.00 | 60 |
| Oct | 47 | 38.96 | 62.00 | 62 |
| Nov | 52 | 38.19 | 60.00 | 60 |
| Dec | 56 | 38.96 | 62.00 | 62 |
| | | | | |
| | | output | 730.0 | |
| | | Limit | 730.0 | |

Figure 18. Solver Parameters for the Minimum Humidity Percentages



Set Objective: $N$36

To: ○ Max ● Min ○ Value Of: 0

By Changing Variable Cells: $M$23:$M$34

Subject to the Constraints:

$M$23:$M$34 <= $L$23:$L$34
$N$23:$N$34 = $O$23:$O$34
$N$36 = $N$37

☑ Make Unconstrained Variables Non-Negative

Select a Solving Method: GRG Nonlinear

Solving Method

Select the GRG Nonlinear engine for Solver Problems that are smooth nonlinear. Select the LP Simplex engine for linear Solver Problems, and select the Evolutionary engine for Solver problems that are non-smooth.

Hence, the system has successfully validated the EcoloBlue statement of 30% RH efficiency to harvest water. If the system has been developed further to cover larger physical areas, such as (Qatarat Al nada) plant in Abu Dhabi that is being installed currently, then it would be a great alternative for source generation and water production—which may provide several regions of the world with enriched agriculture, energy, and most importantly, water (Qatarat Al nada 2013).

Global fresh water requirements have to be fulfilled in order to reduce the everlasting reduction of natural water resources or use of expensive means of water production, such as desalination plants and water treatment.

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# IV. SCALING AND TECHNOLOGY THRESHOLDS (FEASIBILITY STUDY)

## A. INTRODUCTION

As systems are designed, several issues must be considered in order to produce the ultimate system required and fulfill the need of its convenience. These issues are challenges to the engineering that must be fulfilled prior the design phase. From these challenges, scalability of products and services are indicated by their thresholds of utility for uses by the stakeholders. There will be limits to economic viability of the products, limits to the outputs that can be sustained by the level of inputs that are operative in other regions of utility. It is these limits or thresholds that distinguish the regimes in which scaling is effective for a given technology.

In a qualitative sense, the scalability from macro to micro depends on the holonic nature of objects and processes. A Holon is a self-reliant entity that is simultaneously wholes and parts (Koestler 1968). Hence, the physical interpretation of scalable processes means the interrelations between objects through interaction are enabled within the limits of the objects' mechanisms to accept and give up EMMI.

In a more specific sense, scalability can be viewed as engendering greater numbers of things with less enablers. This common view is often expressed as the one—to many increases, a scalable process has taken place. Another common view poses scalability in terms of a distribution, again expressed as the one—to many. A different view of scalability reflects the relative gain in utility by a change in an underlying process. The greater the increase in utility, the greater the scalability of that change in an underlying process.

The process of scaling exposes the essential dimensions and relations between objects, e.g., patterns. Scaling presupposes the sequencing and simultaneity of interactions, their relative interactional strengths, in conjunction with their physical and temporal arrangements (Langford 2014, 114).

According to David S. Rosenblum, the director of software systems engineering at London Software Systems Inaugural Lecture, he indicates that "scalability is a key requirement for the corporate content infrastructure, which needs to be capable of handling high volumes of content as well as fulfilling high performance requirements” (Rosenblum 2004). Additionally, qualitative scalability is an increasingly important issue for systems engineering in the field of water production, as it is involves the amount of water produced to the total number of users. As for the water harvesting system, it is an individual system that satisfies the need of one person, for survival purposes, while scaling up to the desalination plants for instance, the main implication is to fulfill the need of a larger number of population. Scalability in systems engineering lacks well-defined, applicable, quantifiable principles (Rosenblum 2004).

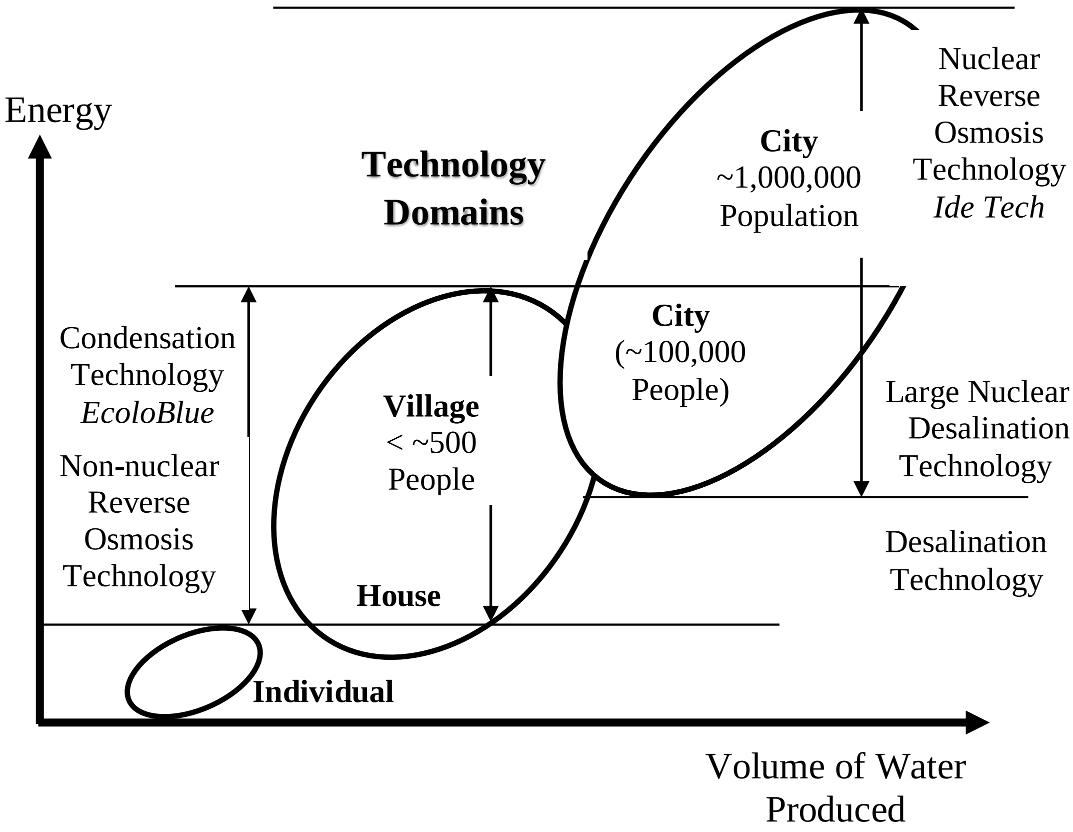
Scalability is considered to be the ability of the system to function properly and continuously as it changes in its volume or size in order to satisfy the need of the user. Scaling is not limited to functioning well once a system is rescaled, but actually take full to be mostly advantageous in all means of its design and availability.

Systems ought to be designed for scalability and flexibility to lower future extensions and upgrades on the system. This will enable the cost to be controlled rather than amplified by replacing the whole system. In this regards, the water production system ought to be scalable with thresholds to satisfy the need of the targeted user. Since the market is segmented into several categories, it is more convenient to satisfy a particular segment of the population rather than focus on the whole as a user. For instance, the water-harvesting system is targeting a particular user, an individual in remote areas or humid and hot areas. If the system was designed to fulfill the need of all the population, it would need to overcome several more aspects of engineering in order to satisfy the fundamental problem of water scarcity in the world.

## B. QUALITATIVE SCALING

Qualitative scalability can be demonstrated in a graphic illustration to give a better perspective of the effect of technology over time and to reflect the scalability influence over the engineering of the water production. Figure 19 shows the thresholds of various water harvesting technologies compared to the volume of water produced. For instance, within a technology domain, such as condensation (EcoloBlue), non-nuclear reverse osmosis (Ampac), and nuclear reverse osmosis (Ide Technologies), the scalability of each product is within the limits of technology employed by the manufacturer. Quantitative scalability will be discussed at the end of this section.

Figure 19. Technology Thresholds for Access to Harvested Fresh Water



EcoloBlue (2015a) has delivered water-harvesting systems to serve cities, villages, and homes. The same technology is scaled across these three different distribution domains. The small unit, which is designed for household use, is 3.63 $m^3$ with an output of 11,000 liters of fresh water per year. The same technology is used in their mid-sized water harvester with a volume of 6.68 $m^3$ and an output of 365,000 liters per year. The small sized unit provides water for home, while the mid-sized unit provides the fresh water needs of a village of 500 people. At the larger end of the scale, EcoloBlue is currently constructing a city-sized water harvester that is 5,140 $m^3$ to service the needs of 200,000 people at a cost of $0.05 per liter. The energy requirements for harvesting water are proportional to the size of the equipment for the condensation technology used by EcoloBlue.

Ampac (2015) also produces a product line of water harvesting equipment that uses non-nuclear power with reverse osmosis instead of condensation. Reverse osmosis is the technique of forcing seawater through a very fine membrane that "catches" minerals and sends fresher water through the membrane and laden water in another path. Several steps help to purify the fresh water, including an acid wash, further filtering, and sometimes a change in pH (a measure of alkalinity/acidity). Typical reduction in salt is greater than 99%. Ampac's city-sized systems produce 138 million liters per year with a volume of 54 $m^3$. Of course that volume represents only the reverse osmosis portion of the installation and excludes the piping, pumps, and filters for the intake of seawater, as well as the storage of freshwater once harvested and the subsequent distribution to users.

Ide Technologies (2015) develops and constructs water harvesting facilities based on nuclear energy to boil the seawater. The technology employed is reverse osmosis. The most recent plant is the Encina Power Station in Carlsbad, California that provides 74.6 trillion liters (19.7 trillion gallons) of water in a year for 1.15 million residential and industrial customers in San Diego County and parts of Orange County California. This major nuclear desalination facility is the largest of its kind in North America.

Comparing only the harvesting portion of the Ampac's city-product with that of the EcoloBlue's city-product, the volume of Ampac system is 95 times smaller than the EcoloBlue system! The Ida Technology's system is 95 times larger than the EcoloBlue system.

There are several types of technologies that are designed into desalination systems to produce fresh water. In aggregate, these technologies produce nominally 40 million liters of water per day, require a nuclear power generation facility to boil seawater from which fresh water is extracted, and a large infrastructure and safety complex must be maintain with highly skilled labor. The cost of fresh water from these desalination technologies varies, but is typically about $0.002 per liter ($0.0031 per liter, Ide (2015)).

However, the installation costs for these desalination technologies can exceed $20,000,000 (Bradley 2014).

With a systems approach to design engineering, the water recovery technology can often be focused on the minimal technology solution to provide an economically feasible product or service across a broad range of product offerings. Here, the goal is to apply the same engineering technology to different market segments, while reaping the benefits of a common technology. However, with every technology, the scaling from domain to another often comes up against thresholds for economic feasibility or technical applicability to satisfy the changes in requirements for volume, energy, materials, and information (Langford 2012). These economic and technical issues may make the scaling of a particular technology less attractive than another more suited technology. In the case of EcoloBlue, the suitability of their technology provides a commercial alternative to other technologies, such as Ampac. However, a strong competitive technology is found with Ampac, whose infrastructure costs are significantly less than EcoloBlue's infrastructure costs. With the reliance of EcoloBlue's technology on power from either the power grid, solar, or wind generation, the costs per liter are significantly higher than desalination technology of any type.

Here we find a key trade space for fresh water harvesting. In the same geographic area, the cost factors are the availability and access to fresh water, the relative humidity, the temperature, and the social/political situation. Installation costs are weighed against life cycle costs, installation costs are juxtaposed with the life cycle costs of competing technologies, and the consequences of construction/installation and operations are weighed in terms of health, environment, and quality of the freshwater. Scaling laws are a convenient, albeit quantitative means of performing multivariate analyses.

From Figure 19, we observe a technology gap for individuals who are mobile. Neither the EcoloBlue condensation technology nor the Ampac reverse osmosis technology are applicable to this specialized niche market for individual users of fresh water. Harvesting products that are designed for use by individuals, whose daily needs are a few liters per day and who need potable water, have no alternative at this time but to carry water in sufficient quantity. Examples of these individuals include members of the military, people active in sports, e.g., bike riders, and people who are health-wise responsible but who do not find water to be either available or convenient. A product such as a cup-sized container with water regenerative means requires miniaturization of and perhaps a new technology. A mobile harvester is beyond the existing technology ability to meet the required size, volumetric efficiency necessary for water extraction, and potential energy requirements. An ideal product for such mobile use would start the process with an empty cup, then in time, the cup would fill and the user would drink the water, to restart the harvesting process again. In other words, the scaling of technology to the micro-sized units of water-harvesting systems is as yet without commercialized mobile products.

The purpose of the introducing the water-harvesting system is to demonstrate its effectiveness and feasibility on individual scalings to a comprehensive scaling law that captures realistic conditions of use. Measures of effectiveness (MOEs) and measures of performance (MOPs) should be identifiable and considered a vital part of the systems engineering process. According to Noel Sproles (2001 2), an Australian systems engineering researcher from the University of South Australia, MOEs are defined as "standards against which the capability of a solution to meet the needs of a problem may be judged." MOEs are statements that represent critical issues and identify goals instead of methodologies. "MOEs must be sufficient to qualify that a system meets stakeholders' requirements; they mostly rely on quantitative objectivity, although qualitative subjectivity is permissible" (Sproles 2001). Measures of performance, on the other hand, according to Robert D. Behn (2003) at Harvard University's Kennedy School, are "the most common and familiar elements of assessment, as they establish a clear abstraction of stakeholders' satisfaction and interest serving off the detailed measurements of the business process fulfillment" (Behn 2003). The INCOSE guide for technical measurement (2015 133) defines MOPs as "the measures that characterize physical or functional attributes relating to the organizational operation, measured or estimated under specified benchmarking and/or operational environment conditions"(INCOSE 2015 133).

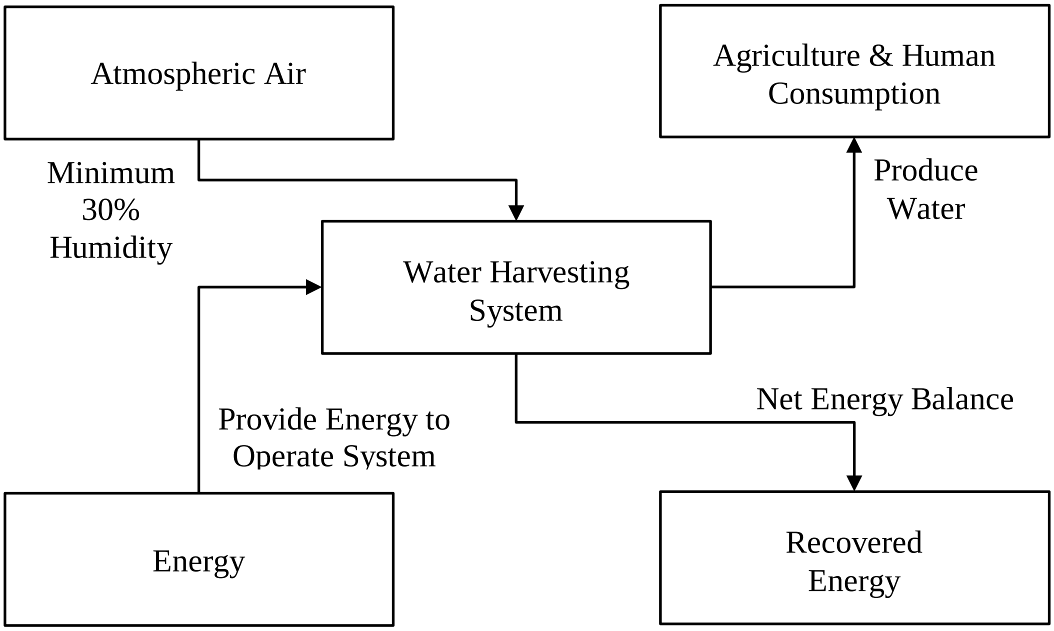
## C. QUANTITATIVE SCALING

The feasibility of developing a quantitative scaling law for harvesting fresh water from the atmosphere, begins with the notional comparisons of technology offerings and volume output indicate in Figure 20, i.e., qualitative scaling. Quantitative scaling laws capture the mathematics of physical principles as represented by various measures. And, sometimes scaling laws are metrics without units. Metrics represent similarities across a broad range of like-kind functions that are packaged into a product or serviced for use. These similarities can be geometrical, dynamic, kinematic, economic, or entropic. Geometrical similarities have common shape, sometimes exhibiting the same dimensional ratios. Dynamic similarities have common movement, representing relations in Newtonian, Relativistic, or Quantum Physics. Kinematic similarities exhibit common changes in vectors, expressed as process or changes in process (which is equivalent to force in a physical sense. Economic similarities are often reflected through standards shown as ratios or as categories or partitions. Entropic similarities characterize behavior of physical objects in response to changes in a system that is in equilibrium and then exhibits degeneracy of structures, configuration, or states.

The key causal relations that determine utility of the water harvesting technology (indicated in Figure 19), are reflected in the boundary conditions by which energy, matter, material wealth (Langford 2012) are transformed by the technology into the system of harvesting water.

A context diagram is developed to illustrate the boundaries limiting the system’s operational theory with boundary conditions to indicate the required interactions. Figure 20 illustrates the context diagram for the Water-harvesting system showing the WHS boundaries and identifying the potential impact on agriculture and human consumption and the energy recovered from the harvesting process (outputs) and the impact(s) of the atmosphere and energy source(s) on the WHS. Humidity is a boundary condition for successful harvesting, as is producing sufficient input energy and output water.

Figure 20. Physical Boundaries of the System



The constraints that represent the tradeoffs of humidity, energy input, energy output, and water harvested are causal to ensure the economic and operational viability of the WHS. The feasibility of various technologies is determinable within the context of life cycle economics premised on the causal relations.

As described by Langford (2015), feasibility Studies are designed to facilitate a decision, in this instance a decision about the commercial viability of one technology versus another technology. There are different dimensions to feasibility studies: including technical, financial, managerial, operational, social, and legal. The limitations are temporal and cost factors. Temporal factors included the events that impact the operations and sustainment activities over the lifetime of the product or service. The feasibility study centers on the rationale for decisions, therefore, the need to ascertain what information shall be included, and the determination of the measures of the outcomes are the essential ingredients to making a sound decision (Langford 2015).

From Figure 20, the dimensions of causal interest are energy kilowatt-year per volume of water in liters (kWyr/l) necessary to harvest water and the quantity of water harvested in liters per year (l/yr). Figure 21 illustrates the data from three technologies—desalination by boiling seawater from the heat of a nuclear reactor; desalination by reverse osmosis energized by solar energy, ship's power plant, or from the primary power distribution grid; water extraction by condensation of humidity from the atmosphere, powered by solar energy, wind driven turbines, or from the primary power distribution grid. These three technologies are plotted according to their energy inputs and water outputs, and then variations of configurations are indicated to show the commercial feasibility for product offers to different number of consumers of fresh water.

Each of the product offerings may require supporting infrastructure that is either available through municipal service, such as prime electrical power or co-generation capability, pumps and pipes to move water from its seawater source to its distribution systems—one for returning higher salinity seawater to its seawater source and one for piping freshwater to end users customers. These supporting infrastructures vary nominally in terms of the number and type of water pumps, sources of prime electrical power, and in facility requirements for sustained operations. The cost models used for this comparison of technologies will be based on the power requirements (kW-yr) kilowatt-year (here we assume on a per 365-day basis). Without sufficient engineering detail, which would be proprietary to each of the technology providers, this analysis assumes that the differences in the need for prime electrical power can be represented as that needed to support the different types of water pumps. Also, there is significant difference in the electrical infrastructure needs to support a nuclear desalination operation versus the condensation or reverse osmosis technologies. Therefore, the makeup of the energy cost models will be based on pricing for the energy needs of the low volume (<400,000 liters per year) from the websites for EcoloBlue and Ampac (condensation and desalination, respectively), and for the high volume nuclear desalination technology (>100,000,000,000 liters per year), the published government reports on prime electrical costs will be used (Ide Technologies). For perspective, the cost per liter of water from a nuclear desalination plant is ~ 30–65 times ***less*** than that of the technologies used by

EcoloBlue or Ampac for city-sized installations. And for smaller distribution, at the household- and village-level the cost per liter advantage reverses to EcoloBlue (condensation) and Ampac (non-nuclear reverse osmosis) with a 105 times advantage over that of Ide Technologies (nuclear reverse osmosis). In other words, the condensation and non-nuclear desalination technologies are compatible with household, village, and small city needs for water harvesting, whereas the nuclear reverse osmosis technology is meant for high volume water harvesting with some amount of "leftover" capacity for generating electrical power to be distributed on the electrical grid. Energy costs to total costs for producing desalinated water run about 35–40%.

Figure 21 depicts the relations between the kW-yr (dependent variable) and the liters-yr (independent variable) produced in the same time period. Data is plotted in Table 7, Three Technology Product Offerings for Commercial Use.

Figure 21. Scaling Law for Water Harvesting Products

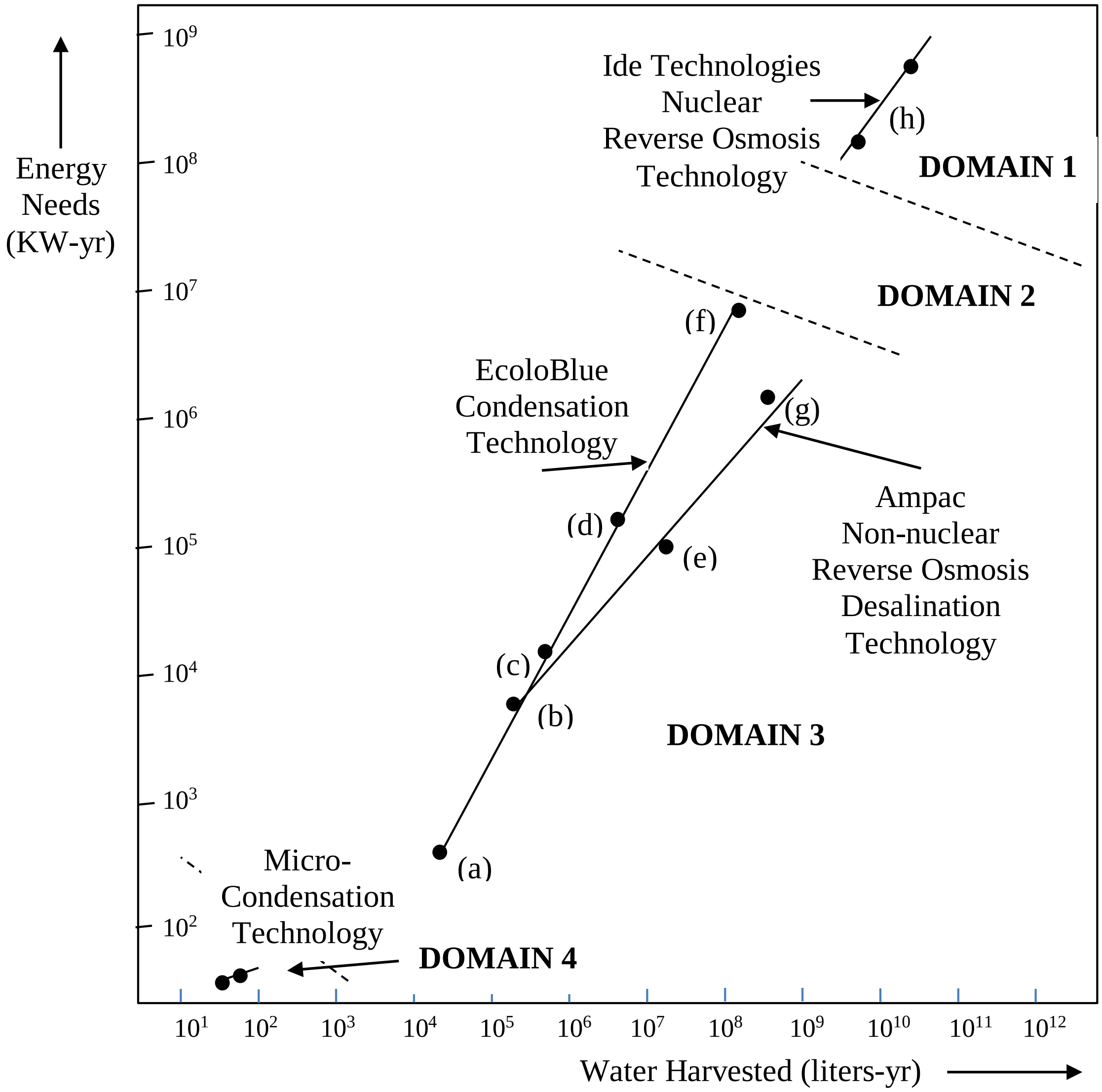


Table 7. Three Technology Product Offerings for Commercial Use

| Supplier | Volume | kW-yr | Liter-yr | Key |
|---|---|---|---|---|
| EcoloBlue | Home | 411 | 11,052 | a |
| Ampac1 | Village | 8,845 | 207,229 | b |
| EcoloBlue | Village | 13,578 | 365,000 | c |
| EcoloBlue | City unit | 138,700 | 3,650,000 | d |
| Ampac1 | Small city | 97,300 | 16,578,300 | e |
| EcoloBlue | City | 8,322,000 | 109,500,000 | f |
| Ampac1 | City | 1,556,800 | 138,152,500 | g |
| IDE Tech | Metro | 486,000,000 | 2,710,000,000 | h |
| IDE Tech | Metro | 957,760,000 | 19,710,000,000 | h |

There are four domains of technology indicated on Figure 21. At the large end of the systems (the first domain), the nuclear technology dominates with its economies of scale for very high-energy outputs of nuclear reactors. As the technology matures for small house-size nuclear reactors (World Nuclear Association 2015), we should expect to find a new technology regime that competes with the city-, village-, and home- systems. But first, we should expect to find products offerings in the 500,000 user domain that will compete with the high-output volumes of products similar to EcoloBlue’s products. The primary issue for this transitional domain between the high volume outputs and the city-units (the second domain) will be the cost per liter. The new nuclear technology will need to be competitive with $0.42 per liter (typical of the EcoloBlue products). The third domain is the product offerings for homes to city-units (typical of EcoloBlue and Ampac products). Whether the new nuclear technology can be cost competitive is to be demonstrated, and whether a new technology emerges that can provide the volume of freshwater necessary is a perennial quest by entrepreneurs (for example, discussions on blogs and forums, e.g., http://www.spacewx.com/). The fourth domain indicated on Figure 21 is a new market for mobile harvesting of fresh water for individual use on a daily basis. None of the existing technologies scale into this fourth domain. Domain 4 is most important for individuals who are out and away from sources of freshwater, e.g., military personnel, bicyclists, mountain climbers, and hikers. A brief consideration of the stakeholder needs in Domain 4 should encompass mobility, small size, limited storage capacity, convenience and ease of use, solar or battery power, and "just-in-time freshwater."

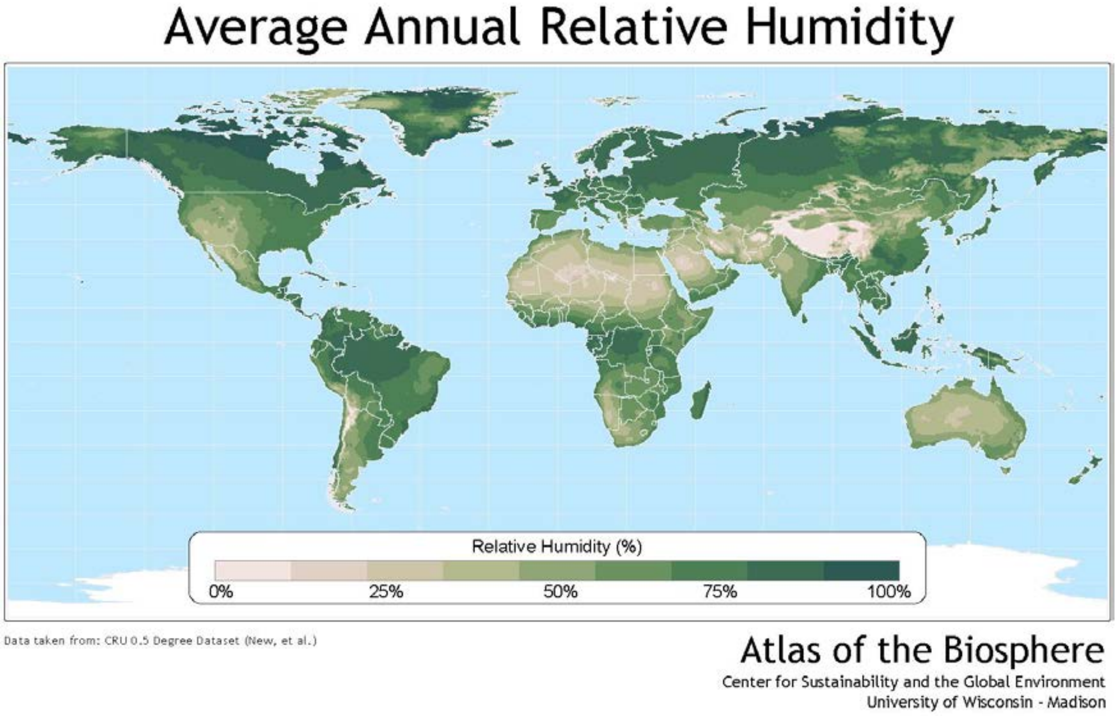
The EcoloBlue product line (EcoloBlue 2015a) scales in output of freshwater to the volume of the condensation system at the ratio of 11,052 liters/year: 3.63 meters$^3$ for the home unit, at the ratio of 265,000 liters/year: 38.68 meters$^3$ for the village unit, and for a small city unit size at the ratio of 2.65 million liters/year: 235.12 meters$^3$. The change in scaling ratios illustrates the change in piping and pumps necessary to move water. Only the EcoloBlue "home" version is a self-contained system which simply runs a small hose to the seawater source. There was insufficient data available for the Ampac systems to be analyzed for volume and output. And, the Ide Technologies data only indicated there was 95 acres of land available for the nuclear desalination plant.

As a design goal for a product designed for Domain 4, a proof of concept should be either on the micro-end of the scale, estimated at a volume of less than 100 cm$^3$ from which to scale up technology or at a volume less than 1000 cm$^3$ from which to scale down technology. Micro-condensation would need a larger volume of air to pass by the condensers (perhaps with a ceramic oscillator driven by a very low voltage potential) so that the harvested volume of water can be greater than the dew-collection equivalent.

## D. PROBLEM CHARACTERIZATION

The findings of this research demonstrate the reliability of the water-harvesting system by finding the minimum percentage of humidity required to generate the desired amount of water needed. Readings may vary depending on the region, as shown in Figure 22, as the system considered valid in the location of the registered humidity percentages. The problem to be solved is to estimate the feasibility of the water-harvesting system in areas where 30% or more relative humidity is obtainable, which would allow the system to benefit the users and water resource management efforts.

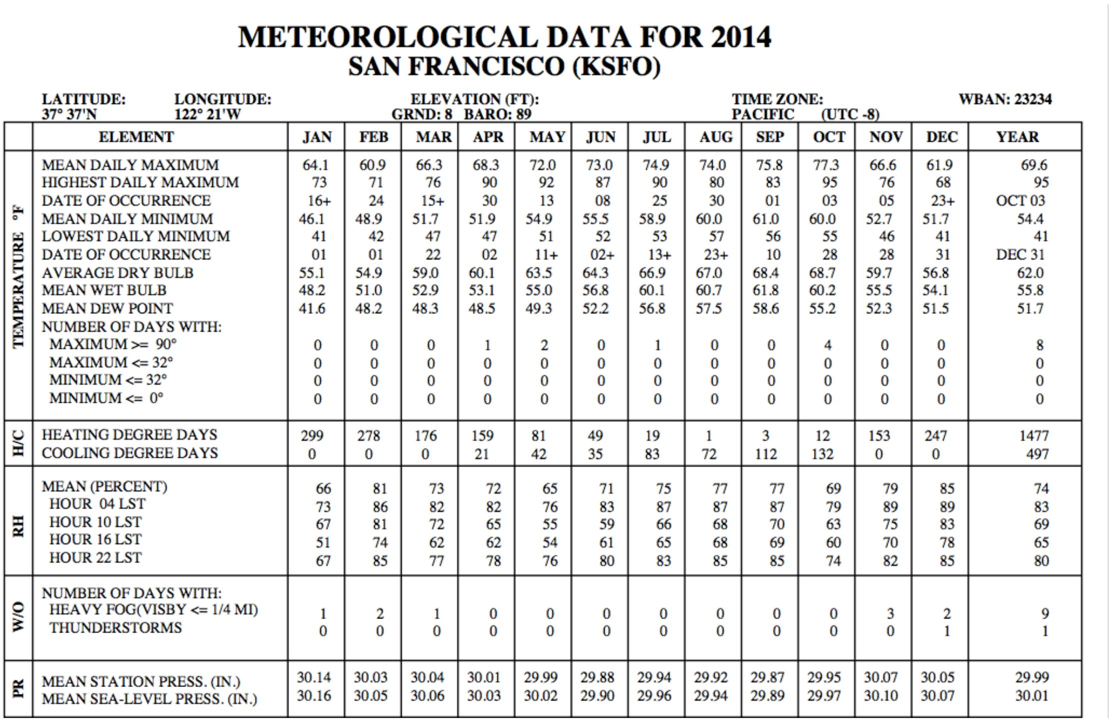
Figure 22. Worldwide Average Annual Relative Humidity



From Center for Sustainability and the Global Environment 2015

According to the global average annual relative humidity representation in Figure 22, relative humidity (RH) varies across the world according to the location. This change in RH has been tracked by a national center for environmental information, the National Oceanic and Atmospheric Administration (NOAA). NOAA has a collective observatory record that tracks the weather changes in the world. For example, the annual RH record of San Francisco in 2014 is shown in Table 8 and shows that the minimum RH recorded at 65% in May 2014, while the maximum RH was recorded at 85% in December 2014. An example from another continent is Cairo, Egypt, where the minimum RH recorded in May 2014 was 50%, while the maximum RH was 70% in December 2014, as shown in Figure 23.

Table 8. San Francisco Relative Humidity Record for 2014



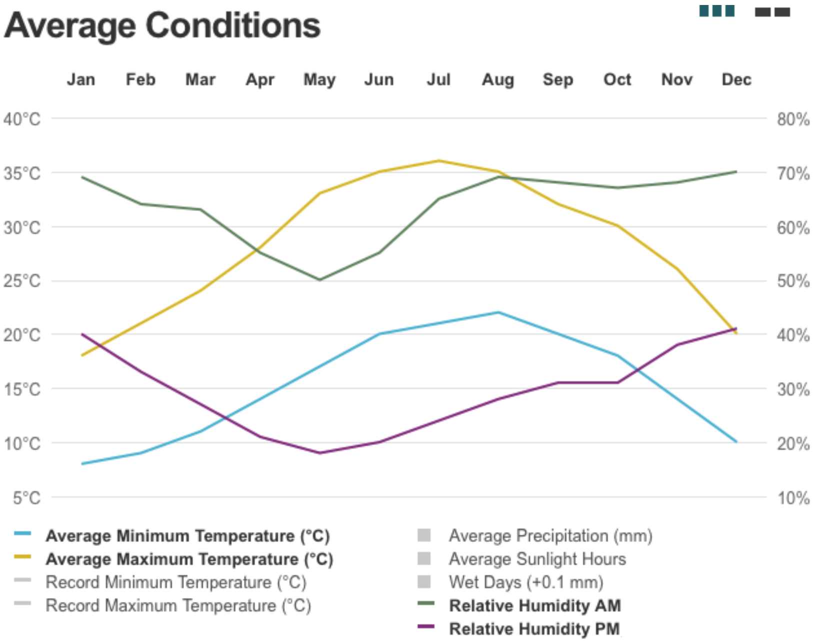
**METEOROLOGICAL DATA FOR 2014**
**SAN FRANCISCO (KSFO)**

**LATITUDE:** 37° 37'N **LONGITUDE:** 122° 21'W **ELEVATION (FT):** GRND: 8 BARO: 89 **TIME ZONE:** PACIFIC (UTC -8) **WBAN: 23234**

| | ELEMENT | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | YEAR |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TEMPERATURE °F | MEAN DAILY MAXIMUM | 64.1 | 60.9 | 66.3 | 68.3 | 72.0 | 73.0 | 74.9 | 74.0 | 75.8 | 77.3 | 66.6 | 61.9 | 69.6 |
| | HIGHEST DAILY MAXIMUM | 73 | 71 | 76 | 90 | 92 | 87 | 90 | 80 | 83 | 95 | 76 | 68 | 95 |
| | DATE OF OCCURRENCE | 16+ | 24 | 15+ | 30 | 13 | 08 | 25 | 30 | 01 | 03 | 05 | 23+ | OCT 03 |
| | MEAN DAILY MINIMUM | 46.1 | 48.9 | 51.7 | 51.9 | 54.9 | 55.5 | 58.9 | 60.0 | 61.0 | 60.0 | 52.7 | 51.7 | 54.4 |
| | LOWEST DAILY MINIMUM | 41 | 42 | 47 | 47 | 51 | 52 | 53 | 57 | 56 | 55 | 46 | 41 | 41 |
| | DATE OF OCCURRENCE | 01 | 01 | 22 | 02 | 11+ | 02+ | 13+ | 23+ | 10 | 28 | 28 | 31 | DEC 31 |
| | AVERAGE DRY BULB | 55.1 | 54.9 | 59.0 | 60.1 | 63.5 | 64.3 | 66.9 | 67.0 | 68.4 | 68.7 | 59.7 | 56.8 | 62.0 |
| | MEAN WET BULB | 48.2 | 51.0 | 52.9 | 53.1 | 55.0 | 56.8 | 60.1 | 60.7 | 61.8 | 60.2 | 55.5 | 54.1 | 55.8 |
| | MEAN DEW POINT | 41.6 | 48.2 | 48.3 | 48.5 | 49.3 | 52.2 | 56.8 | 57.5 | 58.6 | 55.2 | 52.3 | 51.5 | 51.7 |
| | NUMBER OF DAYS WITH: | | | | | | | | | | | | | |
| | MAXIMUM >= 90° | 0 | 0 | 0 | 1 | 2 | 0 | 1 | 0 | 0 | 4 | 0 | 0 | 8 |
| | MAXIMUM <= 32° | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | MINIMUM <= 32° | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | MINIMUM <= 0° | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| H/C | HEATING DEGREE DAYS | 299 | 278 | 176 | 159 | 81 | 49 | 19 | 1 | 3 | 12 | 153 | 247 | 1477 |
| | COOLING DEGREE DAYS | 0 | 0 | 0 | 21 | 42 | 35 | 83 | 72 | 112 | 132 | 0 | 0 | 497 |
| RH | MEAN (PERCENT) | 66 | 81 | 73 | 72 | 65 | 71 | 75 | 77 | 77 | 69 | 79 | 85 | 74 |
| | HOUR 04 LST | 73 | 86 | 82 | 82 | 76 | 83 | 87 | 87 | 87 | 79 | 89 | 89 | 83 |
| | HOUR 10 LST | 67 | 81 | 72 | 65 | 55 | 59 | 66 | 68 | 70 | 63 | 75 | 83 | 69 |
| | HOUR 16 LST | 51 | 74 | 62 | 62 | 54 | 61 | 65 | 68 | 69 | 60 | 70 | 78 | 65 |
| | HOUR 22 LST | 67 | 85 | 77 | 78 | 76 | 80 | 83 | 85 | 85 | 74 | 82 | 85 | 80 |
| W/O | NUMBER OF DAYS WITH: | | | | | | | | | | | | | |
| | HEAVY FOG(VISBY <= 1/4 MI) | 1 | 2 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 2 | 9 |
| | THUNDERSTORMS | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| PR | MEAN STATION PRESS. (IN.) | 30.14 | 30.03 | 30.04 | 30.01 | 29.99 | 29.88 | 29.94 | 29.92 | 29.87 | 29.95 | 30.07 | 30.05 | 29.99 |
| | MEAN SEA-LEVEL PRESS. (IN.) | 30.16 | 30.05 | 30.06 | 30.03 | 30.02 | 29.90 | 29.96 | 29.94 | 29.89 | 29.97 | 30.10 | 30.07 | 30.01 |

From NOAA 2015

Figure 23. 2014 Relative Humidity Record for Egypt

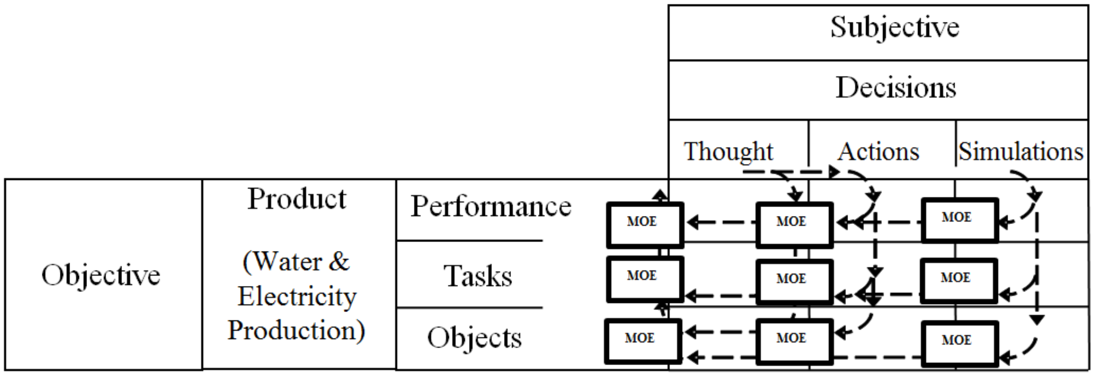


## E. INTERACTIONS ANALYSIS WITH REVENUE PRODUCING FUNCTIONS

Measures of effectiveness (MOEs) can be described through a framework to integrate several features; these features may include reliability of the system, continuity of operation, practicality, and feasibility of the system.

Figure 24 demonstrates the sequencing of the interactions between the objects and the actions for goal-oriented development. This interaction begins with thought structures, succeeding from a subjective item to one objective item, and then continuing to the next subjective item, from left to right (Langford 2014). Research work tracks in the counter-clockwise direction through the integrative framework. "The perspective of management begins with the subjective frame (Thought, Actions, and Simulations)" (Langford 2014).

Figure 24. Interaction Integration Analysis



After Langford 2014

From a technical perspective, the focus is mainly on the objective side of the system. According to "Building the Determinants of Cyber Deterrence Effectiveness" by Langford (2014), there are nine fundamental points within the framework, each resulting from the relationship of an item in one frame intersecting with an item in the other frame. These nine cross-frame intersections of the integrated framework are the nine domains of MOEs.

The Nine Step methodology was developed to unify the concepts of MOEs into a repeatable, validated process to identify MOEs associated with both development and operations of any system. According to Langford (2014), these nine steps are summarized as follows:

**Define Terminology**: Theorize a working definition of terms to prepare to focus and direct the effort within the problem domain.

**Define Boundaries and Functions**: Perform a functional analysis on the main functions of the defined terminology that are measureable. It is here to determine the functions of a water harvesting system.

These functions are designed to increase the opportunity cost instead of the material costs to shift disruptions to another time or place.

**Perform Life cycle Analysis**: Define the life cycle of each of the key functions.

**Define Requirements**: Specify the requirements that satisfy stakeholder needs.

**Postulate Solution Set**: Conceptualize and characterize a set of outcomes that fulfill the problem domain concerns.

**Determine Theoretical Foundations**: Apply one or more theories that support the main notion of the possibility of harvesting water from air using solar power.

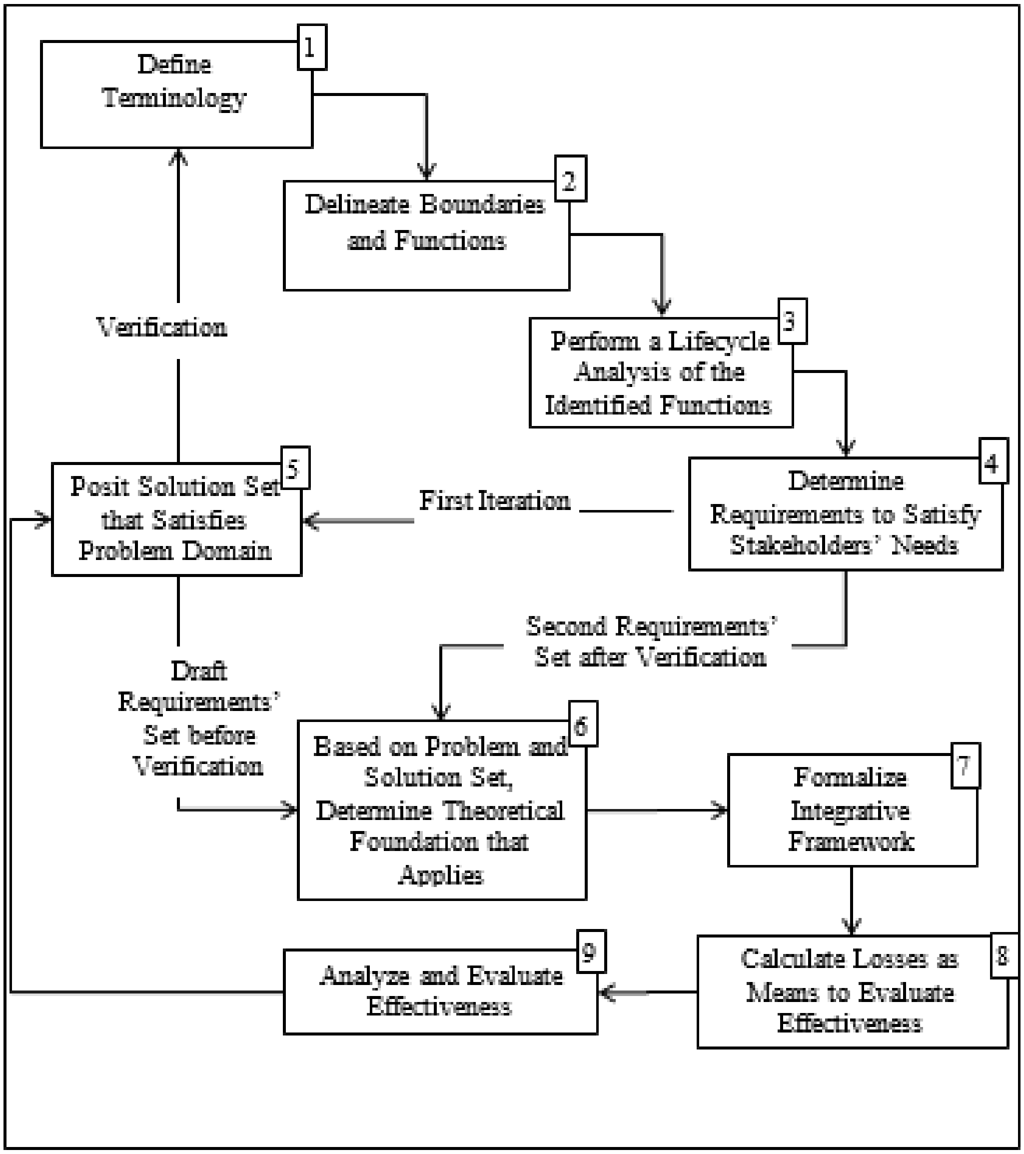
**Formalize Framework**: Map the processes to physical objects through the Integrative Framework (Integration Theory).

**Calculate Losses**: Use the general loss function to measure any encounters that struggle the demonstration of the system performance.

**Analyze and Evaluate Effectiveness**: Compare the effectiveness of the system approach with that of current alternatives of water resources.

The Nine Step methodology to characterize measures of effectiveness is shown in Figure 25.

Figure 25. Nine Step Methodology to Characterize Measures of Effectiveness



From Langford 2014

## F. INTERACTIONS EVALUATION TO SATISFY THE NEEDS

MOE features vary according to the area of study the system needs to be evaluated in. The feature that has been focused on to evaluate the interactions in the WHS has been limited to reliability of the system, continuity of operation, practicality, and feasibility of the system. The reliability of the system measures the extent to which the evaluation procedure yields the expected results on a number of trials according to the collected data of humidity in the region of study. For instance, the reliability of the system has been established and verified in the WHS as the results demonstrate positive findings that the system could operate even with the lowest humidity registered in the region of testing and could improve with more condensing coils or an accelerated air flow input. On the other hand, to overcome the constraint of water decrease in the midyear's months (minimum humidity), the number of coils ought to be increased to 330 in order to generate a sufficient amount of water.

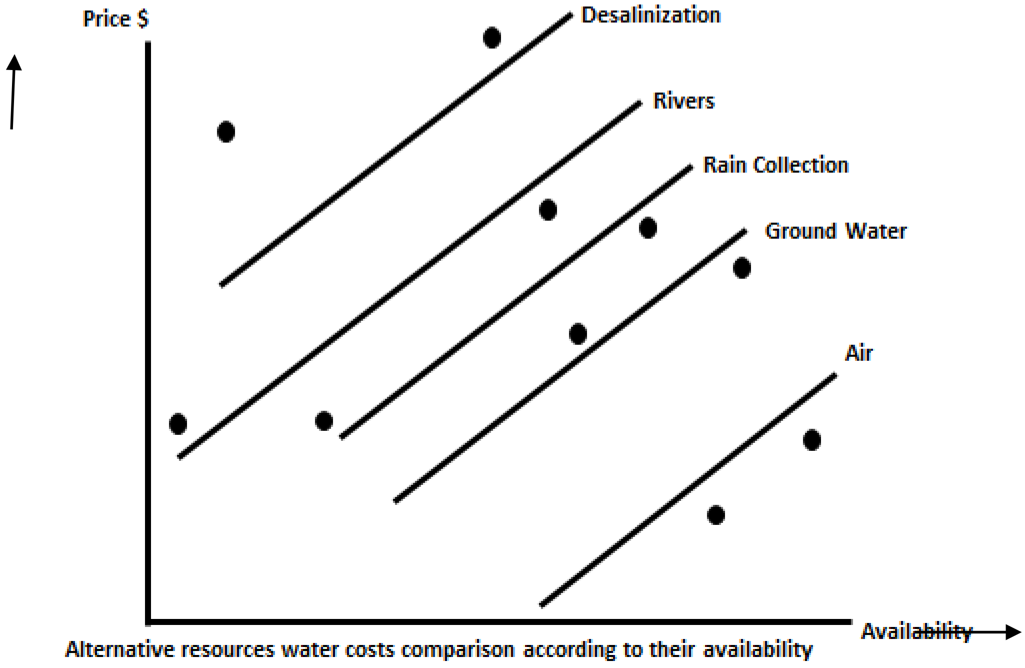
Continuity of operation has been theoretically replicated in the continuous exposure of solar energy and production of sufficient power to continually operate the WHS's components, and therefore to generate a sufficient amount of water to grow the plant in the plant pot example. This example also demonstrates the practicality of the system, as it shall eliminate the watering practices by a person and self-water the plant from the atmospheric air.

Feasibility of the system can be demonstrated through the efficiency of the WHS. The efficiency of the system has been proven to be satisfactory through a practical example demonstrated in the case study example provided at the end of this thesis. The case study provides an example of the validity of the research's findings. In fact, EcoloBlue proves the feasibility of the system in the area of finding alternative solutions to overcome water deficiencies and scarcity.

## G. ALTERNATIVE PROCESSES OUTLINE TO IMPROVE THE INTERACTIONS

Alternative resources of water have been outlined in order to evaluate the system's performance and its feasibility. The alternative resources of water that were introduced into the study were ground water resources, rain collection methods, rivers, desalination plants, and air moisture. Measures of effectiveness of each of the alternative resources were evaluated and compared in order to find the sweet spot among them to validate the operational feasibility. According to several studies, the comparison method is used to illustrate the feasibility of each water resource. Figure 26 demonstrates the most suitable and reliable resources of water according to their price, availability, and feasibility.

Figure 26. MOEs among Alternative Resources Comparison according to Their Availability of Water



The water resources shown in Figure 26 are measured according to their current availability and prices in the region of study. The regions of study were the Middle East (Bahrain) and California in the United States. These regions differ in the availability of water resources, utilization of natural resources, and available funds from governments and private stakeholders. The figure shows that desalination processes are available in the Middle East, while it was not feasible in California due to the abundance of other water resources and the high cost constraints. Ground water, rain, and rivers are mostly available in California as opposed to the Middle East, where ground water wells are scattered sparsely over the region and there is little rain throughout the year (a maximum of two weeks per year on average). Therefore, the use and development of atmospheric air WHSs seem to be most feasible in regions where the price of water treatment and desalination of sea water is prohibitive, or where sufficient water resources are scarce or inaccessible. Figure 26 and Table 9 also show the availability of humid air with the lowest prices required to maintain and develop WHSs in both regions of study, according to Blanchard and Fabrycky's (2011) methodology of systems engineering analogy. According to water resources report in Bahrain, there are three main water resources available: ground water, treated sewage effluent, and desalinized water (Al-Noaimi 2005). Their availability has been decreasing and limited due to an increase in population and water demands.

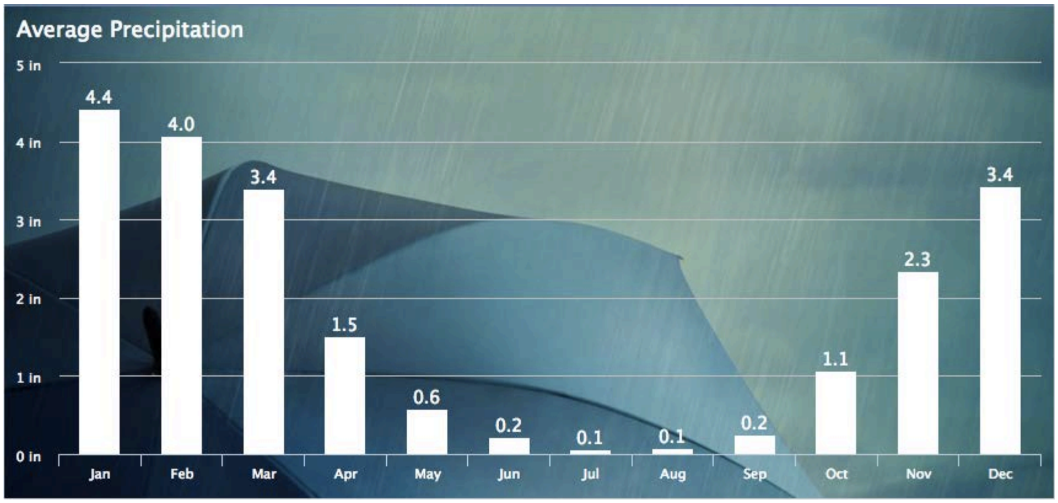
Table 9. Comparison of Water Availability in the Regions of Study

| **Region**<br>**Criteria** | **California** | **Bahrain** |
|---|---|---|
| **Ground Water** | ++ | - |
| **Desalination** | - | ++ |
| **Lakes & Rivers** | ++ | - |
| **Rain Collection** | + | - |
| **Air Moisture** | ++ | ++ |

*Note.* ++ refers to ample availability of water resource
\+ refers to limited availability water resource
\- refers to scarcity of water resource

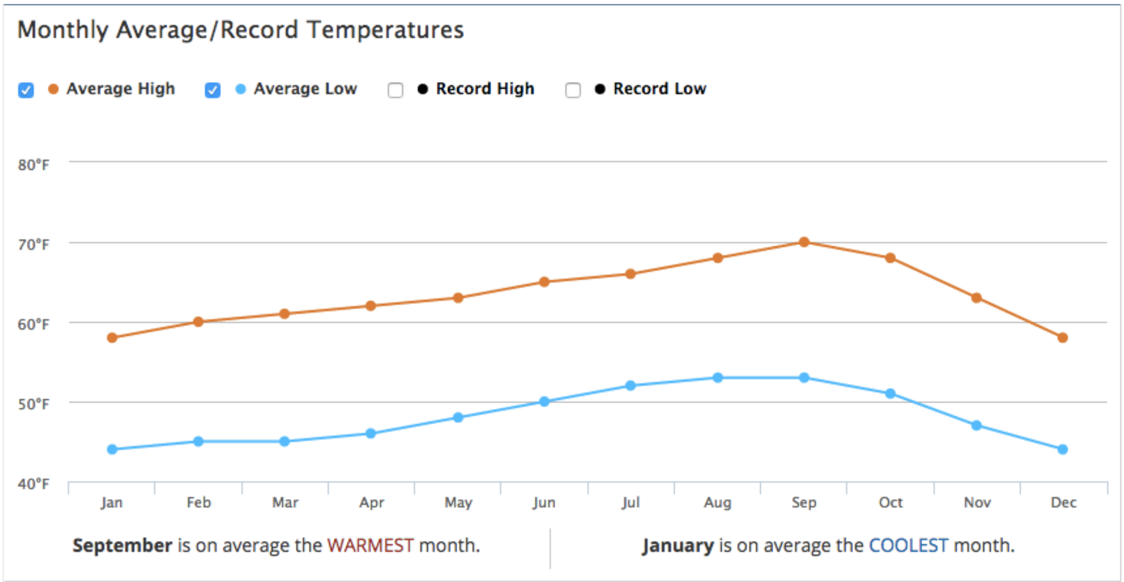
Table 9 also illustrates the availability of water in regions of study, where Bahrain and California were compared in terms of water resources. California is known to have several surface water resources, ground water, long coastal access, rivers, rain and snow in some areas, and air moisture. Banks (1957), the director of water resources for the state of California in 1957, clarified the problem the state was facing: water is running off due to limited resources, an increasing population, and agricultural demands. The study shows that there are around 250 ground water basins in California, with an average area of 5 square miles, while surface water basins, including lakes and rivers, cover over 87 cubic kilometers (over 3,000,000 cubic feet). Rain is limited in scattered areas of the state, as the study shows that the rate of rainfall varies between the winter and spring seasons (October through May), which limits the availability of rain to 20 inches per season in the eastern side of the state (Figure 27 shows the average precipitation for 2014). Desalination in California has not been considered seriously due its high cost of operation. Finally, it is necessary to investigate the weather in California in terms of moisture. Another researcher provides interesting data showing that as the air temperature increases, the air holds more water vapor, and hence the humidity increases (Robertson 2005). For example, 2014 was recorded to be one of the hottest years in California state history (Weather Channel, LLC 2015). Figure 28 shows the annual temperature records and, subsequently, it is possible to envision the humidity percentage increase. Based on that information, Table 9 predicts the availability of water resources in California.

Figure 27. California's Average Precipitation for 2014



Weather.com 2015

Figure 28. California’s Average Temperature for 2014



**September** is on average the WARMEST month.

**January** is on average the COOLEST month.

From Weather.com, 2015

Bahrain, on the other hand, has limited ground water resources, no rivers or surface water, and very little rain, but relies on desalination (44.1 million cubic meters/ year) and water treatment (45 million m/year; Encyclopedia of Earth 2015). Humidity is abundant, as indicated earlier in Figure 16. Consequently, the legend for Table 9 is repeated as follows to illustrate the availability of water resources in both areas of comparison:

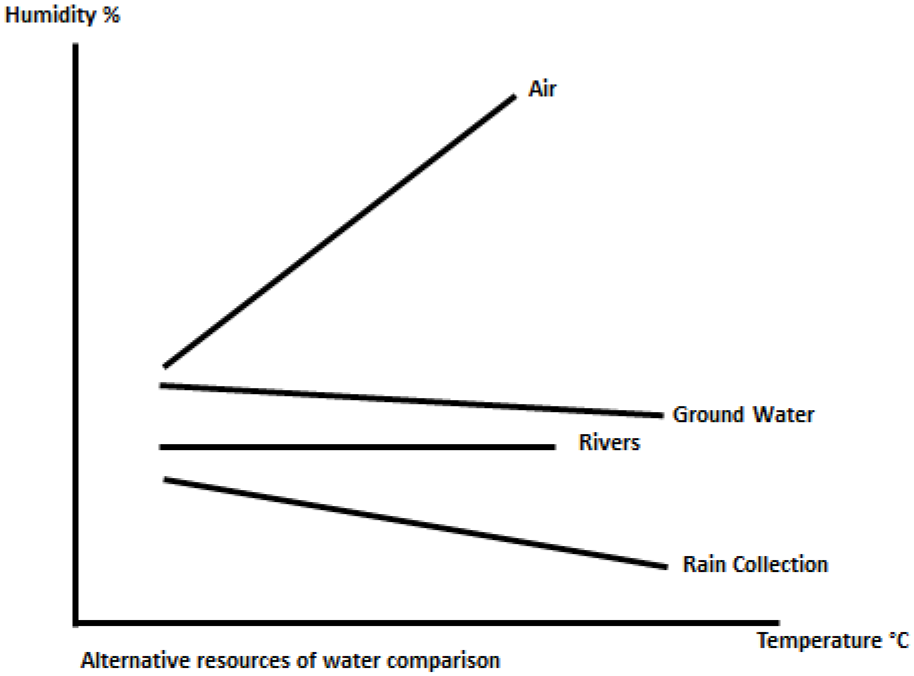
++ refers to ample availability of water resource

+ refers to limited availability water resource

- refers to scarcity of water resource

According to Juhana Häkkänen and Päivi T. Laitinen (2004), “the ability of air to hold water vapor is strongly dependent on temperature, which means that relative humidity is also strongly temperature dependent”(Juhana Häkkänen and Päivi T. Laitinen 2004, 17). Thus, in high temperature regions like Bahrain, the humidity content shall always be abundant, as well as in the California region, and this increases the feasibility of having the WHS in such areas of study. Figure 29 shows the temperature versus humidity percentage relativity and the resources availability interactions. The graph illustrates the combined information from Figure 15 and Table 6 for air moisture, while other water resources data correspond to the estimates from the California Water Plan study (Banks 1957) and the "Water Profile of Bahrain" (Encyclopedia of Earth 2007).The available water resources in the region of study are affected by the humidity percentages and temperature changes; therefore, air moisture remains the greatest feasible resource of water to utilize as other resources diminish over time.

Figure 29. Alternative Water Resources Comparison

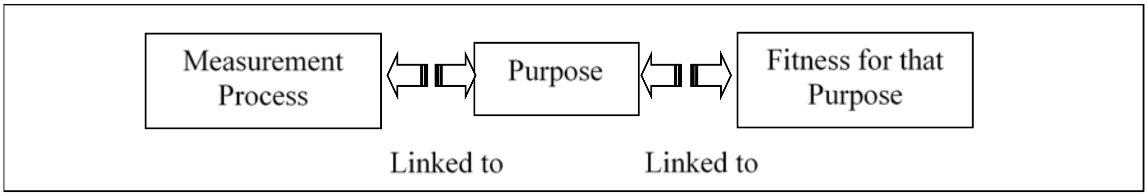


## H. MEASURES OF EFFECTIVENESS DETERMINATION FOR THE OPERATIONS

According to Langford's (2014) research on "Building the Determinants of Cyber Deterrence Effectiveness," MOEs are remarkable at the transitions between the objects of technology that result from work and processes by which these technology objects were produced. MOEs quantify those observations and then infer the measures and measurements from the perspective and biases of the researcher or analyst. For instance, a goal may be unachievable from the perspective of the researcher, but that difficulty has not yet been appreciated by the goal setter or the decision-maker. Their perspectives are different. Their biases may also be quite different. To be unbiased, MOEs must be definitive in both their degree of relation to a full accounting of the work accomplished and the effectiveness of presenting sufficient information to facilitate decision-making. The integrative framework is essential for MOEs to be relevant across organizations, context, and cultures.

Today, the selections of key factors in determining MOEs are made without a consistent approach and with no underlying theory to guide their selection. The current ideas and application of MOEs incorrectly emphasize outcomes based on conjecture that some aspect of a performance measure or metric is an indicator of the utility for a system's fitness (Langford 2014). However, the task should not center on measures of outcomes that are too focused or diffused. Instead, effectiveness can only be determined by what is appropriate and suitable to move the product or service into a perceptible and then sustainable form. In other words, effectiveness for fitness of purpose is desired, not an outcome predicated on knowledge, or gain of information, or even a specific situation. Measures of effectiveness are about the matter of fitness, which is not only about the standard physical measures or metrics, as shown in Figure 30 (Langford 2014).

Figure 30. Measure of Effectiveness Linked to Fitness for Purpose



From Langford 2014

The real knowledge that a potential user needs to have is whether the product or service, decision or judgment, plan or outcome, technology or engineering is good for a purpose, such as the WHS. This view contrasts with most measurements in scientific research where the value of the measure is the critically important goal as it enables the identification of the fundamental characteristics of the entity examined. The difference is related to the Heideggerian hierarchy of science, which is concerned with the engineering development of an equipment to achieve a purpose, hence in this case, is to resolve the water issue with a feasible product.

For example, systems engineering is the branch of engineering that concerns the development of “equipment,” not “things” (Langford 2014). Systems that satisfy real needs are not tangible things that can be analyzed as objects to be inspected and described, but rather as systems that interact with their users and stakeholders in a complex manner, where the introduction of the system agitates the pre-existent situation (Ferris, Cook, and Honour 2003).

To demonstrate the achievement of functional performance of a certain technology with acceptable timeframe and at reasonable cost, can be captured within the two frames of thought: a frame of elements that is related to processes and a frame of elements related to objects. These two frames intersect to form an integrative framework of measures by which ontological aspects interact and relate to the building and results of building that product or service (Langford 2014). Through this framework, nine categories of fitness for every aspect of technology can be expressed as the appropriate MOE. In this context, technology is defined as applying knowledge to create the capability to modify our future (Langford 2014). *Create* is the process; *capability* is the object. Thus, creating water resolves the problem of water shortage and, therefore, satisfies the capability need of water resources.

During the development of the water harvesting technology and then into sustainment by way of transition, the development of technology for a purpose has a need for capital investment, investment timing, and investment opportunities. From the perspective of how one measures the effectiveness of an investment, three questions come to mind, should I invest, how much should I invest, and when should I invest (Langford 2014) These questions must be introduced in the areas of study and must be considered by decision-makers in order to succeed in future challenges of water resources shortages.

# V. CONCLUSION AND RECOMMENDATIONS

## A. CONCLUSION

The impetus for the scalability of the water producing systems lies with the users' need and requirements to be fulfilled. With the advancement of technologies, water harvesting technologies that are cost-effective can be scaled from the very large nuclear power desalination plants to mid-size systems that use condensation or non-nuclear reverse osmosis desalination. Overall, the combination of technologies and product offerings provide a range of options for harvesting fresh water from the sea or the atmosphere. At minimum humidity levels (30% - 35%), a WHS can generate a sufficient amount of potable water with proper means of filtration to be used for human consumption and agricultural uses.

## B. RECOMMENDATIONS FOR FURTHER WORK

There are two recommendations that merit follow-up. First, the personal mobile WHS is identified as a new market niche for individuals “on-the-go” without ready access to potable water. Second, as technologies advance, the option of generating electricity from nighttime solar cells has been proposed by Steven Novack at the U.S. Department of Energy's Idaho National Laboratory in Idaho Falls (Graham-Rowe 2010). These cells are proposed to have an overall efficiency of 46% at nighttime. That means a new breed of Nano scale light-sensitive antennas would have the ability to harvest infrared radiation at night. Almost half of the available energy in the solar spectrum resides in the infrared band, and IR is re-emitted by the Earth's surface after the sun sets, meaning that these antennas can capture energy during the night. Lab tests have already proven that, under ideal conditions, the antennas can collect 84% of incoming photons.

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# APPENDIX

Table 10. Drinking Water Tests

| Test for | Description | Tests Included |
|---|---|---|
| Standard contaminants | Basic tests for which drinking water samples should be routinely tested | Total coliform bacteria, E. coli bacteria, pH, and total dissolved solids |
| Aesthetics/Corrosivity plus lead | Tests for water components that can contribute to bad taste, staining, scaling, Corrosivity, and lead | Test for dissolved solids plus hardness, Corrosivity index, copper, iron, manganese, and water lead |
| Agriculture/Septic | Tests nitrate-nitrogen which may be elevated in water supplies located near intensively managed agricultural sites or in proximity to densely spaced or poorly operating septic systems | Tests for total dissolved solids plus nitrate-nitrogen |
| Mining | Includes tests for those of greatest importance for water supplies located near existing or future mining activity | Test for dissolved solids plus aluminum, iron, manganese, and sulfate |

From Penn State College of Agricultural Sciences 2015

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# LIST OF REFERENCES

Al-Noaimi, Mubarak. 2005. Water Use and Management in Bahrain: An Overview. September. http://noa.bh/niad/wp-content/uploads/2014/05/Water-Use-and-Management-in-Bahrain.pdf

Ampac. 2015. Accessed on September 8, 2015. http://www.ampac1.com/

Andrew, Rachael, Blake Barkley, Raj Bhinder, Steven Chadwick, Patrick Chapman, Bartek Drobniak, Kimo George et al. 2013. *Around the River Bend: Global Climate Change, Water Security, and the Implications for Canada*. April. http://history.uwo.ca/international_relations/docs/2012-RiverBend.pdf.

Banks, Harvey. 1957. *The California Water Plan.* University of California at Davis.

Barbut, Monique. 2004. *"Challenges of Water Scarcity."* New York, NY: The United Nations Environment Programme Finance Initiative (UNEP FI) & Stockholm International Water Institute (SIWI).

Behn, Robert D. 2003. "Why Measure Performance?" *Public Administration Review* 63 (5): 586–606. http://academic.udayton.edu/richardghere/IGO%20NGO%20research/Behn_Robert_D.pdf.

Blanchard, Benjamin S., and Wolter J. Fabrycky. 2011. *Systems Engineering and Analysis*, 5th ed. Upper Saddle River, NJ: Pearson Education.

Borenstein, Seth. 2007. "Global Warming: It's the Humidity." *Washington Post*, October 10. http://www.washingtonpost.com/wp-dyn/content/article/2007/10/10/AR2007101001278.html.

Boualem, Remini, and Kechad Rabah. 2012. "The Foggara in the Arab World." *Technical Geography* 1: 1–7. http://technicalgeography.org/pdf/1_2012/01_remini_boualem_kechad_rabah_the_foggara_in_the_.pdf.

Bradley, Eric. 2014. "Long Beach desalination plant cleaned 300,000 gallons of water daily using new method." Press-Telegram. June 24. http://www.presstelegram.com/environment-and-nature/20140624/long-beach-desalination-plant-cleaned-300000-gallons-of-water-daily-using-new-method

Cartwright, Matt, and Michael Shank. 2015. "Water Shortages Are Coming. It's Time for Us to Act." *Guardian.* March 12. http://www.theguardian.com/commentisfree/2015/mar/12/water-shortages-are-coming-time-to-act.

Center for Sustainability and the Global Environment. “Average Annual Relative Humidity” (map). Accessed July 29, 2015. http://nelson.wisc.edu/sage/data-and-models/atlas/maps.php?datasetid=53&includerelatedlinks=1&dataset=53.

Coanda, Henri. 1968. Water purifying apparatus. U.S. Patent 3410758 A. http://www.google.co.in/patents/US3410758.

Costhelper, Inc. 2015. “Water Filter Cost.” Accessed on August 31, 2015. http://home.costhelper.com/water-filters.html.

EcoloBlue. 2015a. “About EcoloBlue.” Accessed May 21. http://ecoloblue.com/about-ecoloblue.

EcoloBlue. 2015b. “Atmospheric Water Generators” Accessed on August 31, http://store.ecoloblue-world.com/en/6-atmospheric-water-generators.

Emery, Alan. 2012. “Exponential Population Growth.” *KIVU Nature* (blog). May 10. http://www.kivu.com/exponential-population-growth/.

Encyclopedia of Earth. s.v. “Water Profile of Bahrain.” Accessed July 30, 2015. http://www.eoearth.org/view/article/51cbef2b7896bb431f69cd91/

Engel, Daniel R., and Matthew E. Clasby, Jr. 1993. Apparatus and method for extracting potable water from atmosphere. U.S. Patent 5259203 A. https://www.google.co.uk/patents/US5259203#backward-citations.

Ferris, T. L. J., Cook, S.C., and Honor, E.C. 2003. A Structure for Systems Engineering Research. Proceedings of SETE 2003, Rudges Capital Hill, Canberra, Australia.

Fraunhofer-Gesellschaft. 2009. “Drinking water from air humidity.” Fraunhofer-Gesellschaft, Jun 01. http://m.igb.fraunhofer.de/en/press-media/press-releases/2009/drinking-water-from-air-humidity.html

The Going Blue Foundation. 2015. “Why Go Blue Too.” Accessed July 15. http://gobluetoo.com/why-blue-2-3/.

Graham-Rowe, Duncan. 2010. “Is Night Falling on Classic Solar Panels?” *New Scientist*. December 15. http://www.newscientist.com/article/mg20827915.000-is-night-falling-on-classic-solar-panels.html#.VXDPT8_BzGd.

Grid-Nairobi and University of East Anglia’s Climatic Reseach Unit. 1991. “Global Digital Data Sets for Land Degradation Studies: A GIS Approach.” http://www.grid.unep.ch/data/summary.php?dataid=GNV172&category=atmosphere&dataurl=http://www.grid.unep.ch/data/download/gnv172.zip&browsen=http://www.grid.unep.ch/data/download/gnv172.gif.

Koestler, A. (1967). *The Ghost in the Machine*. New York: McMillan.

Häkkänen, Juhana, and Päivi T. Laitinen. 2004. "The Many Faces of Water Vapor." *Vaisala News*. http://www.vaisala.com/Vaisala%20Documents/Vaisala%20News%20Articles/VN166/VN166_The_Many_Faces_of_Water_Vapor.pdf.

Labajo Salazar, J. L., F. de Pablo, and E. L. Garcia. 1991. "An Equation Relating Temporal Changes of Relative Humidity and Temperature: Case of Variable Intervals in Time." *Atmósfera* 4 (4): 257–264.

Langford, Gary. 2012. *Engineering Systems Integration: Theory, Metrics, and Methods.* CRC Press, Boca Raton, FL.

Langford, Gary. 2014. "Building the Determinants of Cyber Deterrence Effectiveness." Monterey, CA: Naval Postgraduate School, Department of Systems Engineering.

Langford, Gary. 2015. Naval Postgraduate School. Lecture Notes from SE4151, Lecture 6 on Feasibility Analyses, given 17 August 2015.

Lewis, Schuyler. 2015. "Potable Water by Condensation." February 6. http://greenergood.com/index.php/homestyle/item/603-potable-water-by-condensation.

Ministry of Transportation & Telecommunications–Meteorological Directorate. 2015. "Maximum and Minimum Relative Humidity" (graph). Accessed July 15. http://www.bahrainweather.gov.bh/web/guest/humidity.

National Oceanic and Atmospheric Administration (NOAA). 2015. "Monthly Climatic Data for the World." https://www.ncdc.noaa.gov/IPS/mcdw/mcdw.html?_finish=0.31893620845530324.

Natural Habitat Adventures. 2015. "Guided Machu Picchu Adventure." Accessed July 20. http://www.nathab.com/south-america/machu-picchu-adventure/itinerary/.

Nelson, Robert A. 2003. "Air Wells, Fog Fences & Dew Ponds." http://www.rexresearch.com/airwells/airwells.htm.

New Logic, International Inc. 2015. *River Water Treatment for Ultrapure Water Production: A cost-effective and environmentally-sound solution*: 2015. http://www.vsep.com/pdf/UltraPureWater.pdf

Nilsson, T. M. J., William E. Vargas, Gunnar A. Niklasson, and C. G. Granqvist. 1994. "Condensation of Water by Radiative Cooling." *Renewable Energy* 5 (1): 310–317. http://www.researchgate.net/publication/245188991_Condensation_of_water_by_radiative_cooling.

Oak Ridge National Lab. 1992. *An Assessmentof desiccant cooling and dehumifdifcation technology*: (xii). June 1992. http://web.ornl.gov/sci/ees/etsd/btric/eere_research_reports/thermally_activated_technologies/desiccant_systems/performance_evaluations/ornl_con_309/ornl_con_309.pdf

Otero, Maria. 2011. *Global Water Issues: A Compendium of Articles.* Washington, DC: U.S. Department of State.

*Patriot Daily*. 2006. *Creating drinking water from air*.November 6, 2006. http://science.the-environmentalist.org/2008/04/creating-drinking-water-from-air.html

*Patriot Daily*. 2008. *Creating drinking water from air*.April 20, 2008. http://www.dailykos.com/story/2008/04/21/499240/-Creating-Drinking-Water-From-Air

Penn State College of Agricultural Sciences. 2015.”Drinking Water Testing.” http://agsci.psu.edu/aasl/water-testing/drinking-water-testing.

Qatarat Al Nada. 2013. Qatarat Al nada presentation. March 8, 2013. Accessed on Septemeber 1, 2015. https://prezi.com/p_miuqjrojha/qatarat-al-nada/

Robertson, William C. 2005. *Air, Water, and Weather.* Arlington, VA: National Science Teachers Assosiation Press.

Rogers, Paul. 2014. *Nation’s largest ocean desalination plant goes up near San Diego; Future of the California coast?* May 29. http://www.mercurynews.com/science/ci_25859513/nations-largest-ocean-desalination-plant-goes-up-near

Rosenblum, David S. 2004. “*The Good, the Bad, and the Ugly*.” December 13, 2004. http://www.slideshare.net/dsrosenblum/scalability-in-software-systems-engineering-the-good-the-bad-and-the-ugly-inaugural-lecture-as-professor-of-software-systems

Schirber, Michael. 2007. *Why Desalination doesn’t work (yet)*.June 25. http://www.livescience.com/4510-desalination-work.html

SEBoK. 2015. “Stakeholder Needs and Requirements.” Accessed July 29. http://sebokwiki.org/wiki/Stakeholder_Needs_and_Requirements.

Sharan, Girja. 2007. “Harvesting Dew to Supplement Drinking Water Supply in Arid Coastal Villages of Gujarat.” IIMA Working Paper. August 5. Ahmedabad: Indian Institute of Management Ahmedabad.

Smakhtin, Vladimir, Carmen Revenga, and Petra Döll. 2004. *Taking into Account Environmental Water Requirements.* Research Report 2. Washington, DC: Center for Environmental Systems Research.

Sproles, Noel. 2001. *Establishing Measures of Effectiveness for Command and Control: A Systems Engineering Perspective*. DSTO-GD-0278. Salisbury, Australia: Department of Defence.

United Nations Environment Programme (UNEP). 2008. *Vital Water Graphics*, 2nd ed. http://www.unep.org/dewa/vitalwater/article77.html.

United Nations Environment Programme Finance Initiative (UNEP FI) and Stockholm International Water Institute (SIWI). 2004. *Challenges of Water Scarcity*. Stockholm: UNEP FI.

U.S. Geological Survey Water Science School. 1984. *The Hydrologic Cycle*. USGS pamphlet. 1984. http://water.usgs.gov/edu/earthhowmuch.html.

U.S. Government. 2015. “Going Green.” Accessed July 15. https://www.usa.gov/green.

Weather Channel, LLC. 2015. “Monterey, CA (93940) Weather.” Accessed July 30. http://www.weather.com/weather/monthly/l/93940:4:US.

World Health Organization (WHO). 2003. *The Right to Water*. Health and Human Rights Publication Series No. 3. Geneva: WHO.

World Nuclear Association. 2015. “Small Nuclear Power Reactors.” Accessed September 5, 2015. http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Power-Reactors/Small-Nuclear-Power-Reactors/

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