Drink the Air:

A Proposal To Democratize Safe Drinking Water

Adam Pollock

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Creative Component

Contents

ABSTRACT:

Scarcity of easily attained clean drinking water is a threat to a growing global human population. New discoveries in materials science are yielding potential opportunities to harvest freshwater from our atmosphere in even arid climates of low relative humidity. The advent of these new materials provides an opportunity to partially address this global challenge.

This project reviews the current crisis facing the world's population and the state of technology related to atmospheric water harvesting (AWH) and the potential it embodies to democratize access to safe drinking water. This review concludes with a conceptual proposal to develop a device that leverages basic physical properties in a simple, portable form that could efficiently harvest drinking water from air using the power of the sun and gravity. The goal is to design a device that could be built at low cost with no electrical componentry which relies on simple and repairable gearing mechanisms that are easy to maintain. The device should provide continuous harvesting of water during daylight hours in temperate and arid climates sufficient to sustain at least one person or a household per day. Ideally the device could be produced locally with minimal components that rely on the global supply chain.

Preface:

In June 2022 I was anticipating that I would need a topic for my Master of Industrial Design Project to conclude my degree in spring 2023. I follow scientific developments as a layman and receive updates pushed to me in my morning news feed on recently published discoveries.

One morning in June I was presented with a curious announcement of a material that was developed at the University of Texas, Austin by a research group led by Youhong Guo. They had developed a thin film that could harvest moisture from the air even in arid environments. This was interesting on its own merit but the fact that it could be synthesized using a simple casting method with sustainable and readily accessible materials caught my attention. I located and downloaded the original research article and was surprised to find how accessible the content was. They projected that this material could provide enough water in desert environments to sustain an individual per day.

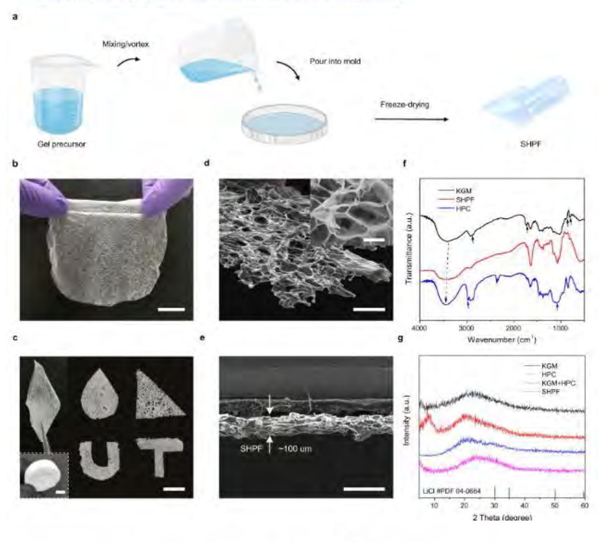


Fig. 2: Fabrication and characterization of SHPFs.

From: Scalable super hygroscopic polymer films for sustainable moisture harvesting in arid environments

I had been struggling with a definition for what an industrial designer was that was distinct from a designer of products or an industrial engineer. The industrial design program at the Masters level was oriented towards problems at a larger, systemic scale as opposed to simply developing tangible products or solutions to meet a design brief. I began to see one of the key roles of an industrial designer as that of an entrepreneur of sorts. Like an entrepreneur, a good designer identifies a need or opportunity and begins to imagine potential solutions and then coordinates resources to achieve a solution. This may require a broad polymathic understanding of many different disciplines, process, or materials that can be brought to bear on a problem. Additionally, an industrial designer needs to embrace discovery, research, and trial and error in an attempt to uncover paths that may not be immediately obvious as potential solutions.

When I became aware of this new material developed by Guo and associates (Scalable Super Hygroscopic Polymer Film -SHPF) the entrepreneur in me saw that this material could address a growing problem across the planet by potentially providing drinking water in areas of scarcity and need. However, as a material discovery on its own, it did not have the power to deliver on this promise. As an industrial designer I saw an opportunity to take this discovery closer to practical application by building a device around this material. My own previous design and manufacturing experience told me that the completion of a working prototype may be outside the realm of my available resources, however I might be able to contribute to the discussion and lay groundwork for others to join or continue this pursuit. I committed myself to the process of exploration and development to see how far I could get.

I began thinking about what might be the constraints related to a device design and began to sketch and work through a range of possibilities. I recognize that this process is somewhat old-school relying on the capacities of a single individual. Currently promoted methods of approaching problems such as Design Thinking emphasize collaborative and systemically explorative information-gathering prior to embarking on a design path. I was entering this process backwards from the perspective of Design Thinking. Design Thinking would have me explore a problem with stakeholders using a variety of investigative tools whose implementation would result in a broader range of potential solutions to explore, test, and narrow down. One of the challenges I saw of employing a Design Thinking approach to this problem was the scale, diversity, and geographic dispersity of the user/stakeholders. It would be challenging within the scope of this master's project to truly reach out and engage such a diverse group of users from Ames, Iowa. So, alternately, I embarked upon this design task using processes most familiar to me and honed through many years of professional experience.

My process involved identification of the key material, identifying the problem it could resolve and then working through iterative potential designs mentally and through rough sketches until I came to a design I thought should be explored further through prototyping. I was clear that a device like this could serve many different audiences, so I worked broadly on the design rather than specifically on researching the needs of a particular audience. It was obvious that a device that could create drinking water from air would be an obvious boon for the billions of people facing water scarcity across the planet in varying urban and rural settings, but a device like this could also serve homesteaders, researchers in the field, deployed military, humanitarian disaster responses, and even homeowners in developed countries with stressed water distribution systems.

As I embarked on my design exploration, I began the process of literature review and research on the issue related to water scarcity and to find out what else has been done in the area of atmospheric water harvesting. This research would inform my own design process as I went along and provide the foundation for this project document.

It was through this research that I discovered that others had engaged this problem before me with promising achievements. I initially found this dispiriting, hoping that I had been original in seeing the potential of this problem space and potential solution, but later came to recognize that while others had come to some of the same design elements that I was beginning to develop there were still original elements that my self-directed design offered that hadn't been expressed in the previous work. I was encouraged to continue to pursue my path of design exploration even if it meant only bringing nominal new information or developments to the discussion.

I recognize that I am working in parallel with research groups at major institutions, some of them even supported by government organizations as well-funded as the Defense Advanced Research Projects Agency (DARPA) in the US. General Electric was awarded $14 million in 2021 to continue development of a device. [1] The military sees this as a very promising area for development to support troops in the field. While this was intimidating to discover, it also suggested that this path of exploration was valid and that others felt there was real potential to be developed. I believed that there may still be gaps in development that a fresh perspective could identify and explore.

Creating drinking water from the air is a futuristic idea today but the foundations to a viable device are laid out in front of us to build on. It is my hope that the work developed here can be shared in the public domain for others to build upon and develop as technological capacities evolve to make the hopes of this project a reality.

[1] www.Wikepedia.org "Atmospheric Water Generator"

INTRODUCTION:

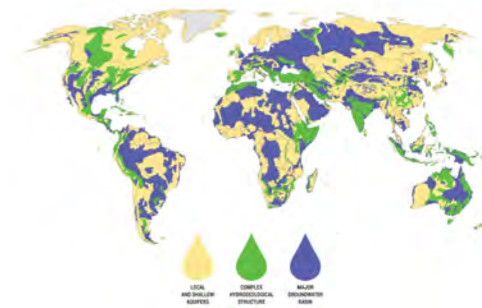
What if we could literally drink water from the air we breathe in all around us?
Are we on the brink of technological developments that would make this proposition a reality?
This is the promise of Atmospheric Water Harvesting (AWH).

A human adult is made up of up to 60% water by weight and we lose up to 12 cups of water a day through natural processes.[2] While it is possible to survive as long as two months without consuming food,[3] survival without water is limited to only a few days.[4] Access to clean drinking water is a requirement of human life second only to the air we breathe.

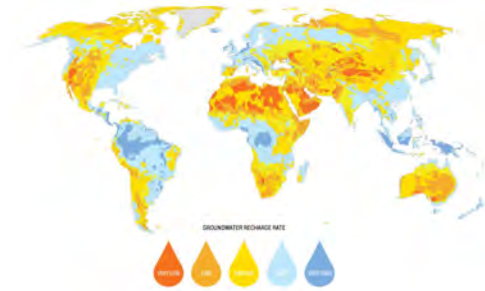
About 71% of the earth is covered by water, of which 96% is contained in the oceans as non-potable saline water. Of the available water on earth only 1% is available for drinking water and is mostly located in underground aquifers. These aquifers are not evenly distributed across the globe and the recharge rate from rain and snow are equally as variable. The majority of potable drinking water is not easily accessible to us and is a scarce resource under pressure in many parts of the world.

Approximately 0.001% of the earth's water supply can be found in the atmosphere.[5] Dissimilar from ground water and surface water sources, atmospheric water can be found distributed across the planet even in locations where other freshwater sources are not readily available. This atmospheric water could provide an additional 15% of fresh water to existing sources which is equivalent to nearly three times the yearly global water consumption level.[6] The ubiquity of atmospheric water provides an opportunity to harvest it as needed, where needed, independent of natural resources and geographic conditions. If we can harvest drinking water from the air, we democratize access to this basic necessity for life.

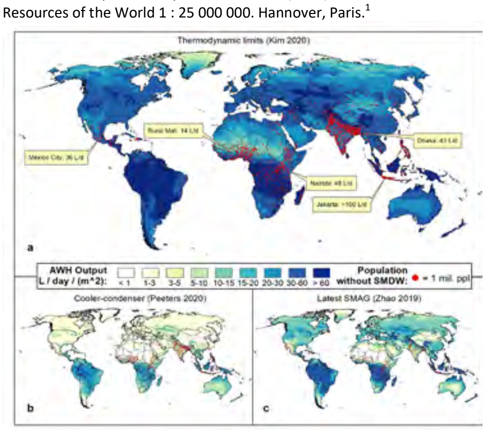
This project seeks to explore the question of whether current technological knowledge exists to create a low-cost, low-tech device that can sustainably harvest drinking water from the atmosphere at a production level sufficient to meet the daily human requirement of an estimated to be 2 to 3 liters per day per person.[7]



Just as the distribution of lakes and rivers varies around the world, so too does the distribution of aquifers. Major basins (purple) hold abundant, relatively easily extracted groundwater. More complex basins (green) might contain multiple aquifers separated by impermeable rock or have layers of saltwater as well as fresh. Local and shallow aquifers provide only limited quantities of water. Map created by Peder Engstrom and Kate Brauman of the Institute on the Environment's Global Landscape Initiative. Data provided by BGR & UNESCO (2008): Groundwater Resources of the World 1 : 25 000 000. Hannover, Paris[1]



The rate at which rain, snow and surface waters are able to replenish groundwater varies tremendously from one place to another, mostly due to geology and climate. Along with aquifer size and type, the recharge rate determines the extent to which groundwater can be sustainably withdrawn for human use. Map created by Peder Engstrom and Kate Brauman of the Institute on the Environment's Global Landscape Initiative. Data provided by BGR & UNESCO (2008): Groundwater Resources of the World 1 : 25 000 000. Hannover, Paris.[1]



Map from the Nature paper by Lord. et. al. shows the overlap between where people without safely managed drinking water live (red dots) and climates where AWH devices have the potential to perform best (dark

[2] https://www.mayoclinichealthsystem.org/hometown-health/speaking-of-health/water-essential-to-your-body
[3] https://www.scientificamerican.com/article/how-long-can-a-person-survive-without-food/
[4] https://www.medicalnewstoday.com/articles/325174#:~:text=As%20a%20general%20rule%20of,age
[5] How Much Water is There on Earth? | U.S. Geological Survey (usgs.gov)
[6] (Haechler et al.)
[7] The Water in You: Water and the Human Body | U.S. Geological Survey (usgs.gov)

A GLOBAL GOAL:

Photo: https://x.company/blog/posts/sharing-project-h2e-with-the-world/

The United Nations (UN) has identified clean water and sanitation as the sixth of their 17 sustainable development goals for the world set out in 2015. Water scarcity affects more than 40% of the global population and is projected to rise. Nearly 1,000 children die daily due to preventable water and sanitation-related diarrheal diseases. Only one in three people on the planet currently has access to safe drinking water.[8] The UN goal 6.1 looks to "achieve universal and equitable access to safe and affordable drinking water for all by 2030."
It is important to note that many parts of the planet experience water shortages for only part of the year.

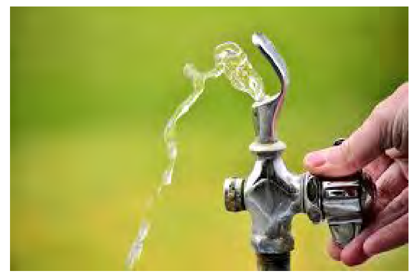
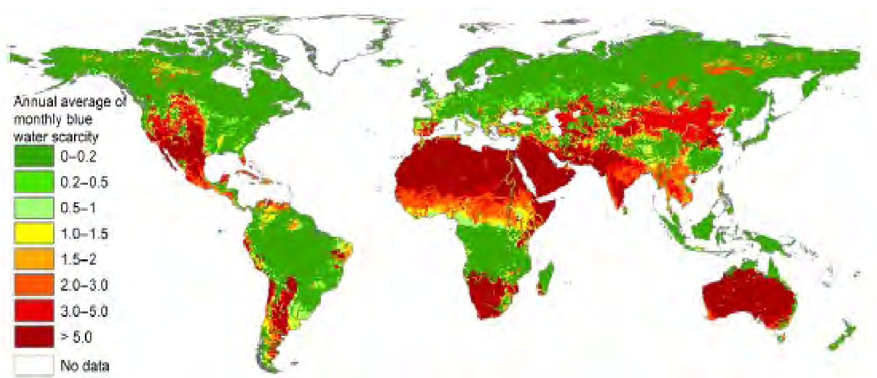


Photo: https://indysoftwater.com/blog/safe-water-fountain/

Rainy seasons can be separated by long periods of drought leading to water stress for the local population.[9] As of 2016 71% of the global population (about 4.3 billion people at that time) lived under moderate to severe water shortages at least one month out of the year and about 66% or 4 billion people lived in areas of severe water scarcity at least one month out of the year. Of these about 1 billion lived in India and another 0.9 billion lived in China. Up to 3 billion people face water scarcity at least 4 to 6 months out of the year and half a billion people face severe water scarcity all year around.[10]



Graph: Mekonnen, Et al Number of months of water scarcity per year globally

[8] Water and Sanitation - United Nations Sustainable Development United Nations: Gender equality and women's empowerment
[9] (Lasage and Verburg)
[10] (Mekonnen and Hoekstra)

GENDER EQUALITY:

It is important to note that water access and inequality affects women and girls disproportionately and has secondary ramifications as well. Women and girls are responsible for water collection in 80% of households without access to water on premises.[11] The daily collection of water sufficient to sustain a household creates a tremendous burden on those responsible, often taking many hours of each day. This has the additional impact of keeping women and girls from accessing educational opportunities and providing time for other activities that would provide long term economic and quality of life gains. Carrying water long distances also places an enormous physical burden and can expose children to safety risks and exploitation.[12]

Photo: Unicef/UNI315914/Haro

Water scarcity is therefore, also closely tied to the 5th UN goal related to increasing global gender equality:

> "Gender equality is not only a fundamental human right, but a necessary foundation for a peaceful, prosperous and sustainable world."

Photo: https://www.concernusa.org/story/water-is-a-womens-

The UN Goal 5.4 is to:

> "Recognize and value unpaid care and domestic work through the provision of public services, infrastructure and social protection policies and the promotion of shared responsibility within the household and the family as nationally appropriate"

In a 2022 article the World Health Organization (WHO) noted that:

> "When water comes from improved and more accessible sources, people spend less time and effort physically collecting it, meaning they can be productive in other ways. This can also result in greater personal safety and reducing musculoskeletal disorders by reducing the need to make long or risky journeys to collect and carry water. Better water sources also mean less expenditure on health, as people are less likely to fall ill and incur medical costs and are better able to remain economically productive.
> With children particularly at risk from water-related diseases, access to improved sources of water can result in better health, and therefore better school attendance, with positive longer-term consequences for their lives."[13]

[11] https://www.unwomen.org/en/news/in-focus/women-and-the-sdgs/sdg-6-clean-water-sanitation

[12] https://www.unicef.org/wash/water-scarcity#:~:text=Half%20of%20the%20world's%20population,of%20extremely%20high%20water%20stress

[13] Water and Sanitation - United Nations Sustainable Development United Nations: Gender equality and women's empowerment

THE HEALTH CHALLENGE:

The UN Sustainable Development Goal 3 is Good Health and Well-Being:

> "Ensure healthy lives and promote well-being for all at all ages"

Photo: https://www.concernusa.org/story/water-is-a-womens-issue/

The World Health Organization (WHO) reports that at least 2 billion people use drinking water sources microbially contaminated with feces which can cause diarrhea, cholera, dysentery, typhoid and polio and is estimated to cause 829,000 deaths a year from diarrhea alone. [14] Diarrhea is the most common disease linked to contaminated food and water but in 2017, over 220,000,000 people required preventative treatment for schistosomiasis – an acute disease caused by parasitic worms contracted through exposure to infected water. The WHO found that:

- 1.2 billion people with *basic* services, meaning an improved water source located within a round trip of 30 minutes.
- 282 million people with *limited* services, or an improved water source requiring more than 30 minutes to collect water.
- 368 million people taking water from unprotected wells and springs; and
- 122 million people collecting untreated surface water from lakes, ponds, rivers, and streams.

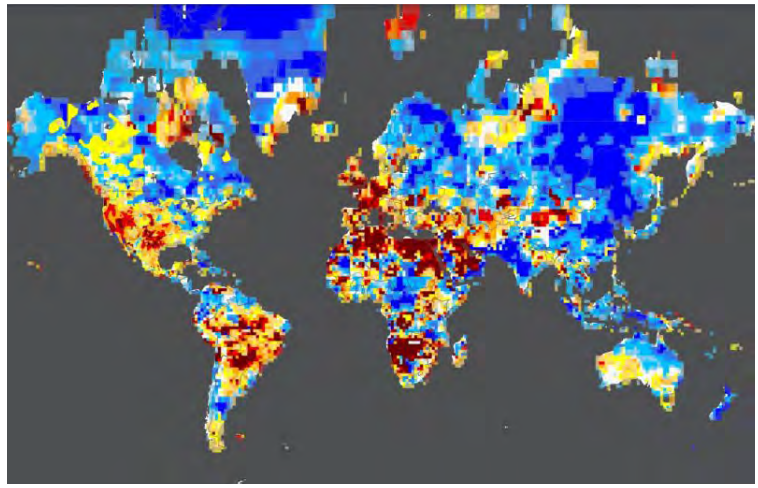
Photo: Donorbox.org

UNICEF states that half the world's population could be living in areas facing water scarcity by as early as 2025 and that some 700 million people could be displaced by intense water scarcity by 2030. [15]

[14] https://www.who.int/news-room/fact-sheets/detail/drinking-water
[15] https://www.unicef.org/wash/water-scarcity#:~:text=Half%20of%20the%20world's%20population,of%20extremely%20high%20water%20stress

CLIMATE CHANGE

Climate change is disrupting weather patterns, which leads to extreme weather events, unpredictable water supply and increasing water scarcity. [16] Specifically, climate change contributes to drought by enhancing evaporation due to warmer temperatures. This reduces surface water and dries out soils and vegetation. Periods of low precipitation end up being drier than they would be in cooler conditions. The timing of water availability is also being affected. [17] Four billion people experience severe water scarcity for at least one month each year.[10]



Global drought map August 25, 2022 Image via NOAA https://earthsky.org/earth/drought-around-world-2022-revealing-hidden-artifacts/

Droughts can create a vicious cycle where very dry soils diminish plant cover, absorb more solar radiation and heat up, which encourages the formation of high-pressure systems that further suppress rainfall making an already dry area even drier. [18] This creates a cycle of increasing water scarcity in areas already hard-hit by climate change.

Photo:WaterAid.org / Abir Abdullah

Additionally rising sea levels are infiltrating freshwater aquafers making them non-potable and compromising the resources that millions of people rely on. [19]

A research article "Emerging Trends in Global Freshwater Availability" Published in *Nature* in 2018 asserts that "the key environmental challenge of the 21st century may be the globally sustainable management of water resources." [20]

THE POLITICS OF WATER:

The WHO notes that, "Sharp geographic, sociocultural and economic inequalities persist, not only between rural and urban areas but also in towns and cities where people living in low-income,

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[16] https://www.unicef.org/stories/water-and-climate-change-10-things-you-should-know
[17] https://www.c2es.org/content/drought-and-climate-change/#:~:text=How%20climate%20change%20contributes%20to,the%20timing%20of%20water%20availability.
[18] https://www.c2es.org/content/drought-and-climate-change/#:~:text=How%20climate%20change%20contributes%20to,the%20timing%20of%20water%20availability.
[19] https://www.unicef.org/stories/water-and-climate-change-10-things-you-should-know
[20] (Rodell et al.)

informal or illegal settlements usually have less access to improved sources of drinking-water than other residents." [21]

The problems presented by dilapidated or non-existent infrastructure for water access and distribution are exposed during times of drought and natural disaster. This year (2022) has been a year of severe water shortages across the globe. Europe is experiencing the worst drought in 500 years and several European rivers have run dry. [22]

Photograph by Brent Stirton

Photograph by Brent Stirton

SOUTH AFRICA:

In February 2018 the city of Cape Town, South Africa was forced to severely limit its water usage in the face of an approaching "zero day" when the city's taps would run dry. That day never came to pass because of the water rationing and rains that broke the drought but the city and others in South Africa have been facing a drought since 2015.

In June of 2022, "city officials (in Gqeberha, South Africa) announced that one of its four major dams had reached a level so low that barges trying to extract water sucked in mud instead. Another dam is expected to fail in the next two weeks, a third in about a month. Large parts of the city could be completely without running water by the end of the month, according to local officials." [23]

(Charlie Shoemaker for The Washington Post/Charlie Shoemaker)

[21] https://www.who.int/news-room/fact-sheets/detail/drinking-water
[22] https://earthsky.org/earth/drought-around-world-2022-revealing-hidden-artifacts/
[23] https://www.washingtonpost.com/world/2022/06/19/south-africa-water-day-zero/

Gqeberha's water shortage is a study in inequality. Although water outages have affected the entire area, residents of the city's walled suburbs can offset the impact by drilling boreholes or simply buying bottled water. A large percentage of Nelson Mandela Bay's population lives in areas laid out under apartheid that were built around South African cities to house black workers. These areas still have the least functional infrastructure and the most-dense populations. [24]

Photograph by Brent Stirton

> "Across South Africa, water stress is a priority problem, but with no single cause there is no single solution. Each area experiences water issues caused to different degrees by excessive use, growing demand, pollution, theft, thirsty plants, inadequate infrastructure, and poor practices. Solving these issues not only requires financial investment but also a change in attitude. South Africa cannot support the water lifestyle some residents consider to be their right, fueling a water consumption that's 35 percent above the global average. The Draft National Water and Sanitation Masterplan laid it out clearly: without a fundamental mind shift in the way South Africa thinks about water to accompany and underpin a massive $60 billion (R899 billion) investment, the country will run out of water by 2030." [25]

IRAQ:

Iraq and the fertile crescent are also experiencing extreme shortage of water. "The green land has been transformed into a barren desert," says Abdul Hadi Mizher. "I don't remember seeing this in my lifetime." [26] Water levels on the Euphrates and Tigris have dropped by half. The government points to the proliferation of hydrology projects in Turkey and Iran but this is only a partial explanation. Water management and low rainfall are also major contributors to the shortage. Iraq relies on a network of open-air canals that date back thousands of years. This results in high rates of evaporation in the summer and more water is squandered when it reaches the fields and farmers use flooding rather than more precise drip or sprinkler irrigation. "With the current technique, which has been used for 8,000 years, water loses are very high." [27] These systems are no longer suitable to the changes brought on by climate change. The crisis is having political ramifications in this region. "Tens of thousands of people have been displaced across southern Iraq due to water scarcity. Many have headed for overcrowded cities, where the lack of jobs and services has stirred unrest." [28] Here in Egypt we see the scarcity of water as another contributing factor to political instability in the region.


photograph: Muntadher Adel

[24] https://www.washingtonpost.com/world/2022/06/19/south-africa-water-day-zero/
[25] https://www.nationalgeographic.com/science/article/partner-content-south-africa-danger-of-running-out-of-water
[26] https://www.theguardian.com/global-development/2022/sep/07/water-scarcity-hits-iraq-fertile-crescent-drought-farming
[27] https://www.theguardian.com/global-development/2022/sep/07/water-scarcity-hits-iraq-fertile-crescent-drought-farming
[28] https://www.theguardian.com/global-development/2022/sep/07/water-scarcity-hits-iraq-fertile-crescent-drought-farming

CHILE:

Chile is experiencing water shortages due to an extended draught but more importantly due to political policies around how water has been treated.

"The process of water privatization in Chile which began in 1981 under General Pinochet established a model for water management that strengthened private water rights, adopted a market-based allocation system and reduced state oversight. That model became emblematic of neoliberal reforms heavily promoted by the World Bank and International Monetary Fund. These reforms fundamentally changed the way water is valued and managed globally. No longer a mere necessity for human survival, water has become an object of international financial speculation and experts predict that "blue gold" will soon become the most important physical commodity worldwide, dwarfing oil and precious metals." [29]

The 1981 Water Code enables the government to grant permanent and transferable water rights to private owners free of charge. This code is written into the constitution changing access to water from a basic human right to a commodity.

> "More than 1 million people across the country lack access to safe drinking water, while some parts of Chile are facing more frequent and prolonged droughts because of climate change. All the while, water has been overexploited by individuals and industry for decades.
> Thirsty, extractive industries such as lithium and copper mining drive Chile's economy. Nearly 80% of the country's freshwater goes to agriculture, most infamously to the avocado. Each fruit takes around 70 liters (about 18 gallons) of water to produce." [30]

The crisis is so severe that people have taken to the streets in protest annually and a new constitution is now under consideration that may change this structure and return water to its former status as a resource owned by the people. [31] Until access to water becomes equitable in Chile we will continue to see people take to the streets demanding change from their political leadership.

Photograph: Miguel Hechenleitner /Movimiento por la Recuperación del Agua y la Vida
Protest over water rights Santiago Chile 2016

[29] https://www.theguardian.com/sustainable-business/2016/sep/15/chile-santiago-water-supply-drought-climate-change-privatisation-neoliberalism-human-right
[30] https://www.dw.com/en/the-struggle-over-water-rights-in-chile-millenial-president-gabriel-boric/a-60895657
[31] https://www.theguardian.com/sustainable-business/2016/sep/15/chile-santiago-water-supply-drought-climate-change-privatisation-neoliberalism-human-right

PERU:

Water scarcity and conflict is not new to the western seaboard of South America. Archaeologist Kevin Lane from the University of Buenos Aires notes that, "the problem of water scarcity is not new in Peru…Water scarcity is so intertwined with Andean history" he added that he, "believes water wars were fought there in the past." [32]
The Andes in Peru have an annual dry season between May and September, however they too have been experiencing sparce rainfall over the past few years. In the district of Pamparomas one community has found an ancient solution ready to be re-deployed. Lane identified 18 abandoned dams built before the Spanish Colonization of the Americas. The process of rehabilitating these ancient structures cost only $100,000, while the estimate of building a concrete dam would have been $1,000,000.

Photograph: Reuters

CHINA:

Human-made dams provide an opportunity to generate clean electric power and manage seasonal flooding through water storage and release management. This comes at an environmental cost as ecosystems and communities are displaced or destroyed by the rising waters and separation of ecosystems. They also become geo-political hot issues when rivers cross arbitrary, non-natural, nation-state borders as one country can radically influence the health and well-being of their neighbor downstream.

Photograph: Reuters/Thomas Peter

Drought conditions exacerbate these issues as the water resource becomes limited. In China this year the province of Jiangxi declared a water supply "red alert" for the country's biggest freshwater lake, Poyang. The shrinkage of the mighty Yangtze River basin severely curtailed hydroelectric power output and damaged crops. A total of 10 reservoirs in Anhui province have fallen below the "dead pool" level where they are unable to release water downstream. Officials have resorted to seeding clouds (addressed later in this document) and diverting water from elsewhere. [33]

Photo: Peter Dynes

[32] https://www.reuters.com/world/americas/perus-andes-farmers-turn-pre-hispanic-dams-fight-water-scarcity-2022-09-12/
[33] https://www.thehindu.com/children/why-is-chinas-new-dam-a-concern-for-india/article61734775.ece

This has not dissuaded China from proposing a new hydroelectric dam in the Tibet Autonomous Region that will be built on the Brahmaputra and will generate 60 gigawatts of power, which is three times that of central China's Three Gorges Dam on the Yangtze River, the largest installed hydropower capacity in the world. This will bring China closer to their goal of carbon neutrality by 2060. There are several concerns from its downstream neighbor India, who is worried that during the dry season it will reduce water flow and that water releases during monsoons when the northeastern states of India experience floods could be disastrous. This new proposal creates additional strain on an already fragile political relationship between the two neighboring countries.[34]

Photograph: AP

ETHIOPIA, SUDAN, EGYPT:

The nations that border the Nile River in Africa are engaged in an existential battle over water rights that has come close to outright military conflict. The Grand Ethiopian Renaissance Dam (GERD) on the Blue Nile River is a part of a long-standing feud between the downstream states of Egypt and Sudan and the upstream state of Ethiopia over access to the Nile's waters. The water of the Nile is considered critical to millions of people living in the downstream states. Despite intense disagreements, Ethiopia has announced that they have started filling the GERD reservoir before an equitable allocation of the Nile's waters has been reached. Egypt has increased its call to the international community to get involved. Ethiopia continues to move forward with the dam, arguing that the hydroelectric project will significantly improve livelihoods in the region more broadly.[35]

Photo: Google Earth

Photo: https://www.hydroreview.com/world-regions/fast-track-approach-to-design-and-construction-at-grand-ethiopian-renaissance-dam/#gref

[34] https://www.thehindu.com/children/why-is-chinas-new-dam-a-concern-for-india/article61734775.ece

[35] https://www.brookings.edu/blog/africa-in-focus/2020/08/05/the-controversy-over-the-grand-ethiopian-renaissance-dam/

AMERICAN SOUTHWEST

Dams and the politics of water management are not constrained to international conflicts, however. An extended drought in the southwestern states of the America has laid bare a broken system of water management and the chasm between different interest groups.

Photo: Lake Powell 2017 and 2022NASA Earth Observatory

The Colorado River Compact was signed in 1922 where seven states divided the watershed resource between them. It has been followed by a series of additional agreements throughout the 20th century. Unfortunately, these agreements have allocated 16.5 million acre-feet while the mean discharge of the Colorado river stands at 15 million acre-feet. This shortfall has become visible as the river volume has radically fallen to 9 to 10 million feet due to long term drought in the southwest, presumably a result of climate change. [36]

The federal government has asked the states to agree to severe voluntary reductions in the range of 40 to 50% of current use on the Colorado River. The seven states have not yet agreed to the terms of a split and the federal government continues to press for renegotiation of the current water rights. [37]

FAILING INFRASTRUCTURE AND RACIAL ECONOMIC DISPARITY IN THE USA

The greatest of human engineering projects and manipulation of the landscape cannot temper the vagaries of nature and the effects of climate change. Even in the developed United States we have seen failures of infrastructure due to deferred maintenance and poor management. It is not a coincidence that the communities where we are seeing such dramatic failure of service are composed primarily of minorities who are economically disadvantaged and have been historically excluded from infrastructure funding and subject to poor infrastructure management. The need for ubiquitous clean and safe drinking water is not just an issue for developing countries, even here in the United States we see failure in providing safe drinking water at a massive scale.

[36] https://www.e-education.psu.edu/earth111/node/720
[37] https://www.npr.org/2022/09/29/1125905928/the-colorado-river-water-shortage-is-forcing-tough-choices-in-7-states
https://crsreports.congress.gov/product/pdf/R/R45546

FLINT, MICHIGAN

Photo: https://www.nrdc.org/stories/flint-water-crisis-everything-you-need-know

Flint, Michigan is a city of 100,000 people where the majority of the population is African American with about 45 percent living below the poverty line. Twenty percent of the city's homes have been abandoned since its peak in the late 20th Century. In 2013 city management changed its practice of piping treated water from Detroit to a cheaper alternative of piping water from the Flint River. The water was not treated and its high corrosivity leached lead from the aging pipes into thousands of homes. By September 2015 Flint pediatrician Mona Hanna-Attisha was finding that the incidence of children's lead poisoning citywide had nearly doubled since 2014 and tripled in certain neighborhoods. She noted that, "Lead is one of the most damning things you can do to a child in their entire life course trajectory." [38] The switch in water supply also coincided with the third largest outbreak of Legionnaires' disease in US History. The city's response of adding more chlorine without addressing other issues led to increased levels of total trihalomethanes (TTHM) which cause cancer as a by-product of the chlorination in the water.

The city, after Federal intervention, has finally replaced all the lead pipes that serve the community and built a modern processing facility so that water now meets national quality standards. However, the damage has been done and people's lives are now changed forever. There is little trust in the water system, or the municipal management and residents still purchase bottled drinking water.

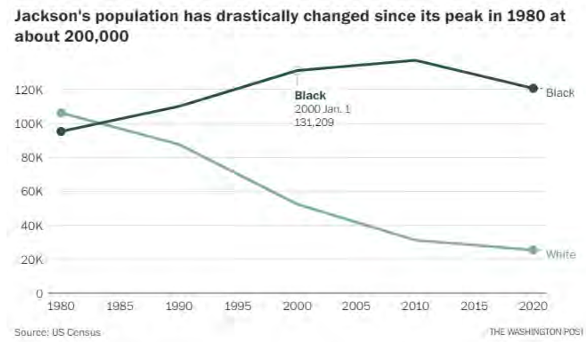
JACKSON, MISSISSIPPI

Rory Doyle or the Washington Post

The municipal water treatment system in Jackson, Mississippi failed for one month in 2021 due to poor infrastructure maintenance. From that time forward residents were instructed to boil the water from their taps before drinking it. Then in 2022 the capital city suffered severe floods, completely overwhelming the broken system causing it to fail completely.

[38] https://www.nrdc.org/stories/flint-water-crisis-everything-you-need-know

"It really is just government mismanagement and a lack of caring about what happens in the inner-city community," Kwame Braxton said. "You go to these different communities outside of Jackson and you can see the difference; they will put funding towards fixing their infrastructure over there." [39]



WEST BALTIMORE, PENNSYLVANIA

> "Systemic racism and redlining has put people at a disadvantage and is magnifying the impact of the disinvestment in our water system, because Black and Brown families are facing the worst impacts of this," Rianna Eckel [40]

In September 2022 West Baltimore announced a "must boil" water advisory after they found E.coli contaminating the water system. They city was unable to find the source of the contamination. Cities like Baltimore don't have the resources to put improvements in that would stave off larger problems down the road—they are left to react. Rectifying this shortcoming is the responsibility of a civil society,

A Look at Some Solutions

[39] https://www.washingtonpost.com/nation/2022/09/03/jackson-mississippi-water-crisis/
[40] https://www.washingtonpost.com/dc-md-va/2022/09/06/baltimore-water-ecoli-sandtown-harlem/

Non-Governmental Organizations (NGO) – Wells and Education

There are many government and non-governmental organizations working across the globe on alleviating water scarcity. Some examples of NGO work include: [41]

- **Charity:Water** have funded 38,000 water projects for nearly 10 million people in 24 countries around the world. They have dug more than 16,000 water projects and raised more than $200 million in donations to fund their work.
- **Water.org** uses microfinancing to bring small, easily repayable loans to those who need assistance in making improvements to household water and sanitation solutions. They have empowered more than 10 million people across 13 countries in Africa, Asia, Latin America and the Caribbean.
- **Water Aid** uses a two-tiered approach to the water crisis. It works from field offices around the world that work together with local partners on access to clean water, sanitary toilets, and good hygiene. They also work with key decision-makers in governments to develop more of these resources and services. They have brought clean water more than a million and a half people and changed legislation around the world to improve conditions in over 34 countries around the world.
- **Drop in the bucket** builds wells across sub-Saharan Africa. They had completed over 350 wells by 2016 including local training on basic well maintenance for self-sufficiency.
- **Generosity.Org** has completed more than 800 water wells in 20 different countries**.**

This is far from a complete list and does not include the work being done by governmental agencies both in their own countries and abroad. While there are many organizations working on this problem who have reached and improved the lives of millions of people across the planet, the scale of effort is still insufficient to meet need.

Desalination

At a government project level Saudi Arabia leads the world in desalination plants with a current production of more than 7.9 million cubic meters per day representing 22% of all global desalination according to a report released by Saline Water Conversation Corporation. The scarcity of freshwater resources has made desalination crucial to achieving water self-sufficiency in the Kingdom. Saudi Arabia has invested in the largest barge-based desalination plants yet to be produced. The barges would be transported according to the needs of each region across the Kingdom. The barges are powered by a massive solar panel farm to reduce oil dependency. [42]

Core Power is proposing a nuclear-powered desalination plant that would be located offshore where seawater could be more easily pumped aboard. [43] They could travel to islands or coastlines struck by

[41] https://donorbox.org/nonprofit-blog/nonprofits-fighting-global-water-crisis#2
[42] https://english.aawsat.com/home/article/3433061/saudi-arabia-inaugurates-floating-desalination-plant
[43] https://www.bbc.com/news/business-61483491

drought bringing with them both clean drinking water and power. In fact, the US navy has provided desalination services during natural disasters from its nuclear-powered ships. Unfortunately, desalination is considered one of the most expensive ways of creating drinking water as it requires pumping large volumes of water across membranes at high pressure, which is an extremely energy intensive process. The highly concentrated saline brine solution that is the byproduct of desalination is also particularly damaging to local aquatic ecosystems.

Water Generators

The WEDEW company created a device called Skysource that won the $1.75 million Water Abundance Xprize in 2018 as the most feasible solution to meeting the world's growing water crisis. The machine is able to generate at least 2000 liters of water from the atmosphere every day using organic trash. The projected cost was $0.02/liter which is still shy of the UN goal o $0.003/liter. The device is housed inside a standard shipping container where biomass gas is created from organic material inside the container producing a moist environment and water vapor as the material decomposes. The vapor is trapped inside the container and extracted from the air. The device produces potable water but also provides nutrient-rich waste called biochar, that can be used as a natural fertilizer for crops.[44]

The Bill and Melinda Gates Foundation determined that sanitation was fundamental to the problems of water-borne contamination and illness and focused their resources on programs which would address sanitation. One of their investments was the proof-of-concept model device called the Janicki Omni Processor. The Omni Processor boils off and thermally dries sewage sludge during which water vapor is captured and recovered. The dry sludge is left behind which is then combusted as fuel to heat a boiler. This boiler produces steam and the heat necessary for the boiling process. The steam is then used to generate electrical energy. Some of this energy is used in the final water purification process as well as providing power to the machine itself. The device has been piloted in Dakar, Senegal and now converts the fecal sludge of 50,000-100,000 people to clean drinking water and electricity.[45]

Atmospheric Water Harvesting Solutions

My area of interest is atmospheric water harvesting (AWH) where we pull the moisture, we need from the air to produce drinking water. There are several methods of AWH being used across the globe currently.

[44] www.Skysource.org

[45] https://en.wikipedia.org/wiki/Omni_Processor

Rainfall Collection

The collection of rainwater is an ancient solution to providing drinking water. There are many examples of systems throughout the world that use catchments and reservoirs to contain this resource as it is provided by nature.


Photo: Acroterion/Wikimedia

In Bermuda, where groundwater sources are insufficient the island has historically relied on a unique stepped roof design which slows down the water flow while the limestone washed roof coating both reflects heat keeping houses cool but also naturally disinfects the rainwater as it flows over it. Each house is required by law to capture 80% of the water that falls on its roof and have a cistern to store it underground. [46]

Rainfall is inconsistent across the world and about 4 billion people live under conditions of severe water scarcity at least part of the year and the number of people facing severe water scarcity at least 4 to 6 months a year is upwards of 2 to 3 billion people. [47] Climate change is also affecting natural weather patterns and we are to expect more impactful droughts in the future as atmospheric temperatures rise over the century.

Cloud seeding is a technology that has been around for about 75 years. It is an expensive approach which experts say is inconclusive in its effectivity. Israel ended their program in 2021 after 50 years because they deemed it economically inefficient while providing only marginal gains in precipitation.

The traditional method is to seed the clouds by aircraft releasing silver iodide at the base of the cloud where it is then lifted by updrafts into the cloud. Theoretically the seeding material which is made of hygroscopic molecules bonds to the water vapor particles that make up the cloud. These molecules attract other vapor particles until they become heavy enough to become a rain drop from the sky.

> "With 12 of the 19 regional countries *(Mideast)* averaging less than 10 inches of rainfall a year, a decline of 20 percent over the past 30 years, their governments are desperate for any increment of fresh water, and cloud seeding is seen by many as a quick way to tackle the problem"
>
> "And as wealthy countries like the Emirates pump hundreds of millions of dollars into the effort, other nations are joining the race, trying to ensure that they do not miss out on their fair share of rainfall before others drain the heavens dry — despite serious questions about whether the technique generates enough rainfall to be worth the effort and expense." [48]

Morocco, Ethiopia, Iran and Saudi Arabia have large scale cloud seeding programs with other Middle Eastern and North African countries considering them as well. China has the largest program covering half its country as it tries to force rain to the Yangtze river which is running dry in certain areas.

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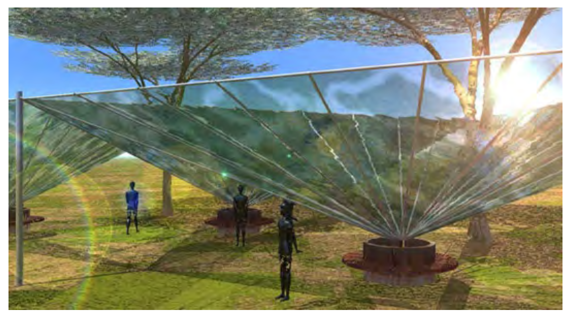
[46] (Patowary)
[47] (Mekonnen and Hoekstra)
[48] (Rubin)

Fog and Dew Capture

In areas of the world where geography favors nighttime or morning relative humidity followed by warmer days there is an opportunity to take advantage of the dew point and capture moisture using mesh structures.

Although there is evidence that human-made devices to capture fog have existed for centuries, one of the first recorded modern fog collection projects was developed in 1969 in South Africa as a source of water on an air base. Two fences, totaling 200m2 collected 11 liters of water per day (0.05L/m2) over a 14 month study. Another large study in northern Italy placed one hundred 48m2 fences and was able to also collect 0.05L/m2.

Mesh netting is coated to be hydrophilic and hydrophobic, thereby attracting, and repelling water to increase condensation. The efficiency changes as the size of the filaments and the holes decrease. Netting can capture between 2% and 10% of moisture in the air depending upon the mesh design. The droplets run down the fence and are gathered in a trough below and stored for use. The mesh can also collect rainwater. [49]



WatAir was developed by Joseph Cory and Eyal Malka for Arup and the WaterAid water challenge in 2006. The WatAir produces water from the air through its inverted pyramid arrays of panels and was inspired by spiderwebs and the dew catching properties of leaves. [50]

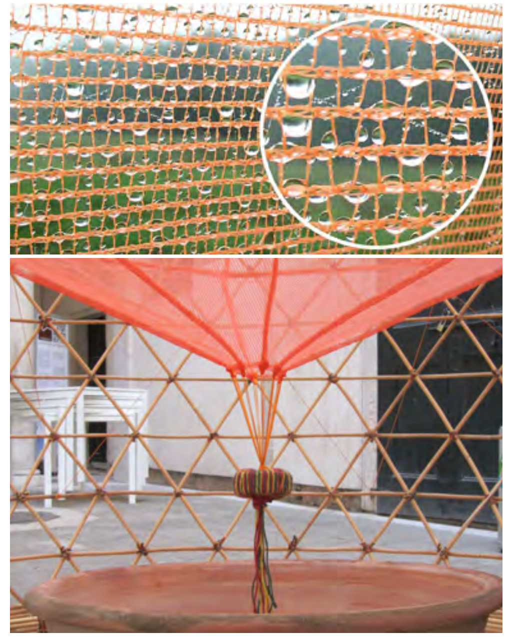
The Warka Water Tower designed by Arturo Vittori began development in 2012. The first prototype was installed in a pilot project in Dorze, Southern Ethiopia in 2015. In 2019 a second pilot was constructed in the South Region of Cameroon. The Warka tower is constantly evolving and being refined in real-world application and is currently in its fourth significant version with 12 full-scale prototypes in operation.

Warka Water Tower V1 Ethiopia

[49] Fog collection - Wikipedia

[50] WATAIR: Turning Air Into Water (inhabitat.com)

Their design philosophy is to build using only local, natural and/or biodegradable and 100% recyclable materials. The structures can be constructed onsite with minimal hand tools and no scaffolding. They have used bamboo, hemp rope, earth, wood, raffia palm leaves and bamboo canes, lianas, dry straw, and dry reeds with polyester mesh as the dew catching screen. A framework structure is assembled to support a mesh material upon which water condenses and then drips to a catchment in the center of the structure.



Warka Water Tower V1 Ethiopia

The Warka tower collects potable water from the atmosphere collecting rain, fog and dew and is powered by natural phenomena of gravity, condensation, and evaporation. The canopy provides shade and the towers become a hub for local community gatherings as well as potable drinking water. The concept has gone through many evolutions of computer modelling to optimize its design which is then articulated in local materials and construction techniques creating a feedback loop of improvement to the design through a continuous iterative process that engages local partnerships. The design concept is flexible and can be adapted to different local conditions, however it is still dependent on a relative humidity and temperature differential between night and daytime to initiate condensation.[51]

"Atrapanieblas" fog collection in Alto Patache, Atacama Desert, Chile

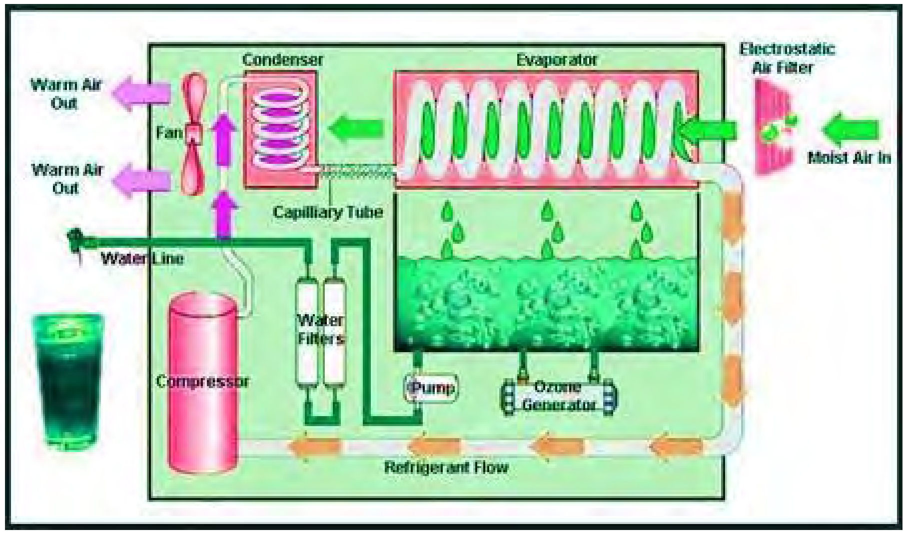
Fog collectors can function in regions and deserts that receive less than one millimeter of rain each year but require fog and light winds to work. Each cubic meter of fog contains 0.05 to 0.5grams of water. FogQuest, founded in 2000 by Sherry Bennett and Robert Schemenauer is a non-profit organization dedicated to the development and installation of fog catching systems around the world. Their larger fog collectors, measuring 40m2 can produce up to 200 liters per day and can be set up for between $1000 and $1500. The systems are completely passive, requiring no energy inputs and can last up to 10 years yielding a cost per liter well under $0.01.[52]

[51] WARKA TOWER – Warka Water

[52] The Fog Collectors: Harvesting Water From Thin Air (columbia.edu)

Compressor/Condenser Systems

There are a number of commercial systems on the market to produce water from air using technology similar to an electric air conditioning unit. A compressor is employed with a closed loop refrigerant and a heat exchanger. As the coolant is condensed using a compressor motor, heat is released as a byproduct and the refrigerant is thereby chilled. The chilling causes the surface of the containment coils to drop below dewpoint and water nucleation occurs on the coils which is then collected. Usually, a waste biproduct of standard air conditioning units this same technology has been employed with the primary purpose of collecting drinking water. These devices work well in higher humidity environments; however, their efficiency drops off greatly as relative humidity drops to the levels found in arid environments. Simultaneously, energy consumption increases as yield decreases making them poorly suited to many areas of the world with poor access to electricity and low humidity levels. The devices can be technologically, mechanically complex and are expensive.



https://cdn.openpr.com/S/2/S201264540_g.jpg


Photo: Tsunami Products

There have been some new developments in this field marrying the highly sorbent materials described later in this document with the compressor technology to achieve broader working ranges, however these devices are still expensive to purchase, run and maintain and find their market primarily in industrial requirements and not personal drinking water.

Sorbent-based systems

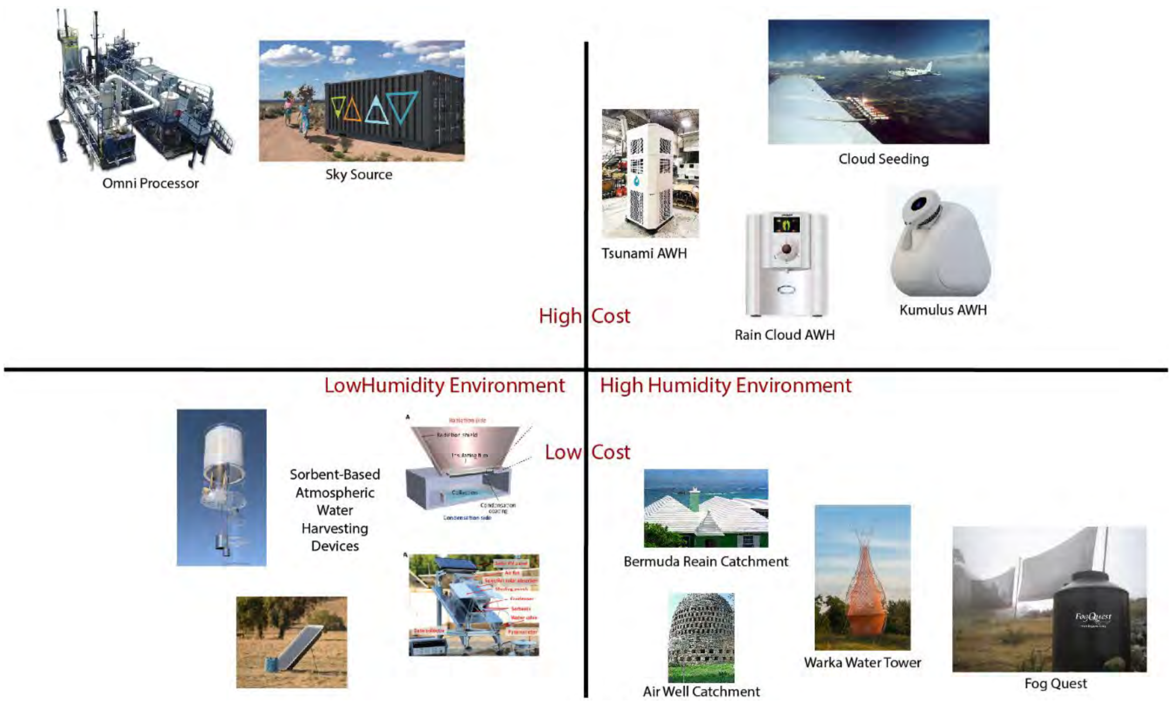
Compared with other methods, Sorbent-based systems offer a critical advantage in that their ability to produce water at low relative humidity as well as high humidity. [53] In sorbent-based systems for water harvesting desiccants:

> "Such as metal-organic frameworks, silica gels, zeolites, deliquescent salts, or activated alumina are used to adsorb water vapor…Once the desiccant is saturated, the system is closed and naturally heated with sunlight, causing it to release the water as vapor. Last the vapor condenses on the enclosure walls (or a cooling plate) and can be collected. Sorbent-based systems have shown that water vapor can be harvested at a very low RH (as low as 15%)." [54]

[53] (Ejeian and Wang)
[54] (Haechler et al.)

The primary advantage of using a sorbent-based approach to AWH is the possibility of using low-temperature heat sources as an energy source. Researchers are most focused on using solar energy because there is a direct relationship between water demand and solar radiation. [55]

The area of interest this document focuses on is designing a sorbent-based AWH device that would serve the broadest population in need in the most diverse geographical conditions. Sorption-based systems offer the most promise to achieving that goal out of the various atmospheric water harvesting methods investigated.

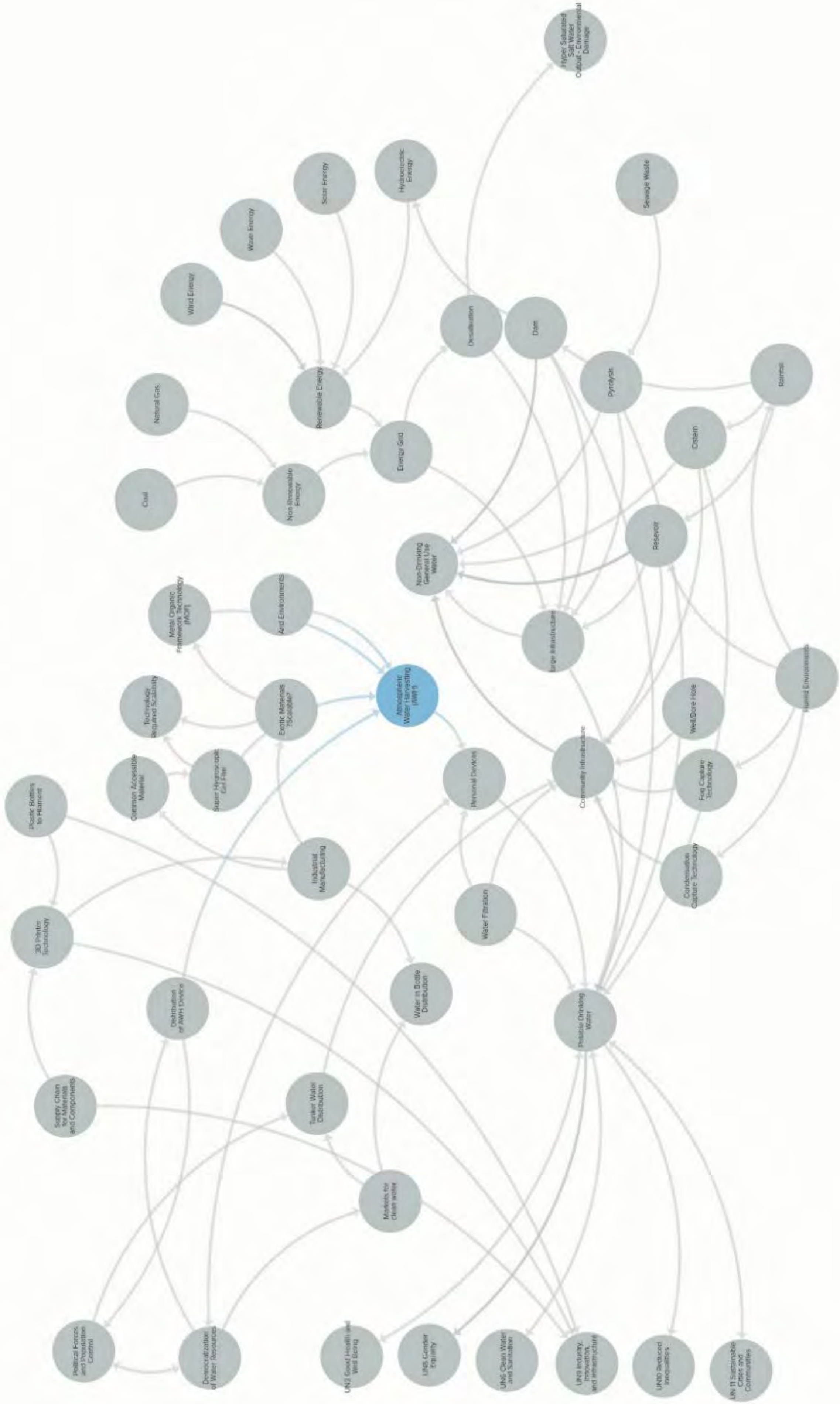


[55] (Ejeian and Wang)

DEMOCRATIZATION

Systems thinking analysis looks at complex, wicked problems and instead of breaking the problem down into parts, embraces the complexity and looks at relationships between stakeholders and various factors to see how they influence each other. A systems thinking approach is a dynamic map that shows positive and negative influential relationships between these 'nodes'. As the world evolves the systems map that describes it must adapt and change with it. Developing a systems map can be challenging as the nodes and relationships can vary in scale and granularity and knowing where to end your level of analysis can be difficult. The great power of applying a systems thinking approach to a problem is that you may see multiple relationships to particular node which can lead to insight on where an intervention may have the most potential impact across the larger wicked problem. Sometimes these points of intervention can come in very unexpected and innocuous places that can be reasonably addressed efficiently. One small nudge in the right place has the potential to impact much larger systems.

Below is a simplified systems map or causal loop diagram demonstrating some of the interrelated nodes and relationships associated with the wicked problem of safe, accessible drinking water. This is by no means comprehensive but does provide some insight into the relationships underlying this wicked problem.


Hyper Saturated Salt Water Output - Environmental Damage
Sewage Waste
Hydroelectric Energy
Solar Energy
Wave Energy
Wind Energy
Natural Gas
Coal
Renewable Energy
Non-Renewable Energy
Energy Grid
Desalination
Dam
Pyrolysis
Rainfall
Ocean
Reservoir
Non-Drinking General Use Water
Large Infrastructure
Humid Environments
Well/Bore Hole
Community Infrastructure
Fog Capture Technology
Condensation Capture Technology
Potable Drinking Water
Water Filtration
Personal Devices
Atmospheric Water Harvesting (AWH)
Arid Environments
Metal Organic Framework Technology (MOF)
Exotic Materials
Technology Required Scalability
Super Hygroscopic Gel Film
Common Accessible Material
Plastic Bottles to Filament
Industrial Manufacturing
3D Printer Technology
Distribution of AWH Device
Water in Bottle Distribution
Supply Chain for Materials and Components
Tanker Water Distribution
Markets for clean water
Political Forces and Population Control
Democratization of Water Resources
UN3 Good Health and Well Being
UN5 Gender Equality
UN6 Clean Water and Sanitation
UN9 Industry, Innovation, and Infrastructure
UN10 Reduced Inequalities
UN 11 Sustainable Cities and Communities

I believe that atmospheric water harvesting (AWH) represents a node of possibility in this complex wicked system that could have a powerful impact upon the larger problem of availability of safe drinking water. AWH is by no means a solution to all of the issues presented by water scarcity, but it does have the potential to be a democratizing intervention that could provide a foundational basis of drinking water access to anyone nearly everywhere.

What if clean drinking water was as available as the air we breathe?

The promise of atmospheric water harvesting is to draw moisture from the air that is available in even arid, desert-like environments and condense it into clean drinking water. This could be done anywhere that the temperature is high enough that water would not freeze. Geographically this happens to overlap with the areas of largest population and need. This freedom of access to water wherever there is atmosphere would require a harvesting device but may be able to be accomplished at a micro economic level of the individual or small community as opposed to major infrastructure projects that require greater complexity and financing mechanisms.

To take this concept to the extreme, imagine a water bottle that could be provided to everyone on the planet that would systematically fill itself with the water required to sustain an individual each day. While this may be a fantastical framing of the promise of atmospheric water harvesting, the concept of developing a device that would provide sufficient water to sustain individuals or small groups of people could have a revolutionizing impact on related issues of the politics of water scarcity, gender equality, education and health. If we can develop a way to provide water at a most basic and personal level that is independent of any greater infrastructure, then we democratize water distribution. The right to clean drinking water would become independent of market, legal or governmental control and become a fundamental human right of access.

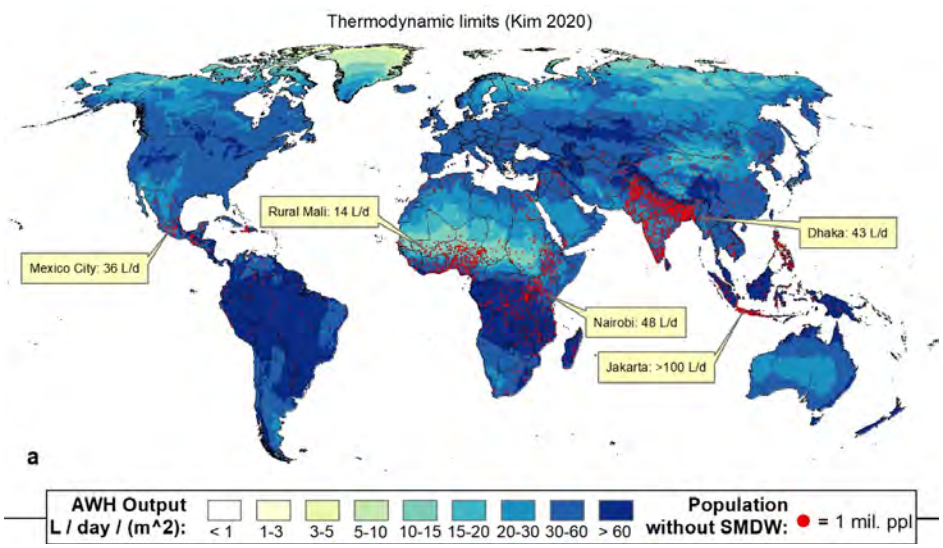
Is Atmospheric Water Harvesting a solution?:

While a small-scale AWH device may not provide the solution to this great challenge alone, it could play a contributing part in a larger, more comprehensive set of interventions to mediate the current and future needs of a growing global population. AWH can continue to provide clean drinking water even when wells run dry, and droughts keep surface and well water unavailable. AWH does not purport to address the needs of agriculture, livestock, or daily hygiene requirements, but may provide access to potable drinking water.

Could AWH even work? This question was taken up by a group of researchers in a paper "Global Potential for Harvesting Drinking Water From Air Using Solar Energy" [56] who mapped the global potential yield for AWH across the planet. Their analysis "demonstrates that daytime climate conditions may in fact be sufficient for continuous-mode AWH operation in world regions with the highest human need."

[56] (Lord et al.)

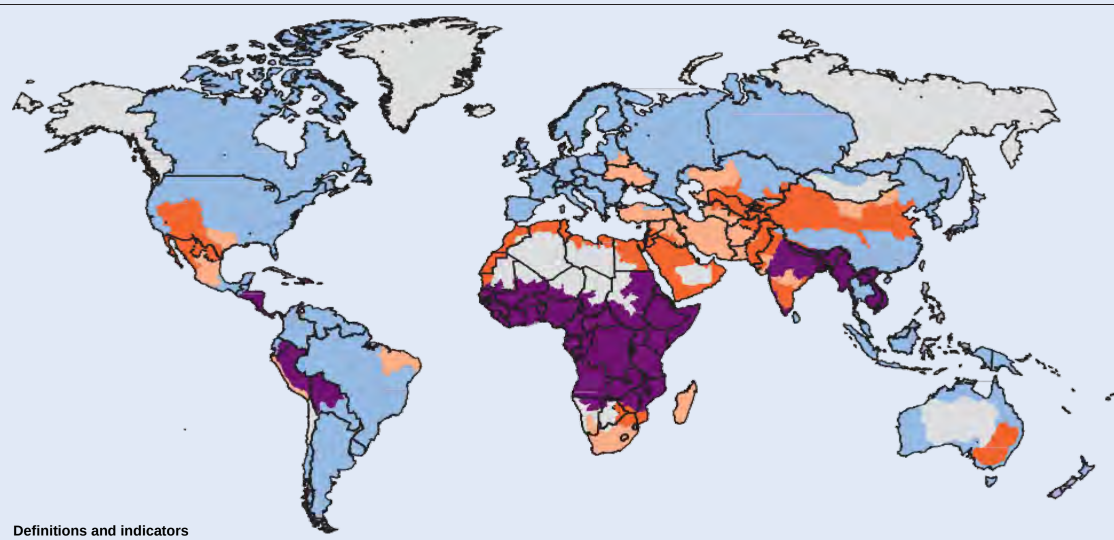
Potential for Atmospheric Water Harvesting



Map from the [Nature paper by Lord. et. al.](#) shows the overlap between where people without safely managed drinking water live (red dots) and climates where AWH devices have the potential to perform best (dark blue shaded areas).(Lord et al.)

map **2** **Areas of physical and economic water scarcity**

Little or no water scarcity
Physical water scarcity
Approaching physical water scarcity
Economic water scarcity
Not estimated



Definitions and indicators

- *Little or no water scarcity.* Abundant water resources relative to use, with less than 25% of water from rivers withdrawn for human purposes.
- *Physical water scarcity (water resources development is approaching or has exceeded sustainable limits).* More than 75% of river flows are withdrawn for agriculture, industry, and domestic purposes (accounting for recycling of return flows). This definition—relating water availability to water demand—implies that dry areas are not necessarily water scarce.
- *Approaching physical water scarcity.* More than 60% of river flows are withdrawn. These basins will experience physical water scarcity in the near future.
- *Economic water scarcity (human, institutional, and financial capital limit access to water even though water in nature is available locally to meet human demands).* Water resources are abundant relative to water use, with less than 25% of water from rivers withdrawn for human purposes, but malnutrition exists.

Source: International Water Management Institute analysis done for the Comprehensive Assessment of Water Management in Agriculture using the Watersim model; chapter 2.

Will it work?

There are 12.9 trillion tons of water in the air at any moment even including the Sahel Desert and central desert of Australia which experiences relative humidity levels as low as 20%.[57] There is sufficient water in the atmosphere to fulfill human drinking water requirements without negatively affecting hydraulic environmental processes.[58]

In 2020 the Defense Advanced Research Projects Agency (DARPA) of the United States awarded five contracts and selected one government partner to "develop technology to capture potable water from the air in quantities sufficient to meet critical Department of Defense needs, even in extremely dry climates."[59] The contractors include GE Research, Physical Sciences Inc., Honeywell International Inc., Massachusetts Institute of Technology, University of Texas at Austin, and U.S. Naval Research Laboratory. The goal of the Atmospheric Water Extraction program is to:

> "Provide fresh water for a range of military, stabilization, and humanitarian needs through the development of small, lightweight, low-powered, distributable systems that extract moisture from the atmosphere. DARPA is open to various approaches, with an emphasis on advanced sorbents that can rapidly extract water from ambient air and release it quickly with minimal energy inputs."

Clearly the United States government sees both potential and a need to apply significant development resources to address the "numerous financial, maintenance, and logistical challenges" that distributing water to troops in the theater of war and humanitarian and disaster relief efforts.

In addition to the military objective in developing this technology there are other civilian projects engaged in this area of research. Two groups of researchers publishing in 2021 have shown the valid potential for AWH using passive solar energy thus confirming the foundational premise of my AWH design project—that drinking water can indeed be harvested from the air.

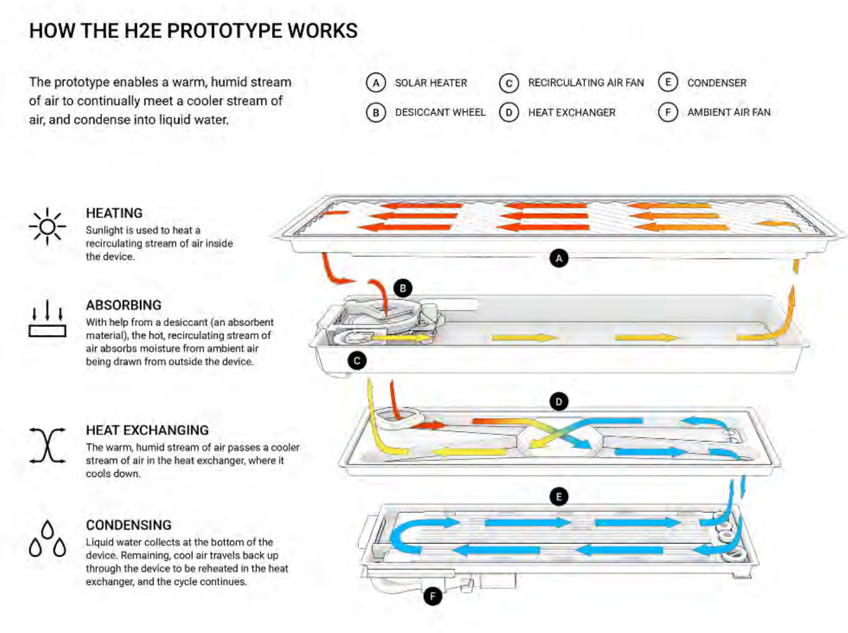
X.Development Group is a subsidiary of Alphabet (Google) focused on attacking wicked problems and coming up with moon-shot solutions. The article "Global Potential for Harvesting Drinking Water From Air Using Solar Energy" published by Lord, et al in 2021 was a result of their research into this topic which included developing a functioning prototype AWH device. The H2E ("Hydration to Everyone")[60] was developed as a functioning test bed prototype whose data and design are freely shared and published under a non-assertion patent pledge to encourage others to continue development in this area. Their goals were to build a device that:

- Could be affordable to people living on $2-8 a day
- Could work even in dry places (as low as 30% humidity)
- Individual households could adopt on their own, without having to rely on community infrastructure
- Could be entirely powered by sustainable, renewable energy

[57] (J. Guo et al.)
[58] (Haechler et al.)
[59] https://www.darpa.mil/news-events/2020-12-18
[60] https://x.company/blog/posts/sharing-project-h2e-with-the-world/

- Could produce water at a cost target of $.01 a liter
- Could become the foundation of a large, sustainable business

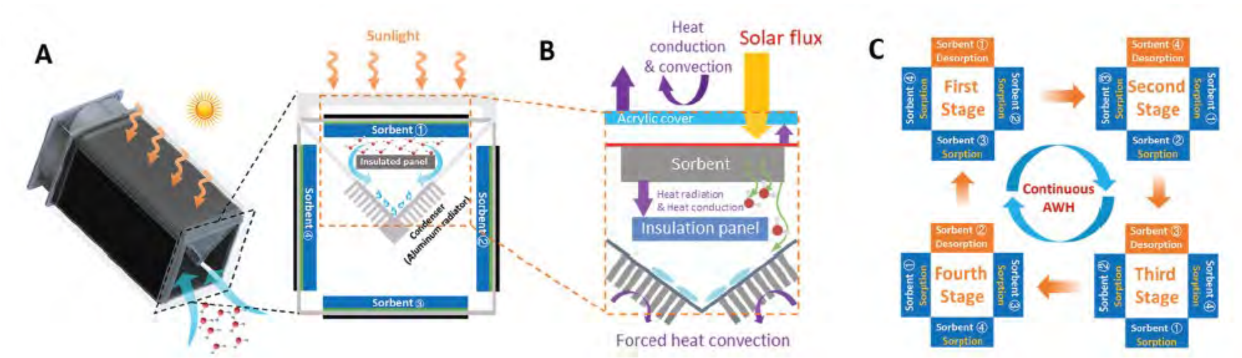
Their device was successful on many fronts, and they projected that as-built it would produce water at 150mL/hr/m^2 which could keep a person hydrated in many arid places. The design team felt that their device could produce water at a cost of $0.10 per liter but that it would take significant additional development and resources to achieve $0.01 per liter goal. The mass production required to achieve this next level of performance was outside their project scope at which point they opened all of their research, data and design to the world to carry on development.



Their design along with the work of Jiaxing Xu, et al [61] have shown that sun-powered semi-passive atmospheric water harvesting devices are feasible. Both devices rely on solar cell produced electric energy to power recirculating fans in their designs. Solar irradiance provides both the heating required for the convection and temperature differential inducing dew point condensation and the electric power to create a device that is portable and independent of the electric grid. Xu's work was semi-continuous in its collection cycles achieving eight continuous water capture-collection cycles per

[61] (Xu et al.)

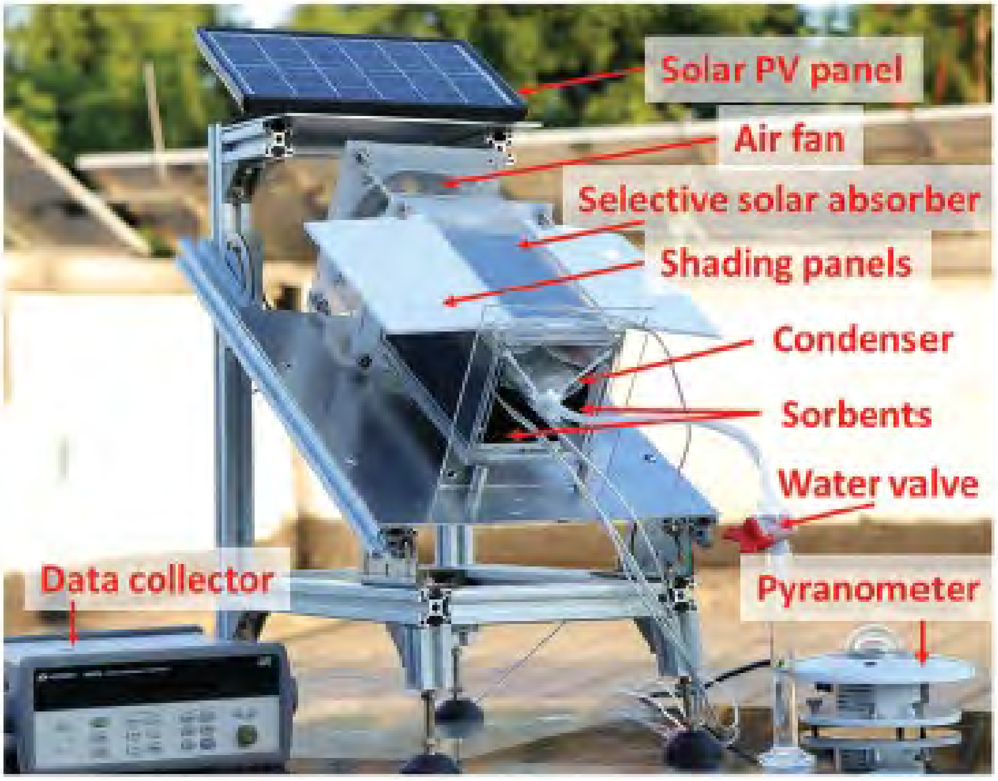
day with production of 2120mL of water per kg or sorbent material per day from ‘dry air’. Their device was an experimental proof of concept prototype that relied on four absorbent panels being manually rotated from cooler, shaded collection zones to a solar-powered heat and desorption chamber where water was released and collected.



The sorption material used in their device was a vertically aligned nanocomposite Lithium Chloride (LiCl) in a reduced graphene oxid (rGO) and sodium alginate (SA). This material showed water uptake at a level three times its weight. This high water uptake allows for better absorption of water at lower relative humidity levels. Other, compressor-driven, energy-intensive approaches to harvesting water from the atmosphere perform poorly in low huidity environments. The research group found that sorption-based AWH (SAWH) “is one of the most promising technologies for realizing water extraction from dry air at low RH. More importantly, the operation of SAWH can be directly driven by low-grade thermal sources such as solar energy, making it more attractive for low-cost operation and thus economy-friendly for wide application in poverty-stricken regions” [62]

They also found that “SAWH systems can be more compact and efficient where forced convecion air is introduced and the sorbent can be packed layer by layer.” [63] Additionally, the introduction of forced air convection accelerated the diffusion of water molecules, but also efficiently took away the sorption heat released by the sorbant material. Their findings suggest that the introduction of forced air convection is “highly necessary to enhance the sorption kinetics even providing a low air flow rate.” This independently confirmed the importance of the fan component in my proposed AWH design.

[62] (Xu et al.)
[63] (Xu et al.)



Their study also confirmed another practical question that challenged my design; could Solar Irradiance be enough to achieve the 40°C temperature required to release moisture from the sorbent material. They found that it only took about 15 minutes to rise from ambient to high temperature and with the active airflow cooling the temperature was able to drop quickly back into absorption-level temperatures.

The group also proposed that a DC motor could be employed to "drive the rotation of gears, and the gears drive the rotation of spokes and shells of the SAWH device". The suggestion to explore a gear-driven device for continuous rotation of a sorption-desorption cycle something I also independently came to in my design process, however my approach did not rely on solar-powered DC motors.

The X group found that "AWH has a much lower specific yield than infrastructural water sources such as desalination, however, SC-AWH devices sized to produce sufficient daily drinking water output for an individual or household could address both the water quality and the water access dimensions of safely managed drinking water (SMDW) solutions at the household level." [64] They found that a hypothetical one meter square device providing 0.2 to 2.5 liters per kilowatt hour at 30% to 90% relative humidity could provide up to 5 liters of water per day per person. Their study assumed that the SC-AWH output would be used for drinking water only and not replace water for other domestic uses such as hygiene, cooking and sanitation.

[64] (Lord et al.)

Is it feasible to create safe drinking water from the air using passive energy-neutral systems? These well-researched experiments show that yes, it is feasible. With additional effort it could be made practical.

Who is the Audience?

Who might use an atmospheric water harvesting device? There are many considerations that ultimately influence where a device with this functionality may be adopted.

- DARPA has clearly stated that they are actively pursuing a device which would alleviate supply-line challenges of getting water to troops in the field in both an individual level and for groups of 150 or more troops and have provided funding for continued research and development.
- The military also views AWH as a means of assisting in humanitarian disasters as they are often part of first response and relief operations. Non-governmental agencies such as the Red Cross/Red Crescent and others working with displaced populations would find AWH an integral component in their ability to deal with water logistics and refugee camp requirements in undeveloped areas.
- There may be an increasing market for AWH in developed countries that are experiencing water scarcity issues and individuals with the means who would want to augment their infrastructure-supplied water supply with an independent source. This would be similar to a solar panel model of additive electrical independence from the energy grid that we are seeing installed throughout the USA today.
- Researchers and outdoorspeople who work or live in extremely rural or remote locations where drinking water might otherwise be inconvenient or not readily available.
- Urban dwellers who have access to sunlight and space to install an AWH device may relieve the need to use water that is compromised from other sources.
- There are 775 million people who live more than half an hour from an improved water source as mentioned earlier in this document. These are a primary audience for an AWH device.

Ultimately the purchase price or distributed cost of a manufactured device will strongly affect which groups can afford to purchase and use such a device. Durability and cost of maintenance also factor in as well as space and cultural considerations. As is the case with many technological developments we may see initial adoption by populations who can afford the initial cost and then with successful market response, good management, and design improvements see later versions become less expensive and more broadly distributed. My goal in this document is not to identify a specific target audience but to make proof of concept and a potential design direction clear for further development work.

Design Criteria

The goal of my device is to create sufficient safe drinking water to supply an individual or household each day. This amounts to about 2 to 3 liters per individual.

The device would run entirely on solar and gravity as energy sources and produce continuously during daylight hours for 10 hours once set in the morning.

Ideally the device would work using old technology that is readily repairable locally and made from materials that are locally attainable.

The design would be provided open source to allow others to build on its contributions to the field.

How it Works: Mechanism and Principals

The AWH device of my design, (Let's call it the Pollock Atmospheric Water Harvester (PAWH) for distinction from other designs or the general term AWH), consists of three primary components:

1. Sorbent Material (to retrieve water and release it)
2. Solar Heat (to release moisture from A/D material)
3. Gravity-driven Kinetic Energy (to create continuous cycling environment)

Sorbent Materials

Sorbent materials are the heart of atmospheric water harvesting devices that passively use solar energy to harvest. There have been many recent developments in material science that have propelled these new materials to new high-level capacities of water take-up that make AWH viable. Desiccant type materials can function fundamentally in different ways. One key difference is whether a material is absorbent or adsorbent.

> "Absorption can be considered a bulk phenomenon where gas/liquid molecules diffuse into liquid/solid materials, changing the structure and volume of absorbent materials."
>
> "Adsorption is a surface phenomenon in which the molecules of gas or liquid adhere to a surface through chemical or physical interactions…for chemical adsorption the sorbent surface needs binding sites to adsorb molecules through strong chemical bonding such as hydrogen bonding, coordination effect and electrostatic interactions." [65]

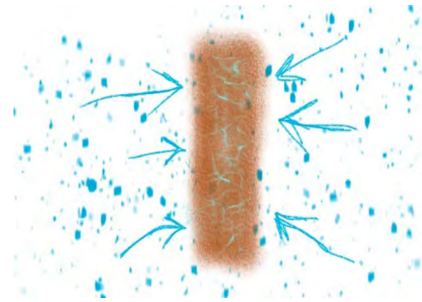
Absorption can be seen when a sponge absorbs moisture into the porous vacancies within its structure. As the sponge is laden with water it increases in size. The release of that moisture either requires the input of high energy in the form of heat to convert the water into gas which escapes the porous structure, or you have to apply mechanical energy to squeeze it out.

Adsorption is a chemical process where individual water molecules are attracted through atomic bonding to open structures in a matrix that is chemically created. The water molecules join and are bound to the sorbent material. This creates a qualitatively different relationship between the water molecules and the sorbent material.

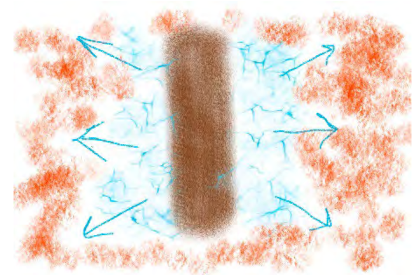
Absorbent materials require much more energy to dislodge than adsorbent materials which require a change in state from hydroscopic (water attracting) to hygroscopic (water repelling) modalities.

[65] (Zhou et al.)

Adsorbent materials-enabled moisture harvesting:



"Relies on the water affinity provided by the functional components. Instead of creating high local relative humidity by cooling the surface, moisture harvesting materials enable spontaneous vapor sorption to trap water molecules, extracting vapor from the air, and hence concentrating the moisture. They are capable of harvesting water in low RH condition as well as saturated RH condition through adsorption." [66]



"The fundamental challenge (of many desiccant type materials) is the intrinsic high energy demand during the desorption or dehydration processes caused by their high affinity with water molecules, which is difficult to be solved. Thus, new materials with highly tailorable properties have been propose as alternatives to meet the demand for efficient AWH." [67]

"The ideal moisture harvesters are required to have high water uptake, low energy demand for water release, fast water capture/release, high cycling stability, and low cost," [68]

Examples of adsorption type sorbent materials are

- **Silica gel** which is used in many sorbent applications however it "generally has a low adsorption capacity, especially at low RH, and is not a good thermal conductor, limiting its use" [69] in AWH devices.

- **Zeolite** (a type of alumina silicate crystal combined with alkaline or alkaline earth elements) is the first material used in a device based on adsorption and is still one of the main adsorbents of adsorption technology. However, "high regeneration temperature, low adsorption capacity and poor thermal conductivity can be weaknesses of zeolites. [70]

- **Metal-Organic Frameworks (MOF)** is field of chemistry pioneered by Professor Omar Yaghi at University of California at Berkeley. MOFs are a "polymer that includes metal ions or clusters of ions coordinated with organic ligands to form one-, two-, or three-dimensional structures. High adsorption capacity, high porosity, very high specific surface area, the ability to adjust the uniform pore size, low density, high biocompatibility, and low enthalpy of desorption process are the most critical advantages of MOFs." [71]Another interesting aspect of MOFs is that their 3D structure and qualities can be manipulated and tuned for preferred characteristics. The downside to MOFs are that they are expensive and barely commercially available and the toxicity of residual metal ions in solution needs to be studied further.

- **Chemical sorbent** Hygroscopic salts such as LiCl and $CaCl_2$ have high sorption characteristics that can provide additive capacity to other materials such as Hydrogels which is what Gu et al achieved in their Super Hygroscopic Films. They can improve mass and heat transfer and/or boost the hydrophilic properties. When mixed with other materials such as MOF, Silica Gel and Hydrogels they can provide faster uptake of moisture as well as allow the composite to work in a wider variety of RH environments. [72] Hygroscopic salts are inexpensive and readily available on the market.

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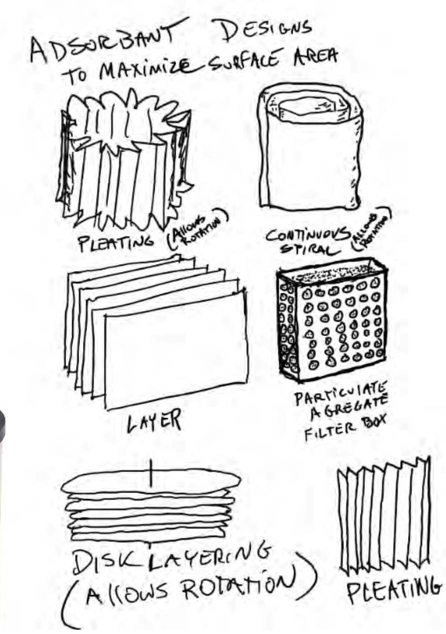
[66] (Zhou et al.)
[67] (Zhao et al.)
[68] (Zhou et al.)
[69] (Ejeian and Wang)
[70] (Ejeian and Wang)
[71] (Ejeian and Wang)
[72] (Ejeian and Wang)

- **Hydrogels** are already in wide use in industry in products such as personal hygiene and tissue engineering that absorb water from the liquid phase in significant volumes. Hydrogels have "high adsorption capacity, high adsorption density, cyclic stability, and operation in a range of relative humidity are the main advantages." [73] Hydrogels are not as inherently porous as MOF but this can be addressed through different techniques including electrospinning, the use of reduced graphene oxide, or controlled freezing.

The material developed by Guo et al which inspired this project was a hydrogel whose performance met or exceeded the performance of any of the other category of materials (to date). The material developed by Guo et al is a Super Hygroscopic Polymer Film (SHPF). It "Consists of earth-abundant biomasses, konjac gucomannan (KGM), and hydroxypropyl cellulose (HPC) as the hybrid polymer matrix to hold uniformly dispersed LiCl solution." [74] The material is made from inexpensive and readily available materials with simple production techniques yet provides performance equal to or exceeding other sorbent materials. The ingredients are mixed and then left for a few hours to gel. From there they are doused in liquid nitrogen and then placed in a freeze-drying machine which creates the porous structures in the process. I exchanged emails with one of the authors on the paper, Youhong Guo who informed me that it would also be possible to use a regular deep freezer in the process, however it would take longer, and the porous structure and performance may not be as effective as freeze-drying. The fact that this material can be made from readily available materials using simple production methods is one of the key features for me basing my device on this formulation

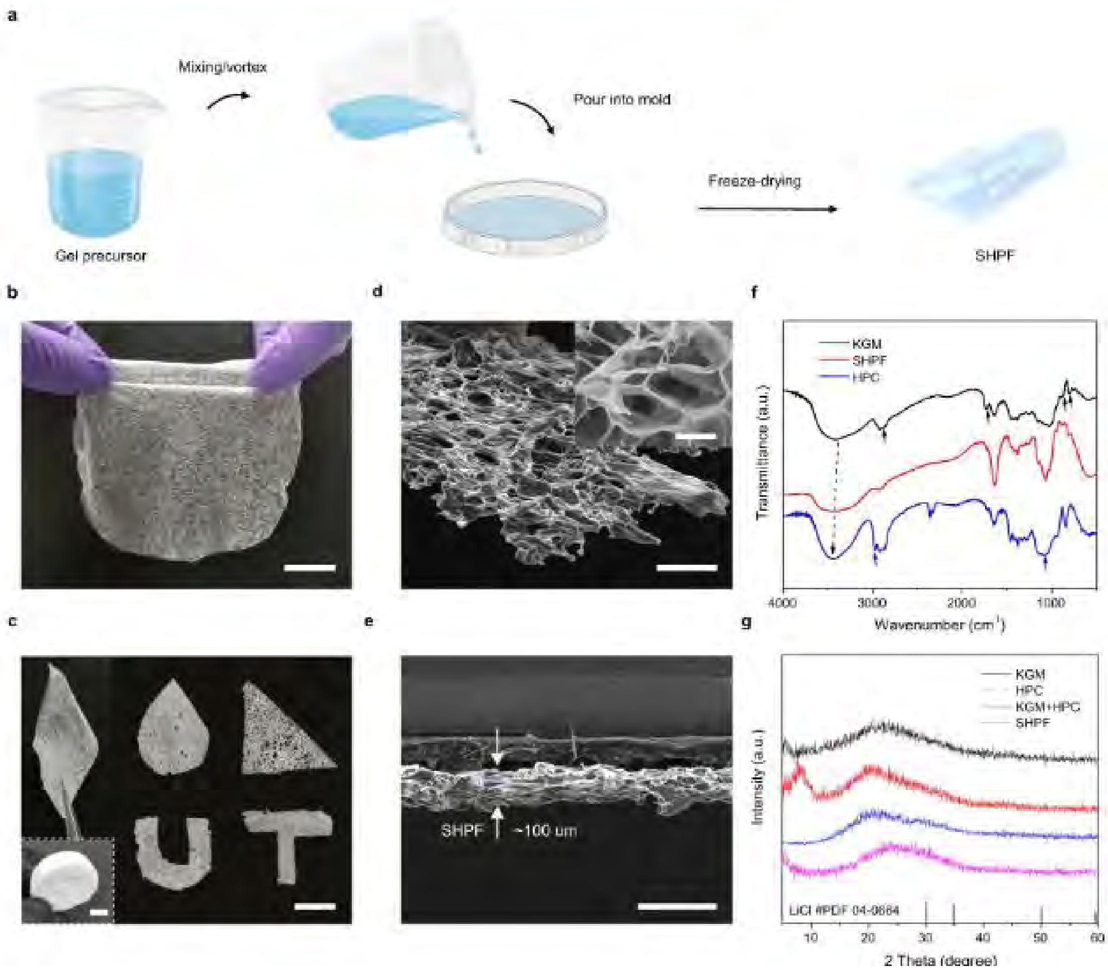


The SHPF that was created by Guo et al was a film approximately 0.1mm or .004" thick. Youhong Guo expressed in our email exchange that, "the density of this film is very low so you have to make an adsorption bed in layers or design a compact device without scarifying its exposure area." This prompted me to consider a design that would provide the maximum adsorption surface area. The delicacy of the film also suggested that a carrier might be necessary to maintain its structure and hold it in place. Either a porous material as a support or binding the film between two mesh layers of hydrophilic perforated material may be necessary. I could foresee a structure similar to a workshop vacuum filter which uses pleating to maximize surface area.

[73] (Ejeian and Wang)
[74] (Y. Guo et al.)

Fig. 2: Fabrication and characterization of SHPFs.

From: Scalable super hygroscopic polymer films for sustainable moisture harvesting in arid environments



Dust infiltration:

One major challenge of any AWH design working in a real and dirty world is the, "inevitable presence of environmental pollutants such as dust and sand, which are naturally present in most target areas. The penetration of soil particles into the device can fill the porous structure of the adsorbent bed and reduce the adsorption capacity. On the other hand, depositing on the device's inner surfaces disrupts the internal mass transfer, acts as an insulation layer, and resists heat transfer. Although the severity of this phenomenon varies according to the situation in the area, if no equipment is provided to prevent dust entry, even a weak storm can disable the entire device." [75]

[75] (Ejeian and Wang)

Design Constraints

Photo: Bill Hammack, the Engineerguy, Youtube

The prototype devices developed by X.Development group and the researchers led by Xu both used solar cell powered electric motors to drive the moving components (fans) that their devices depended upon to function. Neither device was continuous in operation without hourly, periodic intervention by the operators. I set myself the goal of creating a device that could function entirely on solar flux for heat and gravity for kinetic movement. I wanted to avoid electronic components that might be difficult to find in developing economies and which would rely on a global supply chain. I chose to design a device that would distinguish itself from these models by using mechanical kinetic energy to activate the required moving parts. I wanted the device to be able to run independently throughout the solar period of the day without intervention (10 hours). It would be set it in motion in the morning and run until evening when the water would be collected. This design goal was set out of the respect for the many household activities that require time throughout the day. Having to reset a device hourly would be a burdensome interruption and an impediment to its adoption and use.

I wanted to develop a device that could provide water from just gravity, the heat of the sun, and the air around you. These parameters set the constraints for me to design within and push against. The decision to pursue gears and to exploit base mechanical principles in the design was driven by a desire to keep the final device easily replicable and repairable in less industrialized locations where it might be most needed. This decision is a critical juncture in my design process. It is possible an easier route would be to develop a device that would be powered entirely by solar electric power. Such a device could be made to run continuously and autonomously, however it would be heavily tied to a global supply chain for components and repairs and would present additional complexity and challenges unique to its pursuit. The parameters I set for myself may or may not be the most effective path to final production and adoption of an AWH device, but they allowed me to demonstrate in principle that older, established technologies could be employed and may maintain some advantages over modern electrical solutions.

Design Development: Principles and Forms

A combustion engine requires three primary elements to function: air, spark, and fuel.

Similarly, an atmospheric water harvester requires three basic elements: air, heat, cooling.

The sorbent material must collect moisture from the air, then be heated to a point at which it releases that moisture, and then cooled to gather more moisture. Within the heated chamber where water is released there must be a surface cool enough for the water to condense on.

The stages of heating and cooling must either be physically separate or achieved through cyclical periods within the same space.

Thinking through this requirement three options present themselves:

1. Move the sorbent through different heating and cooling zones
2. Move the heating and cooling zones across the sorbent
3. Keep the sorbent stationary but cycle through heating and cooling states

The third option of cycling through periods of heating and cooling would require transition time to achieve each state. This would limit the number of adsorption/desorption cycles possible during daylight hours.

The second option of keeping the sorbent stationary and moving the zones of heating and cooling is a possibility but seemed burdensome and difficult to execute upon further investigation.

I chose to keep the heating and cooling zones stationary and move the sorbent material through them at a pace that matched their adsorption/desorption cycle times.

The design parameters began to formalize:

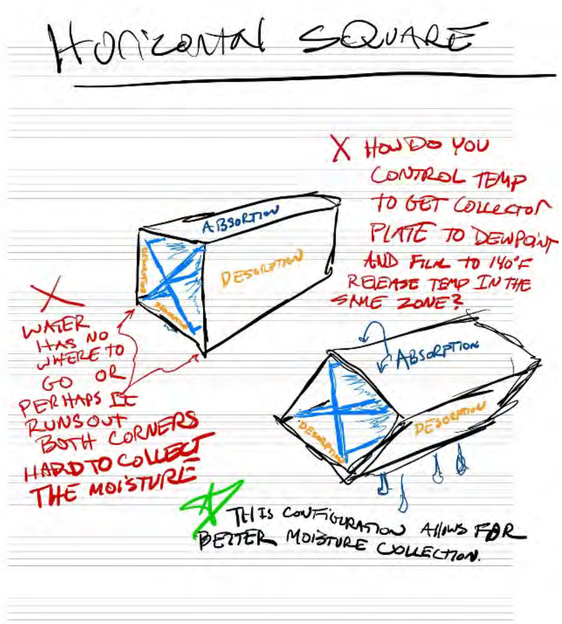
1. Separate zones for heating and cooling must be maintained.
2. Solar flux alone would provide heat.
3. The sorbent material would move between zones continuously at a rate commiserate with their natural adsorption/desorption times.
4. A cooled collector must be present in the heating zone for aerosol water to condense onto.

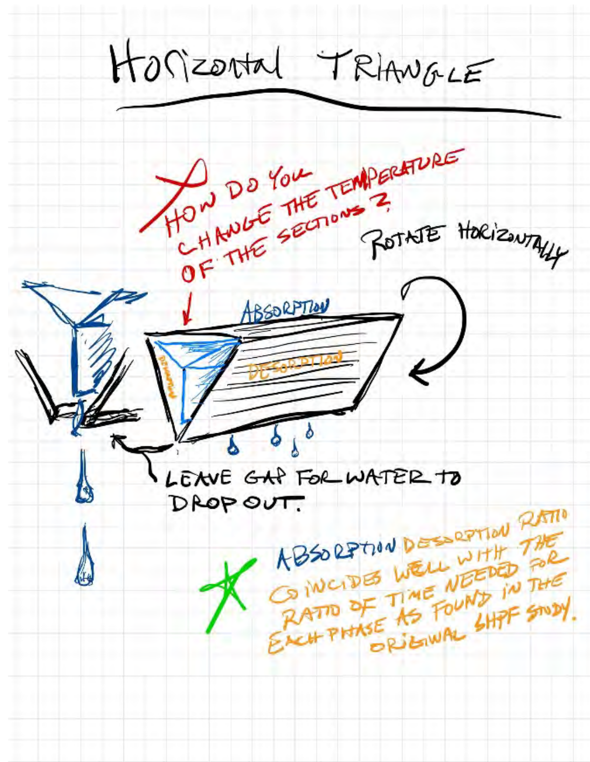
At this point I began to iterate on the potential forms such required mechanics might take. I thought about which shapes of sorbent collector might provide continuous cycling and the most efficient shape.

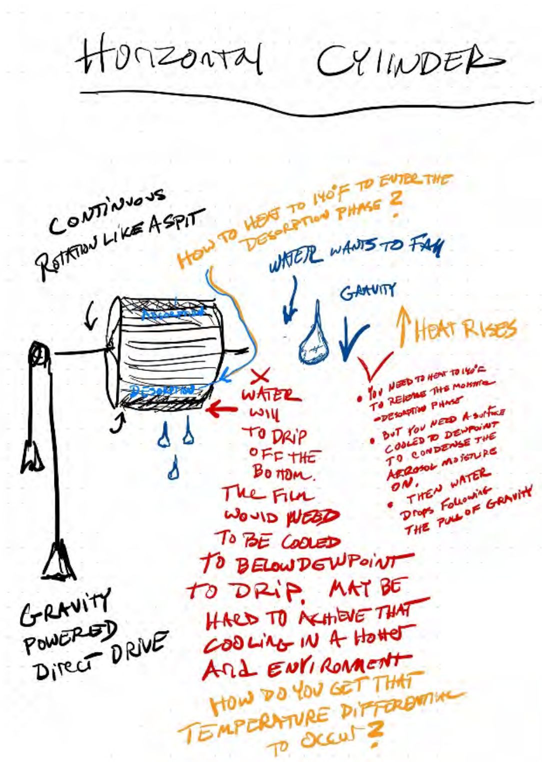
I started with a horizontal form similar to a roasting spit. Based on the earlier constraint of using gravity to power the rotation of the sorbent material this orientation for rotation seemed the simplest. However, explorations into basic square, triangle, and circular sorbent shapes each exhibited impediments in this horizontal position. The cylindrical form was the most efficient for rotation of the sorbent material around the collection plate but the horizontal positioning impeded moisture collection.

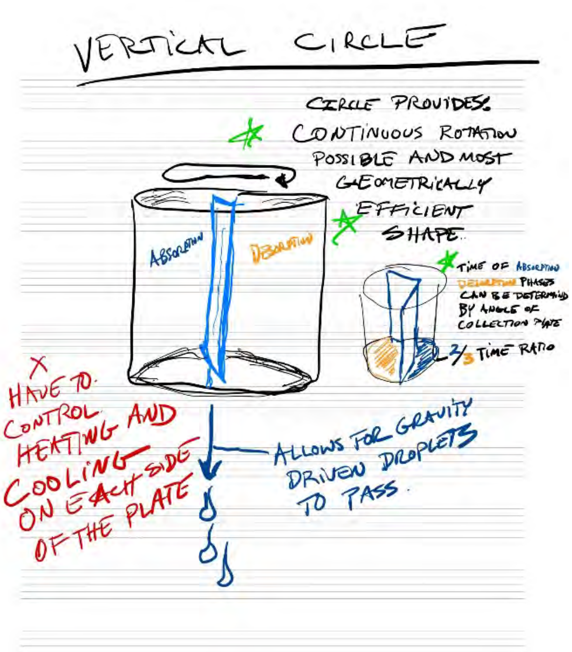
Abandoning a horizontal configuration and considering the efficiency of the circle form in a vertical orientation addressed several problems simultaneously. The moisture could exit through the force of gravity. The sorption cylinder could be rotated continuously through heated and cooled zones. These zones could be separated internally by the condensing plate. While one half of the cylinder could be exposed to the sun the other half could take advantage of shading to assist in cooling. From this forms analysis the most promising vertical configuration emerged and guided further exploration.

Basic Forms Analysis



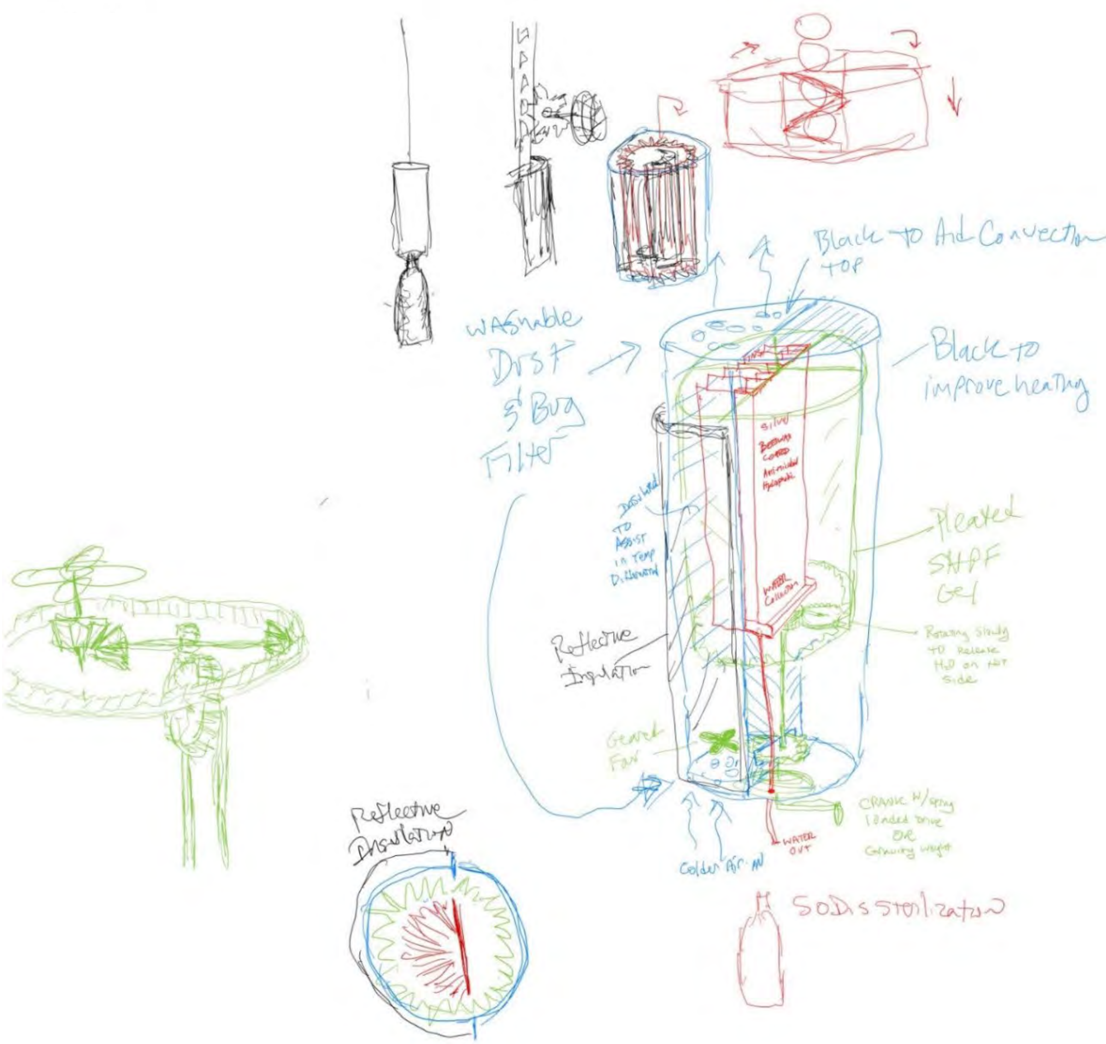






The next step of the design process was to establish how to move the sorption cylinder through the heating and cooling zones and how to achieve heating and cooling for those zones. I realized that both the motion of the sorbent cylinder and the cooling of the collector plate and adsorption zone may be possible through gravity powered, geared mechanisms. Weights could drive gears to turn the sorbent cylinder and a fan to create convection cooling while the sun heated the other half of the chamber.

The following pages illustrate some early rough explorations of how these elements could come together:



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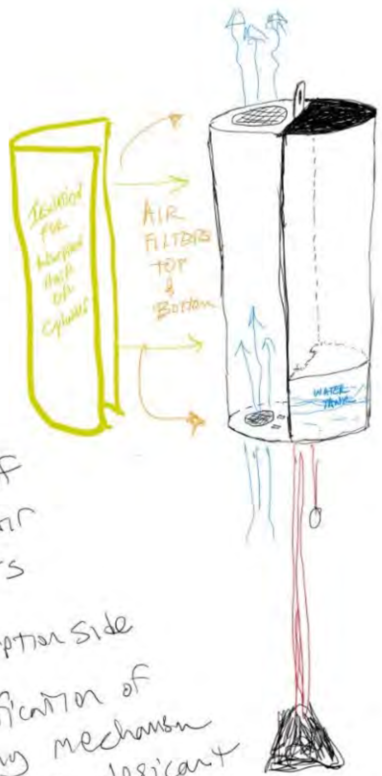
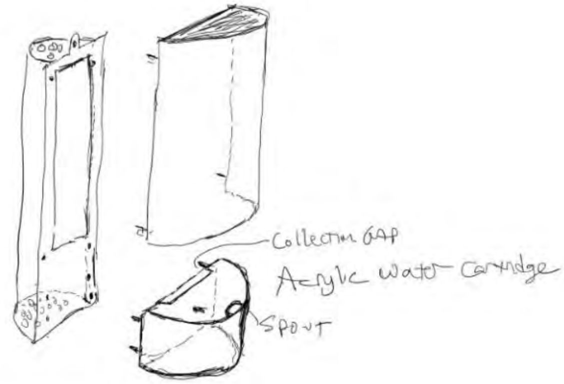
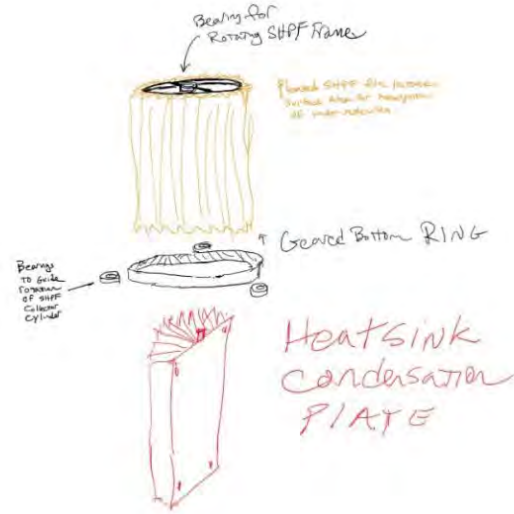
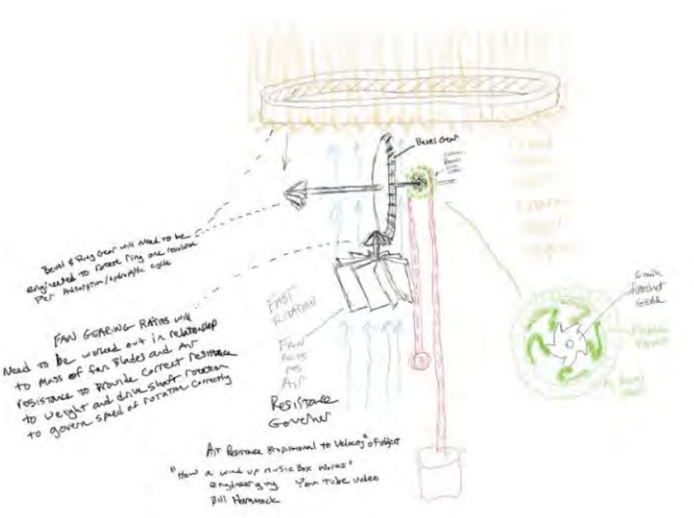


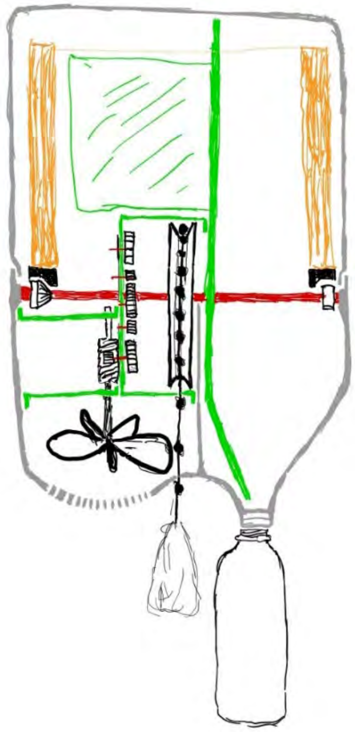


Issues

1. Filtration of intake Air & Insects Dust. To Adsorption Side
2. Simplification of gearing mechanism to Drive desicant & Fan Rotation weight Driven
3. Is There enough Airflow from weight Driven fan to accelerate Adsorption & to create enough temperature differential to initiate Dew point on Collector Plate?
4. Post collection Filtration or Purification
5. Assembly/Disassembly & cleaning.
6. Anti microbial Coatings → Beeswax







No small 8/1/22
Bottle
use tube
to 15 Liter
Jug instead

SOLDIS Sterilization Method.
Use standard 2 Liter PET Bottles

Bottle design provides universality for collection/distribution but also introduces a stress point for breakage at threaded neck.

7/25/22

SHPF Film

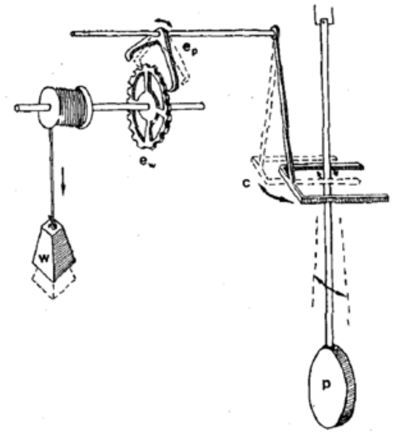
Cylindrical Pleated form to Maximize Surface Area and provide Continuous rotational Absorption/Release Cycling

Lifespan. Need for Replacement?

1. Can SHPF be made without Freeze Drying.
2. Can It be made into large enough Panels and be folded without cracking or breaking? or in Production as a Continuous sheet?
3. Would it require a substrate backing?
4. What is the optimum sheet thickness?
5. What is the optimum recipe for uptake/release cycle times to be equal
6. How Many Utility Cycles can the Material withstand theoretically
   - If enclosed in Black Plastic or Metal No UV exposure But Heat/cooling Cycling and absorption/release Activity.

Gravity, Mechanical Gearing and Regulation

Once I had the basic parameters of design determined I began to work in more detail on the design, configuration, and viability of each of the elements I anticipated needing to incorporate and the operating principles behind them.



The PAWH design requires two different motion-driven components to operate. The first is a rotational drive to rotate the sorbent cylinder between the adsorption and desorption chambers. The second movement required is to drive a fan to force moisture-laden air across the heat sink fins to lower the temperature of the condenser plate and to saturate the adsorbent cylinder.

I believe that both motions can be achieved by using old, or to borrow a term from the book *RANGE, withered technology*. This is to say, technology that has been around before the 20th century and the advent of electric motors. I propose that the PAWH can be driven through gearing mechanisms driven by weights and gravity.

There is precedent and inspiration to this approach by looking at the technology incorporated in grandfather clocks where a weight is lifted manually to a height and then the descent is modulated by a gear and oscillating escapement regulator. It is gravity that ultimately powers the device. Admirably this approach was taken recently by a company called Deciwatt[76] in the UK who designed an LED lamp primarily to address areas of illumination poverty in developing economies. Their elegant design requires a user to lift a weight up and as it descends in a controlled manner. The gearing transfers the kinetic, gravity-driven energy to drive a small electric generator which provides electricity to a low-demand, high-efficiency LED lamp.

Photo: Deciwatt Gravity Lamp

The decision to use gravity as a power source was driven by the desire to make the device as independent of global supply chain manufacturing as possible and to create a device that had more potential for local repair and fabrication because the technology is more accessible. If an electric motor fails, it may be difficult to find a replacement whereas a gear could be fabricated using the talents of local craftspeople (or potentially be 3D printed locally).

Additional inspiration came from another withered technology source--wind up spring powered music boxes. These boxes employed a coiled band of spring steel that after winding would slowly release its energy in a controlled fashion using a governor that spun at high speeds creating wind resistance to counter the

[76] https://deciwatt.global/gravitylight

unwinding tension of the spring. In the PAWH design I sought to use this same governing idea, wind resistance as resistance to gravity pulling on a drive weight to both slow the descent of the weight but in the process generate the movement of wind through a propeller fan blade to provide the cooling breeze to the heat sink and adsorbent cylinder. In this way, the only action needed to engage the PAWH once it was suspended in direct sunlight would be to lift the drive weight.

My goal is to have the descent of the weight take place over the full period of daylight (approximately 10 hours in equatorial regions). This would require the user to only lift the weight once a day and collect drinking water at the end of the day. In this ideal scenario one rotation of the drive wheel from the weight would power a gearing mechanism that would rotate the sorbent cylinder once per hour to coincide with the natural adsorption/desorption cycle of the material. Simultaneously a connected gear train would drive the fan blade to generate the required resistance to the weight falling and provide air flow at a sufficient rate to cool the internal condenser plate. Whether the air resistance and gear ratios can all be calculated to provide these simultaneous outcomes is a question that would need to be addressed in a prototyping stage of development and refinement requiring engineering expertise beyond the scope of this document.

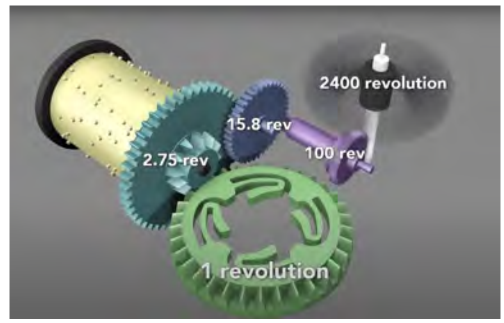


Photo: Bill Hammack, the Engineerguy, Youtube

However, in my modeling of a potential design for the PAWH I did develop a gear train that could potentially provide sufficient airflow per minute equivalent to the fan output of a computer cooling fan. This may be sufficient to provide the cooling required for the PAWH heatsink.

The following gearing parameters were designed into the 3D model that was developed.

Below are the gear ratios used in the 3D printed model which should yield 2000 rpm of fan speed with 1 rotation of the main drive wheel:

If the main drive wheel is to rotate once per hour and achieve fan rotation of 2000 rpM (Rotations per Minute) then:

60 min x 2000rpM = 120,000 rpH (Rotations per Hour)

The geartrain must provide 120,000 revolutions per hour of a single drive wheel rotation.

The gear ratios that were developed and included in the PAWH 3D printed model were:

Gear 1: 12tooth/100tooth= 8.33

Gear 2: 12tooth/100tooth= 8.33 * 8.33 = 69.144

Gear 3: 12tooth/100tooth= 8.33 * 69.44 = 578.24

Gear 4: 12tooth/100tooth= 8.33 * 578.24 = 40,123.49

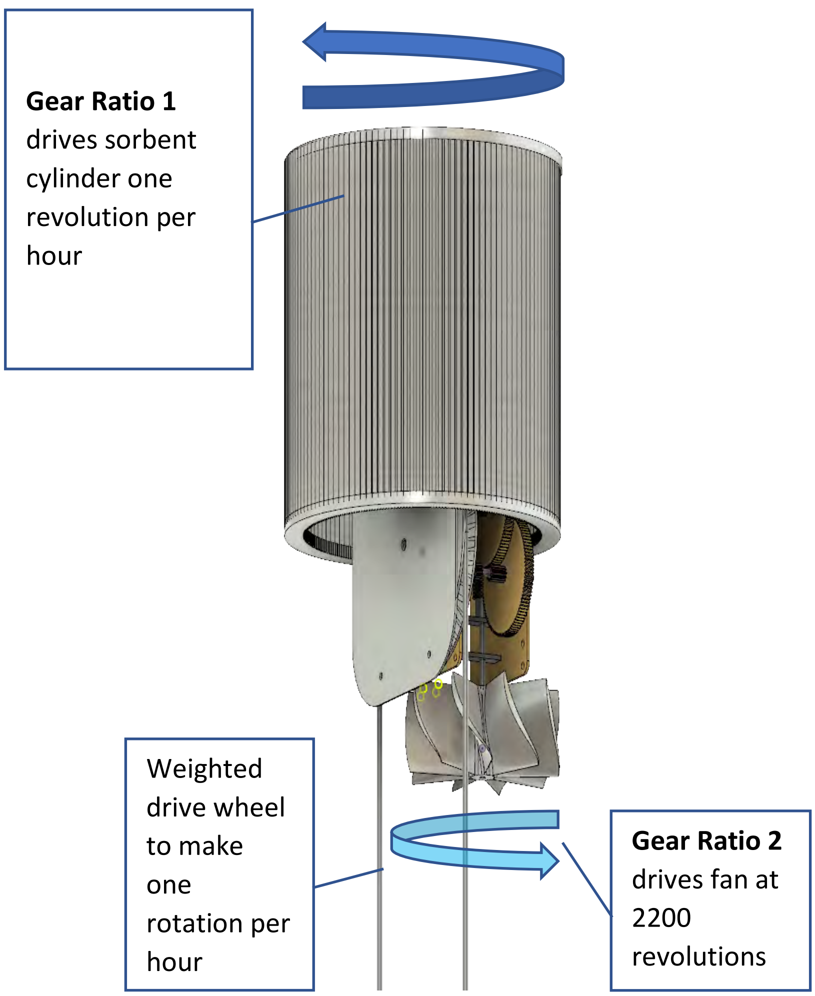
Gear 5 (worm drive to fan spindle): 12 tooth/40 tooth = 3.33 * 578.24 = **133,743 Revolutions per Hour**

Further experimentation would be required to determine if 2230rpM on the fan would provide sufficient resistance in addition to the inherent resistance of the gearbox to control the descent of the drive weight to limit to one revolution per hour and simultaneously provide adequate ventilation airflow.

Photo: Bill Hammack, the Engineerguy, Youtube.com

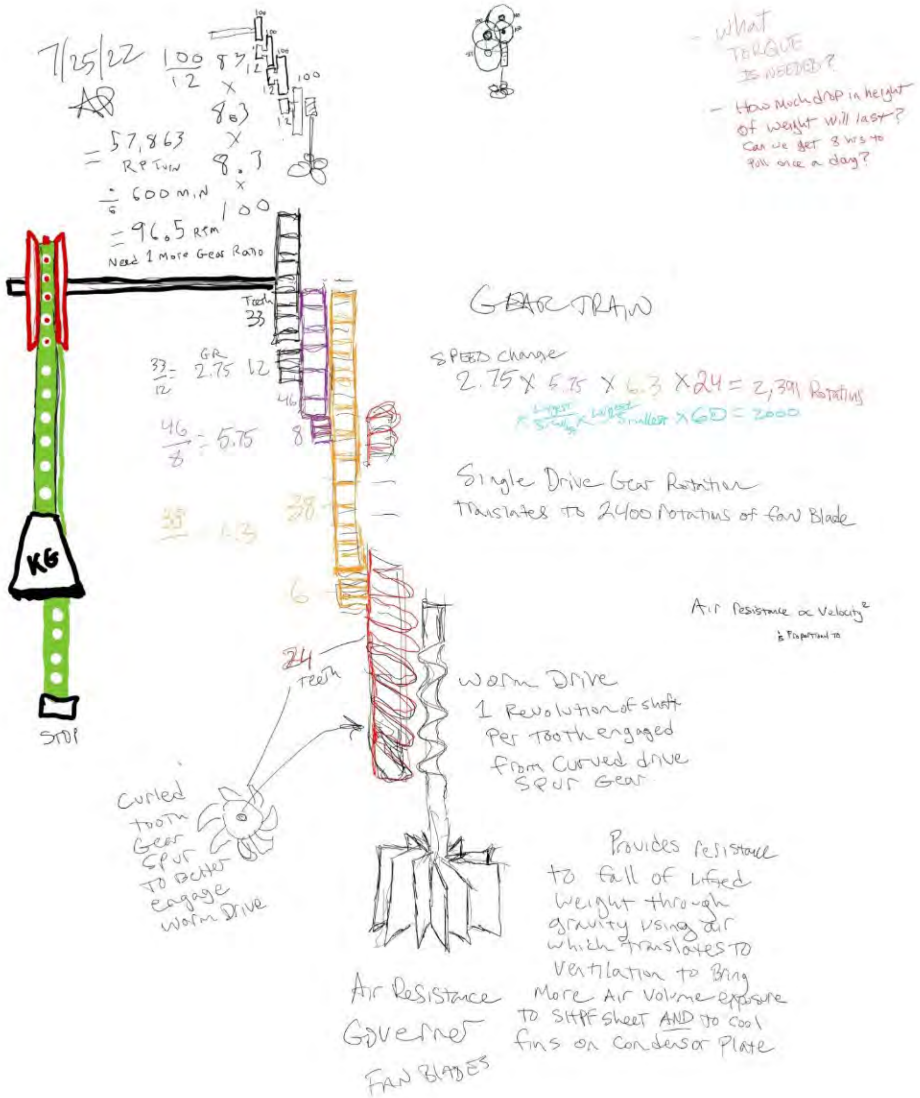
The gear train prototype was included in the 3D model as proof-of-concept that a gearbox of appropriate ratios could fit inside the core of the PAWH without conflicting with the other design elements. The PAWH gearbox fit perfectly within the sorbent cylinder and was successful in its positioning to potentially provide the appropriate drive to the motion requirements of the design.

One additional design element borrowed from the music box is the inclusion in the drive gear of pawls which allow the weight (or spring) to be lifted into place with the gearing ratcheting along freely to allow the lifting without directly driving the gear box in the reverse direction. This element was not modelled in the 3D print of the PAWH, however it would be an integral part of the gear train mechanism when deployed in a true prototype.



(Early ideation of gear train)

Modeled in Autodesk Fusion 360



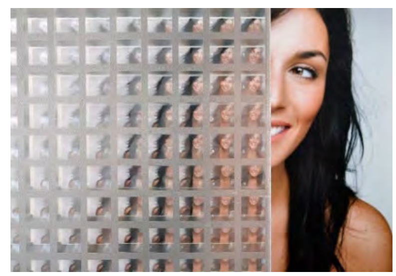
(3D printed model gear train)

Solar Irradiance

As the primary zone of water scarcity need follows the equator, so does the sun and the energy it can provide.

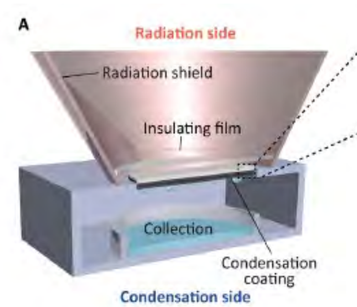
> "Solar energy is a reliable and safe source for adsorption Based Atmospheric Water Harvesters (ABAWH), as there is generally a direct relationship between the need for water and solar radiation." [77]

An AWH device used in these areas should experience adequate sunlight irradiance to provide the heat energy required to push SHPF type adsorbent materials into their desorption phase. While this was proven in several studies in a testing environment there is also precedent in the withered technology of solar oven, where temperatures can be achieved in excess of 165°C/325°F with reflected surfaces focused on the cooking area.



An additional approach to amplify solar irradiance and concentrate it on the sorbent material could be the addition of fresnel lensing on the clear top cover of the device. The micro-lensing could focus additional energy on the surface and increase temperatures. This has precedent in a study by Li, et al who found that a device with a, "magnifying glass delivered more water within a shorter period of time than the one without glass. This result is expected, and the magnifying glass concentrated the light, led to a higher temperature of the hydrogel and thus enhanced water release" [78]

Shading the sorbent material to decrease its temperature and achieve moisture uptake mode was shown to be successful in the Xu et al experiment. An additional research project by Haechler, et al created a completely passive device to harvest water in a 24 hour continuous cycle without the use of solar panel assisted airflow. By careful design of the device shape;



> "a geometrically optimized radiation shield directs thermal radiation toward the normal incidence, i.e., where the atmospheric transmittance is highest. Simultaneously, the radiation shield guards the cooling surface from atmospheric radiation coming from the horizon." [79]

Their careful arrangement of the radiation shield allowed them to achieve a passive temperature differential sufficient to allow dewing during the day and continued functionality in the evening from passive radiant energy. This presents another interesting alternative to more active systems, however the yield is much less and the materials required for the emitter and condensation coating are exotic

[77] (Ejeian and Wang)
[78] (Li et al.)
[79] (Haechler et al.)

and expensive to fabricate. However, this experiment does support the assertion that cooling temperatures can also be managed through selective shading on a device.

Condenser Plate and Dew Point Requirements

The condensation plate serves the purpose of providing a surface within the AWH device that is at a temperature below the dew point so that water can coalesce in small droplets that would roll off into a catchment. This is at the heart of the device as it is the element that ultimately retrieves water from the air and guides it to a collection container.

The condenser plate relies on the temperature differential between the ambient air temperature and its relative humidity (saturation) and the temperature of the plate to create water droplets. The dewpoint is the temperature at which air must be cooled to reach saturation. The greater difference between the temperature and the dew point, the drier the air. The AWH device is designed to rotate the sorbent cylinder to collect moisture when it passes through the ventilated section of the PAWH and then to release it as the sorbent continues to pass into the higher temperature portion of the device receiving direct sunlight. The sorbent material turns hydrophilic (water repelling) starting at about 45°C/113°F reaching full desorption at 60°C/160°F. The device must be able to keep the water uptake portion of the PAWH below 45°C/113°F through convection airflow and shading to be most effective. Once the sorbent enters the hotter side of the chamber and desorbs its moisture the humidity level within that portion of the chamber increases encouraging nucleation of the water droplets on the colder condenser plate. Technically, “Condensation corresponds to the removal of latent heat of vapor by a cold surface when the heterogeneous nucleation occurs” [80]
Here is an example of a dew point graph showing relative humidity (RH) and ambient air temperature and what the dew point would be:

SURFACE TEMPERATURE AT WHICH CONDENSATION OCCURS

RELATIVE HUMIDITY	AMBIENT AIR TEMPERATURE										
	20°F	30°F	40°F	50°F	60°F	70°F	80°F	90°F	100°F	110°F	120°F
90%	18°F	28°F	37°F	47°F	57°F	67°F	77°F	87°F	97°F	107°F	117°F
85%	17°F	26°F	36°F	45°F	55°F	65°F	75°F	84°F	95°F	104°F	113°F
80%	16°F	25°F	34°F	44°F	54°F	63°F	73°F	82°F	93°F	102°F	110°F
75%	15°F	24°F	33°F	42°F	52°F	62°F	71°F	80°F	91°F	100°F	108°F
70%	13°F	22°F	31°F	40°F	50°F	60°F	68°F	78°F	88°F	96°F	105°F
65%	12°F	20°F	29°F	38°F	47°F	57°F	66°F	76°F	85°F	93°F	103°F
60%	11°F	19°F	27°F	36°F	45°F	55°F	64°F	73°F	83°F	92°F	101°F
55%	9°F	17°F	25°F	34°F	43°F	53°F	61°F	70°F	80°F	89°F	98°F
50%	6°F	15°F	23°F	31°F	40°F	50°F	59°F	67°F	77°F	86°F	94°F
45%	4°F	13°F	21°F	29°F	37°F	47°F	56°F	64°F	73°F	82°F	91°F
40%	1°F	11°F	18°F	26°F	35°F	43°F	52°F	61°F	69°F	78°F	87°F
35%	-2°F	8°F	16°F	23°F	31°F	40°F	48°F	57°F	65°F	74°F	83°F
30%	-6°F	4°F	13°F	20°F	28°F	36°F	44°F	52°F	61°F	69°F	77°F

The optimum moisture desorption/release temperature for SHPF is 60°C/160°F which exceeds this chart parameters however, running different scenarios through an online dewpoint calculator provided the following results:

60°C/160°F Ambient Air Temperature

@RH 20% 29°C/85°F

@RH 30% 37°C/98°F

@RH 60% 49°C/121°F

@RH 90% 58°C/136°F

This suggests that our cooling condenser plate would need to achieve a temperature of 29°C/85°F within the device at extremely low arid

[80] (Lee et al.)

environmental humidity levels such as Sub-Saharan Africa and 49°C/121°F in areas such as New Delhi India where humidity averages 55% to be able to maximize the dewing cycle.

This is a key benchmark in performance that the AWH device must achieve to function at all. Creating a device to achieve dew point at 60% RH is seems readily achievable as the temperature differential between SHPF release at 140°F and the dew point of 121°F is viable since ambient air temperature is likely to be less than 121°F. However, creating a device that will work in truly arid environments where the ambient temperature may be higher than the dewpoint could be more challenging using passive air-flow techniques.

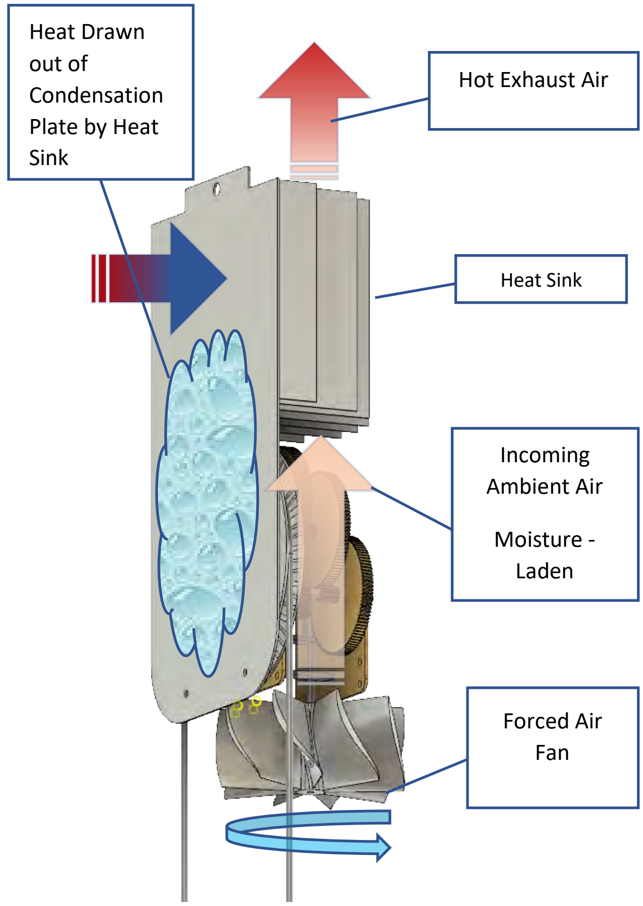
The condenser plate in the AWH device would rely on several features to achieve the task of cooling. The plate would ideally be made of a high heat transfer material such as aluminum or copper. Aluminum is a good choice because it is readily available, malleable, and recyclable. It is often used in heat sink applications to create surface area that will dissipate heat into a transfer medium such as a fluid or air. Increased surface area is often achieved through the creation of fins through a process of extruding aluminum through a die.

This aluminum extrusion acts as a heat sink where the side with the fins and high surface area acts as a passive heat exchanger transferring heat energy from lower surface area to the higher surface area where air can dissipate the heat. The choice of material, air velocity, protrusion design and surface treatment are all factors that affect the performance of the heat sink.[81]

The PAWH design relies on active airflow across the heat dissipating fins of the heatsink side of the collection plate to transfer and dissipate the heat from the backside collection plate which is exposed to the elevated air temperature within the collection chamber. An integrated fan blade design to the AWH device generates airflow across the fins. The alternate, flat side of the collection plate should be cooled to dewpoint level within the collection desorption chamber allowing condensation to coalesce on it and drip down to the collection bottle.

[81] Wikipedia

Initially my design instincts suggested that a highly hydrophobic surface on the collection plate would cause water droplets to grow and run off more readily but upon further research I found that, "uniformly hydrophilic (water 'wetting') surface has higher rates of water condensation and collection than a uniformly hydrophobic surface." [82] This article specifically recommended ideal drainage paths at 2mm wide and noted that "The drainage path does not only provide an effective water exit but also compensates the reduction of hydrophilic area by eliminating a puddle with a high thermal resistance." [83] Also a, "thin hydrophilic lane at the lower portion of the condensation substrate was shown to greatly enhance water drainage and consequently water collection rates." [84]



This suggested a design optimization change to my original collection plate to introduce 2mm extrusion channels into the flat collection side of the plate to facilitate droplet generation and easy gravity fed droplet paths to the collection bottle. I had originally thought that a beeswax hydrophobic surface coating would provide both antibacterial and better water transport qualities to the plate, however this research article suggested the opposite. Introducing 2mm grooves into an extrusion die or creating a similar vertically oriented linear brushed finish to the collection side of the plate would increase surface area for droplet nucleation and simultaneously provide better droplet transport.

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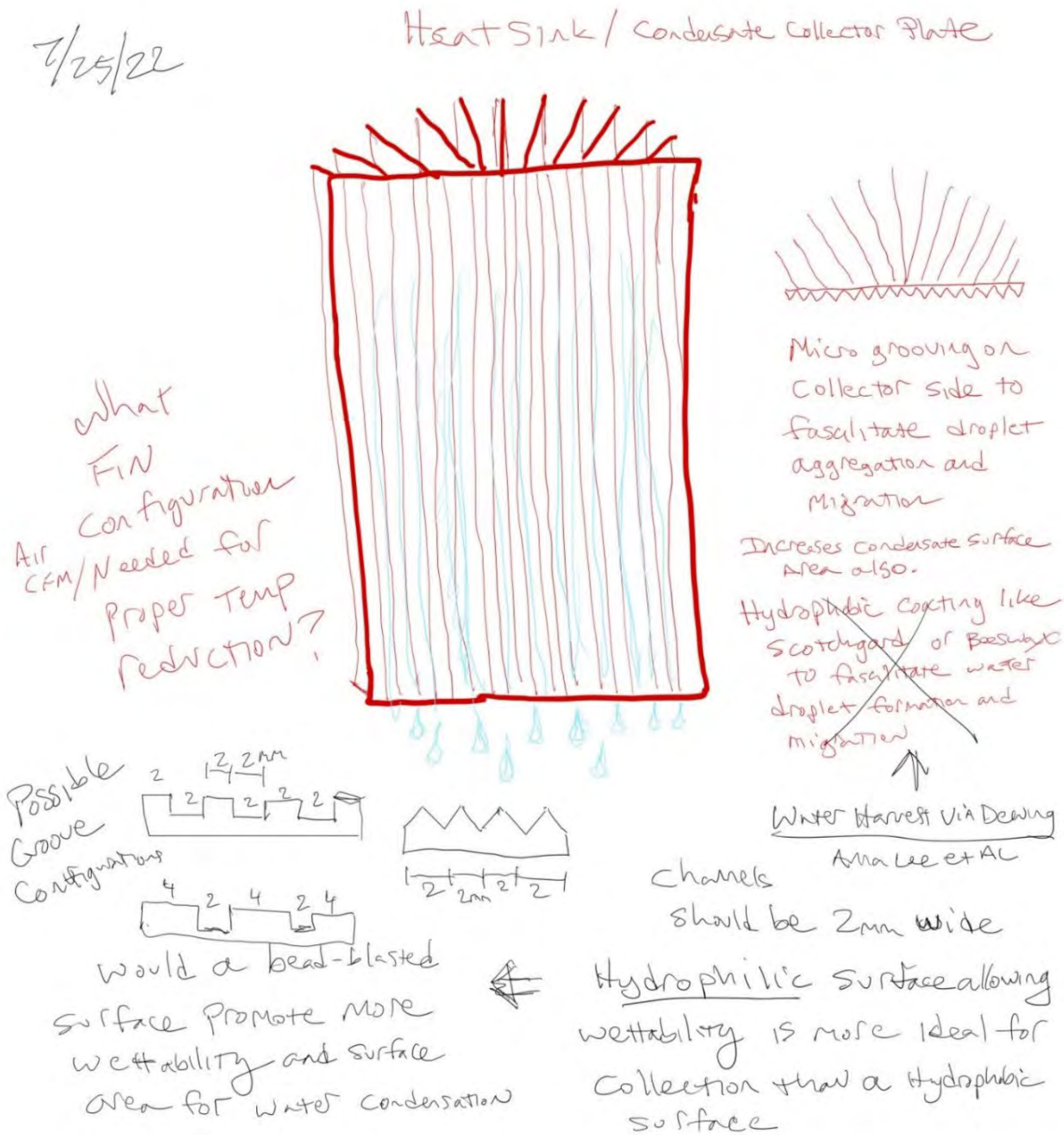
[82] (Lee et al.)
[83] (Lee et al.)
[84] (Lee et al.)

(Early ideation sketch for heatsink)

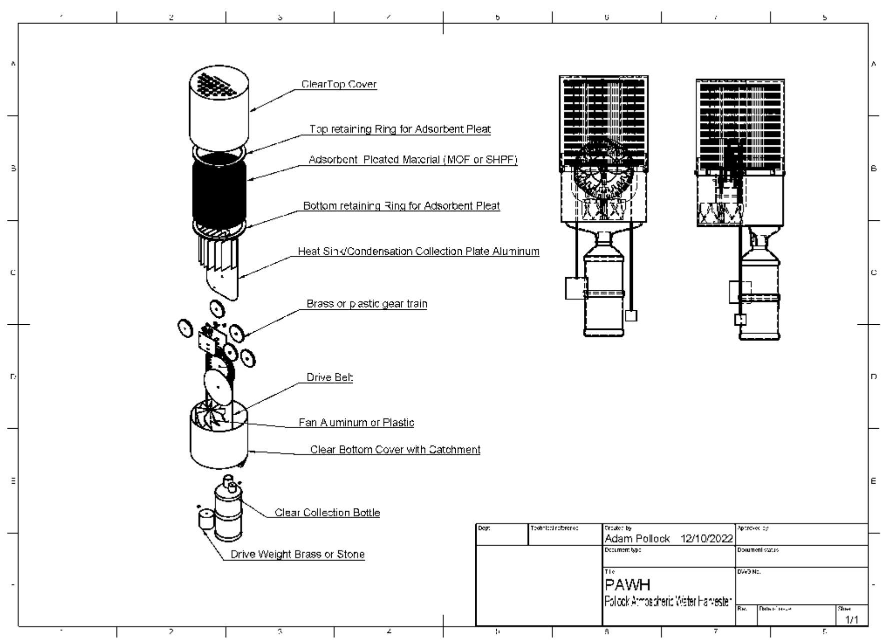


A Prototype Design Model

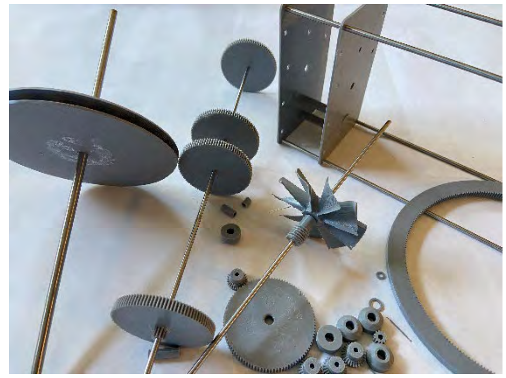
In the process of developing this project I acquired skills in Autodesk's Fusion 360 3D modelling program to take my rough sketches to a better test for fit in a compact three-dimensional space.

The PAWH design consists of a cylinder of adsorbent material surrounding the heat sink/condenser plate which splits the internal space in half to create two chambers with temperature differentials to encourage adsorption and then desorption phases. The cylinder is driven in a continuous revolution by a perimeter ring gear that is attached to the main weighted drive wheel. The drive wheel is also connected to a gear train to increase rotational speed of a connected air fan blade.

Solar Irradiance power is absorbed through one side of the cylinder facing the sun which is enclosed by a clear cylinder cover. The sun heats up that side of the chamber and the revolving adsorbent cylinder to increase the temperature 60°C/140°F where hydrogen bonds are broken (if SHPF is used) and water is released. The alternate side of the cylinder cover can be covered in reflective paint or metal to create shading. The cooler side of the cylinder contains the gearbox, fan and heatsink opposite the condensation plate. The shading and airflow on the cooler side of the cylinder should create a temperature differential keeping the cooled side of the cylinder at a temperature of less than 45°C/113°F to allow for adsorption of water. The cooling airflow through the heatsink should cool the backside of the center plate in the heated half of the cylinder creating an opportunity for dewing condensation on the plate. The water would run down the plate and into a collection bottle below.

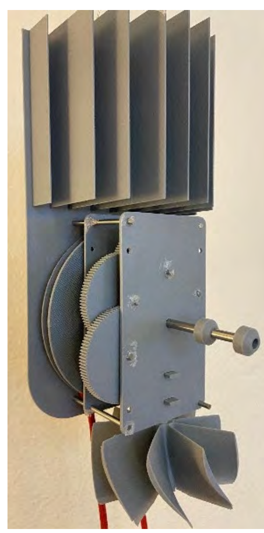


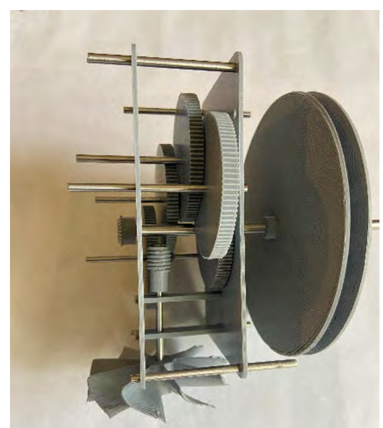
Creating a 3D model allowed me to work through component sizing and fit to see if it was possible to bring all the elements together in a configuration that could be fabricated and assembled. The model was scaled to fit the bed restrictions of the 3D printer available, and the components were printed in PLA material. The model was printed at about half the projected final scale. The components were assembled successfully to create a physical proof of concept. The device was designed to be suspended from a center hook at the top of the heat sink that protrudes through the top cover. The printed model demonstrated good balanced suspension considering the complexity of internal components. The sequence of parts assembly was also successful as well as the ease of access to the internal components for maintenance in the way that the top and bottom covers attached to the mechanical assembly.



The 3D printed model did however suffer from the limitations of printing accuracy at a small scale and did not provide proof of movement and final function. Further development would be required at full scale and may require a different printing material such as nylon which is more appropriate to printed gearing.

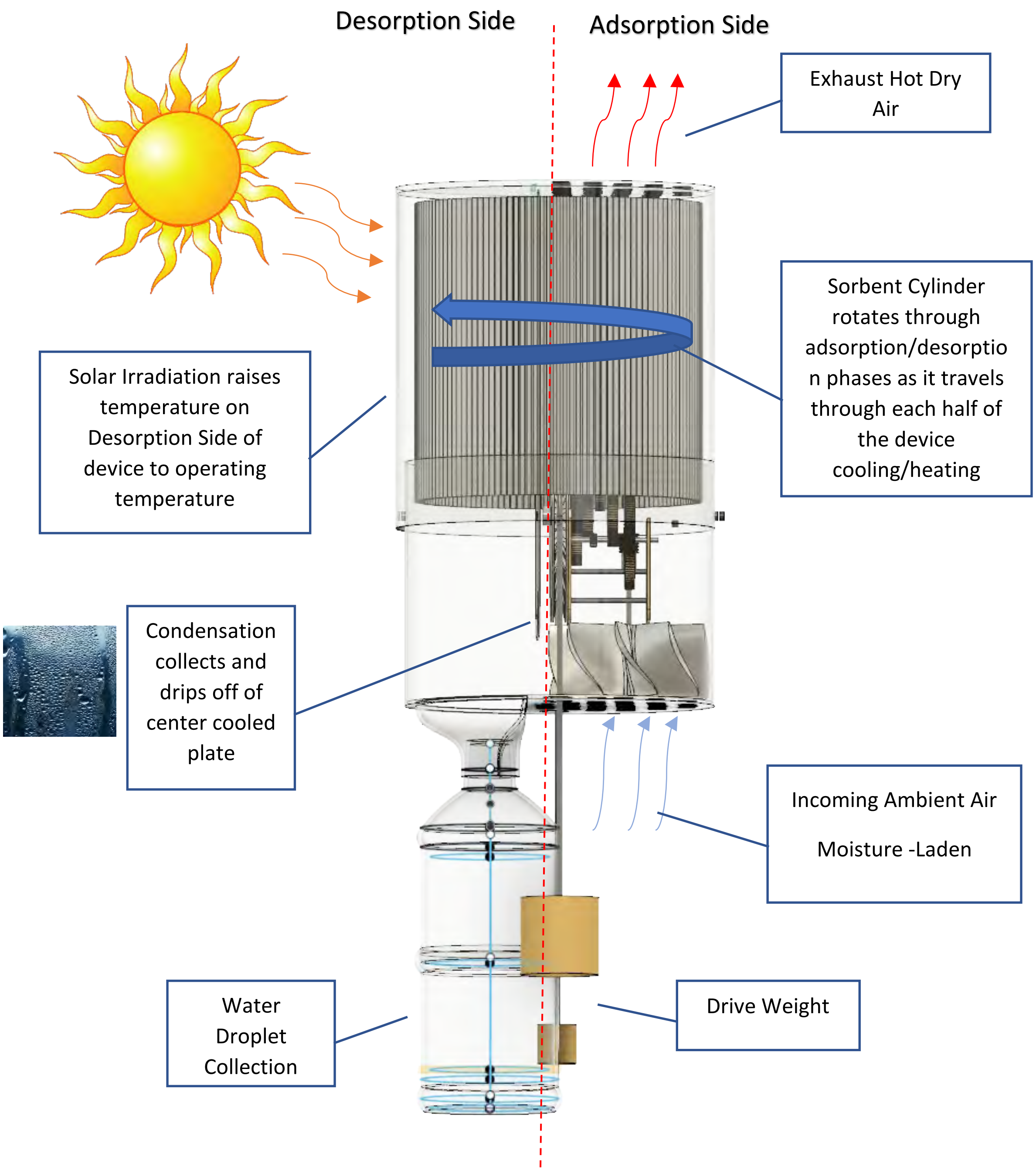
An approximation of the pleated SHPF sorbent material cylinder was also created to confirm fit.





Operation

The operation of the PAWH is meant to be intentionally simple. Lifting up the drive weight sets the device in motion. The Sorbent Cylinder rotates around the enclosure transitioning between the higher heat desorption side that is exposed ot the sun and the adsorption side that is cooled by the airflow from the fan. The goal is to provide continuous adsorption/desorption cycles exposed to sunlight to collect and release moisture that is collected in a bottle drop by drop throughout the day.



Method of Manufacturing

The ideal method of manufacturing and assembly would be local fabrication. There is some precedent here in the work by Deciwatt as they have set up a manufacturing facility in Kenya to bring the assembly of their light fixture closer to the area of need than their headquarters in the UK.[85] Their work has also provided a foundation for local business entrepreneurship. This is a promising model for assembly however the components are still made overseas and require importation. It is hard to completely free oneself entirely from the global supply chain. Without further investigation of specific markets, it is hard to ascertain whether the manufacturing infrastructure exists in these communities to produce the shell, gearing, heat sink and adsorbent material required to assemble the device design. There are some promising technologies that could help in this endeavor, however.

Photo:Reiten Cheng

3D printing as a technology is nascent but developing very rapidly. It is entirely reasonable to project out a few years and expect that the technology might support the re-use of scrap materials in the production of new items. In the maker community there are individuals experimenting with stripping out plastic PET bottles and reconfiguring the strips into filament that can be used to print new plastic items.[86] Given the quantity of waste plastic bottles throughout the world this could provide a source of local raw material to produce the gearing and housing of the AWH device. Clear PET has light transference capacities on par with glass without its fragility, is biosafe and might be an excellent material for a translucent housing to maximize Solar Irradiance to the sorbent material.

An alternative method to 3D printing the exterior shells would be blow molding PET similar to how water bottles are made however this requires manufacturing infrastructure that may not be available in local settings.

If 3D printing technology can drop in cost and become more widely distributed there is opportunity for developing countries and communities to leverage the on-demand additive printing capabilities that 3D printing can offer to produce short-run components for AWH or other local needs. If you can

[85] https://deciwatt.global/about
[86] https://www.zdnet.com/article/this-device-recycles-plastic-water-bottles-into-3d-printing-filament-and-its-open-source/

make it locally from waste material, you are one step further away from the yoke of the global supply chain.

Another interesting development was documented by a maker who is experimenting with casting molten aluminum using a small microwave oven as the kiln, plaster as the investment and 3D printed wax as the item to be cast through a traditional lost-wax casting process. [87]

The Virtual Foundry offers a different approach with a filament of metal material that can be printed into an item and then sintered into the final metal product, "using any simple, low-cost, hobby-grade kilns often used in ceramics, glass." [88]

This same company has products that can be printed and converted to glass and ceramic parts. Direct metal printers that do not require additional processing are also entering the marketplace at this time and while expensive they may come down in price and accessibility as the technology evolves.

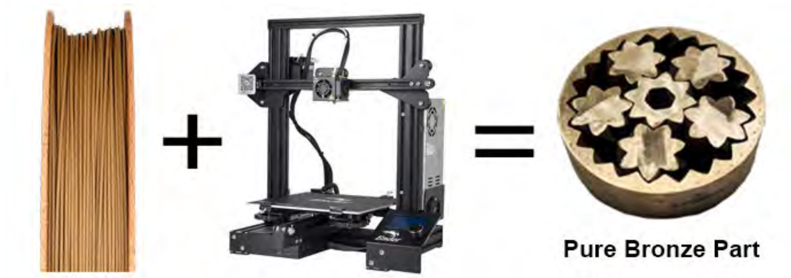


Photo: Virtual Foundry

While the Virtual Foundry filament may not be readily available in many parts of the world currently, I believe that it is reasonable to project that this type of technology will become more widespread and accessible to many parts of the world leading to a revolution in local manufacturing and entrepreneurial opportunity in the future.

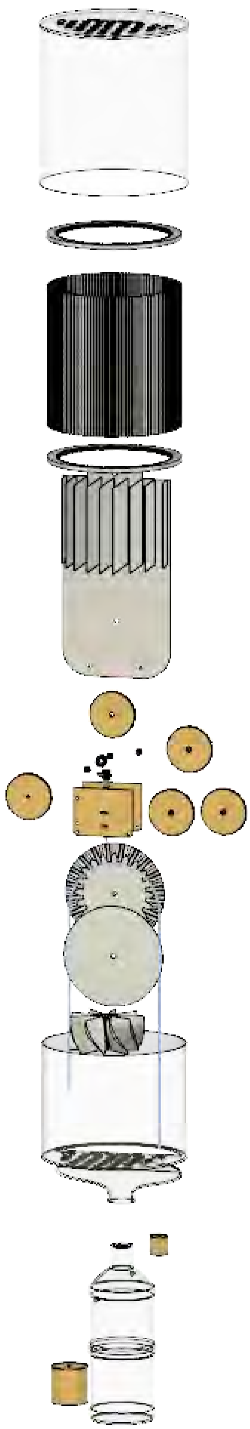
Another waste product, aluminum cans, could be converted into components for the AWH device such as the gearing and particularly for the heat sink condenser plate. Aluminum can be melted at a relatively low temperature and recast easily using a sand-casting technique that would be readily accessible anywhere in the world today. Aluminum also does not rust in a humid environment such as the inside of an AWH device.

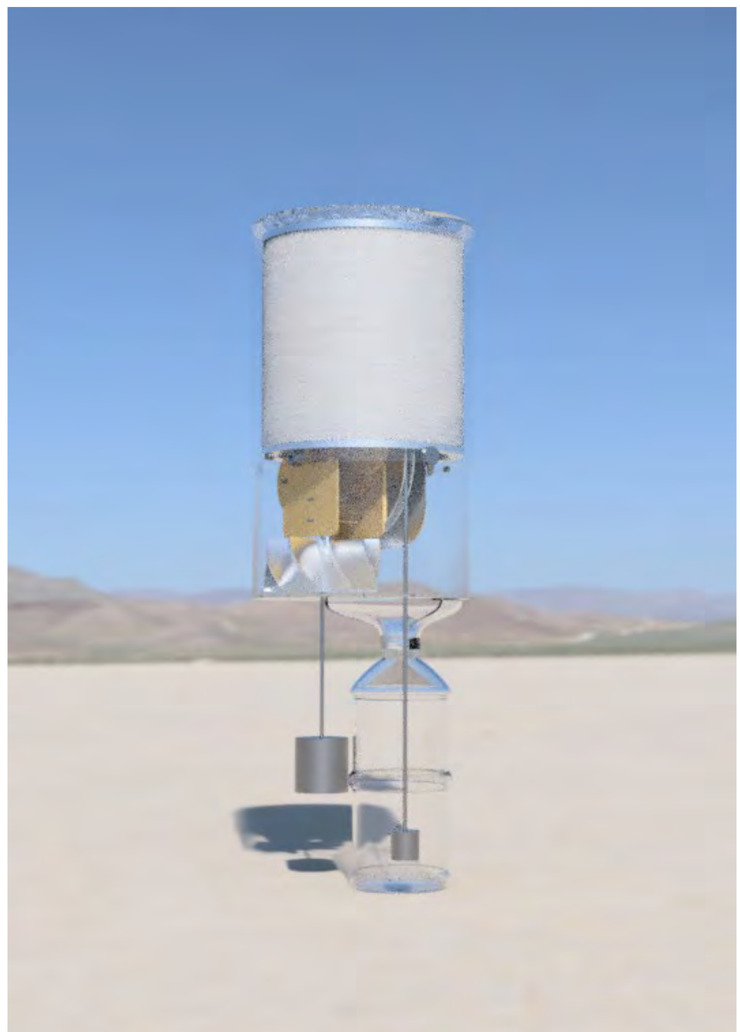
It is possible that 3D printing technology could provide the method for fabrication of the majority of the components for the PAWH device. This would leave the sorbent material as the last component that would have to be imported if it could not be created locally. The SHPF material is made from readily available ingredients and may be able to be fabricated using a standard freezer. These qualities may mean that it could be produced in less developed economies lacking the manufacturing infrastructure that other sorbent materials would require.

[87] https://www.youtube.com/watch?v=KUmnOsjCGzI
[88] https://3dprintingindustry.com/news/3d-print-metal-on-a-sample-scale-with-the-virtual-foundrys-filamet-evaluation-kit-215443/

Production Costs

The actual production costs for the PAWH are admittedly unknown at this writing. More development and engineering would need to occur before a production method and material costs could be reasonably calculated. Higher cost would drive the device towards markets with higher income until improvements and efficiencies of production can be achieved.





Concerns and Areas of Future Development

Water Safety and AWH

One of the inherent advantages of AWH for drinking water is its inherent purity. If the device and collection bottles are kept clean then there is no potential for the introduction of contaminants you might encounter in ground water such as feces, pesticide, or other contamination. AWH water is by its nature and process distilled. This does, however, mean that it is lacking in the minerals that give water its good taste leading to a 'flat' quality. These minerals, normally supplied in groundwater would have to be acquired through other dietary means.[89] Drinking distilled water, while lacking in satisfaction is not a health risk.

Photo: https://www.cdc.gov/healthywater/global/household-water-treatment/solardisinfection.html

While the water pulled from the air is inherently pure and distilled, there is the potential if MOF materials are used or adsorbent salts (LiCi) that there could be leaching of the material into the water that should be studied as a potential health risk. But initial studies seem to indicate that this will not present a problem.

In addition there is the potential for contamination in the device itself as the, "warm and humid environment of the device provides suitable conditions for growth of microorganisms and algae, so in long term use a solution should be considered to prevent it."[90] One potential solution to water treatment is the SODIS method promoted by the Center for Disease Control (CDC).[91] SODIS is a simple and effective method for sterilizing drinking water by simply leaving clear plastic bottles exposed to sunlight for several hours using passive solar energy to purify the water. This method is proven to be effective but is dependent upon clear sunny weather as the sterilization period goes from a few hours to potentially days in cloudy, low solar-flux days. However, as the PAWH device is primarily driven by solar energy it is compatible with this process of sterilization and days of water harvesting would coincide with days of high potential for sterilization. If a clear water bottle is used for collection of the PAWH produced water, then the process would already be initiated while it was filling up.

It is important to note here that the water collected is only as clean as the container it is kept in. If pathogens are not cleaned from a container using bleach or some other method than there is the risk of continued contamination of the stored water even if the initial source is clean.

Sorbent materials

The sorbent materials considered, MOFs and SHPFs both have constraints that make them exotic and difficult to obtain in many parts of the world. MOFs are new and expensive to produce in large

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[89] Nutrients in Drinking Water, WHO file:///C:/Users/APollock.FireFarm/Downloads/9241593989_eng.pdf
[90] (Ejeian and Wang)
[91] https://www.cdc.gov/healthywater/global/household-water-treatment/solardisinfection.html

quantities currently. While there is potential that BASF Corporation in cooperation with researchers at University of California at Berkeley may be developing methods of mass, cost-effective new production techniques this would still be relegated to production in developed economies with appropriate capital-intensive machinery and techniques. These materials would still be subject to supply chain distribution challenges to areas of local need.

The alternate SHPF technology does have the advantage of being able to be produced using more readily available materials, however at this time the researchers required the processing of the material through a freeze-drying process which involves extracting moisture from the material under vacuum conditions. It may be possible to produce similar effects through several week-long exposure to standard freezing conditions but that may still be outside the scope of local fabrication in areas of need.

It is uncertain whether either of these materials could be produced in continuous roll type manufacturing process as opposed to less-efficient batch production. The question of mass production and cost efficiencies related to the key ingredient of the AWH device is yet to be resolved.

Alternate Designs

While I have intentionally placed the design constraint to power my device using gravity and solar irradiance alone, it is reasonable and perhaps even more effective to consider a design that uses solar energy converted to electricity to power motors for the movements required and potentially to augment cooling through the Peltier effect (whereby heat is emitted or absorbed when an electric current passes across a junction between two materials). My design approach avoided the use of solar panel driven motors to minimize technical complexity and dependency on a global supply chain and try to maximize local production and repair by using more readily available technology such as geared, gravity-driven mechanisms.

Fouling

The complex gearing mechanism of my design may be subject to environmental fouling through dust and debris that would eventually enter the device. This may require regular maintenance and cleaning to keep it in working order. There is also the question of how much wear there will be on the gearing components over time and their longevity. Filtration for incoming and outgoing airflow would assist with this problem.

Longevity of the Sorbent Materials

While the researchers of the SHPF material achieved several hundred cycles of adsorption/desorption without a decrease in productive output, it is unknown what the long-term work-cycle potential of these materials may be or their susceptibility to clogging or fouling through environmental airborne contaminants.

Gearing Mechanism

Can the gearbox proposed for the PAWH provide the torque required to rotate the sorption cylinder while simultaneously drive the fan blade at a rate that will provide the proper wind resistance to the gravity weight? What will the wear factor be on the gears and particularly the fan spindle travelling at high velocities? How will this affect the longevity and maintenance schedule of the mechanisms?

Adsorbent Physical Properties

Guo et al, specified that 2kg of SHPF could produce 2 liters of water per day. The translation of weight to resultant thickness and surface area of SHPF has not been explored to know if or how large a pleated filter would be required and if the expectations for compactness represented in this design can be achieved. If the volume is too large to accommodate the proposed design either the design would need to be revisited in its entirety or it would have to wait for new efficiencies as materials are further developed.

The integrity of the SHPF or MOF material to hold together and allow pleating or whether it would need to be supported by a mesh or other membrane that could be shaped into the desired filter form is yet to be determined. This would require access to these materials directly to experiment with potential form factors.

Adequate Solar Irradiance

While there are prototype research devices that have demonstrated that AWH is possible using Solar Irradiance alone, further temperature testing of the proposed device design would be required to confirm temperatures for desorption could be achieved.

Adequate Cooling for Dewing

Similarly, the question of adequate airflow to achieve cooling of the condensation/collection plate to dew point levels would need to be engineered to the volume of the chamber, the design of the fan blades, and gearing for required revolutions. Can the cooling effect be contained to one half of the device while the other half achieves desorption temperatures?

Production Costs

Can the design be produced either locally or imported at a cost that is appropriate to the economic capacity of the area of need and can it thereby deliver water at an amortized cost of less than $0.01/gallon.

Adoption

If a device is developed that delivers on all the challenges and goals, there is still the question of adoptability. The purchase, fabrication, distribution and use of such a device will always be subject to cultural mores, regional politics and psychology of the individual user as it pertains to actual adoption of the technology.

Maintenance

Is it possible to maintain the device using readily available local materials and craftsmanship or will it depend on materials and components unavailable to users in areas of need that are poorly served by the global supply chain or because of economic disparity?

Summary

While the PAWH device does not provide answers to all potential questions of viability it introduces a new form-factor into the discussion of atmospheric water harvesting devices. The principals behind its operation have precedence to indicate that they have a likelihood of success with continued prototyping and development. The presence of working research devices and the interest in the field by governmental entities indicate that this is an area of research that will expand and grow. Like so many nascent concepts and technologies the impediments to immediate satisfaction are significant, however the promise is clearly within reach with continued research and development. If atmospheric water harvesting can be achieved in a portable, inexpensive, and well-distributed device it could have a profound impact on the health and well-being of over half the world’s population and is worth pursuing.

References Cited:

Ejeian, Mojtaba, and Ruzhu Wang. "Adsorption-Based Atmospheric Water Harvesting." *Joule* (2021). Print.

Guo, Jining, et al. "Hydrogen Production from the Air." *Nature Communications* 13.1 (2022): 5046. Print.

Guo, Youhong, et al. "Scalable Super Hygroscopic Polymer Films for Sustainable Moisture Harvesting in Arid Environments." *Nature Communications* 13.1 (2022): 2761. Print.

Haechler, Iwan, et al. "Exploiting Radiative Cooling for Uninterrupted 24-Hour Water Harvesting from the Atmosphere." *Science Advances* 7.26: eabf3978. Print.

Lee, Anna, et al. "Water Harvest Via Dewing." *Langmuir* 28.27 (2012): 10183-91. Print.

Li, Renyuan, et al. "Hybrid Hydrogel with High Water Vapor Harvesting Capacity for Deployable Solar-Driven Atmospheric Water Generator." *Environmental Science & Technology* 52.19 (2018): 11367-77. Print.

Lord, Jackson, et al. "Global Potential for Harvesting Drinking Water from Air Using Solar Energy." *Nature* 598.7882 (2021): 611-17. Print.

Mekonnen, Mesfin M., and Arjen Y. Hoekstra. "Four Billion People Facing Severe Water Scarcity." *Science Advances* 2.2: e1500323. Print.

Patowary, Kaushik. "How Bermuda's Chronic Water Shortage Shaped the Islands' Iconic White Roof." 2018. Web.

Rodell, M., et al. "Emerging Trends in Global Freshwater Availability." *Nature* 557.7707 (2018): 651-59. Print.

Rubin, Alissa. "Cloud Wars: Mideast Rivalries Rise Along a New Front." 2022. Web.

Xu, Jiaxing, et al. "Ultrahigh Solar-Driven Atmospheric Water Production Enabled by Scalable Rapid-Cycling Water Harvester with Vertically Aligned Nanocomposite Sorbent." *Energy & Environmental Science* 14.11 (2021): 5979-94. Print.

Zhao, Fei, et al. "Materials for Solar-Powered Water Evaporation." *Nature Reviews Materials* 5.5 (2020): 388-401. Print.

Zhou, Xingyi, et al. "Atmospheric Water Harvesting: A Review of Material and Structural Designs." *ACS Materials Lett.* XXXX (2020): XXX-XXX. Print.

Additional References

Fathieh, Farhad, et al. "Practical Water Production from Desert Air." *Science Advances* 4.6: eaat3198. Print.

Guo, Youhong, et al. "Molecular Engineering of Hydrogels for Rapid Water Disinfection and Sustainable Solar Vapor Generation." *Advanced Materials* 33.35 (2021): 2102994. Print.

Hanikel, Nikita, et al. "Rapid Cycling and Exceptional Yield in a Metal-Organic Framework Water Harvester." *ACS Central Science* 5.10 (2019): 1699-706. Print.

Lasage, Ralph, and Peter H. Verburg. "Evaluation of Small Scale Water Harvesting Techniques for Semi-Arid Environments." *Journal of Arid Environments* 118 (2015): 48-57. Print.

Liu, Xiaoyi, Daniel Beysens, and Tarik Bourouina. "Water Harvesting from Air: Current Passive Approaches and Outlook." *ACS Materials Letters* 4.5 (2022): 1003-24. Print.

Lu, Hengyi, et al. "Materials Engineering for Atmospheric Water Harvesting: Progress and Perspectives." *Advanced Materials* 34.12 (2022): 2110079. Print.

Powers, Julie E., et al. "Design, Performance, and Demand for a Novel in-Line Chlorine Doser to Increase Safe Water Access." *npj Clean Water* 4.1 (2021): 4. Print.

Tu, Rang, and Yunho Hwang. "Reviews of Atmospheric Water Harvesting Technologies." *Energy* 201 (2020): 117630. Print.

Xu, W., and O. M. Yaghi. "Metal-Organic Frameworks for Water Harvesting from Air, Anywhere, Anytime." *ACS Cent Sci* 6.8 (2020): 1348-54. Print.

Qtaishat, Mohammed Rasool, et al. "Desalination at Ambient Temperature and Pressure by a Novel Class of Biporous Anisotropic Membrane." *Scientific Reports* 12.1 (2022): 13564. Print

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