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MÁSTER UNIVERSITARIO EN INGENIERÍA INDUSTRIAL

Master Thesis

Water obtention from salted water using greenhouse effect and photovoltaic and thermal solar technology.

Author: Álvaro Morate Solís

Director: Alberto Mascareñas Brito

Madrid

August 2021

Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título .”Water obtention from salted water using greenhouse effect and photovoltaic and termal solar technology”

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Fdo.: Álvaro Morate Solís   Fecha: 15/ 08/ 2022

Autorizada la entrega del proyecto

EL DIRECTOR DEL PROYECTO

Fdo.: Alberto Mascareñas Brito Fecha: 15 / 08 / 2022

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DESALINIZACIÓN DE AGUA DE MAR MEDIANTE EVAPORACIÓN POR "EFECTO INVERNADERO"

Autor: Morate Solís, Álvaro.

Director: Mascareñas Brito, Alberto.

Entidad colaboradora: Fundación de Ingenieros ICAI, Manos Unidas.

El objetivo del proyecto es desarrollar una solución sostenible para la obtención de agua destilada a partir de agua salada mediante sistemas de invernadero para abastecer a una comunidad de aproximadamente 300 personas. El proyecto parte de un ejemplo de caso base en Mozambique, pero pretende ser una guía para el desarrollo de un sistema de este tipo en cualquier otro lugar donde sea necesario el estudio. Los parámetros más relevantes son el bajo coste tanto en la inversión inicial como en el mantenimiento, debe aprovechar el efecto invernadero, y su operación debe ser sencilla.

El proyecto ha contado con la colaboración de la fundación de ingenieros ICAI y con la ONG Manos Unidas gracias a su aportación de conocimientos sociales y técnicos en la materia.

El proyecto comienza con una introducción y descripción del motivo del desarrollo del sistema, seguido de la proyección del estado del arte incluyendo soluciones similares que pueden apoyar el diseño del sistema. Posteriormente se incluye el diseño de las soluciones encontradas, centrándose en las características encontradas en la región de Mozambique, y finalmente se definirán los cálculos y conclusiones del proyecto.

Palabras clave - Destilador solar, desalinización, efecto invernadero, modelo matemático, modelo físico

1. Introducción

Existen diferentes tecnologías en el mercado que permiten producir agua dulce a partir de una fuente salobre. Las más comunes son la ósmosis inversa y la destilación flash multiefecto. Aunque estas soluciones son eficaces y tienen un gran rendimiento, requieren energía externa para procesar el agua, en el caso de la ósmosis inversa para aumentar la presión, y en el caso de la destilación, el combustible quemado para aumentar la temperatura de la caldera. Estos aportes de energía externa pueden ser escasos en lugares remotos, donde se centra el objetivo de este proyecto. Para aprovechar la irradiación solar y el efecto invernadero la solución a estudiar es el destilador solar.

Un destilador solar es un sistema de destilación fuera de la red que transforma el agua salada en agua destilada con la ayuda de la irradiación solar. El destilador solar estándar consta de tres partes: la piscina con agua salobre/agua salada, la cubierta, generalmente de vidrio o plástico transparente (metacrilato) y el compartimento de salida donde se recoge el agua dulce. El proceso es el siguiente:

Primero, el agua salada se calienta con la irradiación solar hasta que alcanza la temperatura de ebullición, que depende de la presión y la humedad dentro de la estructura.

En segundo lugar, una vez que el agua alcanza la temperatura de ebullición, el vapor sube a la parte superior del alambique hasta alcanzar la tapa de cristal. Una vez que la humedad del interior del vidrio alcanza la saturación, comienzan a formarse gotas de agua, y debido a que la superficie está inclinada y a la tensión superficial, estas gotas bajan por la tapa hasta caer al final de la misma.

Finalmente, las gotas aumentan de tamaño y caen, el agua se recoge y se almacena en un depósito. La figura siguiente ofrece una representación de un destilador solar estándar.

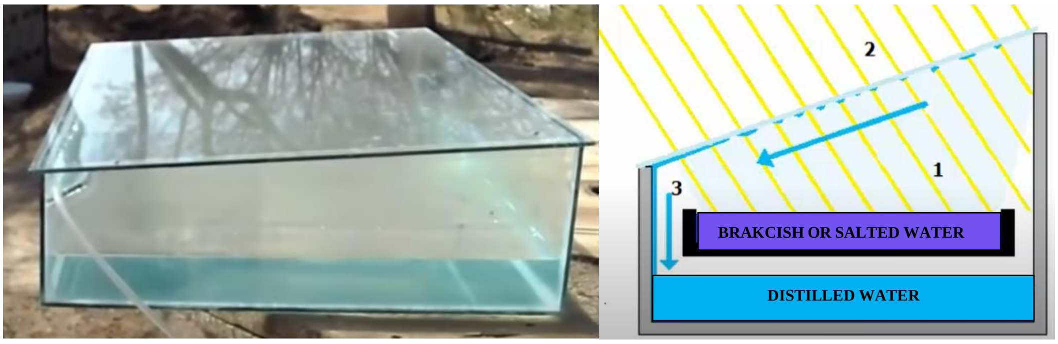


Figura 1 Destilador solar

2. Methodología

El proyecto se divide en dos estudios principales: el estudio matemático y el estudio experimental. El análisis matemático proporciona una representación de las temperaturas dentro del sistema y del agua producida dada la temperatura ambiente, la irradiación solar, la velocidad del viento y el volumen o flujo de agua salada.

Las ecuaciones que determinan la producción de agua son el balance térmico en la cubierta de vidrio (1), el balance térmico en el recipiente de agua salada (2) y la obtención de agua dulce por condensación (3) proporcionadas por K Abdenacer [1].

El balance térmico de la cubierta en la parte superior se define como:

$$\alpha_g G = h_{c,g-aext}(T_g - T_{aext}) + h_{r,g-aext}(T_g - T_{aext}) + h_{ew}(T_g - T_w)$$
$$+h_{r,g-w}(T_g - T_w) + h_{c,g-w}(T_g - T_w)$$

(1)

El equilibrio térmico entre el agua y el entorno dentro del destilador:

$$\alpha_w \tau_w G - 2\dot{m}_w c_w (T_w - T_{wi}) = h_{e,w}(T_w - T_g) + h_{r,w-g}(T_w - T_g) + h_{c,w-g}(T_w - T_g)$$

(2)

Considerando que la irradiación se mantiene constante durante periodos de una hora, la producción de agua puede describirse como:

$$m_h = 16.273\ 10^{-3}\ h_{c;w-g}\ \frac{(p_w - p_g)}{\lambda}\ 3600$$

(3)

El modelo físico consiste en una estructura de 0,5 x 1 x 0,2 hecha de madera, PVC y sellador adhesivo como materiales principales. La construcción del prototipo se describe con más detalle en el Anexo 1. Previo a la construcción del destilador, se diseñó un modelo 3D para visualizar la solución.

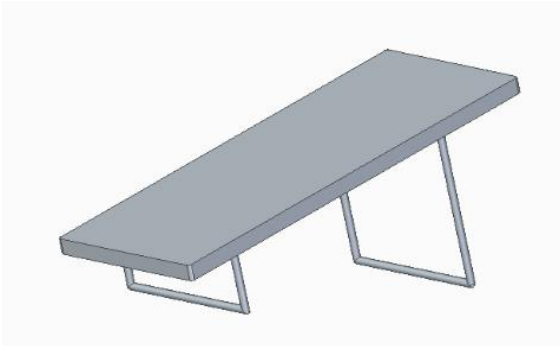


Figura 2 Diseño 3D en SolidEdge

Figura 3 Prototipo

3. Resultados

Para el modelo matemático, se han recogido los datos climáticos horarios de Solcast a partir de 2021 en Mozambique. Se han estudiado cuatro casos atendiendo a las condiciones climáticas: escenario más favorable el escenario medio, escenario más desfavorable y el escenario más favorable con aporte calorífico adicional de 300W. A continuación, se presentan los resultados del mes de noviembre (mes de gran aporte solar en Mozambique).

Escenario más favorable

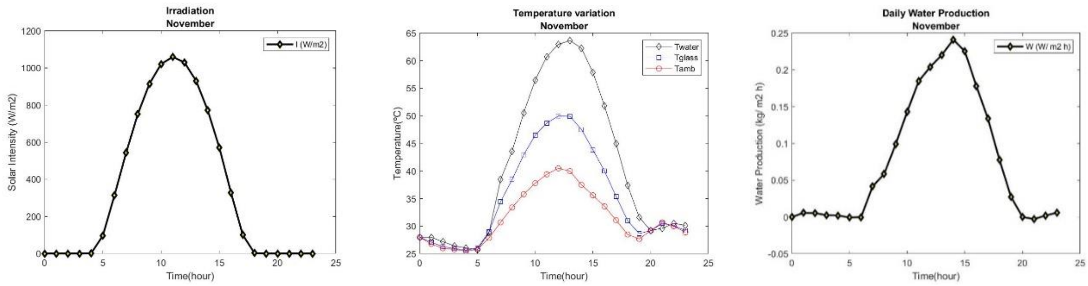


Figura 4 Escenario más favorable

Escenario medio

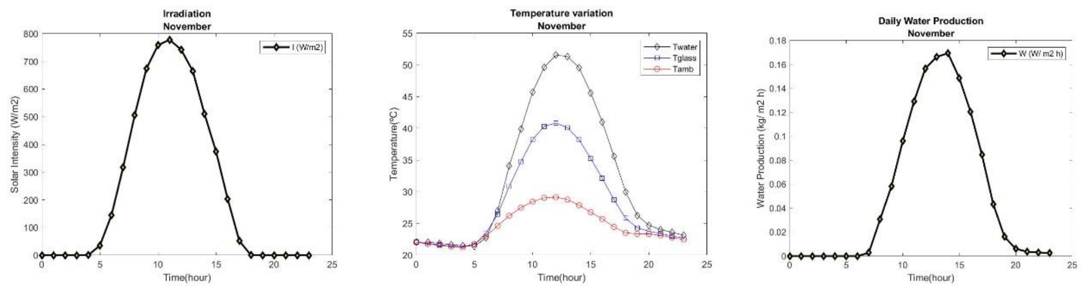


Figura 5 Escenario medio

Escenario mas desfavorable

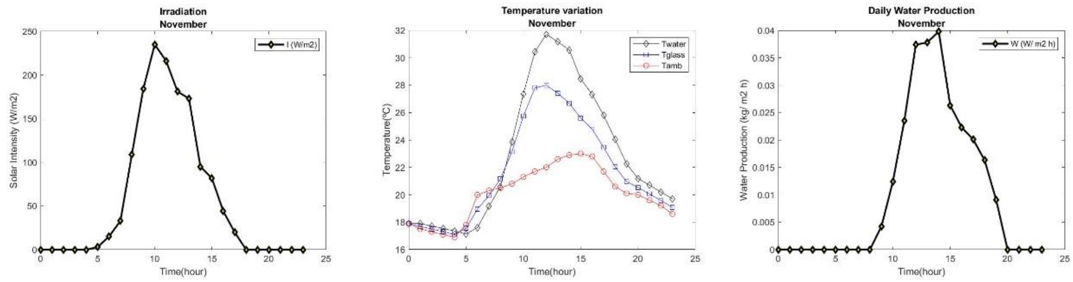


Figura 6 Escenario más desfavorable

Escenario más favorable con aporte calorífico de 300 W

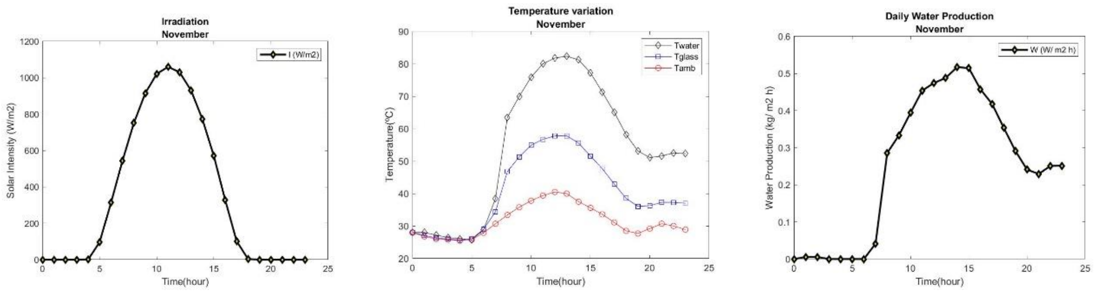


Figura 7 Escenario más favorable con calefacción adicional

Por otro lado, los resultados del prototipo no son tan consistentes debido a problemas técnicos con el sellador del colector que hizo que recogiera menos de 200 ml por día. La temperatura en el interior del destilador solar llegó a alcanzar los 70 ºC.

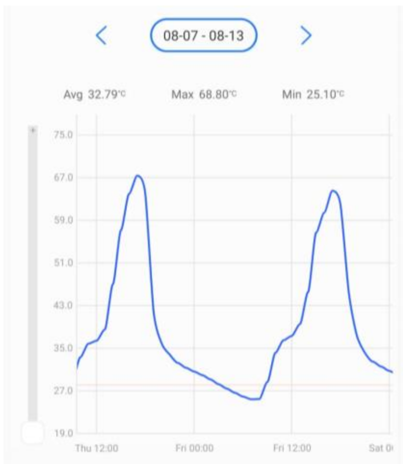


Figura 8 Datos del sensor de temperatura

4. Conclusiones

Este sistema de destilación solar en particular tiene múltiples beneficios como la relevancia de la modularidad que permite aumentar el número de destiladores si es necesario y facilita la operación y mantenimiento, ya que si un solo panel se avería sólo hay que sustituirlo mientras los demás siguen produciendo agua para la comunidad.

A partir del modelo matemático y con los datos de temperatura y radiación de la región, se obtiene una media de 1,3 -1,5 L/m2 por día de agua destilada, lo que reduce considerablemente la viabilidad del sistema sin el aporte energético externo de la resistencia con paneles solares. Fcubed, empresa que fabrica e instala alambiques solares, afirma que la producción de agua puede alcanzar hasta 5 litros por metro cuadrado utilizando los materiales adecuados, pero la configuración del prototipo no llega a ser una solución viable para el problema planteado. El siguiente gráfico representa la consolidación de la producción diaria de agua según el caso de estudio: mejor, media y peor.

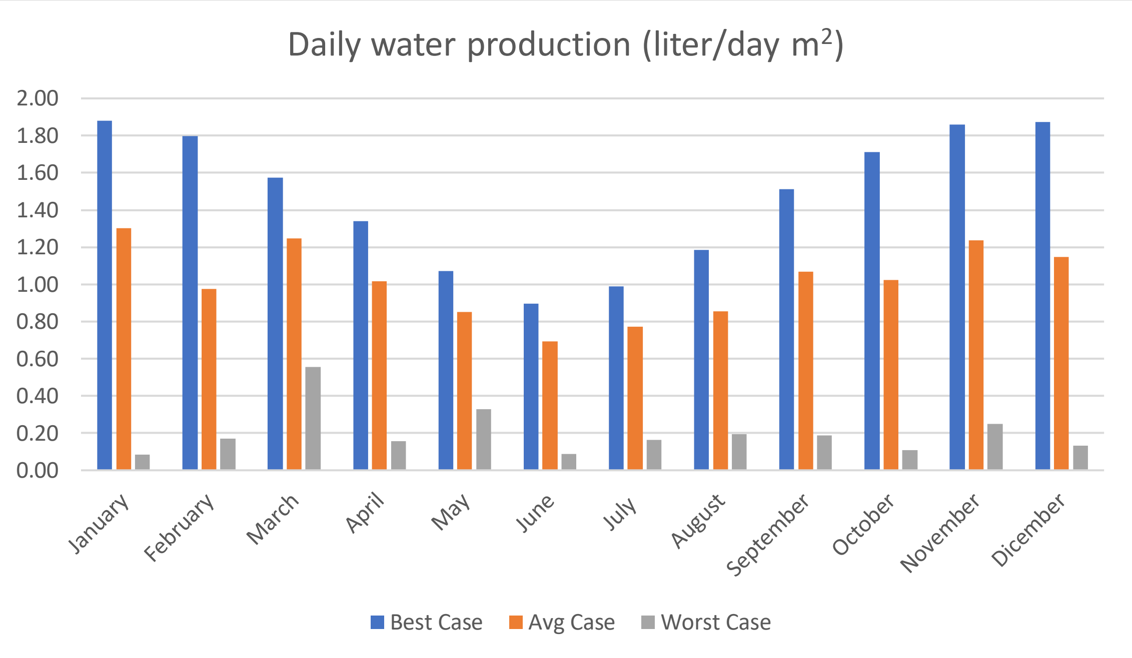


Figura 9 Producción diaria de agua

La desalinización no es la solución a la escasez de agua, pero en casos particulares, como en las zonas rurales o después de catástrofes naturales, podría servir de ayuda hasta que se ponga en marcha una solución más adecuada y escalable.

5. Bibliografía

[1] Abdennacer, Kaabi and Trad Rachid. *Study of the optical performance of a solar still with a double slope and greenhouse effect*. Constantine, 2005.

WATER OBTENTION FROM SALTED WATER USING GREENHOUSE EFFECT

Author: Morate Solís, Álvaro.

Director: Mascareñas Brito, Alberto.

Collaborative Entity: Fundación de Ingenieros ICAI, Manos Unidas.

The project objective is to develop a sustainable solution for the obtention of drinking water from salt water using greenhouse systems to supply a community of approximately 300 people. The project starts from a base case example in Mozambique but is intended as a guide for the development of such a system in any other location where the study might be needed. The most relevant parameters are low cost in both initial investment as well as maintenance, must use the green house effect, and easy to operate.

The project has been supported by the collaboration with the ICAI engineering foundation and with the NGO Manos Unidas thanks to their contribution of social and technical knowledge in the field.

The project begins with an introduction and description of the reason for the development of the system, followed by the projection of the state of the art including similar solutions that can support the design of the system. Later on, the design of the solutions found will be included, focusing on the characteristics found in the Mozambique region, and finally, the calculations and conclusions of the project will be defined.

Key words – Solar still, desalination, greenhouse effect, mathematical model, physical model

6. Introduction

Different technologies in the market enable the production of fresh water from a brackish source. The most common are Reverse Osmosis and Multi Effect Flash Distillation. While these solutions are effective and have a great performance they require external energy to process the water in the case of Reverse Osmosis to increase the pressure and in the case of standard distillation, the burnt fuel increases the temperature of the boiler. These external energy contributions can be scarce in remote locations where the aim of this project is focused on. To take advantage of the solar irradiation and greenhouse effect the solution to study is the solar still.

A solar still is an off-the-grid distillation system that transforms distilled water from brackish water with the help of solar irradiance. The standard solar still has three parts: the pool with brackish water/ salted water the cover usually glass or transparent plastic (methacrylate) and the output compartment where the fresh water is collected. The process is as follows:

First, the salted water is heated with solar irradiation until it reaches boiling temperature which depends on the pressure and humidity inside the structure.

Second, once the water reaches the boiling temperature the vapor rises to the top of the still until it reaches the glass cover. Once the humidity of the inside of the glass reaches saturation, water drops begin to form, and due to the tilted surface and surface tension, these drops run down the cover until they drop at the end of the cover.

Finally, the drops increase in size and fall, the water is collected and stored in a deposit. The figure below provides a representation of a standard solar still.

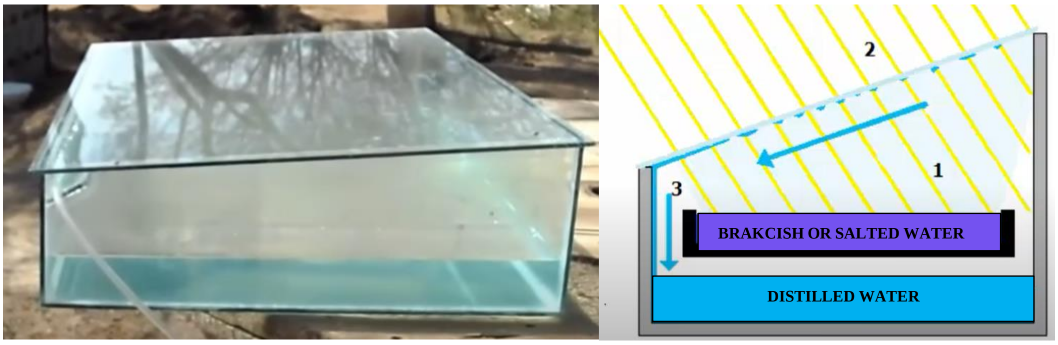


Figure 1 Experimental one sided still

7. Methodology

The project is divided into two main studies the mathematical study and the experimental study. The mathematical analysis provides a representation of the temperatures inside the system and the water produced given the ambient temperature, solar irradiation, wind speed, and salted water volume or flux.

The equations that determine the water output are the heat balance in the glass cover (1), the heat balance in the salter water container (2), and the fresh water obtention from condensation(3) provided by K Abdenacer [1]

The heat balance of the cover on the top is defined as:

$$\alpha_g G = h_{c,g-aext}\left(T_g - T_{aext}\right) + h_{r,g-aext}\left(T_g - T_{aext}\right) + h_{ew}\left(T_g - T_w\right) + h_{r,g-w}\left(T_g - T_w\right) + h_{c,g-w}\left(T_g - T_w\right) \quad (4)$$

The heat balance between the water and the environment inside the still:

$$\alpha_w \tau_w G - 2\dot{m}_w c_w (T_w - T_{wi}) = h_{e,w}\left(T_w - T_g\right) + h_{r,w-g}\left(T_w - T_g\right) + h_{c,w-g}\left(T_w - T_g\right) \quad (5)$$

Considering that the irradiation remains constant over one hour periods the water production can be described as:

$$m_h = 16.273\ 10^{-3}\ h_{c;w-g}\ \frac{\left(p_w - p_g\right)}{\lambda}\ 3600 \quad (6)$$

The physical model consisted of a 0.5 x 1 x 0.2 structure made of wood, PVC, and adhesive sealant. The construction of the prototype is described in more detail in Annex 1. Before the construction of the still, a 3D model was designed to visualize the solution.

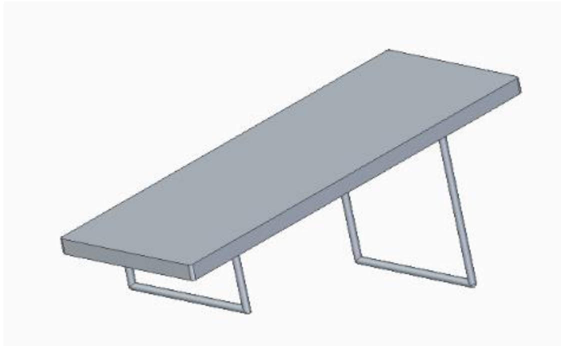


Figure 2 Solid Edge Still design

Figure 3 Prototype

8. Results

For the mathematical model, the hourly climate data was gathered from Solcast as of 2021 in Mozambique. Four cases have been studied attending to weather conditions: best case scenario, average case scenario, worst case scenario, and best case scenario with additional heating support.

Best case scenario

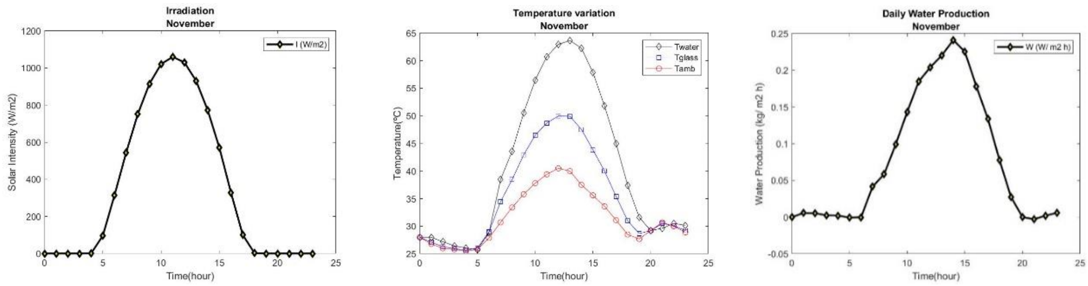


Figure 4 Best case results

Average case scenario

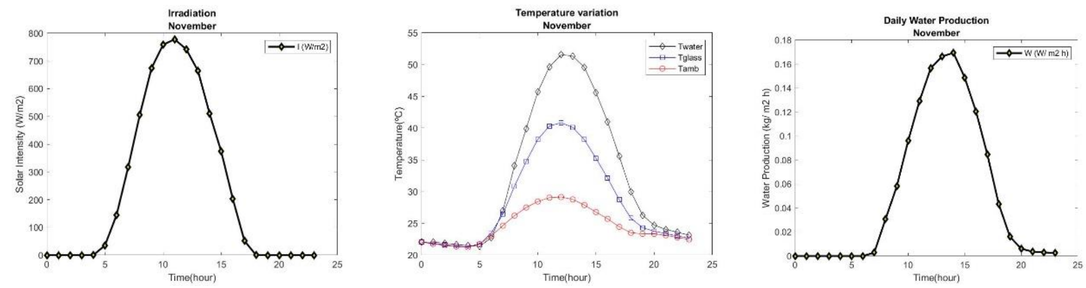


Figure 5 Average case results

Worst case scenario

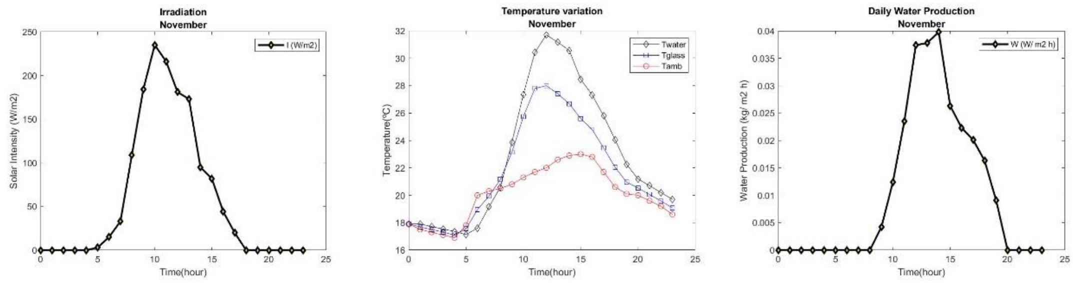


Figure 6 Worst-case results

Best case scenario with additional 300W resistance

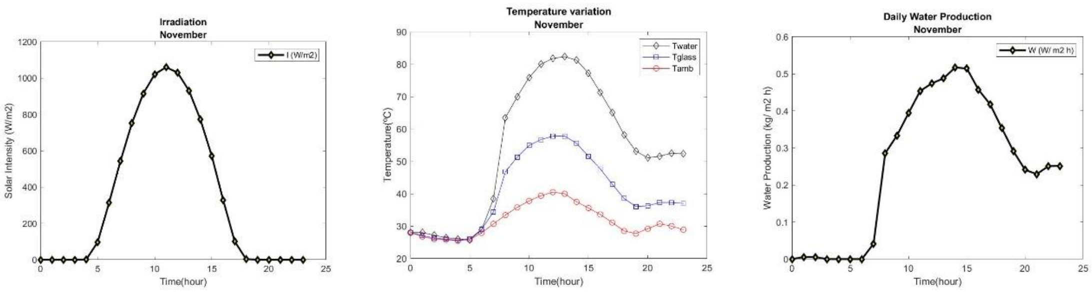


Figure 7 Best case with additional 300W

On the other hand, the results from the prototype are not as consistent due to technical problems with the collector sealant which made it collect less than 200 ml per day. The temperature inside the solar still reached up to 70 ºC.

Figure 8 Daily Sensor Temperature

9. Conclusions

This particular solar still system has multiple benefits such as the relevance of the modularity which allows increasing the number of stills if needed and it makes operation and management, easier as if only one panel is faulty only one panel must be replaced while the others remain to produce water for the community.

From the mathematical model and with the temperature and radiation data of the region, an average of 1.3 -1.5 L/m2 per day of distilled water is obtained, which considerably reduces the viability of the system without the external energy contribution of resistance with solar panels.

Fcubed, a company that manufactures and installs solar stills states that water production can reach up to 5 liters per meter squared using the right materials but the configuration of the prototype does not come to a viable solution for the problem stated. The graph below represents the consolidation of the daily water production per day depending on the case study: best, average, and worse.

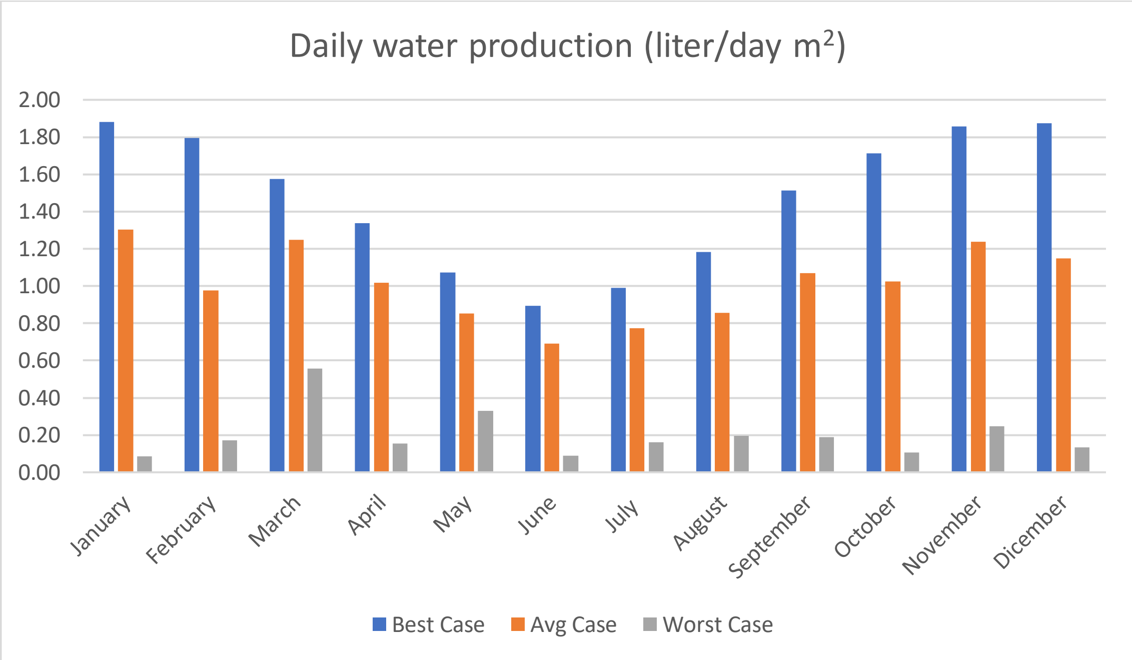


Figure 9 Daily water production comparison

Desalination is not the solution to water scarcity however for particular cases such as rural locations or after natural catastrophizes it could provide aid until a more suited and scalable solution is put in place.

10. References

[1] Abdennacer, Kaabi and Trad Rachid. *Study of the optical performance of a solar still with a double slope and greenhouse effect*. Constantine, 2005.

Table of contents

Table of figures

Project Introduction

71% of our planet's surface is covered by water, which means more than 200 billion liters of water for each person on earth, but today still one-third of the population does not have access to drinking water. As of today, there are more than 785 million people without access to water [1]. Some studies show that by 2050 more than half of our population will live in water-stressed areas, or more than 4 billion people. While the math shows an immense amount of water, a problem arises: 96.5% of that water is saturated with salt found in our oceans, it is not drinkable and, on the other side, most of the earth's fresh water is contained in glaciers so deep underground that less than 1% is available to the world. Even in the most developed countries, such as the United States, there are large numbers of people who do not have access to safe drinking water. So why can't we filter seawater and get an unlimited supply of clean drinking water?

As of today, there are two common ways to desalinate: thermal desalination, which is a more traditional method, involves heating the salt water and condensing the steam to obtain fresh water; the other procedure is more complex yet it is the dominant technology in the market, its called reverse osmosis, which uses salt water at high pressure and pushes it through a semi-permeable membrane to separate the salt; membrane systems are often more energy efficient than thermal desalination, but the economic and environmental impact of both methods still comes at a huge cost. After the freshwater is extracted, the brine is returned to the ocean. The problem is that seawater is less dense than brine and brine sinks to the bottom, where it can damage ecosystems by increasing salt content and causing oxygen levels to plummet. [2]

Some figures to keep in mind:

- 2.2 billion people lack access to safely managed drinking water services (WHO/UNICEF 2019).

- Nearly 2 billion people rely on sanitation facilities without basic water services (WHO/UNICEF 2020).

- More than half of the world's population, or 4.2 billion people, lack safely managed sanitation services. (WHO/UNICEF 2019)

- 297,000 children under the age of five die each year from diarrheal diseases due to poor sanitation, lack of hygiene, or lack of safe drinking water. (WHO/UNICEF 2019)

- 2 billion people live in countries experiencing high water stress (UN 2019).

- 90% of natural disasters are climate-related, including floods and droughts. (UNISDR)

- 80% of wastewater flows back into the ecosystem without being treated or reused. (UNESCO, 2017)

According to data published on access to water by WHO and UNICEF in 2019, of the 8 billion people living in the world, more than 884 million do not have access to safe drinking water, and 785 million do not have access to at least essential water services [1]. To solve the problem, NGOs such as Manos Unidas [3] work to eradicate hunger, malnutrition, evictions, and poverty by providing aid to impoverished communities. In this case, the project aims to develop a sustainable solution for obtaining water through seawater desalination. It is intended to design a water harvesting system that can be used by Manos Unidas in case it is necessary to implement it in the future. Since MMUU is focused on developing the plan in a remote location, this project will study seawater desalination by evaporation in a greenhouse at ambient temperature. In addition, access to energy in these locations cannot be guaranteed, so power generation must be obtained through photovoltaic or solar thermal systems. The project will focus on the development and analysis of the construction and infrastructure and not on the distribution of the water obtained, which will be assumed by the local community by providing clean water to each member by transporting it from the collector to their home or each member collecting their share from the collector as well. Approximately, each MMUU project is funded with no more than 100,000 euros per year. In case more funding is needed (although it is not advisable to exceed the budget), the project could be designed for more with external funding or projecting the project for more than one year [4].

Manos Unidas is a Spanish NGO that works in collaboration with 58 countries around the world today. Its mission is to eradicate hunger, malnutrition, disease, underdevelopment, and lack of education. Its vision is to provide these people with the tools that allow them to have better material, moral and spiritual life so that they can have a dignified life.

Manos Unidas has 72 different delegations formed by:

- Donors, Partners, and Associates who spread the message to others. Manos Unidas has more than 73,000 donors who represent 40.7% of its income.

- Inheritances represent 17.1% of its income.

- Volunteers who, thanks to their work, Manos Unidas can develop its ongoing projects. They have more than 5,300 volunteers. 97% of the workload of Manos Unidas is made up of volunteers.

- Schools and Universities that explain the problem to the new generations so that they can also be part of the solution. Schools and Universities contribute 2.1% of the income.

- Churches and Parishes that raise money to fight for human rights and Christian values. Churches and parishes account for 21.1% of Manos Unidas' income.

- Public funds and local administrations, represent 12.7% of Manos Unidas' income.

All these branches have raised around 47.25 million euros to benefit more than 1.4 million people directly and 6 million people indirectly. It is present in three different continents with different proportions of investments: Asia (25%), Africa (49%), and South America (26%). They have more than 900 projects underway and have a strong connection with 400 local organizations.

For the project to be viable, access to resources must be analyzed according to region and location. The final location will be crucial to determine what resources can be obtained and what challenges and benefits these regions could bring to their development [4].

Motivation

Desalination broadly is the process of removing salts from water, it's been practiced for years it's a natural process. It occurs when the sun heats the ocean and freshwater evaporates off and it falls again as rainfall. If you mix salt into water it dissolves, and if you could watch microscopically while you did that, you'd see that the water is breaking apart the salt into charged particles that chemically interact with the water, so salt water is a chemically new solution it's not just water with some salt brains floating around in it and that's why desalination is a fundamentally tricky process. The two main types of desalination are thermal desalinization and reverse osmosis. Thermal desalination is the oldest form of desalination, it's essentially boiling water and then capturing the steam and turning that into fresh water but in the 60s reverse osmosis processes were developed at UCLA and these have now started to dominate the market so one of the big differences between the two is: reverse osmosis doesn't use heat, doesn't boil anything, you just pressurize the water through tremendous amount and you're forcing it through a membrane doesn't want to go it wants to stay with the salt but with this high pressure it is forced to separate from the salt. [5]

Broadly speaking what you want to look at for desalination is where's my fresh water coming from. Do I have enough of it? If I don't have enough of it do I need to augment the supply desalinization then starts to become a very attractive or interesting option which is why the vast majority of desalinization efforts right now are happening in places like the Middle East and North Africa rich with fossil fuels but also experiencing extreme water scarcity

Just two countries Saudi Arabia and UAE produce 1/4 of the desalination water that is produced currently on this planet. Concerns about these desalination systems fall broadly into three categories:

1. The amount of energy required
2. How much does it cost
3. The environmental impacts

Ocean water desalination can be 25 times as energy intensive as other freshwater approaches but beyond the environmental costs of producing the energy needed to power these plants another concern arises because they're not just outputting clean desalinated water there are also producing huge amounts of hyper salty water called brine as a byproduct. Seawater desalination plants that use reverse osmosis typically operate at a 50% efficiency in that if you take 2 gallons of seawater, you're going to produce one gallon of fresh water and one gallon of hypersaline brine. It's a fixed volume of salt that I'm trying to remove so whether I put it in half a gallon of water or 1/10 of a gallon of water it's still going to be there and it's just going to be much more concentrated.

As desalination efforts grow it's not clear what should be done with these huge amounts of brine globally right now, we're producing over 37 billion gallons a day. Most brine is in one way, or another emptied back into the ocean but because it has a much higher salt concentration than regular seawater it has the potential to among other things sink so the sea floor and interfere with the plants and animals found there. In addition, because these facilities are taking in millions of gallons of seawater a day the intake itself could destroy local marine life [6]

While in occidental countries average society lives comfortably and with access to basic resources, there is still a water crisis to be solved in the world. With the aid of this system, many communities without access to water could be provided with such. With the knowledge of Manos Unidas and the *Fundación de Ingenieros de ICAI*, this problem can be solved for a small community without the requirement of additional costly resources. Manos Unidas is a key stakeholder in this operation as they have many ongoing projects in the field. MMUU also provides the most important information which is the context and resource capabilities of the community which is crucial for the feasibility of the project. On the other hand, *Fundación de Ingenieros de ICAI* provides the engineering support to turn an idea into a real solution. They have done many projects before including previous ones with the collaboration of Manos Unidas. The problem to solve is not only to provide the community with water but to help them grow using the water not only for drinking purposes but for agricultural and livestock necessities as well.

State of the art

As mentioned before, the most popular way to obtain clean water is by boiling it, this practice is standard in remote locations where there is no access to other types of technology or resources such as reverse osmosis membranes, UV filters, and chlorine… Before boiling it, the water used as input must not contain big debris or turbidity. While boiling the water all the pathogenic organisms on the water as well as viruses such as Hepatitis A (more heat resistant than other similar viruses) are eliminated by rising the temperature of it. When high temperatures are reached, the bacteria cannot survive the environment and therefore dies. Another interesting element is how much time is needed for the water to be safe, according to the United States Environmental Protection Agency (EPA) water should be brought to a rolling boil for at least one minute, and in case of altitudes of above 1000 meters for at least 3 minutes [7].

Since the system requires multiple heat transfers to obtain distilled water from seawater, another interesting alternative is using commercial seawater reverse osmosis systems. Reverse osmosis is a simple and direct way to filter water. The water is filtered due to a semipermeable membrane that stops the debris from passing through. Reverse osmosis eliminates harmful substances such as fluoride, chlorine and chloramine, nitrates and sulfates, and pesticides [8] [9].

Table 1 Reverse osmosis on numbers

Distilled water costs around 2000 dollars per year for each family of 5 people
Energy consumption is the biggest individual cost on inverse osmosis plants. This cost represents half of the production cost.
The plan consumes 8 liters of seawater to make 4 liters of distilled water
Desalination plants operate in more than 100 countries.

Figure 10 Reverse Osmosis System [10]

For the obtention of distilled water, the system design will be centered on two different procedures, evaporation, and the greenhouse effect. Evaporation is a heat transfer procedure where two volatile compounds are separated from a dissolution where the solute is not volatile, essentially the two compounds have very different boiling temperatures. With evaporation, the two compounds are separated compared with distillation where both compounds have not so different boiling temperatures thus having on the vapor side some percentage of both compounds. On the other hand, the greenhouse effect uses a structure that encloses an area sun rays impact and passes through that layer onto the area that it is covering. The sun rays travel from the sun, they impact the outer layer of the structure made of an insulator material, usually glass or plastic. This procedure raises the temperature inside the structure and therefore the solar panels don’t have to generate so much electricity.

Water Distillation Technologies

Multiple technologies can obtain distilled water from salted water. The main desalination techniques can be classified into three large groups according to the principle they apply:

a) Phase Change:

1. Evaporation

-Sudden multiple-stage evaporation (ESME or SPS)

-Multiple Evaporation Effect (EME or MED)

-Vapor compression (CV)

2-Freezing

It is based on the different melting points of fresh water and salt water.

The ice crystals obtained are separated in the brine, then washed to extract the salt, and melted into fresh water.

b) Selective Membranes

-Reverse Osmosis (RO)

-Electrodialysis (ED)

c) Chemical Bond

-Ion Exchange (IQ)

-Solvent extraction

Reverse Osmosis

This process applies pressure to overcome the osmotic pressure of the water to be treated. The reverse osmosis process is perhaps the simplest method to desalinate and in which better energy efficiency is obtained. The system takes its name for performing the passage of solutions in a way contrary to normal osmotic processes. That is, the less concentrated solutions move, by potential energy difference, towards the more concentrated ones, through a semipermeable membrane, with the need to apply an external force to achieve the separation of water and salt.

Therefore, the higher the salinity of the water, the greater its osmotic pressure to overcome. It consists of a seawater harvesting system, followed by a physical and chemical pretreatment system, consisting of sand filters and activated carbon (physical) filters; (chemical) dosing to regulate the pH of the feed water, and the addition of anti-crusting to prevent salt deposits in the membranes; as well as reverse osmosis membrane frames to remove salts, as can be seen in Figure 2.10. Desalinated water, an after-treatment train is connected to disinfect the water, using individually and according to the final use of the product water, UV lamps, chlorination, and ozonation, which allows ensuring the quality of the water in distribution and storage lines.

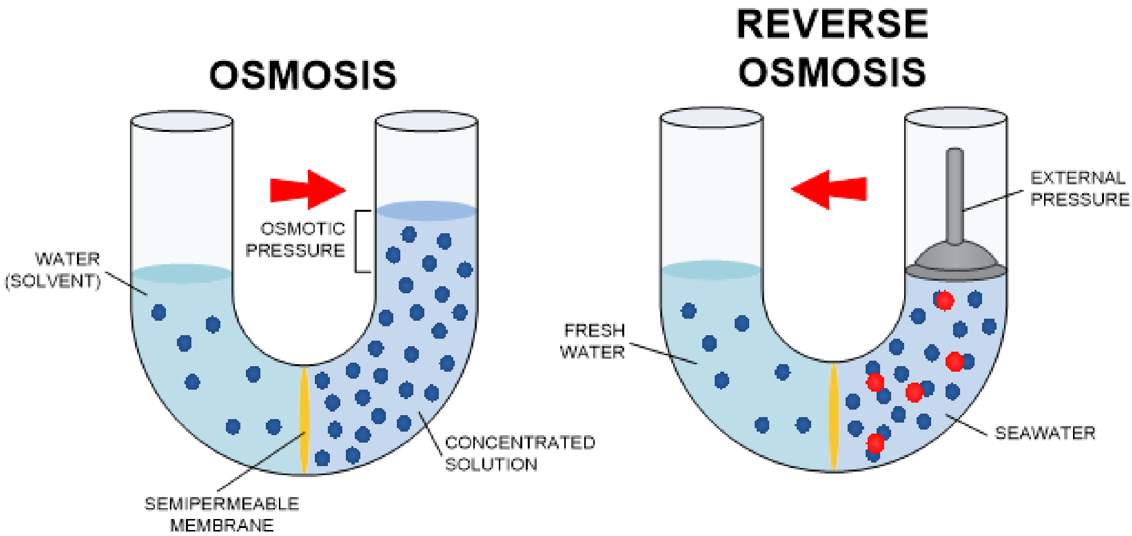


Figure 11 Reverse Osmosis

The professional approach by the INCLAM group

To obtain information for the development of a system as viable as possible, INCLAM was contacted. INCLAM is a company dedicated to the realization of sanitation, purification, water purification, and infrastructure development projects in communities around the world. They have carried out several projects in Latin America, Africa, Asia, and Europe. They work not only at the industrial level, but they have developed water purification and purification projects for rural communities mainly with the use of reverse osmosis technologies.

<u>Recommendations for project implementation:</u>

Water supply projects in rural communities must have not only the appropriate technologies that allow the system to function but also and more importantly, there must be social work with the community to learn about good water practices, the importance and benefits of quality water versus untreated water that may contain viruses or bacteria that can make the population sick.

The inclusion of the community in the project, not only in the installation and development but also in the operation and maintenance part, training certain members so that they can carry out this work.

One of the biggest challenges when carrying out projects in rural communities is logistics. The geographical location of these communities often prevents easy access by road, so other more costly means of transporting material and system components are needed.

It is recommended that the input water to be treated should preferably be river water since it requires less treatment and, therefore, lower cost than salt water obtained from the sea.

Among the wide variety of projects, the project carried out in Peru is of great relevance for this work. This project, financed by the Peruvian government, consisted of a water supply system for 65 rural communities using Reverse Osmosis systems.

GRUPO INCLAM

Figure 12 INCLAM RO Machine

The objective of their technological machines is to develop a solution to remove water pollution with considerable ease of transport, high autonomy, ease of operation, and which can withstand climatic conditions of the area. The following are a 3D and a real representation of the project in Perú.

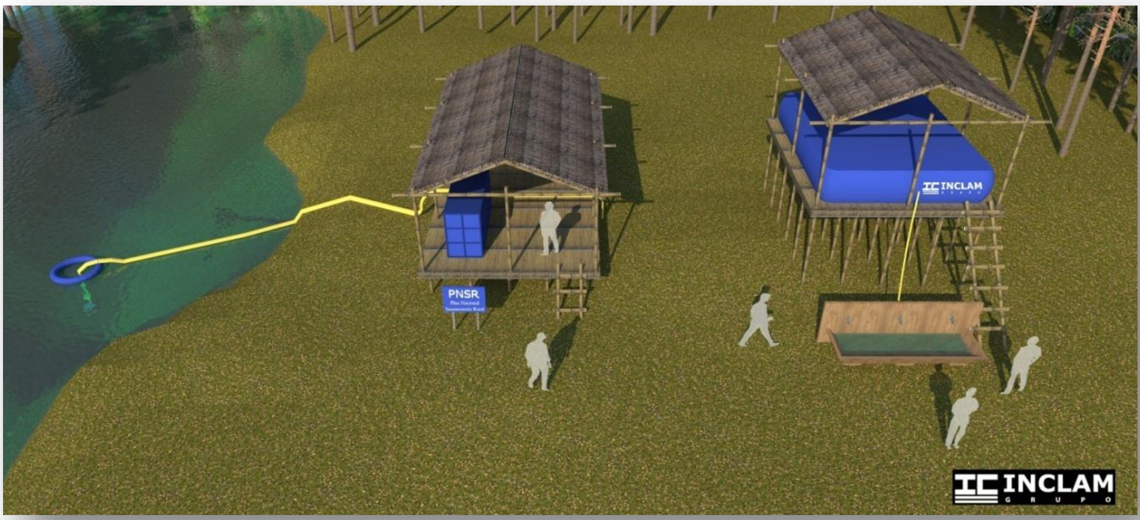


Figure 13 INCLAM 3D Representation

Figure 14 INCLAM Picture from the project

Compressed Vapor

This technology is usually used in combination with other processes, when it is used by itself it is only in cases of small and medium-scale applications. The energy needed to evaporate water comes from the compression supplied to the steam, rather than direct heat exchange with the steam produced in a boiler. MVC systems work by compressing water vapor, which causes condensation onto a heat transfer surface (a tube), which allows the heat from the condensation to be transferred to the brine on the other side of the surface, resulting in the vaporization of the brine. The compressor is the main energy requirement. The compressor increases the pressure on the steam side and lowers the pressure on the saltwater side to lower its boiling temperature .

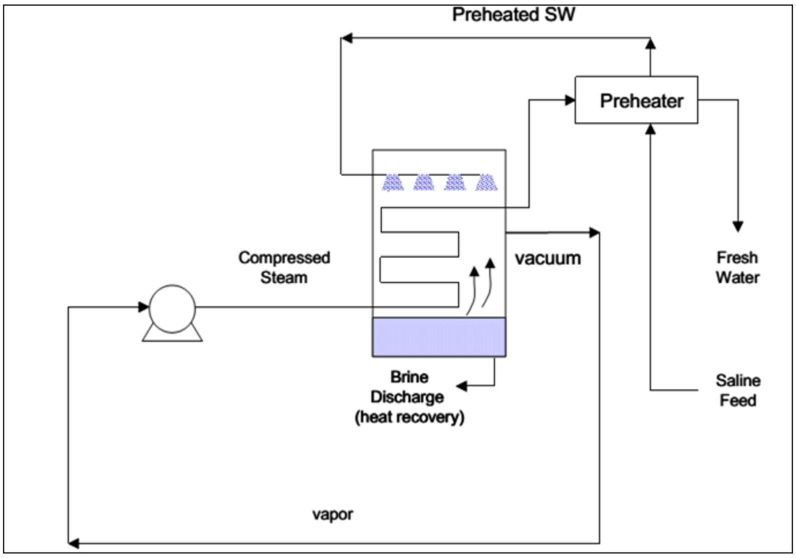


Figure 15 Compressed Vapor Schematic [11]

MED & MSF (Distillation)

As water temperature raises, heat is transferred and once the inside temperature reaches the boiling point water starts to boil and the salt remains in the basin. Once the water reaches the top of the structure; the water drops transfer heat into the inside of the glass and as a result, the water is condensed and will run to the bottom part of the glass due to surface tension between the glass and the water drops and gravity itself. Once this process is completed the output resulting will be distilled water with a much lower concentration of salt and the salt will increase its concentration in the basin.

The distillation operation unit consists of the separation of a dissolvent and a solute with different boiling points. In the distillation of salted water, the thermal input provided by a boiler or solar irradiation will increase the salted water temperature. In the case of salted water, the water boiling temperature is increased due to the addition of salt this phenomenon is called boiling point elevation.

Evaporation Note:

Evaporation and distillation are commonly confused between each other. The difference lies in the output obtained from the operation. In the case of evaporation, the solute and the solvent have a significantly different range of boiling points and the output only contains only one of both solutions. On the other hand, in the case of distillation, the boiling points of the two substances (in our case water and salt) are not separated enough to obtain an unmixed output even though the proportion of the solute in the output is reduced. The proportion of the solute on the output will depend on the efficiency of the distillation stage as well as the number of distillation stages.

In this process, seawater is heated in a tank using a coil or parallel tubes containing some hot fluid; it is then passed to another tank, called a stage, where the reduced pressure allows the water to boil. The vaporized water is cooled and condensed to obtain the product. This rapid introduction of hot water into the chamber causes rapid, almost explosive evaporation. The steam generated by sudden evaporation is transformed into drinking water condensing as it passes through the heat exchanger tubes.

Like the previous method, MSF consists of a series of vessels whose temperature drops in the direction of the water flow, which allows the reduction of the boiling point of the feed seawater without the need to heat it after the first effect. In general, an effect consists of a container, a heat exchanger, and devices for transporting fluids between these containers. In the process, there are a series of condensation and evaporation effects, with the lowest pressure in each successive effect.

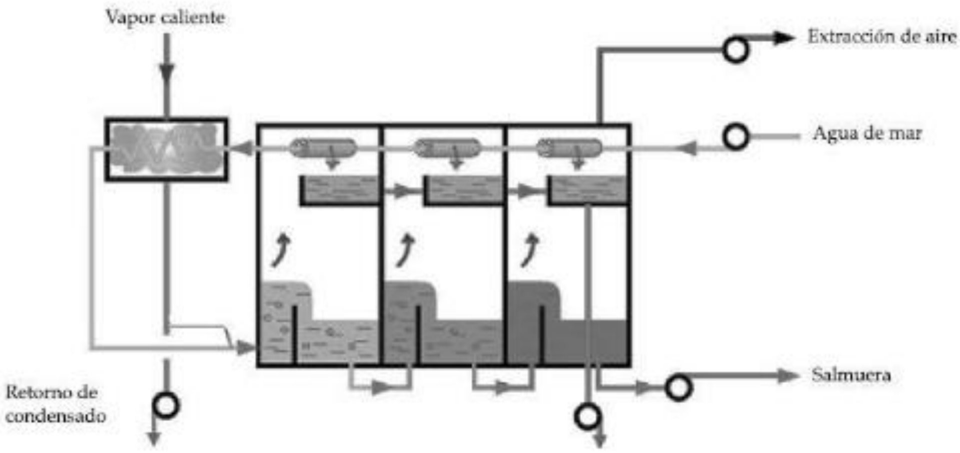


Figure 16 Multi-stage flash distillation [12]

Reverse Electrodialysis

Electrodialysis is a process to separate substances using electricity. It is commonly used to separate water into oxygen and hydrogen just by introducing a cathode and an anode and applying some electricity.

The difference between reverse electrodialysis and standard electrodialysis is that in reversed electrodialysis, the driving force is the concentration difference between the mixed substances while in standard electrodialysis, the driving force is the electrical potential

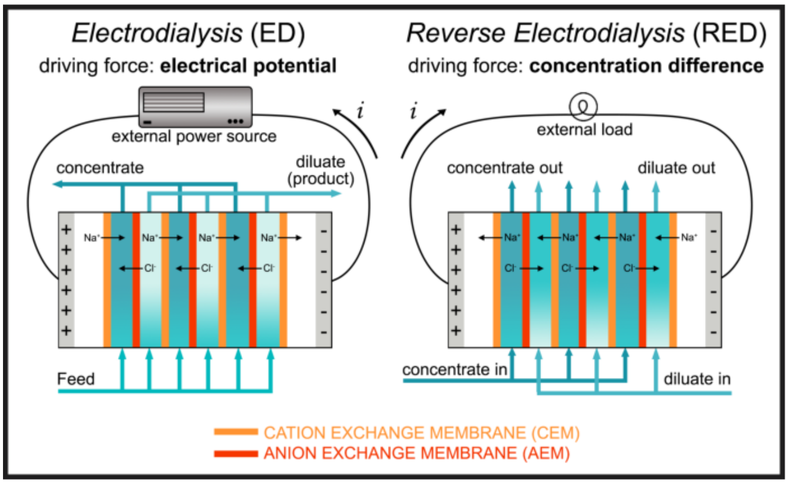


Figure 17 Forward and Reverse Electrodialysis [13]

Electro Dialysis (ED) is a membrane process, during which ions are transported across a semipermeable membrane, under the influence of an electrical potential. Membranes are cationic or anionic, which indicates which ions, whether positive or negative, will flow through. Selective cation membranes are polyelectrolytes with the negatively charged matter, which rejects negatively charged ions and allows positively charged ions to flow.

By placing multiple membranes in a row, allowing ions to flow with positive or negative charges alternately, ions can be removed from the wastewater. In some columns, the concentration of ions will take place, and in other columns, the ions will be removed. the concentrated flow of salt water is circulated until it reaches a value that allows precipitation. At this point, the flow is discharged.

This technique can be applied to remove ions from water. Particles that do not carry an electric charge are not removed. Selective cation membranes are composed of sulfonated polystyrene, while selective anion membranes are composed of quaternary ammonium polystyrene.

Sometimes pretreatment is necessary before electrodialysis can take place. Suspended solids with a diameter exceeding 10 µm need to be removed, or else they will clog the pores of the membrane. Some substances can neutralize a membrane, such as large organic anions, colloids, iron oxides, and manganese oxide. That hinders the selective effect of the membrane.

Pretreatment methods that help prevent these effects are activated carbon filtration (for organic matter), flocculation (for colloids), and filtration techniques.

Electrodialysis (ED) is a membrane process in which ions are transported across an ion exchange membrane using electrical energy as a driving force.

The membranes have a high density of ionic groups fixed in them, which allow the selective transport of ions through the membrane depending on their charge. The passage of counter-ions (of opposite charge) is allowed while the passage of co-ions (same charge) is prevented due to

Donnan's repulsion. This process is carried out between two electrodes under the influence of an electric field.

The applied electrical energy allows the transfer of ions to be from the least concentrated solution to the more concentrated solution. Thus, by removing the solute, a purification of the solvent occurs; contrary to what happens in the processes of reverse osmosis or ultrafiltration, in which transport of the solvent occurs through the membrane while the passage of the solute is prevented.

Reverse or reversible electrodialysis (EDR) works using the same mechanism as electrodialysis, except in the fact that in EDR the polarity of the electrodes is periodically reversed (approximately 3 to 4 times per hour) and, utilizing automatic valves, the outputs of the concentrated solution and the diluted solution are exchanged. In this way, the ions are transferred in opposite directions, which hinders the formation of scales and allows the membrane to be washed.

The benefits of electrodialysis compared to reverse osmosis are the lower amount of rejection, the lower sensitivity to suspended solids, the longer life of the membranes, the no need for a complete pretreatment, and the greater ease of operation and low electricity consumption.

Technology Comparison

The following table attaches the most important desalination processes, as well as their main characteristics. Where it can be observed that the reverse osmosis method is the cheapest, but in it, lower water quality is obtained than in the other desalination methods. At present, the Reverse Osmosis method is used more, because its energy consumption is lower.

Table 2 Technological comparison

Characteristics	MSF	MED	CV	RO	RE
Type of Energy	Thermal	Thermal	Electric	Electric	Electric
Energy consumption (Kj/Kg)	High(<200)	Medium/High(150-200)	Medium(100-150)	Low (<80)	Low (<80)
Initial cost	High	Medium/High	High	Medium	Medium/Low
Production (m3/day)	High (>50000)	Medium (<25000)	Low(<5000)	High(>50000)	Medium (<25000)
Scalability	Difficult	Difficult	Difficult	Easy	
Reliability	High	Medium	Low	High	High
Output salted water quality (ppm)	High(<50))	High(<50)	High(<50)	Medium (300-500)	Medium (300-500)
Surface required for development	big	medium	small	small	small

A critical need for treating these contaminated water sources is desalination. Other conventional thermal processes, e.g., multistage evaporation (MSE) and multi-effect distillation (MED), and membrane-based desalination, i.e., reverse osmosis (RO) amongst others, have been applied at different scales to desalinate and purify water from different sources.

However, desalination is a high energy-intensive process. Reverse osmosis (RO) consumes1.5 to 2.5kWhm−to desalinate seawater; it requires big capital investment and extensive pretreatment to control membrane proper functionality. Also, water recovery of RO desalination systems is between 50 and 85%, leaving large volumes of concentrated brine.

For desalination plants that are located away from the coastal line, disposal of the RO brine poses a major challenge and is very costly.

Similar Projects

Rice University (NESMD) [14]

Other relevant solutions include the one developed by Rice University. The project consists of a standalone solution sustained by solar power. The desalination system includes a NESMD (nanophotonic enhanced solar membrane distillation) reactor to obtain a low-cost and high-efficiency solution for the desalination of seawater and hypersaline brine. The nanophotonic material acts as a photothermal coating collector to preserve the heat and generates high heat in the area where the membrane is localized.

A stand-alone small-scale nanophotonic enhanced solar membrane distillation (NESMD) system was developed for desalinating seawater. This NESMD solution can take almost any source of water and turn it into clean water using sunlight as the standalone energy source. The NESMD technology includes a nanophotonic coating material on top of a commercial hydrophobic polypropylene membrane surface. The photothermal coating acts as a solar energy absorber, and generates localized heat on the membrane, while the other parts of the membrane are used for distillation purposes.

The conditions of the study include high salinity simulated feedwaters (total dissolved solids (TDS) of 113 200–200000 PPM) were tested under the weather conditions of Houston, Texas. The field-testing results showed stable desalination performance in consecutive 5–8-hour operation cycles, with a TDS removal of over 99.5% in their experimental design. An average daily membrane flux over 0.75 L m−2h−1was achieved with a solar intensity close to 1 kW per meter squared without an external heat exchanger.

A good approach to reducing the energy consumption of desalination is to use renewable energy. The authors propose a novel nanophotonic enhanced direct solar membrane distillation process to treat real seawater and high salinity simulated feedwaters. The proposed process uses sunlight instead of electricity from the power grid or solar photovoltaic panels to drive membrane distillation.

The overall objective of the NESMD project was to develop an independent desalination testbed with low maintenance requirements for its use in remote areas with a lack of drinkable water but have seawater with high solar irradiation.

Membrane preparation

The NESMD membrane is a unique two-layer nanostructure consisting of a solar-absorbing, hydrophilic, carbon black nanoparticle-infused polypropylene (PP) layer, overlying a microporous hydrophobic layer of polytetrafluoroethylene (PTFE). Two different solutions, a polydopamine (PD) solution, and a carbon black (CB) solution have been used for preparing the NESMD membrane.

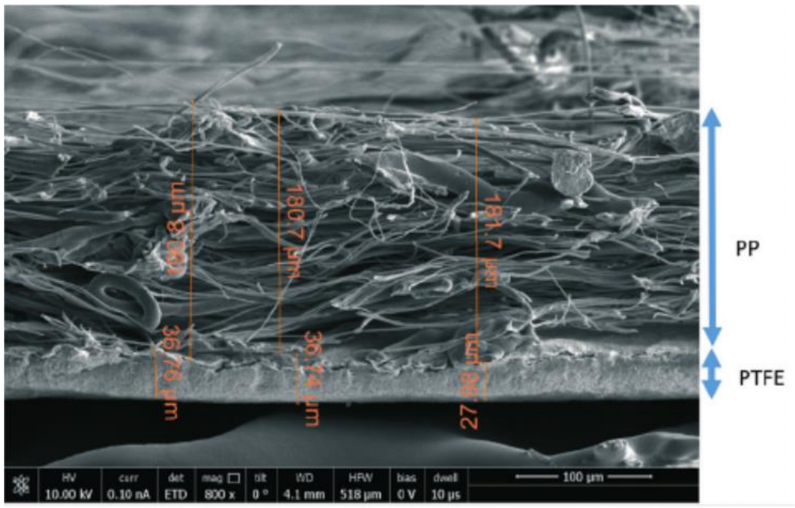


Figure 18 Dual membrane configuration

A flow of cold air underneath the membrane was applied to sweep off and collect the permeate. The SGMD advantages address primary issues with other MD modes. The reduction of heat transfer via conduction reduced resistance to mass transfer as a result of the flow of gas on the permeate side and a low risk of pore wetting highlight the potential of SGMD and make it an attractive area of research & development.

Prototype

The prototype was designed as a three-channel plate and frame NESMD reactor with an effective membrane surface area of 20 squared centimeters

The membrane module consists of three channels:

First, is the coolant (bottom) channel where the cold feedwater exchanges heat with the vapor in the sweep air (middle)channel to condense the vapor and become heated itself.

Second, a feed (top) channel is formed between a transparent window and the photothermal membrane, where the preheated feedwater evaporates at the feed–membranes interface, and the vapor is transported through the membrane.

And finally, the sweep air channel where the vapor is in contact with a heat exchange surface and condenses. The figure below shows the design of the different components of the NESMD membrane module, which form the flow channels.

Hydraulic conditions in each of the flow channels determine the contact time each flow stream has for evaporation, heat exchange, or condensation, and also strongly affect the mass and heat transfer.

Material selection procedures were performed to choose the right materials for the reactor. In the light of the material selection diagram, the transmittance window was made of clear Plexiglas with 92% light transmission. The Plexiglas acrylic is crystal clear and colorless and has high impact resistance, low water absorption, and corrosion and chemical resistance. The closure plates were made of high-density polyethylene with UV resistance.

It is worth mentioning that the NESMD reactor is equipped with a photovoltaic panel (0.70 ×0.52 ×0.025 m) at an inclination angle of 45°to provide electric power for pumping the feedwater and sweeping air to the reactor. Also, a solar charge controller is used in conjunction with the solar panel and two parallel-connected lead acid batteries to avoid overcharging and control the power system.

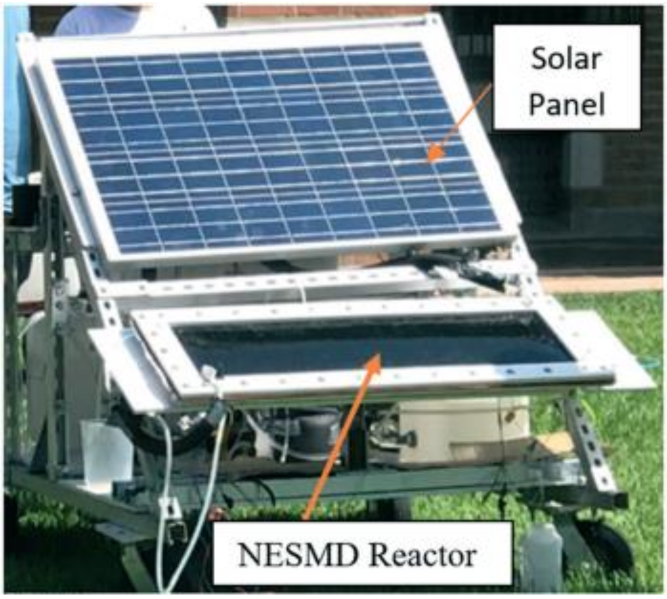


Figure 19 RICE Solar solution

System operation

Pretreated cold feedwater enters the bottom channel and gains heat by internal heat recovery. The preheated feedwater then leaves the bottom channel and enters the solar top channel. The hot feedwater flows through the top channel (evaporation) in a co-current direction to the sweep air in the middle channel. The hot exit feedwater from the top channel is recirculated back to the top channel. The generated water vapor passes through the photothermal membrane and condenses in the middle channel. The sensible heat and latent heat are transferred through the heat exchanger material foil (0.2 mm thickness) to preheat the feedwater in the bottom channel. The sweep air and condensed distillate exit the NESMD prototype at the permeate outlet into a product tank with a vent. It is worth mentioning that in all the experiments, there is no external condenser for heat recovery used.

The NESMD system is self-running since its pump, pumps, and control system are electrically powered by the photovoltaic panel.

The operation of the NESMD is carried out only during the daytime since there is no other source of heat or electricity used. It is worth mentioning that in the absence of solar energy, the current system can be coupled with an external heater to serve as a conventional membrane distillation module.

Experimental conditions

The environmental parameters include barometric pressure, airspeed, ambient temperature, relative humidity, and solar irradiance.

Two different feed flow rates in the top channel were investigated, including 1.8 liters per hour and 3.8 liters per hour while the airflow rate was ranging between 120 and 240liter per hour. In the experiments, the flow rate of the bottom channel was set at 17 liter per hour, which is much higher than that of the top channel to achieve a higher rate of heat transfer between the vapor in the middle channel and feedwater in the bottom channel.

The outlet preheated feed flows are divided into two streams, one flows to the top channel, while the other one is continuously circulated in a counter-current flow mode concerning the air in the middle channel, where the feed is in the bottom channel and distillate streams flow in the opposite directions. The reason to split the exit feed flow from the bottom channel is that the feed flow rate in the top channel is much lower than that in the bottom channel.

The feed in the top channel was continuously circulated through the membrane module using a magnetic drive pump where the feedwater in the top channel and distillate streamflow in the same direction. Using the feed recirculation loop enhances the performance of the NESMD reactor in terms of maximizing heat recovery and thermal efficiency. This recirculation step allows the use of the sensible heat lost within in the form of the heated feed output of NESMD and consequently increases the overall permeate production of the NESMD system by reducing the brine production

Results

The experiment results show that the bottom chamber is obtaining more energy from the vaporing of the middle channel (condensation), which is clear in the temperature gained across the bottom chamber (Tin, bottom and Tout, bottom).

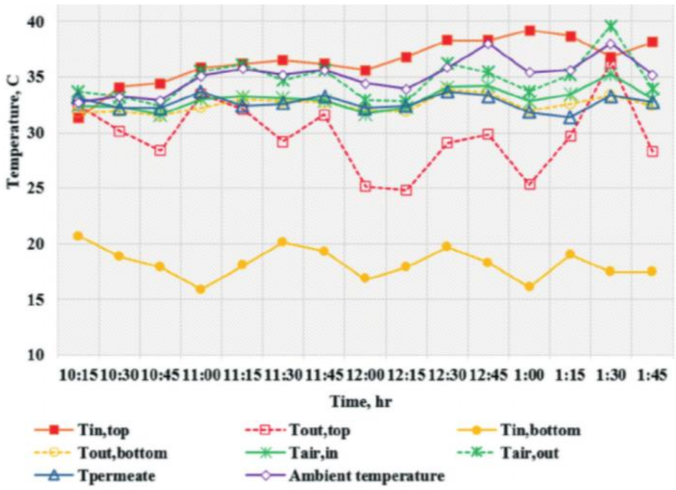


Figure 20 Temperature timeframe

The humidity of the air (in and out) is logged and compared with the relative humidity of the outgoing air is a little bit lower than that of the incoming air. The figure confirms that the majority of generated vapor is condensed within the middle channel.

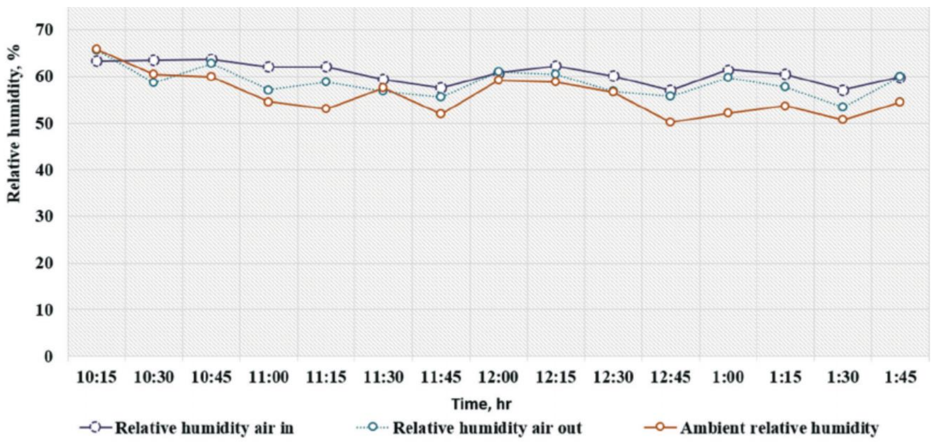


Figure 21 Relative humidity

Water qualities of the feedwaters permeate in terms of TDS and conductivity, and the TDS and conductivity removal values are greater than > 95%, meeting the World Health Organization standards.

It is worth mentioning that the current NESMD reactor is still in an early stage of Research and Development(R&D). Further investigations, improvements, and optimization are required to enhance the performance of the NESMD reactor.

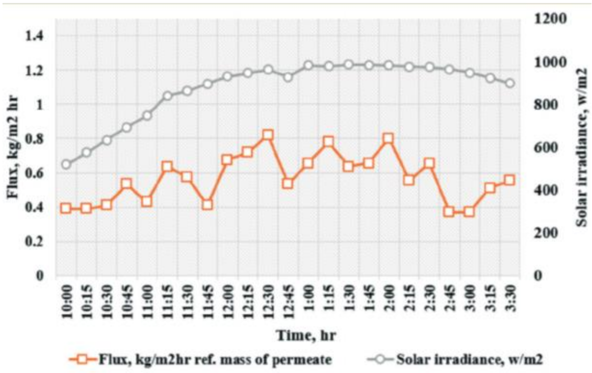


Figure 22 Water production

The membrane is considered one of the potential solutions for improving the production of purified water using the NESMD system. Concentrating the sunlight on the photothermal membrane leads to a linear gain in the amount of heat, and consequently generates a nonlinear increase in the water vapor pressure. Hence, the produced clean water is exponentially dependent on the solar intensity

This NESMD solution is still under development since the membrane is manufactured in the laboratory as it is not available on the market. Unlike other distillation systems, this one has a solar panel that provides the extra energy needed to reach the boiling point of the water. Finally, it should be noted that this system is capable of producing a flow rate of 0.75 l/(m2*h).

Fcubed

F Cubed provides an off-grid Carocell system that is simple to install, modular and scalable; It also eliminates contamination from all water sources and requires limited expertise to install, maintain or operate. It is environmentally friendly using solar energy only and rainwater harvesting and can actively engage local communities in installing and maintaining the off-grid water solution.

Figure 23 FCubed Carocell 5 panel system

F Cubed has provided the Carocell System globally for over 10 years

- The technology is fully tested and accredited and F Cubed has already provided the Carocell System to:
    - Over 3,000 installations worldwide;
    - Across over 30 different countries;
    - Global NGOs and Charities (such as World Vision, Oxfam, UNICEF, USAid); and
    - Governments.

The off-grid simplicity makes it ideal for remote, rural, or island communities The system is generally installed in increments of 5-panel Water Farm Kits which are readily expandable to rural schools, health and community centers individual homes or island communities via seawater desalination. It can function as a central system for a community and/or multiple smaller farms within communities or for rural agricultural and farms.

How a Carocell Panel Works

- Distillation Process
    - Each Carocell panel is fed water (from any water source including seawater) into the inside of the panel
    - The contaminated source water flow is spread evenly across and down the panel via an internal element (treated fabric). The fabric is not a filter and its purpose is to ensure the contaminated source water is spread evenly across and down the panel;
    - As heat builds up the water evaporates and condenses inside the panel
    - The condensed water exits the panel from an outlet identified at the bottom of the panel
    - Any source water that does not evaporate will exit a separate outlet (and can be fed back into the panel to be processed again (thereby conserving the source water)
- Distillation Effect:
    - Solids in the source water cannot evaporate (i.e. salt, metals minerals, etc.);
    - Water-borne bacteria (i.e. E.coli and other coliforms) cannot survive the evaporation process and are therefore eliminated;
    - The output is purified (potable) water for drinking, cooking, washing, and cleaning.
- Rainwater Harvesting
    - Rainwater is collected off the face of the panels.
    - The rainwater flows into a customized guttering system as integrated as part of the Water Farm Solution.
    - Rainwater is passed through a simple filter and can be collected with the distilled water from the panels or into a separate tank.
- Output Expected - 5 Panel Farm
    - Each standalone panel will produce (on average) approximately 15 liters per day
    - Therefore, a 5 panel water farm (previous slide) will:
        - Produce around 75 liters of distilled water each day and will harvest rainwater (ranging from 5-10 liters per day)
    - In total, a 5 panel water farm will provide a combined output (on average) of 100-125 liters of potable water per day and provide a year round solution
- Each 5 Panel Water farm can be joined together (in 5 Panel increments) to increase in size to provide more water

Water Farm Kits

Whilst we do supply individual Carocell panels, for a complete solution we recommend an Automated Carocell Solar Powered Water. Farm Kits can be at any scale depending on your water volume needs.

Each Water Farm kit comes ready to assemble and contains:

- The required number of Carocell Panel, in 5 panel arrays
- A complete integrated Racking System with Rainwater Harvesting
- A Photovoltaic Panel and Solar Pump to feed water to panels
- All required irrigation fittings and hosing.

Each 5-panel kit can be joined together to create a larger farm (see table below) to meet your requirements and can be placed on the ground or the roof.

These water farms are ideal for:

- Domestic use
- Rural/Remote communities
- Islands or Coastal areas (seawater desalination)
- Agriculture or Livestock.

Once set up there are:

- No moving parts or filters/membranes requiring constant maintenance or replacement
- No power or other infrastructure requirements
- No expertise required to operate or maintain
- Limited user interaction; and
- Source water can be recycled.

F Cubed has over 1,000 Water Farm kits of varying sizes installed globally.

Seawater Desalination

Figure 24 FCubed Seawater Desalination

MIT University (Reverse Electrodialysis) [15]

There are other types of solutions that despite not including processes such as the greenhouse effect are also interesting due to their use as is the case of the system developed by MIT using reverse electrodialysis and energy contribution with solar panels. It is a project capable of supplying a community of 2000 people in India with a total cost of around 23000 dollars. This project produces a flow of 1.6 cubic meters every hour and a recovery of 96% going from a salt concentration of 3360 parts per million to 250 parts per million.

The electrodialysis process (ED) is the process of pulling ions out of a solution through the application of an electric potential across a series of alternating anion and cation exchange membranes (AEM, CEM).

This project required half the energy (and thus half the power system cost) compared to an alternative reverse osmosis system and reduces water wastage from 60% to less than 10%, for groundwater salinity levels commonly found in India. System cost predictions turned out to be $23,420 (42% less than substitutes).

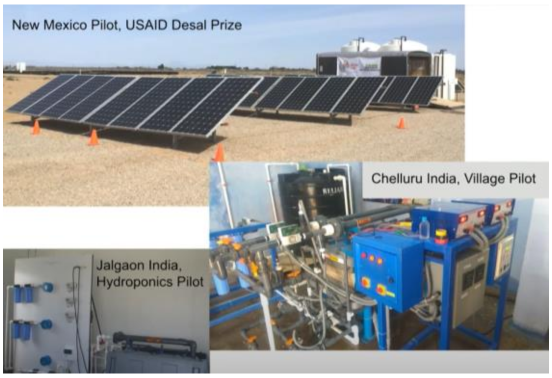


Figure 25 MIT System on the field

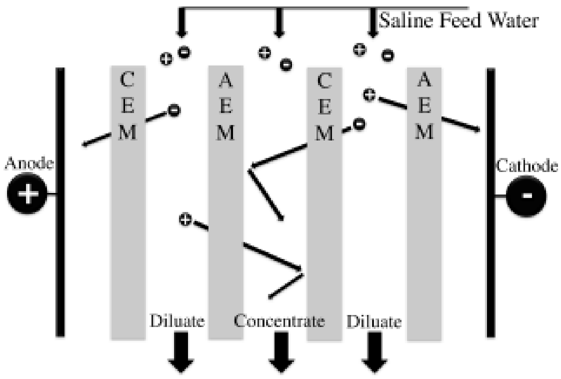


Figure 26 Reverse Electrodialysis

One of the main aspects to take from this project is the cost reduction made possible by flexible water production that accommodates daily changes in solar irradiance with overproduction on sunny days and water buffer storage tanks. The final sensitivity analysis revealed that the capital cost of the total system is most sensitive to membrane area as reducing membrane cost by 87% would be half the system capital cost. These strategies of time-variant operation and load matching with solar irradiance availability could be relevant to our project approach.

The theoretical system was designed for the Indian village of Chelluru, located 70 km northeast of Hyderabad. Compared to the 300 people community aimed for the desalination project, Chelluru has a population of approximately 2000 people Some water characteristics include: groundwater salinity is 1600 mg/L, which is within the typical Indian groundwater range of 1000–2000 mg/L. This study aimed to create a 10 m3 /day system in the interest of targeting the most common village size. Finally, a product water salinity of 300 mg/L was selected for satisfactory palatability, which is below the recommended 500 mg/L.

Today reverse osmosis desalination solutions have been rendered cost-prohibitive for off-grid rural applications; off-grid RO systems costs stand around $11,250 compared to $4500. As a result, the local non-governmental organizations (NGOs) or village municipalities that purchase desalination systems are currently limited to grid-powered solutions even in semi-reliable grid electricity environments. Reducing the cost of off-grid desalination systems would open a substantial and untapped market of villages without reliable grid connections.

Electrodialysis (ED) requires less than 50% of the specific energy compared to RO to desalinate water below 2000 mg/L to a product water concentration of 350 mg/L. The low salinity concentration of India's brackish groundwater remains below 2000 mg/L. These factors suggest that ED could provide a lower-cost, off-grid brackish water desalination solution compared to RO as the concentration doesn't reach such high levels of salinity. In addition to energy savings, ED can achieve high recovery ratios of 80–90 %, compared to only 30–60 % typically achieved by the RO systems used in Indian villages. Additionally, while RO membranes have an expected lifetime of 3–5 years, ED membranes have an expected lifetime of 10+ years, which could improve maintenance and serviceability.

The water distribution model assumes 0.25 m3 of water is collected by users instantaneously every 15 min for 10 h during the day, resulting in 10 m3 per day, with the simplifying assumption that there is no seasonal variability in water demand.

Table 3 Cheluru input parameters

Parameter	Symbol	Value
Input salinity	TDS_{in}	1600 mg/L
Output salinity	TDS_{out}	300 mg/L
Daily water production	V_{prod}	10 m^3
Water production reliability	r_{req}	100%
Solar irradiance	$GHI(t)$	2014 GHI data
Ambient temperature	$T(t)$	2014 data
Nominal PV efficiency	$\eta_{PV,nom}$	15%

The part of conclusions interesting the part where it talks about the development of a generalized model to take inputs of local conditions such as local feed water salinity, desired product water salinity, water demand profile, irradiance data, and temperature data.

Other greenhouse experimental solutions

There are similar projects documented on the obtention of distilled water. One of the most relevant includes the analysis performed by Kaabi Abdennacer and Trad Rachid for the "Study of the optical performance of a solar still with a double slope and a greenhouse effect" [16] in Constantine, Algeria. The study was performed with a glazing cover made of glass instead of plastic. Some of the conclusions from the project are: wind is directly correlated with the production of distilled water reaching peak production when wind speed reaches 10m/s, higher speeds don't provide a relevant increase in production, and the optimum angle for the still cover is 10º, the ideal depth of the basin should be at its minimum value, for this particular project the optimum was at 0.02m, the absorber should be made from aluminum with a black cover to increase the irradiation captured and finally the insulator should be made from polystyrene with a metallic or wooden reinforcement to limit heat losses. At peak performance, their system simulated production of 12.5 l/m^2 per day with a temperature gradient of 14 ºC.

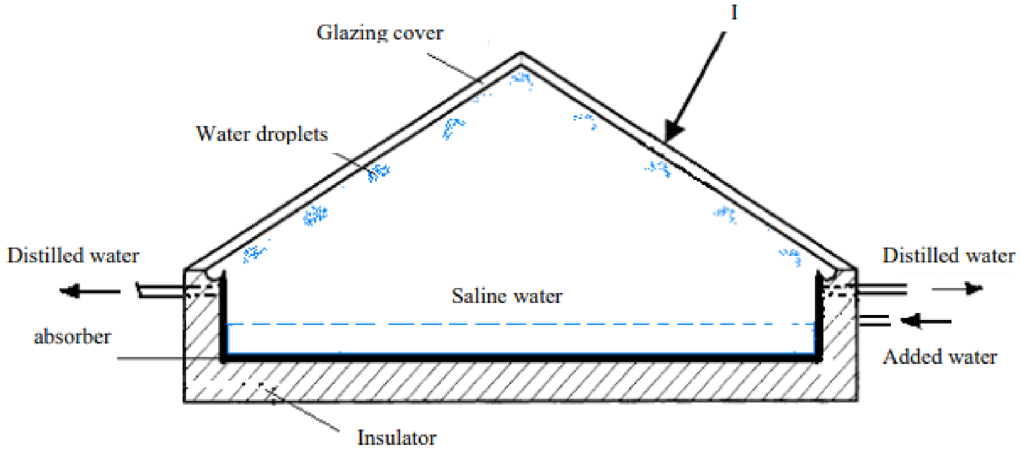


Figure 27 System design [16]

More state of the art references includes "*Solar Water distillation: The roof type still and a multiple effect diffusion still"* by R.V. Dunkle which discusses the heat transfers and calculations

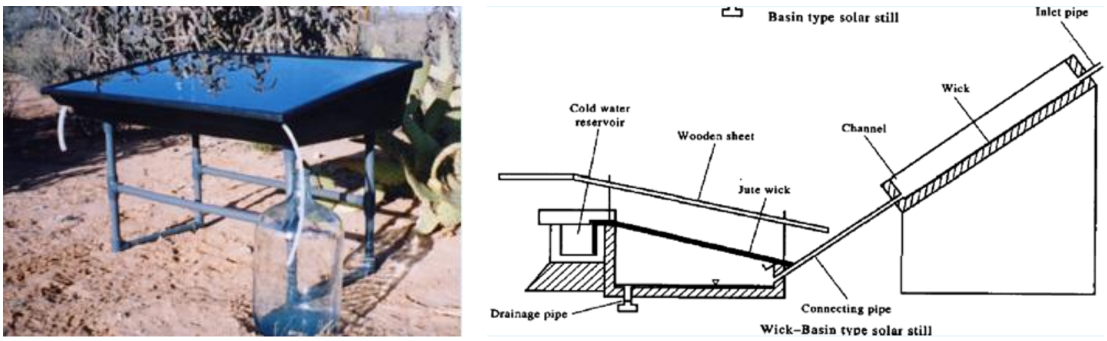


Figure 28 Solar water distillation system [18]

within a conventional roof type still and multiple effect diffusion still [17]. Projects on site include a tested distillation solution that has been designed by the Safe Drinking Water Foundation [18]. Its advantages are low maintenance, no energy costs, no moving parts, and it can be used at the household level. Its disadvantages are low water production (6 liters per sunny day), the materials could be hard to find in some areas, and not suitable for larger consumption if the distillation waste is not correctly disposed it can be a potential source of environmental pollution due to its high concentrations on salts and pollutants and it is solar energy dependent.

Other relevant solutions include experimental desalination designs. Most of them include a glass or plastic cover to benefit from the greenhouse effect, with one or two sides, with an inclination angle between 10º and 35º. These experiments provide important tangible information about the amount of distilled water produced, its maintenance, efficiency, and cost on a prototype scale. The knowledge obtained from these designs is useful to refine the numerical model to achieve a more realistic fit to the conditions whether it surpasses or not reaches the model expectations.

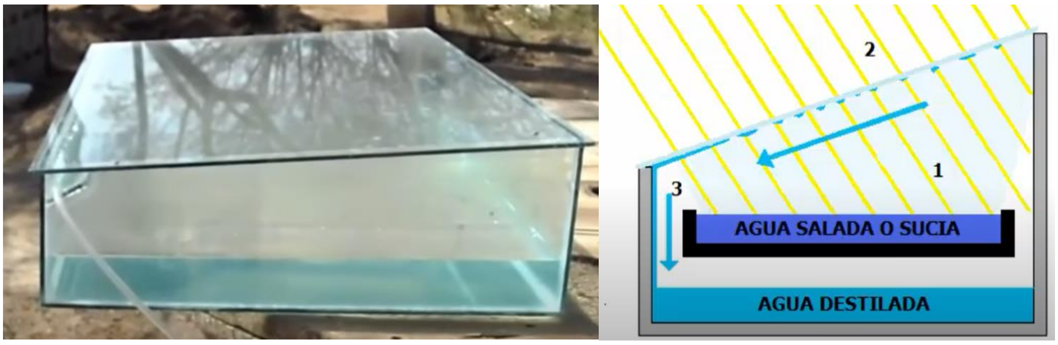


Figure 29 Experimental one sided still

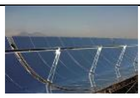
The models contain a basin to accumulate water, the walls are made from wood or glass. In the case of wood, it would need an insulator to prevent the wood from absorbing the water. Two water deposits, one for the sturdy water input and the other one for the distilled water outputted. And some tubing is made from plastic to transport the water in and out of the system.

Photovoltaic panels

Some of the desalination structures mentioned before cannot be sustained only through the greenhouse effect and require an additional input of power, in most cases using solar panels.

To provide energy for the water boilers, the most effective way would be using solar panels. There are four different solar panel technologies on the market for thermal solar purposes.

Table 4 PV Technologies

Thermal solar solutions	Image	Description	Efficiency	Losses	Applications	Market Presence
Flat panel		• Low temperature	+++	+++	Water heater in mild and warm conditions	94%
Vacuum tubes		• Medium and high temperature	++++	++	Industrial processes	4%
Polypropylene collector		• Low temperature • Flexible (plastic)	+	++++	Water heater for swimming pools	2%
Concentration		• High temperature	++++	++	Still experimental	~0%

The most relevant technological solution for our case will be the flat panel, it provides a good compromise between efficiency and losses, but the most relevant parameter is that it is the most accessible which will be the real constraint in our development. The power delivered depends on the efficiency of the panel, its area, and solar irradiation.

Similar PVs are used for Solar thermal energy purposes in Domestic Hot Water (DHW) systems. Solar thermal energy takes advantage of solar radiation to heat a fluid that is used to produce DHW, heating, pool heating... The installation of solar energy is commonly sized so that the accumulation of energy is demanded by users in a day; in those periods when there is not enough radiation, these systems have an extraordinary energy contribution. If they were to cover 100% of consumption, expensive, inefficient energy storage systems would have to be installed in the long run. Solar harvesting systems combine "the blackbody effect" with the "greenhouse effect" to make the most out of the ambient incident radiation and prevent heat losses. Several projects include this technology to increase the efficiency of the system.

Objectives and planning of the project

The objective of this project is to develop a system to obtain water from seawater for a small community of 300 people (around 60 families) who don't have the access to drinkable water. This drinkable water could be used for agricultural purposes, as well as for their livestock/cattle so the community can prosper and use the water for long-term growth. The system could also have the possibility to provide potable water solutions so that the community can benefit directly. These values have been provided by MMUU for a hypothetical development of the project however the solution could be parametrized for the better fitting of alternative circumstances.

According to the United Nations, the average number of liters of water consumed per day in an occidental country comes up to 150 l/day. In the case of Spain, it reaches up to 240 l/day. This number includes water for personal drinking and cleaning (washing…). The UN has determined that the minimum quantity of liters per day in a 3rd world condition environment would be 10% of what is needed in developed countries, therefore a basic consumption per person of 15 l/day. Out of this 15 l/day, 2 L are used for drinking and the rest for other necessities.

Table 5 Liters needed per day

Number of people in the community	**Liters per day**	**Total liters to provide (L/day)**
300	15	4500

Objective: to develop a drinkable water source for a rural community that has access to salted water. (Place icons instead of dots)

- 300 people (15L/ person)
- Water to produce:4500 L/day
- Distilled water salinity 36000 ppm
- Brine salinity: 76000 ppm
- Expected efficiency: 50%

Base Case

Location:

South of Mozambique (South of Gaza province):

-Water project previously carried out in 2017

-Water supply: Mozambique Channel- Indian Ocean

-Capital (Maputo) is also located to the south, which facilitates access to resources.

-Solar irradiation like that of Spain

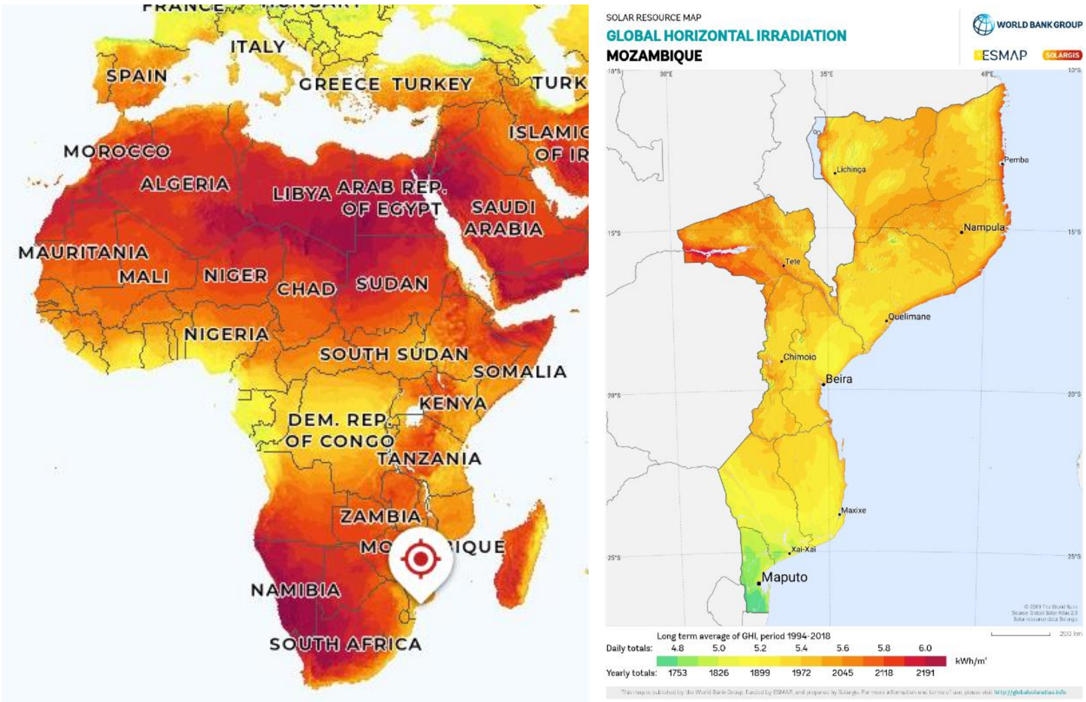
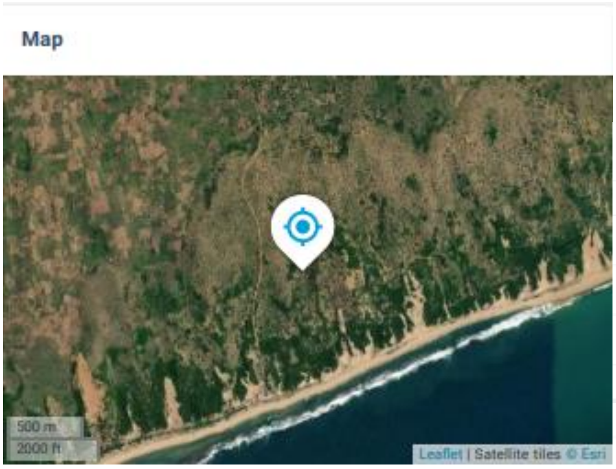


Figure 30 Project location



Map data			Per year
Direct normal irradiation	DNI	1769.1	kWh/m²
Global horizontal irradiation	GHI	1885.9	kWh/m²
Diffuse horizontal irradiation	DIF	717.6	kWh/m²
Global tilted irradiation at optimum angle	GTI opta	2041.3	kWh/m²
Optimum tilt of PV modules	OPTA	25 / 0	°
Air temperature	TEMP	23.6	°C
Terrain elevation	ELE	41	m

Figure 31 Project location II

Average hourly profiles

Direct normal irradiation [Wh/m²]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0 - 1												
1 - 2												
2 - 3												
3 - 4												
4 - 5												
5 - 6	24	1								5	76	81
6 - 7	220	184	125	102	60	18	16	55	140	188	219	238
7 - 8	320	333	318	307	326	299	278	294	296	284	296	328
8 - 9	400	413	412	411	457	454	422	427	397	371	385	409
9 - 10	479	489	484	477	540	533	507	510	471	449	466	492
10 - 11	532	546	536	511	568	572	548	558	525	501	507	546
11 - 12	566	576	553	517	568	563	557	578	546	522	519	571
12 - 13	568	585	560	517	564	551	549	580	554	526	525	578
13 - 14	571	587	563	514	553	541	537	569	548	513	525	570
14 - 15	537	559	540	500	513	500	498	527	518	460	485	528
15 - 16	476	490	452	400	422	410	417	442	411	376	414	462
16 - 17	382	391	336	155	72	68	132	166	210	208	315	365
17 - 18	155	151										137
18 - 19												
19 - 20												
20 - 21												
21 - 22												
22 - 23												
23 - 24												
Sum	5228	5306	4878	4411	4641	4508	4461	4705	4614	4404	4731	5305

Figure 32 Average hourly profiles

Mozambique has a rainy season, which coincides with the local summer, and a dry season, which coincides with the local winter. The rainy season starts in October and lasts until March. Starting in April, the chances of precipitation decrease rapidly. In most places, it hardly rains in winter. Mozambique sometimes experiences hurricanes. However, it is lucky that Madagascar acts as a kind of buffer that absorbs most tropical depressions before they can reach the country. However, in the period from late October to mid-March, you might experience heavy showers and storms with hurricane force.

The following figures show the weather comparison between Maputo and Madrid. The first two figures include the maximum and minimum temperature per month as it is seen Maputo has more stable conditions between the 20-30 ºC range throughout the year compared to the Madrid with a high peak on July-August and a low valley on December-January

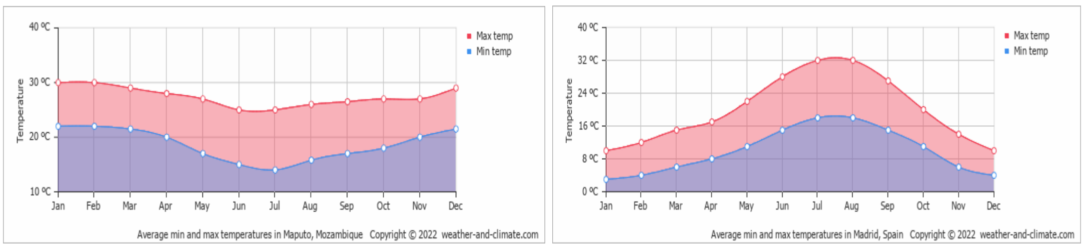


Figure 33 Ambient temperature (Maputo vs Madrid)

The sun hour graph is relevant as the project relies on solar irradiation to function. Although Madrid has a higher peak of sun hours the number of hours per year is about the same around 225 hours per month

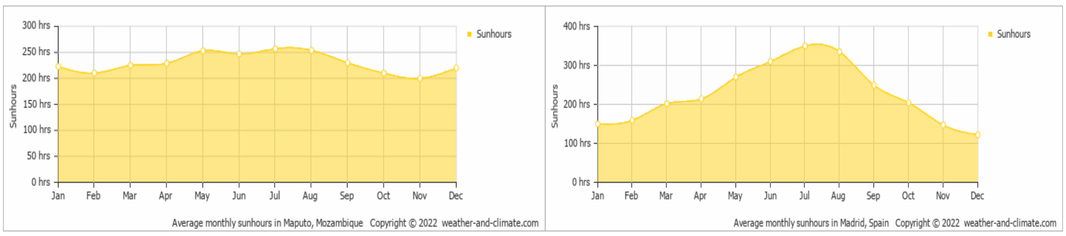


Figure 34 Sun hours (Maputo vs Madrid)

In terms of precipitation there are two relevant indicators: how many days does it rain and how much volume of rain does it fall in those days. On average there are 6 rainy days per month both in Madrid and in Maputo, however Maputo's rain is heavier reaching up to 100 mm compared to Madrids 60 mm.

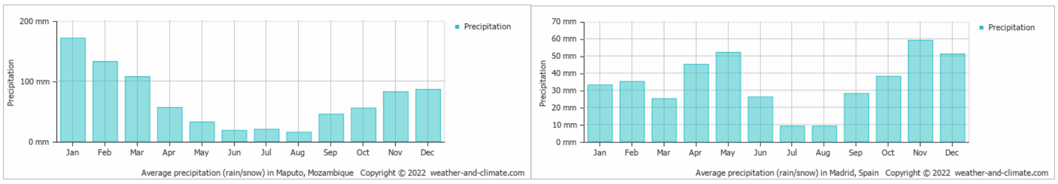


Figure 35 Average precipitation (Maputo vs Madrid)

Even though there are other locations with a better solar irradiance and higher temperatures Mozambique is a great approach since the solar irradiation is high enough, the drinkable water scarcity is a real issue and MMUU has already developed sanitation projects which will increase the chances that the development will be a success. [19]

PVSYST

One of the most widely used systems for the study of solar energy production is PVSYST. In this work, a study has been carried out with this program to estimate the energy production that could be obtained. The following assumptions have been made:

- Regarding orientation:
    - o Inclination of the solar panels 30º.
    - o Azimuth 0º (it reflects the angle of the panel with respect to the north of the planet).

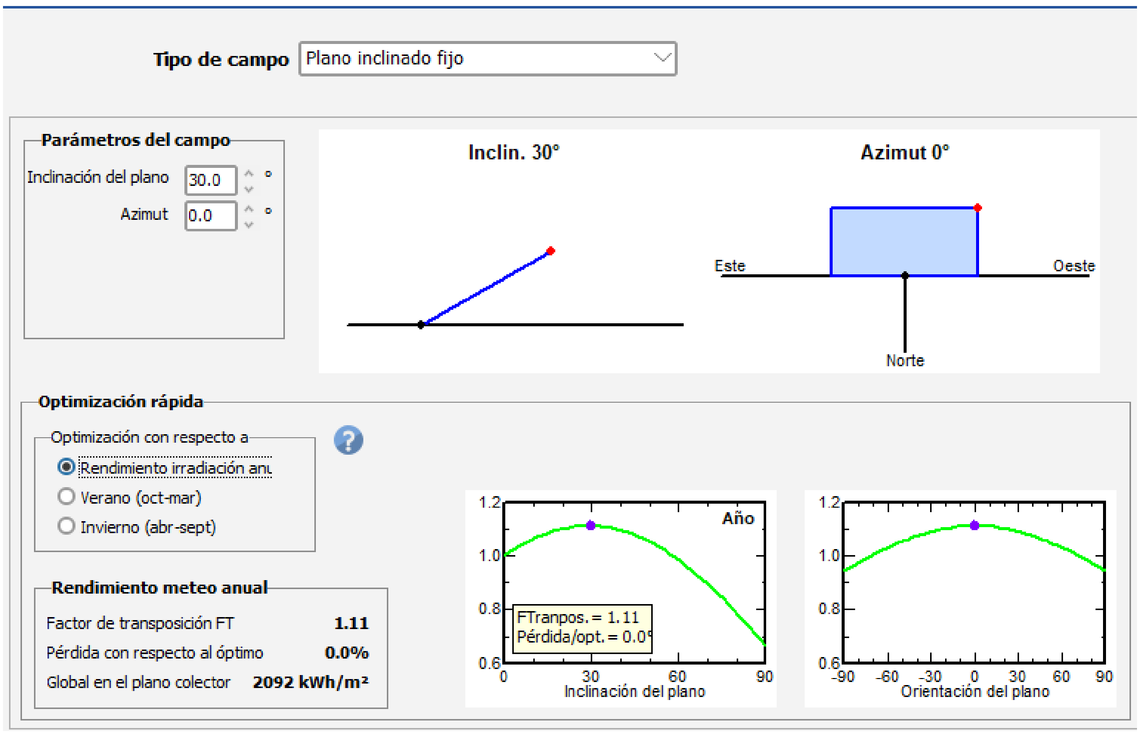


Figure 36 PVSIST

- User requirement (Loads). The following image represents the power consumption by MIT’s solution. It is divided into Stack, pumps, valves, UV, and degassifier which are all the parts in the solution which require additional power from the photovoltaic panels.

Table 6 MIT Solution: power requirements

Component	Power (W)
EDR Stack	1295.3
Feed Pump	370
Concentrate Recirculation Pump	250
Solenoid Valves and PLC	200
UV	42
Degassifier	24
Total	2181.3

The total consumption comes to 2181 W so it will be the number to estimate the power consumption of our installation as it is included in the program below.

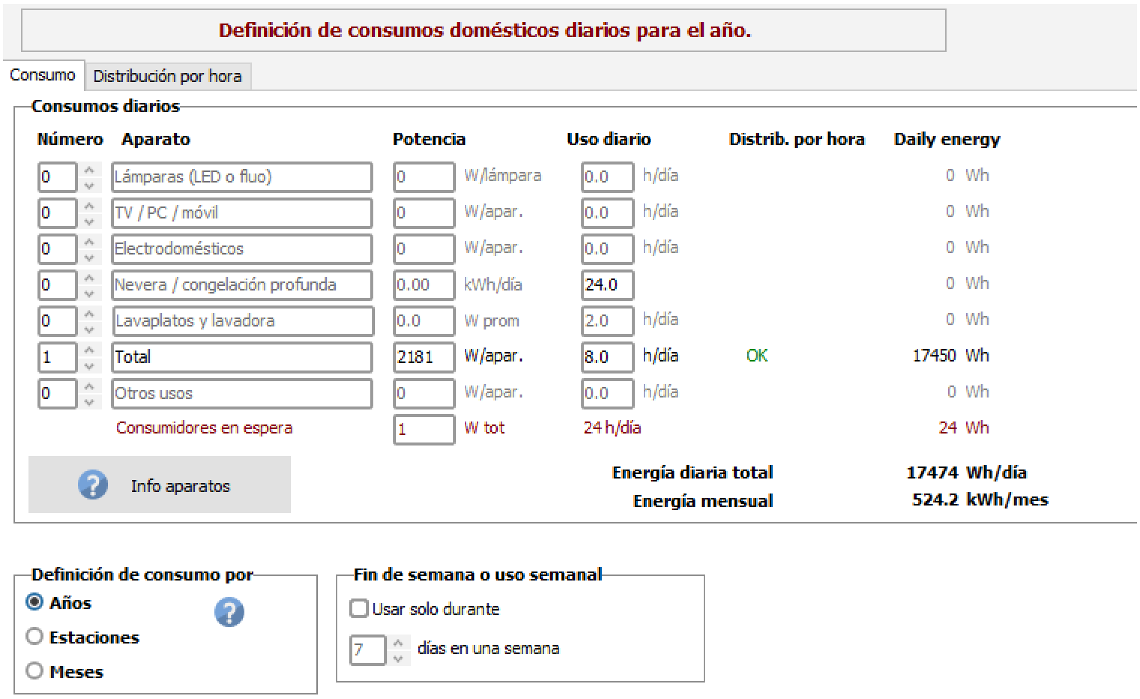
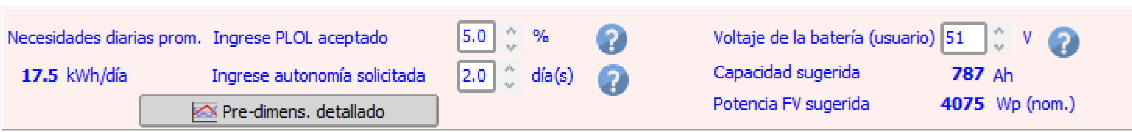
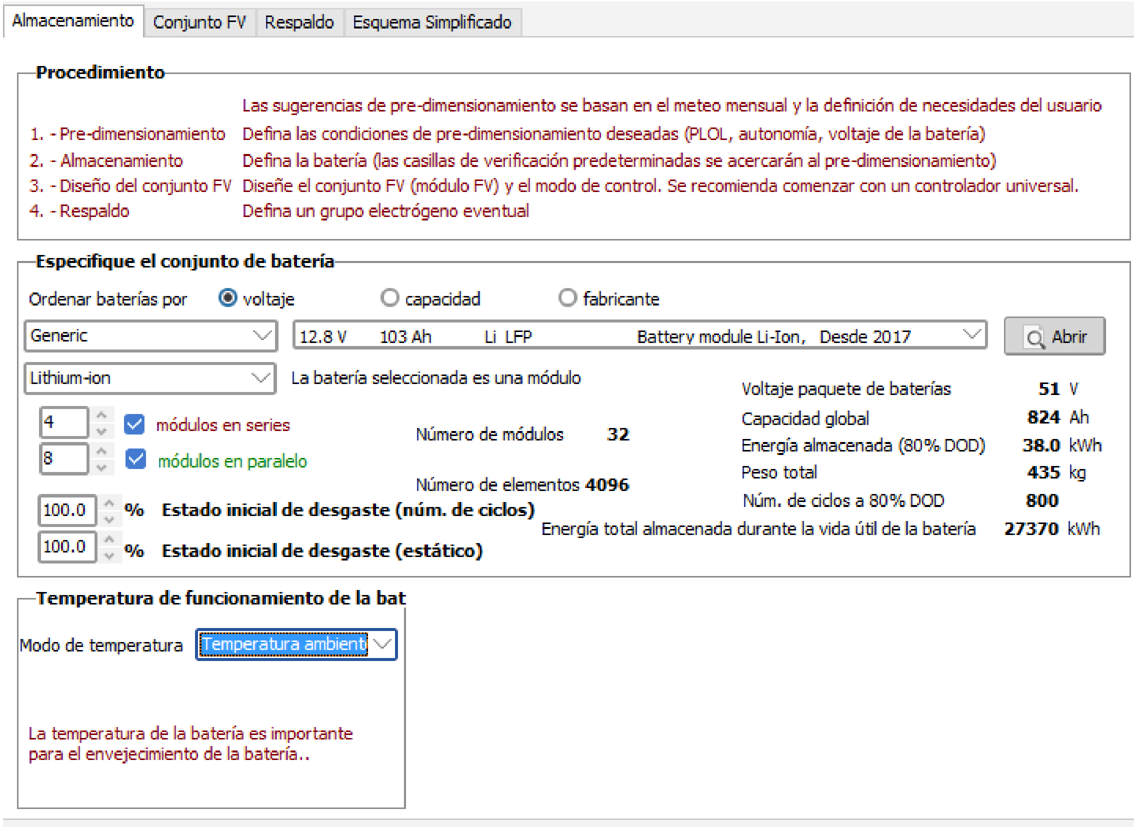
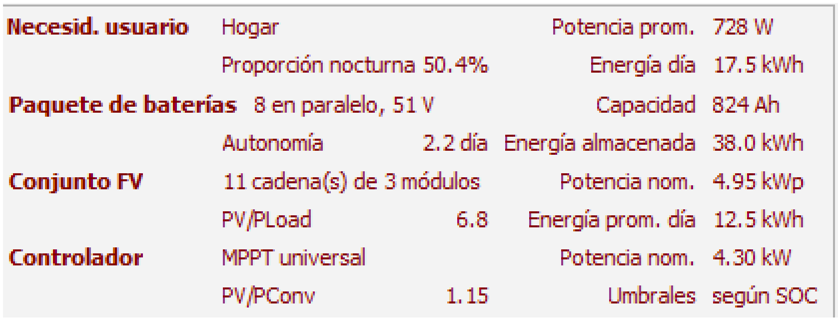


Figure 37 PVSIST: power consumption

- System







In conclusion, the average consumption would be 728 W. The battery stack would be a parallel 8 pack of 51V to provide an autonomy of 2.2 days. The PV/Load ratio would come to 6.8

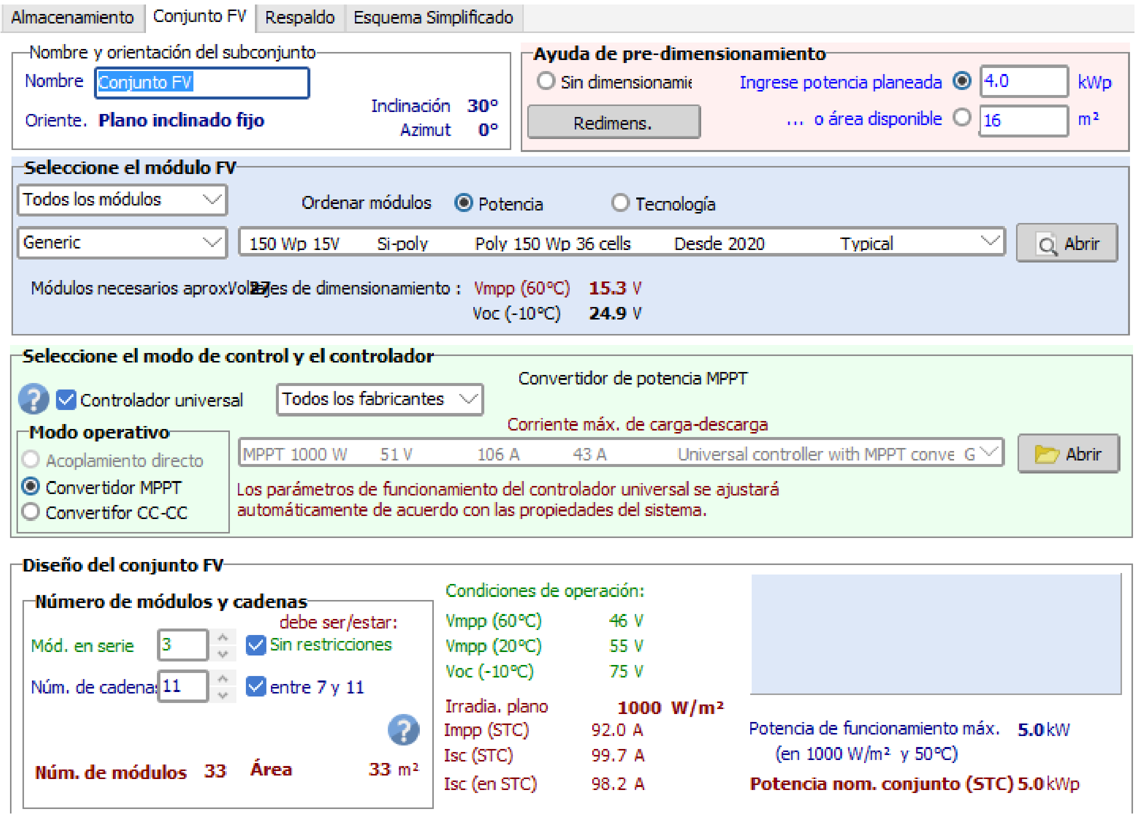


Figure 38 PVSIST Consolidation

With the configuration selected (30 deg incline, 4.KWp of power) we would need 33 modules with a total nominal power of 5Kwp

Water characteristics: seawater

Seawater is water that makes up the oceans and seas, covering more than 70 percent of Earth's surface. Seawater is a complex mixture of 96.5 percent water, 2.5 percent salts, and smaller amounts of other substances, including dissolved inorganic and organic materials, particulates, and a few atmospheric gases.

Seawater constitutes a rich source of various commercially important chemical elements. Much of the world's magnesium is recovered from seawater, as are large quantities of bromine. In certain parts of the world, sodium chloride (table salt) is still obtained by evaporating seawater. In addition, water from the sea, when desalted, can furnish a limitless supply of drinking water. Many large desalination plants have been built in dry areas along seacoasts in the Middle East and elsewhere to relieve shortages of fresh water.

Chemical and physical properties of seawater:

The six most abundant ions of seawater are chloride (Cl^-), sodium (Na^+), sulfate (SO_4^{2-}), magnesium (Mg^{2+}), calcium (Ca^{2+}), and potassium (K^+). By weight, these ions make up about 99 percent of all sea salts. The amount of these salts in a volume of seawater varies because of the addition or removal of water locally (e.g., through precipitation and evaporation). The salt content in seawater is indicated by salinity (S), which is defined as the amount of salt in grams dissolved in one kilogram of seawater and expressed in parts per thousand. Salinities in the open ocean have been observed to range from about 34 to 37 parts per thousand (0/00 or ppt), which may also be expressed as 34 to 37 practical salinity units(psu). [20]

The fact that it contains different salinity values affects the boiling point of the water. The higher the amount of salt, the more energy is needed for the water to evaporate. The oceans have an average salinity of 3.5% (35 g/l, 35 ppm). Taking the density of water as 1kg per liter means that for every kilogram of water there will be 35g of salt. The values and the graph for the increase in boiling point as a function of salinity are shown in more detail below. [21]

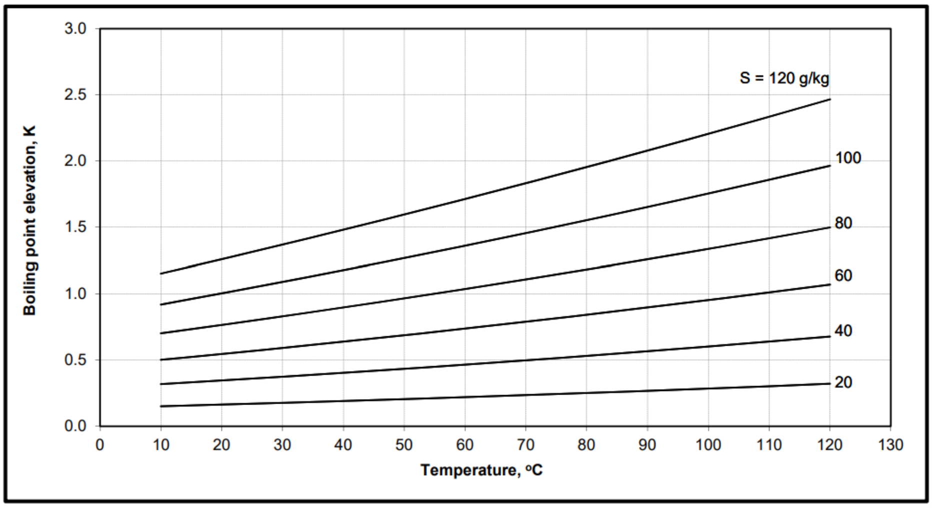


Figure 39 Boiling point increase due to salinity

Calculations

Although there are other places with better solar irradiation and higher temperatures, Mozambique is a great approach as the solar irradiation is high enough, the shortage of potable water is a real problem and MMUU has already developed sanitation projects that will increase the chances of the development being a success. The scope of the project includes the development of a mathematical model for the estimation of liters produced per day along with a prototype that is still under development and will serve to compare with real values the feasibility of the system.

Mathematical modeling

Modeling is one of the most important elements of thermal system design. Most systems are analyzed by considering equations that represent a physical process or behavior. We may also resolve to other means such as experimentation with a physical or scale model.

Nowadays, most engineers resort to some form of numerical modeling with a computer. This may be a simple process or system analysis software or may include a full numerical solution using Finite Element Analysis (FEA) or Computational Fluid Dynamics (CFD). However, these tools are both costly, monetarily and time-wise. Modeling of Systems and Components in engineering design we often encounter four types of models. These include Mathematical models, physical models, numerical models, and analog models. Each is discussed below.

Mathematical models

Represent the performance and behavior of a system employing equations that describe the physical phenomena. These types of models are the most important since they offer the greatest flexibility in the design process. Once constructed, they allow the system to be analyzed under many types of input conditions. This is an important issue for undertaking a system simulation or optimization

Physical Models

Are ones that represent the system closely and are used to obtain experimental data to model the performance of a real system. These models may be constructed at full scale or reduced scale. Often in the early design stages, a scale model is constructed to obtain some preliminary design data, while at the end of a design cycle a full scale (and usually operational) model or prototype is constructed. This is not always possible. In many cases where one kind of design is being constructed the final system is also the prototype. In other cases, it is not possible to build a complete scaled model. In some cases, a model which only satisfies certain elements of the system is built and tested under one set of conditions, while another model which represents other aspects of the system is built and tested under another set of conditions. These types of models are often referred to as distorted models since the system cannot be fully scaled under all conditions.

Numerical models

Are based on a mathematical model but are used when the equations describing the system cannot be solved easily using traditional methods. Often, the engineer must resort to numerical models for undertaking analysis of complex systems. Numerical models are conventionally based on a discretized form of the system equations. These most frequently occur in FEA and CFD simulations, where a system or component is broken down into tiny elements and the equations of elasticity of fluid dynamics are solved for the collective system of elements these approaches offer the engineer very detailed information but can be time-consuming to set up and run.

Analog models

Are based on analogy or similarity between physical phenomena. In fluid mechanics and heat transfer, their types of models are frequently used, i.e., thermal, and hydraulic circuit.

Mathematical modeling has been selected to represent the performance of simple basin solar still. Mathematical equations that describe the performance of each component of the system are presented in this chapter. The computer program is written in MATLAB and is presented in the appendix.

Design considerations of simple solar still

Many parameters must be considered when designing a solar distiller. Among these parameters are:

- Construction materials
- Transparent cover and slope
- Cover elevation Depth of basin
- Size of the distiller
- Insulating materials

Construction materials

A solar still can be constructed from a variety of materials and is likely to be governed by local construction materials, availability, and cost. For this work, wood will be used as the vessel for the solar still along with the help of insulating material to prevent water absorption. It was selected because of its availability in the local market and relatively cheap cost. It is easy to cut in a workshop.

Transparent cover and slope

The angle at which the transparent cover is set will govern the amount of the sun's direct radiation that is reflected in the atmosphere.

The angle will determine the area of the expensive transparent material that will be required to cover the given area of the basin. The amount of cover material necessary will decease as the angle at which its placed decrease. Reduce cover costs will have an important effect on the total cost of the still installation. Most recent designs have used a slope of between 10 and 15 degrees for glass covers, regardless of the latitude of the still

No universal rule can be given about the angle at which plastic covers should be placed because their wettability will vary from one material to another. During the process of designing a plastic covered still, a few simple experiments can establish the minimum angle at which water will collect and run down its inner surface.

Cover elevation

Experiments indicate that the design will be more efficient when the condensing surface of the cover is near the evaporating surface of the water. This distance should be held to a minimum but must be great enough for the collecting trough to be raised well above the brine surface so that there is no danger of accidental mixing. The cover must be high enough to allow opening in the end walls for maintenance and cleaning (need an optimum height). These factors combined with the angle at which the cover is set, and the dimensions of the materials used to support it will determine the practical minimum distance between cover and brine.

Depth of basin

The shallower the depth of water to be heated, the higher will be its temperature. The higher temperature of the water vaporized, the more efficient will be the distillation process. A depth of between 5cm-10cm is frequently used in stills. It's a depth sufficient to ensure that there will no dry over heated sports due to an uneven basin bottom

Insulation

The heat losses from the bottom of the basin to the ground can be cut considerably by providing an insulation layer beneath the basin. There are many insulating materials used, such as sand, fiber glass, and foam polystyrene. For this study, insulating tape will be the final material used.

Factors affecting the performance of solar distillers

For using solar energy to distill brackish and sea water to produce fresh water, there are many parameters affecting productivity. These can be summarized as:

- Solar radiation
- Ambient air temperature
- Wind velocity
- Depth of the brine in the basin
- Cover material and its shape
- Ground and surrounding losses

Solar radiation

The amount of solar radiation received by the solar distiller is the single most important factor affecting the performance. Distiller productivity depends on the intensity and duration of the radiation, which varies both by the hour of the day and by season. The daily output is directly proportional to solar radiation.

Ambient air temperature

A simple solar distiller operates most effectively when the surrounding air temperature is high. This implies both high water and a high condensing-surface temperature. This indicates the temperature effect on the efficiency of the solar distiller.

Wind velocity

The passage of wind over the cover of a solar distiller causes a series of reactions within the distiller that are complicated. The effect of the wind will be a function of the shape and orientation of the distiller concerning the wind direction. In general, the wind outside of the distiller will cool the condensing surface. This indicates the effect of wind velocity on the efficiency of the solar distiller. It harms productivity.

Depth of the brine in the basin

The shallower the depth of the water to be heated, the higher will be its temperature, and therefore the higher the temperature of the water is vaporized, the more efficient will be the distillation process.

Cover material and its shape

The type of cover material is affecting the productivity of the solar distiller, first through the absorption of solar radiation by the transparent cover. The second effect is the distance between the cover and the surface of the water.

Ground and surrounding losses

Heat can be lost to the surroundings and found particularly through the bottom of the basin. This can be reduced by well insulating the basin.

Basic hypotheses of simplification

To avoid complicating the study of this type of solar still, we allowed the following hypotheses:

- Temperatures of respectively the inner and the outer sides of the glass, of the brine, of the absorber, and inside the insulator are supposed uniform
- Water condensation on the cover is homogeneous and continuous
- Lateral sides are at constant pressure (adiabatic)
- Heat loss in the basin comes from the base
- Brine inside the basin is static
- The vault is considered a black body
- Physical properties of materials are considered constant
- Brine concentration does not intervene in the mass and heat transfer, from and to the brine. Finally, an analogy between thermal and electric dimensions has been carried out.
- The lost amount of water through evaporation is small compared to the amount of water in the basin and can be ignored.
- There is no leakage in a well-designed still.
- The areas of the cover, the water surface, and the still basin are equal.
- The temperature gradients along the cover thickness and the water depth are ignored.
- The reflected portion of the radiation is not considered as the reflectance of glass used is very week

The heat balances [22]

Keywords

c_w	specific heat of water, J Kg^{-1} K^{-1}
g	gravitational acceleration, m^2/s
G	global solar radiation intensity, Wm^{-2}
h	heat transfer coefficient, $Wm^{-2}K^{-1}$
k	thermal conductivity, $Wm^{-1}K^{-1}$
m_h	freshwater production, kg $h^{-1}m^2$
$\dot{m}$	mass flow rate, kg s^{-1} m^{-2}
P	partial pressure of water vapor at saturation temperature, Pa
T	temperature, K
V	wind velocity, ms^{-1}

Greek symbols

α	absorption coefficient, dimensionless
λ	latent heat of vaporization of water, J kg^{-1}
τ	transmittance coefficient, dimensionless

σ Stefan Boltzman constant, 56697 10^8, W m^{-2} K^{-4}

ε emissivity f a radiative surface, dimensionless

Subscripts

aext ambient air

aint greenhouse environment

c;$_{g\text{-}aext}$ convective loss between the cover and the ambient air

c;$_{g\text{-}w}$ convective loss between water and the cover

ew evaporative transfer between the water

g glass cover

r;$_{g\text{-}aext}$ radiative loss between the cover and the ambient air

r;$_{g\text{-}w}$ radiative loss between water and the cover

s sky

w water

wi water inlet

The following equations have been taken from S. U. o. C. Lotfi, "Performance of a solar still integrated in a greenhouse roof," 2009. [22]

The heat balance of the cover on the top is defined as:

$$\alpha_g G = h_{c,g-aext}(T_g - T_{aext}) + h_{r,g-aext}(T_g - T_{aext}) + h_{ew}(T_g - T_w)$$
$$+h_{r,g-w}(T_g - T_w) + h_{c,g-w}(T_g - T_w) \quad (7)$$

The following equations represent the radiation heat transfer coefficients:

$$h_{r,g-aext} = \varepsilon_{g-ext}\, \sigma(T_g{}^2 + T_s{}^2)(T_g + T_s) \quad (8)$$

$$h_{r,g-w} = \frac{\sigma(T_w{}^2 - g^2)(T_g + T_w)}{\frac{1}{\varepsilon_w} + \frac{1}{\varepsilon_{gi}} - 1} \quad (9)$$

The sky temperature can be obtained with the ambient temperature:

$$T_S = 0.0522\, T_{aext}{}^{3/2} \quad (10)$$

The convection heat transfer coefficient is described as followed:

$$h_{c;g-w} = 0.884[(T_w - T_g) + \frac{(p_w - p_g)}{(277{,}900 - p_w) * T_w}]^{1/3}$$

(11)

The partial pressure can be related to the temperature through the following equation:

$$p = 293.3\,T - 84{,}026.4$$

(12)

The evaporation heat transfer coefficient is described as followed:

$$h_{ew} = 7\;10^{-9}\;\; h_{c;g-w}\;\; \frac{(p_w - p_g)\lambda}{(T_w - T_g)}$$

(13)

The convection heat transfer coefficient between the glass and the exterior can be expressed as

$$h_{c;g-aext} = 2.8 + 3.0\; v_{aext}$$

(14)

The heat balance between the water and the environment inside the still:

$$\alpha_w \tau_w G - 2\dot{m}_w c_w (T_w - T_{wi}) = h_{e,w}(T_w - T_g) + h_{r,w-g}(T_w - T_g) + h_{c,w-g}(T_w - T_g)$$

(15)

The temperature inside the greenhouse can be described as followed:

$$T_{aint} = 20.87 + 0.940\; T_{aext}$$

(16)

Considering that the irradiation remains constant over one hour periods the water production can be described as follows

$$m_h = 16.273\;10^{-3}\; h_{c;w-g}\;\; \frac{(p_w - p_g)}{\lambda}\;\; 3600$$

(17)

Finally, the water produced in a day can be expressed as the sum of the hourly production in a day

$$m_{day} = \sum_{0}^{24} m_h$$

(18)

The study will be divided into three scenarios (best, average, and worse) according to the data obtained from Solcast source. [23] The data collection includes 2021 meteorological values for the selected Mozambique location. Amongst the variables from the data source the variables that have an impact are the hourly irradiation, the hourly ambient temperature, and the hourly wind speed.

Without additional Power from solar panels

Best case scenario

The maximum values reached per hour for each month for irradiance, temperature, and wind speed are included below. Irradiance values are shown in the form of a bell, reaching a maximum at 11 am (analyzing the monthly average) with a value of 1090.

For the chosen location, significant irradiance values begin to be appreciated from 6-7 am until 3-4 pm. In some summer months (December-January) solar irradiation is detected from 4 am to 6 pm.

Table 7 Hourly Irradiation

Max of GHI	Month											
Hour	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	1	1
5	71	15	5	1	0	0	0	0	10	61	96	94
6	278	171	121	77	42	17	17	53	148	278	313	305
7	509	430	360	309	233	162	170	259	394	523	543	531
8	723	652	582	530	433	349	368	477	619	738	751	730
9	903	837	770	714	598	504	537	656	794	904	915	923
10	1030	960	905	819	709	612	655	776	909	1007	1021	1031
11	1090	1038	975	835	756	660	710	828	954	1039	1060	1073
12	1078	1039	968	845	735	645	701	813	924	997	1030	1043
13	994	966	901	768	647	569	631	728	822	882	931	945
14	847	828	759	627	502	437	500	580	658	717	772	792
15	654	639	582	455	320	263	319	384	448	503	570	584
16	429	414	351	229	112	74	119	168	214	266	327	357
17	200	178	119	36	3	0	3	14	28	57	101	148
18	24	16	2	0	0	0	0	0	0	0	3	13
19	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0

The following graph reflects the average daily value for the best-case scenario

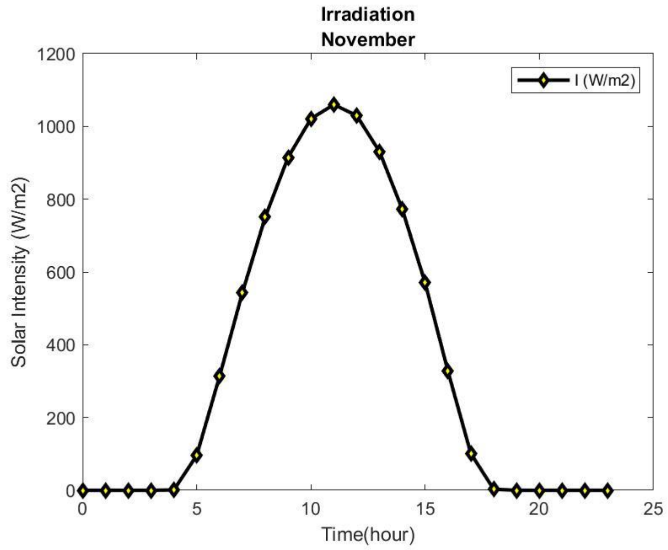


Figure 40 November Irradiation Best case scenario

In the same way, the average maximum values of ambient temperature per hour and month are presented. This temperature is related to the solar irradiation data; however, the highest values are reached between 1-2 pm, reaching 40.5 ºC in November according to data obtained in 2021.

Unlike the solar graph, the temperature values do not present exaggerated peaks and valleys, but rather a stable temperature close to 30 ºC.

Table 8 Hourly ambient temperature

Max of Tamb	**Month**											
Hora	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
0	26.7	26.1	24.7	22.4	22.9	21.1	20.6	23	23.6	26.5	28	26.7
1	26.3	26.1	24.4	22.2	22.9	21	20.6	22.3	23	26.1	26.8	26.1
2	26.4	26	23.9	21.9	22.8	20.6	20.5	21.6	22.2	25.6	26	25.5
3	26.5	26	23.6	21.8	23.1	20.5	20.5	21.3	21.6	25.2	25.8	25.3
4	26.5	25.9	23.6	21.9	23.5	20.5	20.5	21.1	21.5	24.8	25.5	25
5	26.2	25.9	23.8	22	23.4	20.5	20.5	20.9	21.4	25	25.8	25.6
6	27.1	26.1	24.3	22.7	23.1	20.5	20.6	20.9	22.3	26.6	27.9	27.7
7	29.4	27.9	25.6	24.4	23.5	21.1	21.3	21.8	24.8	29.2	30.7	30.4
8	31.6	29.9	27.4	26.1	24.2	22.7	23	24.4	27.8	31.7	33.4	32.6
9	34	31.6	29.4	27.2	26.1	23.7	24.2	26.9	30.2	34	35.8	34.6
10	35.9	33.1	31.4	28.8	28.7	25.9	26.3	29.4	32.3	35.8	37.8	36.4
11	35.9	34.3	32.8	30.4	30.8	27.8	28.4	31.3	34	37	39.4	37.5
12	36.1	35.7	33.2	31.4	32.1	29.2	29.9	32.7	35.1	37.6	40.5	37.5
13	36.9	35	34	32	32.7	30	30.8	33.3	35.7	37.6	40	38.1
14	37.2	32.2	34.3	32	32.8	30.3	31.1	33.3	34.1	37.5	37.5	38.1
15	36.9	31.2	33.7	31.4	31.9	29	30.2	33.1	31.3	37	35.6	34.5
16	35.5	29.5	32.3	29.3	29.1	26.2	27.3	31.8	28.7	35.1	33.6	30.6
17	33.8	28.1	30	26.4	26	23.5	24.6	28.7	25.9	31.1	31.1	30.1
18	32.7	27.3	27.8	24.8	24.6	22.4	23.4	26.5	23.9	28.5	28.5	28.7
19	31.4	27.2	26.6	24.2	23.8	21.8	22.5	25.6	24.1	28.7	27.7	28
20	29.7	27	26.1	24	22.9	21.5	21.8	25.6	25	29.1	29.2	28.5
21	28	26.7	25.4	23.6	22.7	21	21.7	24.9	24.8	28.4	30.7	28.7
22	27	26.5	24.9	23.2	23	20.8	21.2	24.6	24.2	27.6	30	28
23	26.6	26.3	24.9	22.7	23.2	20.8	20.8	23.8	23.9	27	28.9	27.2

Finally, wind speed data are included for the future calculation of methacrylate and water temperatures inside the model.

Table 9 Hourly wind velocity

Max of WindVel								Month				
Hour	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
0	10.6	11.6	6.5	8	7.8	10.8	8.4	13	8	10	8.1	9.1
1	10.4	11.4	6.5	7.7	8	11.9	8	12.4	7.3	10.5	7.6	9.1
2	10	11.6	6.3	7.4	8	12.3	7.4	12	7.5	10.7	7.3	9.5
3	9.8	11.4	6.3	7.2	8	12.2	7.2	11.8	8	10.8	7	9.9
4	9.8	11.1	6.8	6.7	8	11.9	7.5	11.4	8	11	6.9	9.7
5	9.9	11	7.2	6.1	8.1	11.5	7.5	10.6	8.7	11.6	6.7	9.3
6	10	10.9	7.3	6	7.9	11.2	7.4	9.8	8.6	12	6.7	9.1
7	9.7	11.9	7.8	6.3	7.9	10.6	7.6	9.7	9	12	7.2	8.7
8	9.3	13.4	8	8.7	7.9	10	7.9	9.5	9.4	11.6	7.3	8.1
9	9	14.5	7.8	9.3	7.8	9.4	8.2	8.9	9.2	11	7.3	7.7
10	8.9	14.8	7.5	9.9	7.6	9.2	8	8.7	8.7	10.4	7.8	8.5
11	8.7	14.7	7.6	10.5	7	9.1	7.9	8.5	8.3	9.8	8.9	10
12	8.5	14.5	7.7	11	7.2	9	8	8.6	8.6	9.5	9.3	10.7
13	8.4	14.3	7.6	11.1	7.6	9.1	8.1	8.6	9.7	9.2	9	10.6
14	8.2	14.1	7.5	11.1	7.6	9.3	7.9	8.4	9.6	9.1	9.1	10.4
15	8.2	14	7.2	10.8	7.5	9.2	7.6	8.5	9.1	9.2	10.2	10.3
16	8.7	13.8	6.6	10.3	7.4	8.9	7.2	9	8.5	9.1	10	10.4
17	9.5	13.4	6.3	10.1	7.6	8.7	8.2	9.7	8	9.1	10.6	10.4
18	10.1	13	6.3	9.7	7.7	9.8	8.8	10.8	7.9	9.3	10.5	10.3
19	10.2	12.9	6.1	9.6	7.5	10.4	8.6	11.3	8	9.3	10.5	10.3
20	10.2	12.4	6.1	9.4	7.3	10	8.2	11.8	8.2	9.1	10.4	10.1
21	10.4	11.7	6.4	8.9	7.2	9.7	8.2	12.5	8.2	8.6	10.7	9.8
22	10.5	11.6	6.5	8.6	7.3	10.2	8.5	12.9	8.2	8.1	10.5	9.5
23	10.5	11.6	6.5	8.2	7.5	10.4	8.5	13.2	8.2	8.8	9.2	9.3

Mathematical model results:

The model has been developed according to the energy and mass balance equations provided by the studies "Thermodynamics of a Shallow Solar Sill" and "Development of empirical relation to evaluate the heat transfer coefficients and fractional energy basin type hybrid (PV/T) active solar still".

It is assumed that the system will only be in production during the hours of the highest solar radiation (9h-18h).

Best case scenario

The results obtained reflect little difference in the levels of distilled water production from month to month with an average of 1.3 L/m2 per day, which reflects a weak production compared to the needs of the community, so it is interesting to carry out a study with additional energy supply, for example with the use of a resistance. This small difference in production can also be seen because, as shown in previous figures, radiation levels at peak hours are practically constant throughout the year.

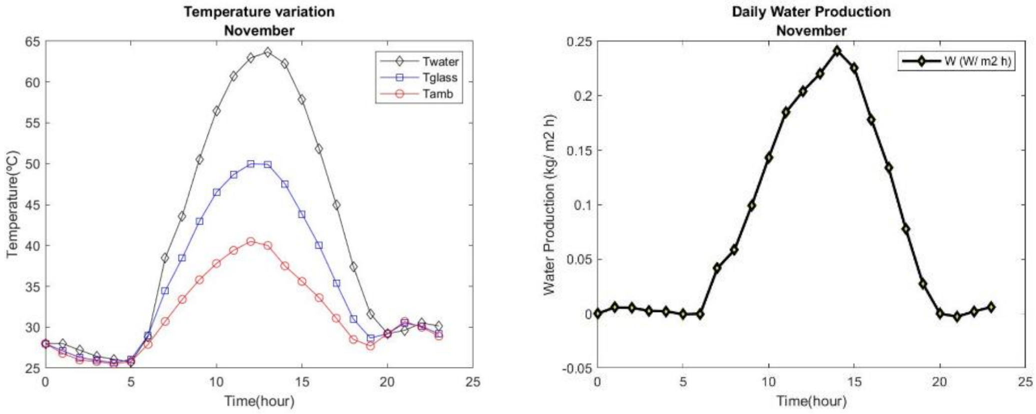


Figure 41 November Temperature and Water Production Best case scenario

Table 10 Average water production per month

HOUR	JANUARY	FEBRUARY	MARCH	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER	OCTOBER	NOVEMBER	DECEMBER
00:00	0	0	0	0	0	0	0	0	0	0	0	0
01:00	0.0014	0	0.00E+00	0.00E+00	0	0.00E+00	0	0.0031	0.0023	0.0014	0.0056	0.0024
02:00	0	0.00E+00	0.0022	0.0012	0.00E+00	0.0016	0.00E+00	0.0042	0.0044	0.0025	0.0055	0.0034
03:00	0	0	0.0018	0.00E+00	0	0.00E+00	0	0.0023	0.0042	0.0024	0.0024	0.0017
04:00	0	0.00E+00	0.00E+00	0	0	0.00E+00	0	0.0014	0.0015	0.0024	0.0021	0.0017
05:00	0.00E+00	0	0	0	0	0	0	0.0012	0.00E+00	0	0	0
06:00	0.0034	0	0	0	0.00E+00	0	0	0	0	0	0	0
07:00	0.027	0.0282	0.004	0	0.001	0	0	0.0024	0.0012	0.0451	0.0416	0.0358
08:00	0.061	0.0553	0.0459	0.0383	0.0359	0.0161	0.011	0.0233	0.0544	0.0615	0.0584	0.0608
09:00	0.0972	0.1039	0.0745	0.0794	0.0519	0.0474	0.0495	0.0535	0.0786	0.1043	0.0989	0.0982
10:00	0.1403	0.145	0.11	0.1155	0.0749	0.0647	0.0695	0.0863	0.115	0.1436	0.1431	0.1508
11:00	0.1938	0.1767	0.1503	0.1434	0.0993	0.0898	0.0939	0.1184	0.1464	0.1759	0.1847	0.1992
12:00	0.217	0.1945	0.1861	0.1585	0.1274	0.1087	0.1168	0.1429	0.1762	0.1998	0.2041	0.2287
13:00	0.2181	0.2293	0.1906	0.1692	0.1433	0.1196	0.1292	0.1573	0.1949	0.2085	0.2203	0.2182
14:00	0.2123	0.2548	0.1905	0.1668	0.1387	0.1175	0.128	0.1551	0.2023	0.1971	0.2412	0.208
15:00	0.1983	0.2111	0.1781	0.1486	0.1268	0.1133	0.1216	0.1373	0.1916	0.1756	0.2252	0.2296
16:00	0.1821	0.178	0.1563	0.1344	0.1171	0.1007	0.1139	0.1157	0.1537	0.1509	0.178	0.2072
17:00	0.145	0.1257	0.1284	0.103	0.0839	0.0639	0.0828	0.0922	0.1081	0.1299	0.1338	0.12
18:00	0.0853	0.0646	0.0826	0.046	0.0376	0.0274	0.0349	0.0473	0.0547	0.0714	0.0779	0.0697
19:00	0.0371	0.0165	0.0372	0.0169	0.0177	0.0122	0.0169	0.0196	0.0155	0.0184	0.0275	0.0255
20:00	0.0234	0.0054	0.0166	0.0065	0.0119	0.0056	0.0099	0.0057	0.00E+00	0.0037	0	0.004
21:00	0.0194	0.0034	0.0107	0.0045	0.0052	0.0047	0.0039	0.0064	0.0021	0.0058	0	0.00E+00
22:00	0.0124	0.002	0.0068	0.0036	0.00E+00	0.0024	0.0041	0.0034	0.0038	0.0063	0.002	0.0042
23:00	0.006	0.0015	0.0024	0.0036	0	0.00E+00	0.0033	0.0056	0.0025	0.0052	0.0061	0.0054
TOTAL PER DAY	**1.8805**	**1.796**	**1.575**	**1.3393**	**1.0725**	**0.8956**	**0.9892**	**1.1846**	**1.5132**	**1.7117**	**1.8584**	**1.8744**

Average case scenario

Table 11 Average water production per month

HOUR	JANUARY	FEBRUARY	MARCH	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER	OCTOBER	NOVEMBER	DECEMBER
00:00	0	0	0	0	0	0	0	0	0	0	0	0
01:00	0	0	0.00E+00	0.00E+00	0	0.00E+00	0	0	0	0	0	0
02:00	0	0.00E+00	0	0	1.20E-03	0	0.00E+00	0	0.0012	0.0012	0	0.001
03:00	0	0	0	0.00E+00	0.0013	0.00E+00	0	0.0011	0.0012	0.0011	0	0.001
04:00	0	0.00E+00	0.00E+00	0	0.001	0.00E+00	0	0.0011	0.0012	0	0	0
05:00	0.00E+00	0	0	0	0	0	0	0	0.00E+00	0	0	0
06:00	0	0	0	0	0.00E+00	0	0	0	0	0	0	0
07:00	0.0036	0	0	0	0	0	0	0	0	0	0.0028	0.0029
08:00	0.0341	0.0273	0.0115	0.0017	0.0017	0	0	0	0.0107	0.0295	0.0308	0.0256
09:00	0.059	0.0449	0.0468	0.0408	0.0412	0.0301	0.035	0.0395	0.0452	0.0496	0.0582	0.0482
10:00	0.0996	0.0772	0.0854	0.0653	0.0645	0.0463	0.0491	0.0585	0.0742	0.0826	0.0961	0.086
11:00	0.133	0.108	0.1203	0.0973	0.0872	0.0694	0.0742	0.0863	0.1031	0.1108	0.1292	0.1142
12:00	0.1605	0.1178	0.1526	0.1264	0.1057	0.0851	0.0936	0.1039	0.129	0.1235	0.1566	0.1387
13:00	0.1664	0.1265	0.1667	0.1409	0.1139	0.0935	0.1043	0.1127	0.1508	0.1314	0.1663	0.1508
14:00	0.1677	0.131	0.1677	0.1457	0.1145	0.095	0.1095	0.1169	0.1569	0.1359	0.1693	0.1529
15:00	0.1525	0.1172	0.1526	0.1325	0.105	0.0864	0.1019	0.1082	0.1408	0.1201	0.1486	0.1399
16:00	0.1222	0.0912	0.1315	0.1085	0.0912	0.078	0.0881	0.0916	0.1121	0.0968	0.1203	0.1156
17:00	0.0918	0.0672	0.1001	0.0767	0.0608	0.0523	0.0595	0.0657	0.0757	0.0726	0.0846	0.0829
18:00	0.0601	0.0397	0.0584	0.0402	0.0296	0.0257	0.0295	0.0341	0.036	0.0388	0.0434	0.0495
19:00	0.0277	0.0159	0.0269	0.0189	0.0141	0.013	0.0137	0.0156	0.015	0.0152	0.016	0.0205
20:00	0.0118	0.0061	0.0126	0.0096	0.0077	0.0073	0.0071	0.0075	6.90E-03	0.0063	0.006	0.0078
21:00	0.006	0.0026	0.0067	0.0057	0.005	0.0047	0.004	0.0048	0.004	0.0035	0.0036	4.10E-03
22:00	0.0037	0.0015	0.0042	0.004	3.40E-03	0.0033	0.0027	0.0043	0.003	0.003	0.003	0.0032
23:00	0.0026	0.0011	0.003	0.0032	0.0023	2.50E-03	0.002	0.0034	0.0028	0.0029	0.0025	0.0028
TOTAL PER DAY	**1.3021**	**0.9753**	**1.247**	**1.0175**	**0.8515**	**0.6925**	**0.774**	**0.8552**	**1.0697**	**1.0249**	**1.2374**	**1.1478**

Worst case scenario

Table 12 Average water production per month

HOUR	JANUARY	FEBRUARY	MARCH	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER	OCTOBER	NOVEMBER	DECEMBER
00:00	0	0	0	0	0	0	0	0	0	0	0	0
01:00	0	0	0.00E+00	0.00E+00	0	0.00E+00	0	0	0	0	0	0
02:00	0	0.00E+00	0	0	0.00E+00	0	0.00E+00	0	0	0	0	0
03:00	0	0	0	0.00E+00	0	0.00E+00	0	0	0	0	0	0
04:00	0	0.00E+00	0.00E+00	0	0	0.00E+00	0	0	0	0	0	0
05:00	0.00E+00	0	0	0	0	0	0	0	0.00E+00	0	0	0
06:00	0	0	0	0	0.00E+00	0	0	0	0	0	0	0
07:00	0	0	0	0	0	0	0	0	0	0	0	0
08:00	0	0	0	0	0	0	0	0	0	0	0	0
09:00	0	0	0	0	0	0	0	0	0	0	0.0042	0
10:00	0.0133	0	0.0058	0.0056	0.0207	0	0	0.0084	0.0138	0.0115	0.0124	0.0168
11:00	0.0123	0.0233	0.0266	0	0.0198	0.0177	0.0082	0.0197	0.0211	0.0092	0.0235	0.022
12:00	0.0077	0.0237	0.066	0.0192	0.0365	0.0105	0.0152	0.0195	0.0228	0.0109	0.0374	0.026
13:00	0.0059	0.0168	0.061	0.0385	0.0497	0.0151	0.0243	0.0292	0.0272	0.0205	0.0378	0.014
14:00	0.0111	0.0214	0.0905	0.0306	0.0494	0.0145	0.0256	0.0406	0.0346	0.0153	0.0398	0.0139
15:00	0.0099	0.0287	0.0945	0.0222	0.0469	0.0074	0.0241	0.0211	0.0215	0.0113	0.0263	0.0117
16:00	0.0112	0.0232	0.0696	0.0125	0.0364	0.0123	0.0224	0.0192	0.0161	0.0063	0.0223	0.0136
17:00	0.0083	0.0173	0.0592	0.0084	0.0259	0.0075	0.0175	0.0133	0.0122	0.008	0.0201	0.0082
18:00	0.005	0.0119	0.0381	0.0082	0.0165	0.0041	0.013	0.0135	0.0092	0.0096	0.0163	0.0073
19:00	0	0.0055	0.0214	0.0064	0.009	0	0.008	0.0057	0.0056	0.0053	0.0091	0
20:00	0	0	0.0117	0	0.0056	0	0.0041	0.0052	5.10E-03	0	0	0
21:00	0	0	0.0067	0	0.0067	0	0	0	0	0	0	0.00E+00
22:00	0	0	0.0051	0.0041	5.40E-03	0	0	0	0	0	0	0
23:00	0	0	0	0	0	0.00E+00	0	0	0	0	0	0
TOTAL PER DAY	**0.0848**	**0.1718**	**0.5561**	**0.1557**	**0.3284**	**0.0891**	**0.1624**	**0.1955**	**0.1893**	**0.1079**	**0.2491**	**0.1334**

With additional Power from resistance connected to solar panels

Table 13 Average water production per month

HOUR	JANUARY	FEBRUARY	MARCH	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER	OCTOBER	NOVEMBER	DECEMBER
00:00	0	0	0	0	0	0	0	0	0	0	0	0
01:00	0	0	0.00E+00	0.00E+00	0	0.00E+00	0	0	0	0	0.0056	0
02:00	0	0.00E+00	0	0	0.00E+00	0	0.00E+00	0.0042	0.0044	0	0.0055	0
03:00	0	0	0	0.00E+00	0	0.00E+00	0	0	0.0042	0	0	0
04:00	0	0.00E+00	0.00E+00	0	0	0.00E+00	0	0	0	0	0	0
05:00	0.00E+00	0	0	0	0	0	0	0	0.00E+00	0	0	0
06:00	0	0	0	0	0.00E+00	0	0	0	0	0	0	0
07:00	0.027	0.0282	0.004	0	0	0	0	0	0	0.0451	0.0416	0.0358
08:00	0.3275	0.3515	0.3718	0.3908	0.4116	0.4438	0.3538	0.3838	0.4559	0.3258	0.2857	0.3033
09:00	0.3397	0.3641	0.3322	0.3547	0.3254	0.3227	0.3128	0.307	0.3543	0.3462	0.333	0.3336
10:00	0.3884	0.406	0.3567	0.3804	0.324	0.3164	0.3179	0.3311	0.3658	0.3906	0.394	0.4065
11:00	0.4508	0.4408	0.4053	0.4111	0.3423	0.3418	0.3436	0.3682	0.3978	0.4284	0.4538	0.4755
12:00	0.4792	0.4602	0.4491	0.4294	0.3834	0.365	0.3736	0.4015	0.4395	0.4593	0.4743	0.5075
13:00	0.4831	0.5016	0.4548	0.4396	0.4101	0.3823	0.3916	0.4208	0.4739	0.4722	0.4877	0.4903
14:00	0.4781	0.5345	0.4565	0.4382	0.4058	0.3851	0.3907	0.4199	0.4783	0.4645	0.5171	0.4783
15:00	0.4679	0.4891	0.4435	0.4185	0.3949	0.3834	0.3858	0.4064	0.4653	0.4469	0.5147	0.508
16:00	0.4612	0.4555	0.418	0.4052	0.3898	0.3731	0.3815	0.3927	0.4243	0.4237	0.4574	0.491
17:00	0.4302	0.3989	0.3938	0.3773	0.3617	0.3354	0.3688	0.3771	0.3773	0.4086	0.418	0.3944
18:00	0.3649	0.3303	0.3518	0.3109	0.3078	0.3037	0.3127	0.3312	0.3225	0.3474	0.3537	0.3394
19:00	0.3052	0.272	0.2987	0.2756	0.2781	0.2807	0.2807	0.2899	0.2741	0.2771	0.2912	0.2871
20:00	0.2886	0.2551	0.2745	0.2593	0.269	0.2609	0.2658	0.2654	2.50E-01	0.2515	0.241	0.252
21:00	0.2858	0.2507	0.2718	0.2537	0.2581	0.2585	0.2573	0.2695	0.2526	0.2542	0.2293	2.45E-01
22:00	0.2743	0.2514	0.2648	0.2531	2.50E-01	0.26	0.2623	0.2616	0.2576	0.2548	0.2509	0.2539
23:00	0.2618	0.2519	0.2546	0.2526	0.2494	2.55E-01	0.259	0.2663	0.2552	0.2647	0.2513	0.258
TOTAL PER DAY	**6.1138**	**6.0417**	**5.8018**	**5.6504**	**5.3617**	**5.2676**	**5.2577**	**5.4967**	**5.8527**	**5.8609**	**6.0057**	**6.0597**

Design

Distillation system

The solution proposed is composed of four parts: the main frame/pool, the glass cover, joints and adhesive, and finally the legs. A visual representation is shown below

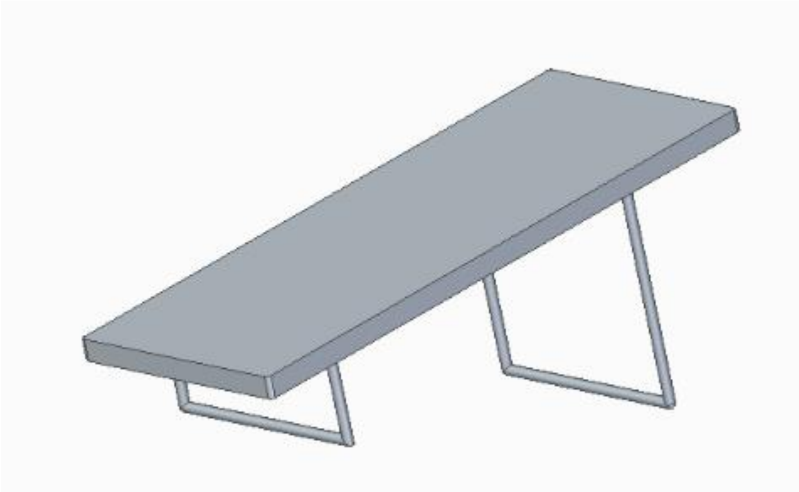


Figure 42 Solid Edge Still design

Moreover, a prototype has been designed and built to obtain experimental results that will provide valuable information to be compared with the mathematical model. The idea is to develop a scale model and then extrapolate the results obtained to the needs of our project. Unlike the final model supported by solar panels and pumps in this case the water flow will be determined by the height of our water intake and the valve setting.

The prototype has 4 phases

1. Input and sand filtering
2. Entering in the solar still
3. Evaporation and condensation process
4. Distilled water collection

<u>Input and sand filtering</u>

For the input water part, the salt water mixture will be put into a decanter with the sand filter. Sand is one of the best filters found in nature in terms of water filtration. Depending on the size of the sand grain it will let more or fewer pollutants through, but it is a cheap and effective solution to remove the solids found in the water in the first pass.

In the lower part of the sand filter, there is a fiber fabric that will act as a membrane to hold the sand and let the water pass through. Once the water comes out of the filter, it passes through a valve that allows regulating the desired flow rate to maintain a stationary regime in the process. After passing the valve, the salt water enters the structure to be evaporated and condensed.

<u>Entering in the solar still</u>

Once inside, the water begins to flow through the accumulators from the top to the bottom. The flow must be carefully regulated at the initial time to avoid overfeeding that could flood the lower part of the system.

<u>Evaporation and condensation process</u>

As the temperature and relative humidity of the system increase, the salt water begins to evaporate until it touches the methacrylate, this contact causes a transfer of energy which causes the condensation of the evaporated water that by the effect of gravity falls to the bottom of the still

Distilled water collection

Finally, when the water has reached the bottom cover it comes in contact with a ramp for the extraction of water to the outside of the system completing the cycle.

Materials

For the selection of materials for the prototype, factors such as availability (easy to find in the market), cost (since the design is aimed at communities with few resources), and properties similar to those desired have predominated.

For the external structure, the desired material would be stainless aluminum due to its low weight and long use in contact with salt water. In the case of the prototype, a wooden structure has been used due to the ease of cutting. Pictures and description are described on Annex 1.

1x methacrylate plate 50x100x0.2 cm

1x ramp

4 screws 3.5x12 (One per corner)

The structure is made of 5 wooden parts joined by wooden dowels of 8mm in diameter.

1x 50x100x2 cm (width, length, height) 1x side planks 50x100x2 cm (width, length, height)

2x side boards 2x100x5 cm

1 upper board 50x2x5 cm (width, length, height)

1 bottom plate 50x2x5 cm (Wx2x5 cm)

10 wooden dowels

3 dowels left side

3 dowels right side

2 dowels bottom side

2 dowels upper side

Accumulators :

14 'L's of PVC

Evenly distributed from top to bottom approximately every 6.4 cm.

For the plate where the water condenses, some models use glass because of its better properties, but the cost and weight make methacrylate the best solution. For this reason, a methacrylate plate of 50x100x0.2 cm has been chosen. It is important to emphasize that for the model there must be an opening system for the salt drainage of the accumulators. This system must include two hinges for opening the methacrylate. In the case of the prototype, to ensure the water tightness of the system, this methacrylate sheet is screwed to the wooden structure with 3.5x12mm screws for the prototype and the purge could be done by unscrewing.

To maintain the correct functioning of the system and to improve its efficiency, correct water tightness must be maintained and for this purpose adhesive glue suitable for high temperatures is used. This is especially important for the joints.

Once the water is inside the still, since it is at an inclination of approximately 35º, the system has to include small tanks as a staircase from the top to the bottom. These tanks have two functions: first as an accumulator including a delay to allow the water time to heat up and second as a container where the brine accumulates. For the design of these accumulators, PVC L-shaped structures cut with a saw have been used to adapt them to the module dimensions. In the case of the real model, a metallic material would be a better option so that the water can receive a greater thermal conduction contribution. A total of 15 accumulators are used for the prototype. The accumulators are glued to the system using a glue gun. All possible leakage points will be sealed with adhesive sealant.

Upgrades

Improvement of the methacrylate fastening to avoid dilatation. For this purpose, the number of screws and the length of the screw has been increased from 3.5 x12 to 3.5x20 and from 2 to 4 screws per side.

Improvement in the contact surface between the methacrylate and the water collection shelf. For this purpose, a second shelf has been included, glued in L with the methacrylate forming a U, thus ensuring the transfer of condensed water between the methacrylate and the collection shelf. Another possible solution would have been to directly glue the collection shelf to the methacrylate; however, this solution is less practical since the contact surface with the methacrylate is smaller and in case of gluing it to the methacrylate it would prevent the future improvement of the system since the methacrylate could not be removed from the structure.

In addition, the sealing joint between the methacrylate and the wood has been improved by changing from a repair tape to a double-sided tape that will fix the methacrylate to a greater extent.

Details will be improved with the white adhesive and the quality of the American tape will be improved to ensure that the methacrylate does not expand.

After testing 2 relevant problems were observed. The first one is a lack of contact between the support shelf and the methacrylate. On the other hand, there is also dilatation of the methacrylate when reaching high temperatures in the system.

To improve these problems, it was decided to improve the fastening of the methacrylate with better materials and more screws, and to improve the contact, a PVC shelf will be fixed to the methacrylate forming a U with the collection shelf.

Other conceptual improvements include the use of gravity instead of a pump to reduce the cost of the prototype by having the salted water tank above the solar still. And take advantage of the remaining brine at the bottom of the pool. Brine can be used for different purposes detergent, dyeing, curing, water treatment …

Economic analysis

It is very important to conduct an economic analysis of an engineering system to test its techno-economic capabilities and viability. The cost of the water produced depends on the capital cost of equipment, the cost of energy, and the operation and maintenance cost other than energy. In the case of solar stills, the cost of energy is a very small fraction of the total cost. In some off-the-grid cases, this cost is not even present. Thus, the major share of the water cost in solar distillation is the amortization of the capital cost.

The focus of the greenhouse desalination still is to provide fresh water at an economic price where there is plenty availability of sun hours and the location is not easily accessible as the still can be built anywhere due to its off the grid and plug and play capabilities. Its modularity also helps achieve a more precise scaling to the community so there are no expenditures or underproduction of water.

The production rate is proportional to the area of the solar still and the water flux the still can hold, which means the cost per unit of water produced is nearly the same regardless of the size of the installation. This is in contrast with conditions for freshwater supplies as well as for most other desalination methods, where the capital cost of equipment per unit of capacity decreases as the capacity increases, this occurs for instance in the case of reverse osmosis. This means that solar distillation may be more attractive than other methods for small sizes. Solar energy may prove to be economical for saline water desalination due to one or more of the following reasons:

1. Location: Many arid and semi-arid areas are coastal and have high insolation rates.
2. Lack of conventional energy sources in many remote areas.

The cost of the produced fresh water depends on the cost of the desalination system. Solar energy systems, in general, are capital intensive but require low operational and maintenance costs. The actual cost of a desalination system depends on the materials used for construction. Prices may differ considerably from one location to another if local materials and local personnel are used. [24]

The general cost analysis can be divided into 2 different phases: Initial investment (Capex) and operations and maintenance (Opex).

In the case of the initial investment, it is helpful to understand the different phases of the project. According to INCLAM, their standard projects include the following phases:

Table 14 INCLAM Project Schedule

Phase	Time spent
Diagnostics	2 weeks
Fabrication	1 month
Logistics	1 month
Structure Construction	2 months
Installation	1 month
Commissioning	1 week
Operation and Management	2 years

In our case the still could be completed within two phases Diagnostics and Fabrication. Logistics are not needed since the construction will be done locally there is no need for construction outside the local area. As the modules don’t require sensible material that could be fatal in case of a natural disaster there is no need for a structure thus the final table would be reduced to:

Table 15 Actual Project Schedule

Phase	Time spent
Diagnostics	2 weeks
Fabrication	2 weeks
Operation and Management	2 years

Diagnostics

During this phase, the design thinking of the solution takes place as well as the analysis of the water characteristics that will define the limitations of the solution. Determine the water quality and other properties that are relevant to the design.

Fabrication

In this phase, the most important cost will reside in the materials of the panel (glass, plastic, wood, metal, and more and more) and the labor to produce it. In the case of the solar still, the fabrication will be developed by the local community using the materials found in the studied location

Operation and maintenance will need the operation and maintenance of 1 person in charge per 50 panels this person will be held responsible for the maintenance of the panels and will be formed to solve the problems. To provide a reference for the O&M INCLAM got to USD 55000 for the 24 months which accounts for 17 USD /m3. The solar still solution may require more surface compared to INCLAM RO however the maintenance is basic and doesn't need the technical training of a machine so the O&M costs can be reduced to 10 USD/m3

As mentioned before INCLAM provides water with RO instead of greenhouse evaporation however it is interesting and relevant to understand the percentages that represent each part of the pie on the overall cost. For context, the project consisted of the installation and O&M of 65 water purification plants in the Peruvian jungle.

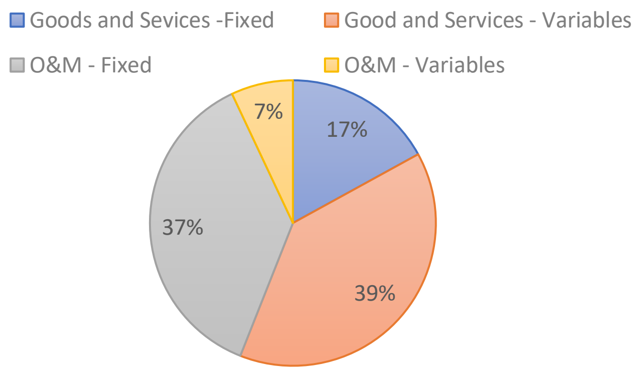


Figure 43 INCLAM Cost pie chart

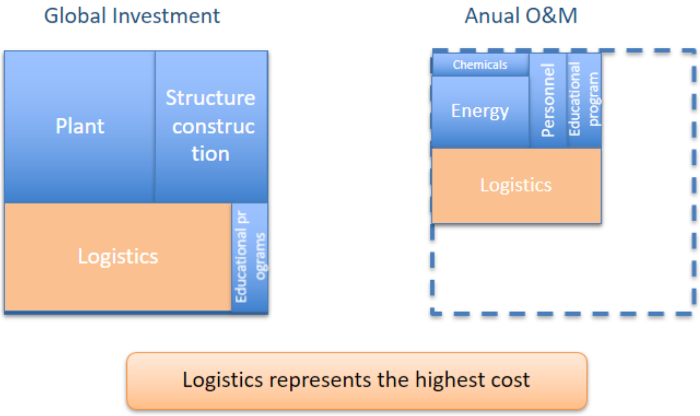


Figure 44 INCLAM Cost analysis

Moreover, a good procedure to determine the cost of the modules is to find how many modules are needed and multiply by the cost of a single module. The cost of the materials of the prototype is described below. The prototype took 11 laboring hours amongst them are 2 hours to design and gather the materials, 5h for construction, and 4h for upgrades and fixes.

The total cost of the prototype is shown below:

Table 16 Prototype costs

Product	Units	Cost per unit	Total cost
Hose	2	2.89	5.78
Wooden board	1	20.79	20.79
Wooden sealer	1	9.99	9.99
Adhesive sealant	1	6.99	6.99
Valve	1	2.95	2.95
‘L’ PVC	3	4.39	13.17
Glue gun	1	7.29	7.29
40 wooden dowels	1	1.79	1.79
Repair tape vulcanizable	1	3.19	3.19
25 screws 3.5x12	1	2.69	2.69
TOTAL			74.63 Eur

This price represents the total cost of the materials used for the prototype, some expenses can be used for other stills in the event of scaling up to a larger number, such as the glue gun, and the dowels, since there would be 30 dowels left over, 21 screws, etc.

To simulate the additional heat provided by the solar panel and the resistance a small 300W resistance connected to the grid will heat the water previous to the inlet of the system with a cost of 18 Eur. The resistance must be integrated, if possible, in a system whose materials do not rust, for the time being, a solution that can be corroded can be considered for the prototype. A water pump has not been considered as a gravity pump could be easily configured with potential energy reducing the cost of the final model. Other tools such as saws or the sealer gun are not included in the final price.

An estimated cost for the model would be a hard guess however given the cost of the prototype at around 70 Eur per module considering the PIB per capita correction between Mozambique and Spain (423€/25,460€) it wouldn’t be inconsiderate to estimate the building cost at around 20-30 Eur per module (1mx1m) with the proper materials (aluminum instead of wood, a proper sandwich panel inside the structure a better sealer and a gripper to open and close the still).

As the prototype should produce around 1.5 liters per day it would require at least 300 1x1 panels for a total of 300 m^2 of land and a total cost of 15000 Eur.

In the case of the company Fcubed

Water Farm Pricing

Each 5 Panel Water Farm Kit is USD$3,500 plus delivery costs and consists of:

- 5 Carocell panels
- A self-priming solar pump with a photovoltaic panel to operate
- Customized racking to mount the panels and harvest rainwater
- All irrigation fittings and hosing required.

Fcubed sends everything above as a Water Farm Kit ready to install except for any storage tanks.

Individual Panel Pricing

FCubed can also provide individual panels which operate standalone

- Carocell 3000 (approx. 15 liters per day) - USD$525 each
- Carocell 2000 (approx. 10 liters per day) - USD$425 each

Installation and Maintenance,

Installation

F Cubed provides details installation guides to make the setup straight-forward without any expertise required: a water farm would require 2 people 1-1.5 days per 5 panels and a standalone panel will take less than 1 hour to assemble.

Maintenance

Once installed the panels do not require ongoing maintenance:

- There are no scheduled maintenance requirements
- There is no scheduled filter or membrane changes
- There is no power requirement, other than solar energy
- The water farm is fully integrated and automated.

Other solutions such as the proposed by MIT for an Indian suburb using electrodialysis to provide drinking water for 2000-3000 inhabitants. The biggest expenses are presented by the batteries and the membrane. It presents a problem and that is that it is not the solution that is sought with this master's thesis

Table 17 MIT RE solution cost analysis

Components	Quantity	Cost	Lifetime(years)	# of times purchased
PV panels	57.5 m^2	\$98/m^2	20+	1
Batteries	22 kWh	$150/kWh	5	4
Water storage	10 m^3	\$110/m^3	20+	1
ED electrodes	2	$2000/electrode	10	2
# ED cell pairs	62 cell pairs	$150/cell pair	10	2
Pump	2	$44/each	3.5	6
Total lifetime cost	$47,063			

Sustainable Development Goals (SDGs)

The Sustainable Development Goals are the master plan to obtain a better and more sustainable future for everybody. There are 17 global objectives that attack specific topics to sutain the basic human needs, reduce inequalities, eradicate hunger, protect the planet and guarantee peace and prosperity amongst all.

From the Sustainable Development Goals standpoint, the project will be involved on:

Table 18 Sustainable Development Goals

	CLEAN WATER AND SANITATION - As this project is based on the obtention of clean water
	NO POVERTY-To eradicate poverty by providing the needed resources to grow in this case water to survive and eat
	REDUCED INEQUALITIES - Reducing the inequality between those who are born in a comfortable home and those who don't have access to clean water GOOD HEALTH AND WELL-BEING – Increase the value of clean water and good water practices
	RESPONSIBLE CONSUMPTION AND PRODUCTION- On a second level, all the production of water will now be obtained through sustainable energy transformations using PV instead of using fuel or coal to boil the water

SDG 6 : Clean water and sanitation

Water stands at the core of sustainable socio-economic development, energy and food production, healthy ecosystems, and human survival itself.

As the global population grows, there is an increasing need to balance the commercial demands on water resources, so that communities have enough for their needs. In particular, in Spain, there is a 240-liter expenditure per day per person. At a human level, clean water production cannot be seen independently from sanitation. Together, they are vital for reducing the global risk of diseases and improving the health, education, and economic productivity of populations.

One of the most important recent milestones has been the recognition in July 2010 by the United Nations General Assembly of the human right to water and sanitation. The Assembly has recognized the right of every human being to have access to enough water for personal and domestic uses, meaning between 50 and 100 liters of water a day per person.

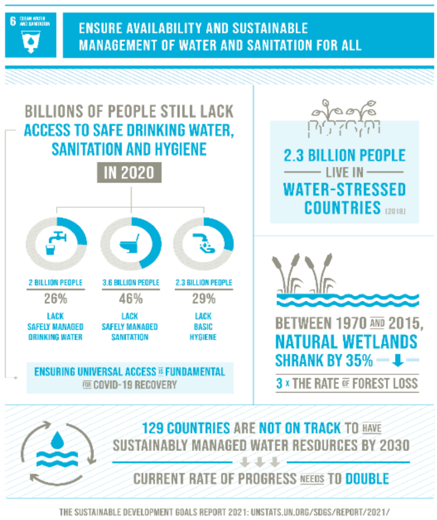


Figure 45 UN Report 2021

The water must be safe, acceptable, and affordable. The water costs should not exceed 3 percent of household income. Moreover, the water source must be within 1,000 meters of the home, and the collection time should not exceed 30 minutes. To provide a reference the average expenditure of water per day in Spain is 240 liters per person.

SDG 1: No poverty

More than 700 million people (10% of global population) still live in extreme poverty as of today with difficulties to satisfy basic needs such as health, education and access to water and sanitation. Amongst the objectives from this goal, the project aids on objective 1.5 which has the goal to promote resiliency amongst the poor and reduce their exposure and vulnerability to climate phenomena or climate disasters. The solar still would help the communities to be sustainable and autonomous for their own water production.

SDG 10: Reduced inequalities

This project motivations is not only to provide a solution to obtain water but to provide the most basic good to the most needed communities. Its about reducing the inequalities of those who are not as lucky of where they were born or the situation they might be involved on (wars, persecution, social alienation…)

SDG 3: Good health and well-being

One of the main problems where communities don't have access to fresh water is that fresh water doesn't become as crucial as the community ingest dirty water for long periods of time. This action ends up resulting on health decrease specially amongst children where they get sick quickly and get dehydration due to diarrhea. The solar still would come as a solution to that problem but as mentioned by INCLAM there should be a social investment on communicating the value of clean water and good water practices.

SDG 12: Responsible consumption and production

The project would impact targets 12.2 to achieve a sustainable management and efficient use of natural resources by 2030, in this particular case the use of the sun irradiation and the salted water. It would also impact target 12.A to support developing countries to improve their technological capacity to go towards a more sustainable patter of consumption and production, the solar still would get rid of fuel consumption to raise the temperature of water to boil it providing the community with more autonomy over their resources in a more responsible manner.

Conclusions

Throughout this project it has been studied and compared different technologies to produce water from salted sources. Two companies (Grupo INCLAM and Fcubed) were contacted to understand the problem better and determine the best approach to a final solution. The conclusion from the physical model, the mathematical model and the information gathered from these two companies are described below.

Conclusions from the physical model

This type of system has multiple benefits such as the relevance of the modularity which allows you to increase the number of stills if needed and in the case of operation and management the great approach is that if only one panel is faulty you would only have to replace one panel while the others remain to produce water for the community. Compared to other more technical systems that may need solar panels or are more delicate this system is off-grid and occasional rain does not have a crucial impact on the design of the system as the system is impermeable. The modules are portable and lightweight and made out of methacrylate(plastic), an insulator, and the structure is made of aluminum to maintain a low-cost volume. As stated by Fcubed the water production can reach up to 5 liters per square meter using the right materials, but the configuration of the prototype does not come to a viable solution for the problem stated. From an economic standpoint the prototype cost came up to 76 EUR however with the PIB correction of Mozambique (423€/25,460€ PIB per capita Mozambique vs Spain) and considering batch manufacturing and installation the cost can be reduced conservatively to 20 to 30 EUR per model. If we assume that the model produces 0.5-1.5 liter per module considering, both the mathematical and experimental water production results with an amortization of 1 year the cost per liter is 0.08 EUR per liter of water produced. On the other hand, considering the externalization of the solution by analyzing Fcubed modules which produce 75 liter per water farm at a cost of 3500 EUR with an amortization of 3-5 years the water cost per liter would be 0.03 EUR per liter.

Conclusions from the mathematical model

The most relevant factors are solar irradiation, ambient temperature, wind speed and the flux or volume the solar still can contain. The temperature and radiation data of the region reflect an average of 1.3 -1.5 L/m2 per day of distilled water obtained, which considerably reduces the viability of the system with or without the external energy contribution of resistance with solar panels.

The graph below represents the consolidation of the daily water production per day depending on the case study: best, average, and worse.

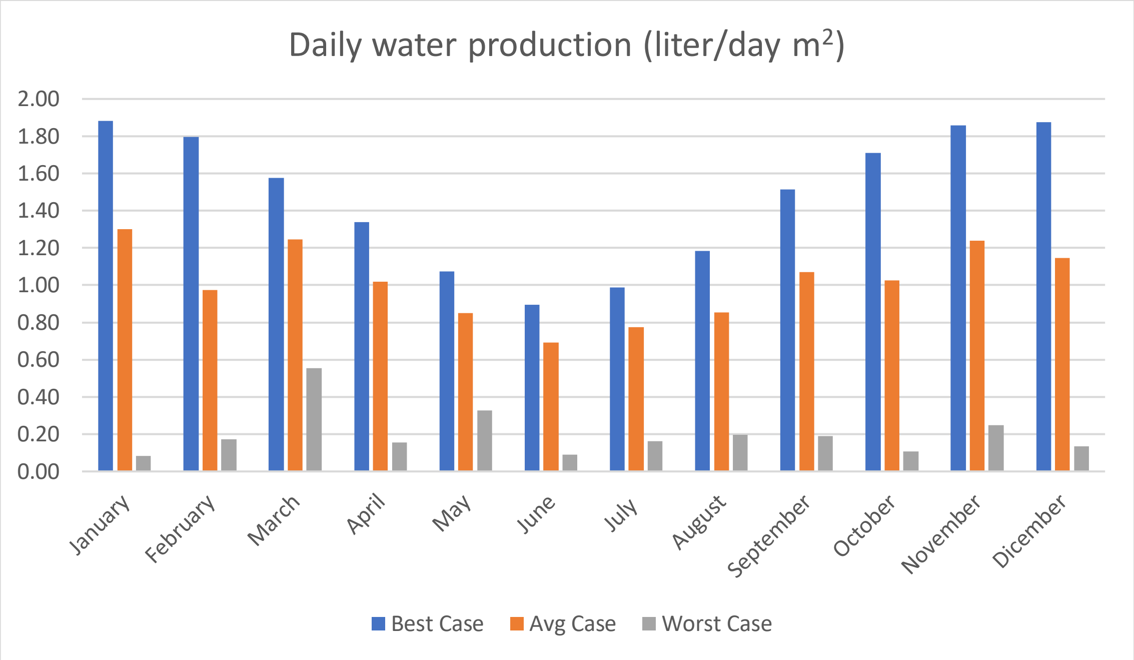


Figure 46 Daily water production comparison

These results were obtained with a 0.5 liter per hour flux and a squared meter module. Compared to the minimum recommended by the UN of 2 liters per person, the solar still does not perform well in terms of productivity compared to other most common solutions such as Reverse Osmosis machines produced and installed by INCLAM

Conclusions obtained from INCLAM.

The project involves great work and social commitment with and from the community since they are the ones who have to be part of the project in key moments such as the manufacture and transfer of materials and also in the operation and maintenance. The project also involves an aspect of social education on hygiene focused on water solutions and teaching the value of drinking water and its good practices. It's up to all of us to handle the valuable resource of fresh water in a saving and sustainable manner and to science and innovation to find the most ecological and least harmful way to provide it water is the most essential resourced formatting the earth we all depend on it.

In their case using RO technologies to provide fresh water, logistics costs represent the biggest portion of the cost analysis (around 43% of total cost), more than the plant itself or the structure construction.

Desalination is not the solution to water scarcity however for particular cases such as rural locations or after natural catastrophizes it could provide aid until a more suited and scalable solution is put in place.

Future steps

Improve the prototype with more suited materials and a construction approach on a set of multiple stills and the logistical structure for shipping. Analyze the water input and its characteristics. Implement a solution for agricultural purposes that could be mixing the water output with the input so that more water can be used as mentioned depending on what the community needs.

About the water input a pump from a salted water source from the sea for example or any other container where the water may be contaminated with solids of any type that will be distilled with the distillation system. If the community doesn't have access to the sea for instance another solution could be centered on the transportation of that water to the community.

Educational workshops should be taught on topics such as the importance of good sanitation and good water practices that will help the community to overcome health problems obtained from water ingestion. Another issue to think about are the roles that some members of the community must have to make the project feasible. There should be some formation and collaboration among a member of the community that will be provided with benefits either financial or other types that will maintain the proper functioning of the system and maintenance in the case needed. In the case of maintenance, the member should know how to repair the system (easy to maintain and function but is responsible for it) and contact providers in case spare parts are needed for the installation of new stills. Depending on the requirements and needs of the community (more litters needed per community) other solutions become more reasonable for example RO or Reverse Electrodialysis

Annexes

Annex 1: Construction of the prototype

Pool Construction

Figure 47 Wood and PVC cutting

Figure 48 Pool wood construction

Figure 49 Hose and adhesive integration

Pool on production:

At first, the structure has been placed on the terrace with approximately 8 hours of accessible sunshine (8-4) with the best time being around 12:00-13:00.

The tilt of the structure has been chosen at approximately 45º to maximize the angle of attack of the sun at peak hours.

In the development of the first iteration, the feasibility of the system reaching temperatures high enough to evaporate the water inside was analyzed.

The first test included the inverted bottle where the inlet water is stored. In this first test, salinity was not a crucial variable, so non-saline water was used as the inlet water.

Once the water passes through the valve, the water enters the system and when the volume exceeds the volume of the shelf it falls making a cascade to the bottom. The idea is that the flow rate is constant, so the flow rate must be initially regulated with the valve to achieve this stationary regime.

As shown in the image the temperature sensor can reach up to 64 degrees inside the system while the outside was 26 degrees, you can also see the evaporated drops that begin to condense on the methacrylate, so it confirms the ability of the system to distill water.

Apart from the temperature, the sensor can measure humidity being a relative humidity of around 30% outside the system while inside the system reaches 80% relative humidity.

- Despite being screwed at its corners and having duct tape for fastening, the high temperatures reached cause the methacrylate to expand so much that it bulges in the form of an arc and creates an escape route through the top of the structure.
- On the other hand, the collection system fails to maintain firm contact with the methacrylate which prevents the transfer of water droplets from the methacrylate to the collection shelf and subsequent exit of water from the system.

Improvements

- Improvement of the methacrylate fastening to avoid dilatation. For this purpose, the number of screws and the length of the screw has been increased from 3.5 x12 to 3.5x20 and from 2 to 4 screws per side.
- Improvement in the contact surface between the methacrylate and the water collection shelf. For this purpose, a second shelf has been included, glued in L with the methacrylate forming a U, thus ensuring the transfer of condensed water between the

methacrylate and the collection shelf. Another possible solution would have been to directly glue the collection shelf to the methacrylate; however, this solution is less practical since the contact surface with the methacrylate is smaller and in case of gluing it to the methacrylate it would prevent the future improvement of the system since the methacrylate could not be removed from the structure.

- In addition, the sealing joint between the methacrylate and the wood has been improved by changing from a repair tape to a double-sided tape that will fix the methacrylate to a greater extent.
- Finally, details will be improved with the white adhesive and the quality of the American tape will be improved to ensure that the methacrylate does not expand.

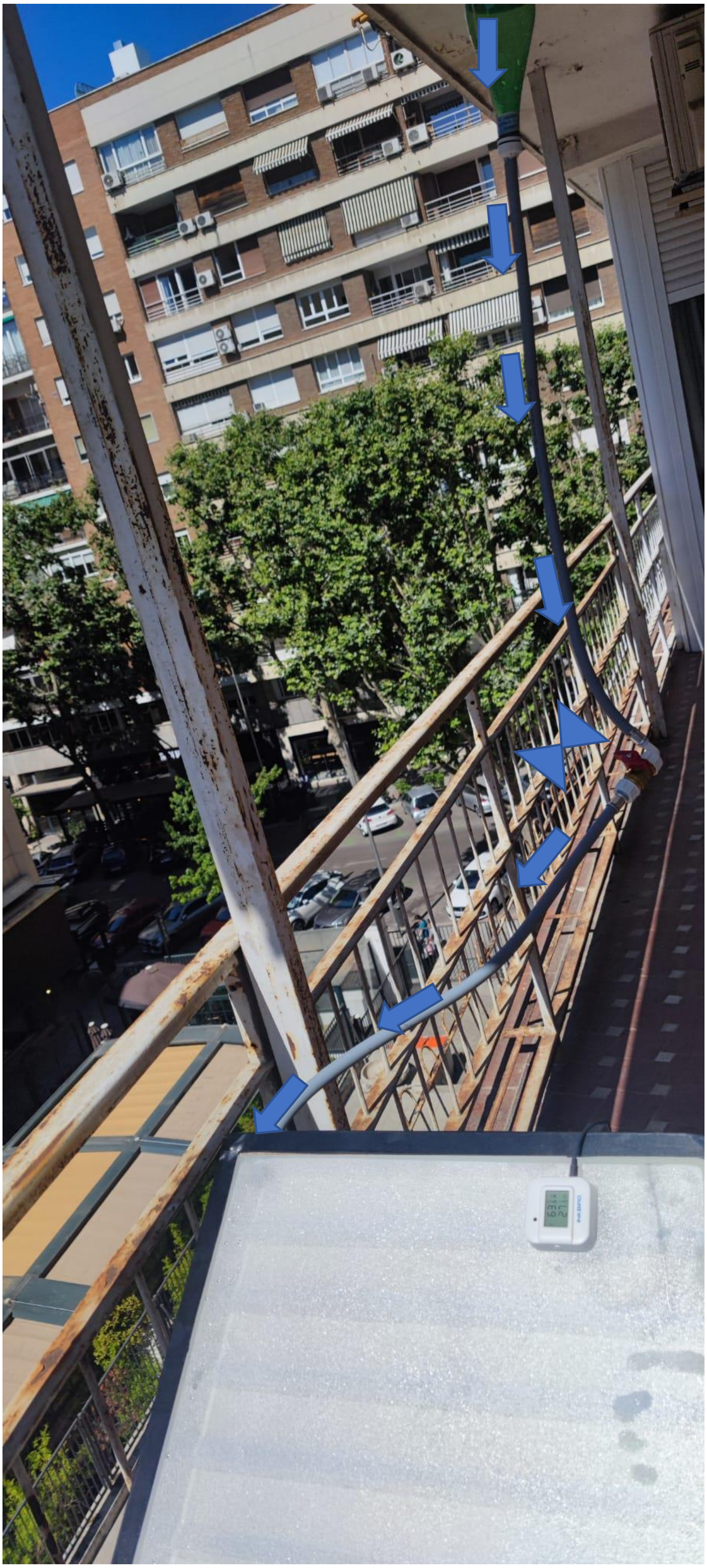


Figure 50 Prototype testing

A digital sensor was included in the system to measure and track the temperature and humidity inside the system. The highest temperature reached was 70 ºC and on average the highest temperature raised around 65º. The figure below shows experimental temperature values.

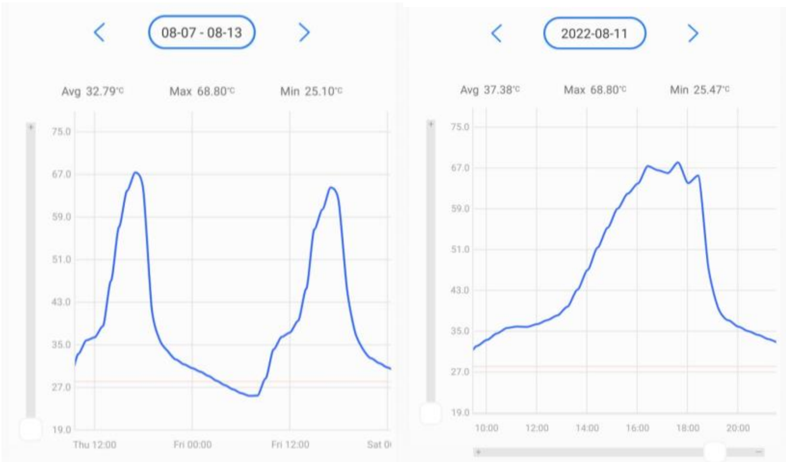


Figure 51 Sensor Temperature

Annex 2: Code

```
clear all
close all
clc
sympref('FloatingPointOutput',true);
%(source 1: Performance of a Solar Still Integrated in a Greenhouse
Roof)
%% %%Parameters%%
%Symbolic variables
syms Tw Tg
global hOperation
hOperation=11;
%% %Structure propperties (Source 1)
%Thickness (m)
    %lg=0.002 lg_source= 0.004
    %lw=0.02;
%From those dimmensions we get the absorption coefficient
%absobtion coefficients [dimensionless]
%Formula α=2.303*A/l
alpha_g = 0.1; %alpha_g = 0.05 for the source
alpha_w = 0.3;
%%emisivity [dimensionless]
epsilon_g_ext=0.9;
epsilon_w= 0.96;
epsilon_gi=epsilon_g_ext;
%Transmitance coefficient [dimensionless]
tau_g=0.9;
tau_w=0.68;
%% %%Water properties (Source 1)
Salinity=35000;%[ppm]
v_aext=2; %outside speed [m/s]
mdot_w=0.5/3600; %mass flow rate (kg/(s*m^2))
g=9.81; %gravity [m/s^2]
sigma= 5.6697*10^-8; %Stefan Boltzman coefficient [W m^-2 K^-4]
c_w=4180; %specific heat of water [J kg^-1 K^-1]
```

```
%% %Code variables initialization
month_s = ["January" "February" "March" "April" "May" "June" "July"
"August" "September" "October" "November" "December"];
Tmatrix=zeros(hOperation,4);
aacount=0;
prod_hv=0;
fig_count=0;
%% Main Code
for month=1:12
%%IMPORT DATA
index=month+1;
%Wind
windData=importWind('Datos');
v_aext=windData.(index);
%Tamb
tambData=importTamb('Datos');
Taext=TKelvin(tambData.(index));
%Ghi
GData=importGhi('Datos');
irradiation_h=GData.(index);

%Temperature water inlet
Tw_i=Taext(1);
Tw=Tw_i; %Taken from data of the paper

for hour=1:24
%hour=1 is tecnically 00:00
Lv=SW_LatentHeat(double(Tw),'k',Salinity,'ppm'); %hfg =
SW_LatentHeat(T,uT,S,uS)
Tmatrix(hour,1)=TCelsius(Tw);
aacount=aacount+1;
Ts=0.0522*Taext(hour)^(3/2);
lambda= Lv ; %   SW_LatentHeat(Tw,S)
pg=P(Tg); %Tg dependent
pw=P(Tw); %Tw in Kelvin
hr_g_aext=vpa(epsilon_g_ext*sigma*(Tg^2+Ts^2)*(Tg+Ts));
hr_g_w=(sigma*(Tw^2+Tg^2)*(Tg+Tw))/((1/epsilon_w)+(1/epsilon_gi)-1);
hc_g_w=0.884*((Tw-Tg)+(pw-pg)/((277900-pw)*Tw))^(1/3);
he_w=(7*10^-9)*hc_g_w*((pw-pg)*lambda/(Tw-Tg));
hc_g_aext=2.8+3*v_aext(hour);
%%

eq1= alpha_g*irradiation_h(hour)== hc_g_aext*(Tg-
Taext(hour))+hr_g_aext*(Tg-Taext(hour))+he_w*(Tg-Tw)+hr_g_w*(Tg-
Tw)+hc_g_w*(Tg-Tw);
%%
hr_w_g=hr_g_w;
hc_w_g=hc_g_w;

Taint=20.87+0.940*Taext;
Tg_temp=real(solve(eq1));
Tg_min=290;
Tg_max=360;
j=0;
for i=1:size(Tg_temp)
    if (Tg_min < Tg_temp(i) && Tg_temp(i) < Tg_max)
        Tg=Tg_temp(i);
        j=j+1;
    end
end
clear Tw;
```

```
syms Tw;
eq2= alpha_w*tau_g*irradiation_h(hour)-2*mdot_w*c_w*(Tw-
Tw_i)==he_w*(Tw-Tg)+hr_w_g*(Tw-Tg)+hc_w_g*(Tw-Tg);
Tw_i=(Tw_i+Tg)/2;
Tw=real(solve(subs(eq2)));

%fprintf('Tw: %s \n',Tw);
%fprintf('Tg: %s \n',Tg);

Tmatrix(hour,2)=TCelsius(Tg);
Tmatrix(hour,3)=Taext(hour);

hc_w_g = hc_g_w;
mh=(16.273*10^-3)*hc_w_g*((pw-pg)/lambda)*3600;

prod_h=subs(mh);
Tmatrix(hour,4)=prod_h;
prod_hv=prod_hv+prod_h;
kk(hour)=hour-1;
clear Tg;
syms Tg;
end

prod_d(month)=sum(prod_hv);
prod_hv=0;
%fprintf('\nProducción diaria: %f\n',prod_d);


%%%%%Figures%%%%
path="C:\\Users\\Alvaro Morate\\Documents\\MATLAB\\Imagenes\\";
%Temperatures
dd=kk(1:24)'; %Hours of production
mm=(1:12)';
fig_count=fig_count+1;
figure(fig_count),plot(dd,Tmatrix(:,1),'-kd',dd,Tmatrix(:,2),'-bs')
str = sprintf('Temperature variation\n%s',month_s(month));
title(str)
xlabel('Time(hour)')
ylabel('Temperature(°C)')
legend({'Twater', 'Tglass'})
saveas(figure(fig_count),sprintf(path +
'Temp_figure_%d.jpg',fig_count));
%Irradiation
fig_count=fig_count+1;
figure(fig_count),plot(dd,irradiation_h,'-
kd','LineWidth',2,'MarkerEdgeColor','k','MarkerFaceColor','y','MarkerS
ize',5)
str = sprintf('Irradiation\n%s',month_s(month));
title(str)
xlabel('Time(hour)')
ylabel('Solar Intensity (W/m2)')
legend({'I (W/m2)'})
saveas(figure(fig_count),sprintf(path + 'G_figure_%d.jpg',fig_count));
%Production
fig_count=fig_count+1;
figure(fig_count),plot(dd,Tmatrix(:,4),'-
kd','LineWidth',2,'MarkerEdgeColor','k','MarkerFaceColor','y','MarkerS
ize',5)
str = sprintf('Daily Water Production\n%s',month_s(month));
title(str)
xlabel('Time(hour)')
```

```
ylabel('Water Production (kg/ m2 h)')
legend({'W (W/ m2 h)'})
saveas(figure(fig_count),sprintf(path + 'W_figure_%d.jpg',fig_count));
end
function P = P(T)
    %T in Kelvin
    %P(partial preassure of water vapour at saturation temperatura) in
Pa
    P=293.3*T-84026.4;
end

function toKelvin = TKelvin(Tcelsius)
    toKelvin=Tcelsius+273.15;
end

function toCelsius=TCelsius(TKelvin)
    toCelsius=TKelvin-273.15;
end
```

%%Data imported from SolCast

#Country	Mozambique
#Data Source	Solcast https://solcast,com
#Time step	1
#Latitude	-251,115
#Longitude	336,905
#Altitude	26
#Time Zone	2

%%%AMBIENT TEMPERATURE%%%%

```
function Datos = importfile(workbookFile, sheetName, dataLines)
%IMPORTFILE Import data from a spreadsheet
%  DATOS = IMPORTFILE(FILE) reads data from the first worksheet in the
%  Microsoft Excel spreadsheet file named FILE.  Returns the data as a
%  table.
%
%  DATOS = IMPORTFILE(FILE, SHEET) reads from the specified worksheet.
%
%  DATOS = IMPORTFILE(FILE, SHEET, DATALINES) reads from the specified
%  worksheet for the specified row interval(s). Specify DATALINES as a
%  positive scalar integer or a N-by-2 array of positive scalar
integers
%  for dis-contiguous row intervals.
%
%  Example:
%  Datos = importfile("C:\Users\Alvaro
Morate\Documents\MATLAB\Datos.xlsx", "GHI", [5, 28]);
%
%  See also READTABLE.
%
% Auto-generated by MATLAB on 29-Jul-2022 00:40:05

%% Input handling

% If no sheet is specified, read first sheet
```

```
if nargin == 1 || isempty(sheetName)
    sheetName = 2;
end

% If row start and end points are not specified, define defaults
if nargin <= 2
    dataLines = [5, 28];
end

%% Set up the Import Options and import the data
opts = spreadsheetImportOptions("NumVariables", 13);

% Specify sheet and range
opts.Sheet = sheetName;
opts.DataRange = "A" + dataLines(1, 1) + ":M" + dataLines(1, 2);

% Specify column names and types
opts.VariableNames = ["RowLabels", "VarName2", "VarName3", "VarName4",
"VarName5", "VarName6", "VarName7", "VarName8", "VarName9",
"VarName10", "VarName11", "VarName12", "VarName13"];
opts.VariableTypes = ["double", "double", "double", "double",
"double", "double", "double", "double", "double", "double", "double",
"double", "double"];

% Import the data
Datos = readtable(workbookFile, opts, "UseExcel", false);

for idx = 2:size(dataLines, 1)
    opts.DataRange = "A" + dataLines(idx, 1) + ":M" + dataLines(idx,
2);
    tb = readtable(workbookFile, opts, "UseExcel", false);
    Datos = [Datos; tb]; %#ok<AGROW>
end

end
```

%%%%WIND SPEED%%%

```
function Datos = importfile(workbookFile, sheetName, dataLines)
%IMPORTFILE Import data from a spreadsheet
%  DATOS = IMPORTFILE(FILE) reads data from the first worksheet in the
%  Microsoft Excel spreadsheet file named FILE.  Returns the data as a
%  table.
%
%  DATOS = IMPORTFILE(FILE, SHEET) reads from the specified worksheet.
%
%  DATOS = IMPORTFILE(FILE, SHEET, DATALINES) reads from the specified
%  worksheet for the specified row interval(s). Specify DATALINES as a
%  positive scalar integer or a N-by-2 array of positive scalar
integers
%  for dis-contiguous row intervals.
%
%  Example:
%  Datos = importfile("C:\Users\Alvaro
Morate\Documents\MATLAB\Datos.xlsx", "GHI", [5, 28]);
%
%  See also READTABLE.
%
% Auto-generated by MATLAB on 29-Jul-2022 00:40:05

%% Input handling
```

```
% If no sheet is specified, read first sheet
if nargin == 1 || isempty(sheetName)
    sheetName = 3;
end

% If row start and end points are not specified, define defaults
if nargin <= 2
    dataLines = [5, 28];
end

%% Set up the Import Options and import the data
opts = spreadsheetImportOptions("NumVariables", 13);

% Specify sheet and range
opts.Sheet = sheetName;
opts.DataRange = "A" + dataLines(1, 1) + ":M" + dataLines(1, 2);

% Specify column names and types
opts.VariableNames = ["RowLabels", "VarName2", "VarName3", "VarName4",
"VarName5", "VarName6", "VarName7", "VarName8", "VarName9",
"VarName10", "VarName11", "VarName12", "VarName13"];
opts.VariableTypes = ["double", "double", "double", "double",
"double", "double", "double", "double", "double", "double", "double",
"double", "double"];

% Import the data
Datos = readtable(workbookFile, opts, "UseExcel", false);

for idx = 2:size(dataLines, 1)
    opts.DataRange = "A" + dataLines(idx, 1) + ":M" + dataLines(idx,
2);
    tb = readtable(workbookFile, opts, "UseExcel", false);
    Datos = [Datos; tb]; %#ok<AGROW>
end

end
```

%%%HORIZONTAL IRRADIATION%%%

```
function Datos = importfile(workbookFile, sheetName, dataLines)
%IMPORTFILE Import data from a spreadsheet
%  DATOS = IMPORTFILE(FILE) reads data from the first worksheet in the
%  Microsoft Excel spreadsheet file named FILE.  Returns the data as a
%  table.
%
%  DATOS = IMPORTFILE(FILE, SHEET) reads from the specified worksheet.
%
%  DATOS = IMPORTFILE(FILE, SHEET, DATALINES) reads from the specified
%  worksheet for the specified row interval(s). Specify DATALINES as a
%  positive scalar integer or a N-by-2 array of positive scalar
integers
%  for dis-contiguous row intervals.
%
%  Example:
%  Datos = importfile("C:\Users\Alvaro
Morate\Documents\MATLAB\Datos.xlsx", "GHI", [5, 28]);
%
%  See also READTABLE.
%
```

```
% Auto-generated by MATLAB on 29-Jul-2022 00:40:05

%% Input handling

% If no sheet is specified, read first sheet
if nargin == 1 || isempty(sheetName)
    sheetName = 1;
end

% If row start and end points are not specified, define defaults
if nargin <= 2
    dataLines = [5, 28];
end

%% Set up the Import Options and import the data
opts = spreadsheetImportOptions("NumVariables", 13);

% Specify sheet and range
opts.Sheet = sheetName;
opts.DataRange = "A" + dataLines(1, 1) + ":M" + dataLines(1, 2);

% Specify column names and types
opts.VariableNames = ["RowLabels", "VarName2", "VarName3", "VarName4",
"VarName5", "VarName6", "VarName7", "VarName8", "VarName9",
"VarName10", "VarName11", "VarName12", "VarName13"];
opts.VariableTypes = ["double", "double", "double", "double",
"double", "double", "double", "double", "double", "double", "double",
"double", "double"];

% Import the data
Datos = readtable(workbookFile, opts, "UseExcel", false);

for idx = 2:size(dataLines, 1)
    opts.DataRange = "A" + dataLines(idx, 1) + ":M" + dataLines(idx,
2);
    tb = readtable(workbookFile, opts, "UseExcel", false);
    Datos = [Datos; tb]; %#ok<AGROW>
end

end
```

%%LATENT HEAT %% Source: https://solcast.com/

```
function hfg = SW_LatentHeat(T,uT,S,uS)
    % SW_LatentHeat    Latent Heat of vaporization of seawater
%=====================================================================
====
    % USAGE:  hfg = SW_LatentHeat(T,uT,S,uS)
    %
    % DESCRIPTION:
    %   Latent heat of vaporization of seawater using Eq. (37) given
by [1].
    %   The pure water latent heat is a best fit to the data of [2].
    %   Values at temperature higher than the normal boiling
temperature are
    %   calculated at the saturation pressure.
    %
    % INPUT:
    %   T  = temperature
```

```
    %   uT = temperature unit
    %         'C'   : [degree Celsius] (ITS-90)
    %         'K'   : [Kelvin]
    %         'F'   : [degree Fahrenheit]
    %         'R'   : [Rankine]
    %   S   = salinity
    %   uS = salinity unit
    %         'ppt': [g/kg]  (reference-composition salinity)
    %         'ppm': [mg/kg] (in parts per million)
    %         'w'   : [kg/kg] (mass fraction)
    %         '%'   : [kg/kg] (in parts per hundred)
    %
    %   Note: T and S must have the same dimensions
    %
    % OUTPUT:
    %   hfg = Latent heat of vaporization [J/kg]
    %
    %   Note: hfg will have the same dimensions as T and S
    %
    % VALIDITY: 0 < T < 200 C; 0 < S < 240 g/kg
    %
    % ACCURACY: 0.01 %
    %
    % REVISION HISTORY:
    %   2009-12-18: Mostafa H. Sharqawy (mhamed@mit.edu), MIT
    %               - Initial version
    %   2012-06-06: Karan H. Mistry (mistry@alum.mit.edu), MIT
    %               - Allow T,S input in various units
    %               - Allow T,S to be matrices of any size
    %
    % DISCLAIMER:
    %   This software is provided "as is" without warranty of any
kind.
    %   See the file sw_copy.m for conditions of use and licence.
    %
    % REFERENCES:
    %   [1] M. H. Sharqawy, J. H. Lienhard V, and S. M. Zubair,
Desalination
    %       and Water Treatment, 16, 354-380, 2010.
(http://web.mit.edu/seawater/)
    %   [3]    IAPWS release on the Thermodynamic properties of
ordinary water substance, 1996.

%======================================================================
====

    %% CHECK INPUT ARGUMENTS

    % CHECK THAT S&T HAVE SAME SHAPE
    if ~isequal(size(S),size(T))
        error('check_stp: S & T must have same dimensions');
    end

    % CONVERT TEMPERATURE INPUT TO °C
    switch lower(uT)
        case 'c'
        case 'k'
            T = T - 273.15;
        case 'f'
            T = 5/9*(T-32);
        case 'r'
```

```
            T = 5/9*(T-491.67);
        otherwise
            error('Not a recognized temperature unit. Please use
''C'', ''K'', ''F'', or ''R''');
    end

    % CONVERT SALINITY TO PPT
    switch lower(uS)
        case 'ppt'
        case 'ppm'
            S = S/1000;
        case 'w'
            S = S*1000;
        case '%'
            S = S*10;
        otherwise
            error('Not a recognized salinity unit. Please use ''ppt'',
''ppm'', ''w'', or ''%''');
    end

    % CHECK THAT S & T ARE WITHIN THE FUNCTION RANGE
    if ~isequal((T<0)+(T>200),zeros(size(T)))
        warning('Temperature is out of range for latent heat function
0<T<200 C');
    end

    if ~isequal((S<0)+(S>240),zeros(size(S)))
        warning('Salinity is out of range for latent heat function
0<S<240 g/kg');
    end

    %% BEGIN

    a = [
         2.5008991412E+06
        -2.3691806479E+03
         2.6776439436E-01
        -8.1027544602E-03
        -2.0799346624E-05
    ];

    hfg_w = a(1)  + a(2)*T  + a(3)*T.^2  + a(4)*T.^3  + a(5)*T.^4;
    hfg   = hfg_w.*(1-0.001*S);

end
```

Figures

Without the additional heating of resistance and photovoltaic panel combination

Best case scenario

Temperature variation

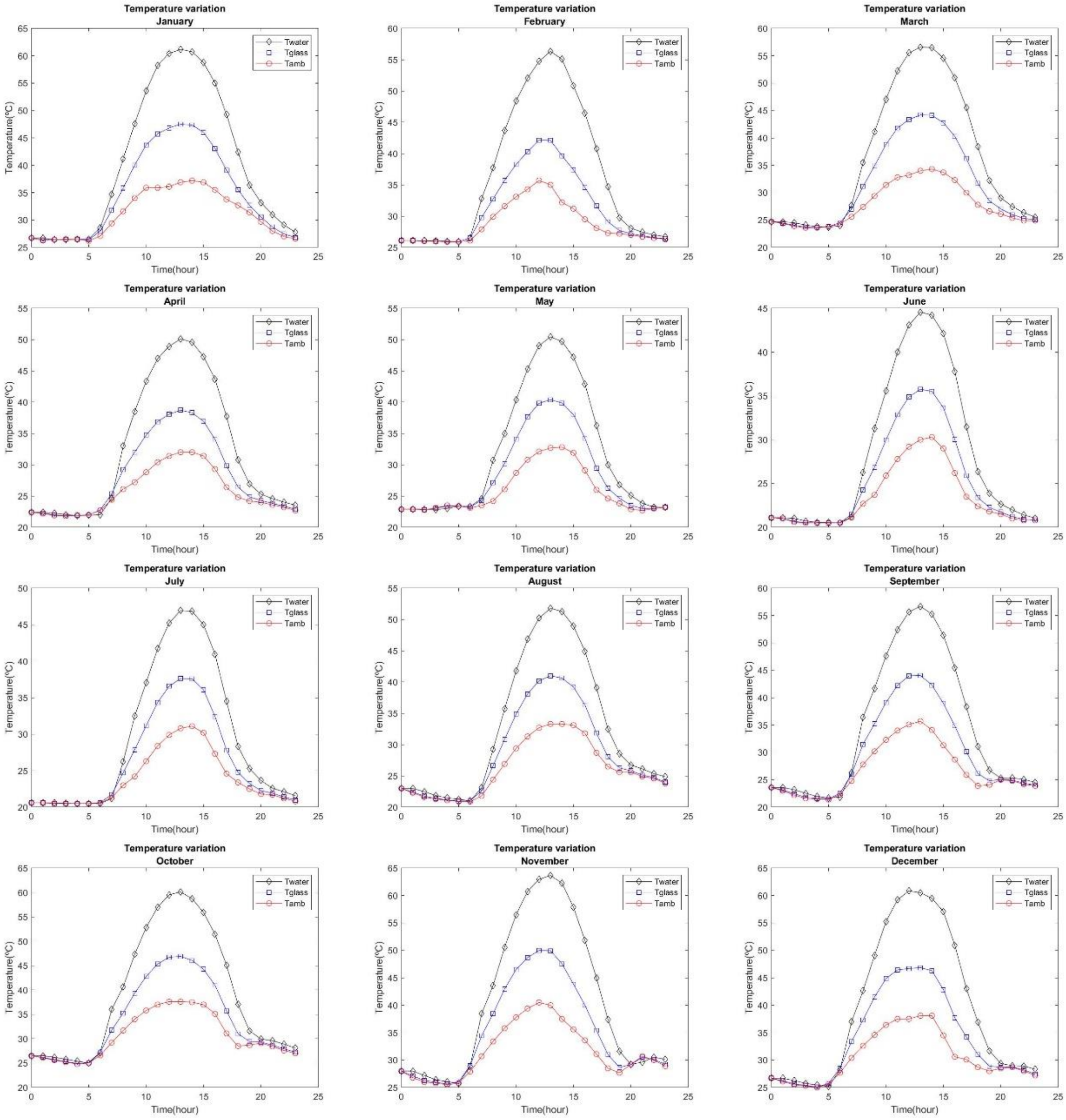


Figure 52 Temperature variation - Best case

Daily Water Production

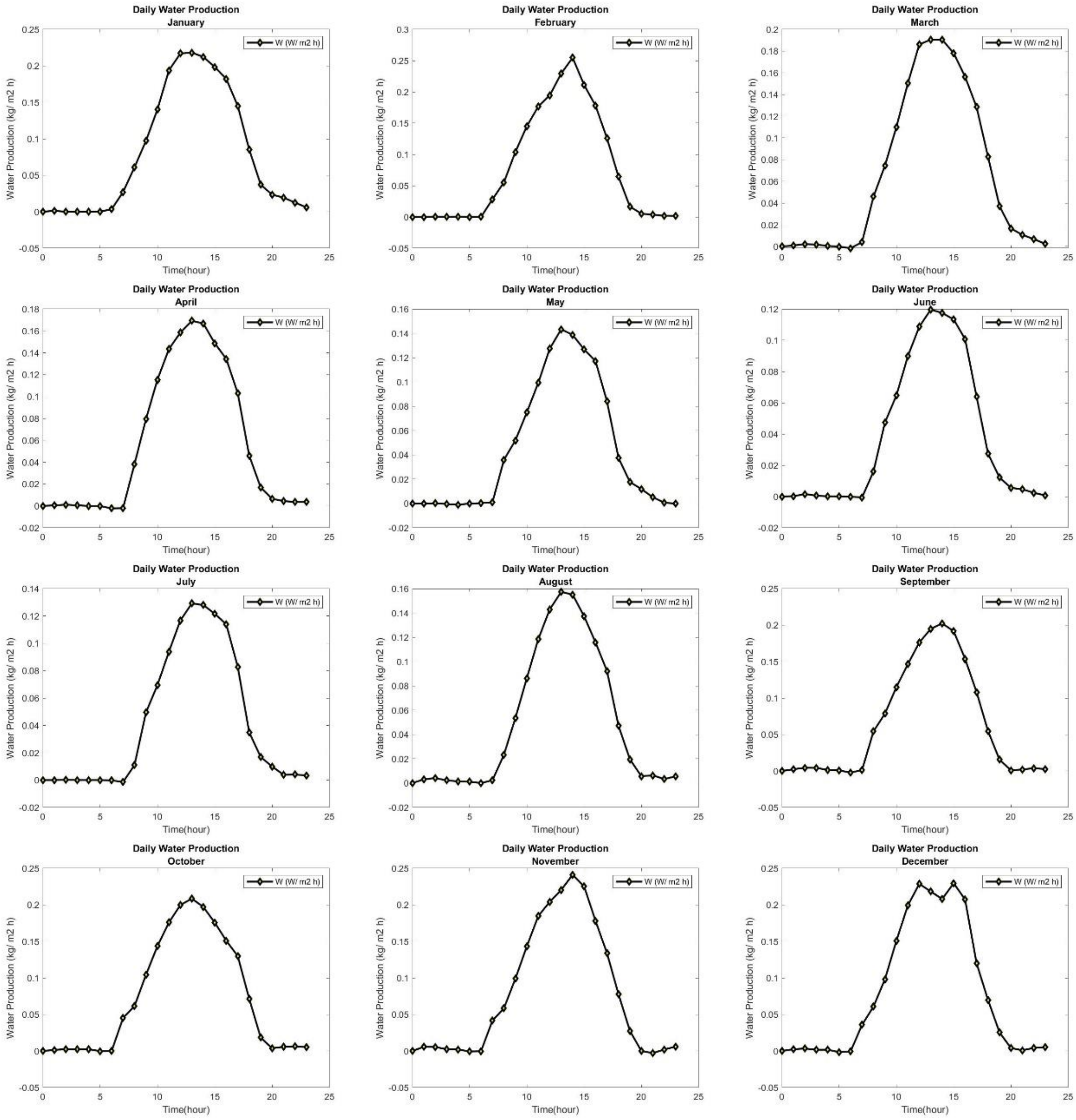
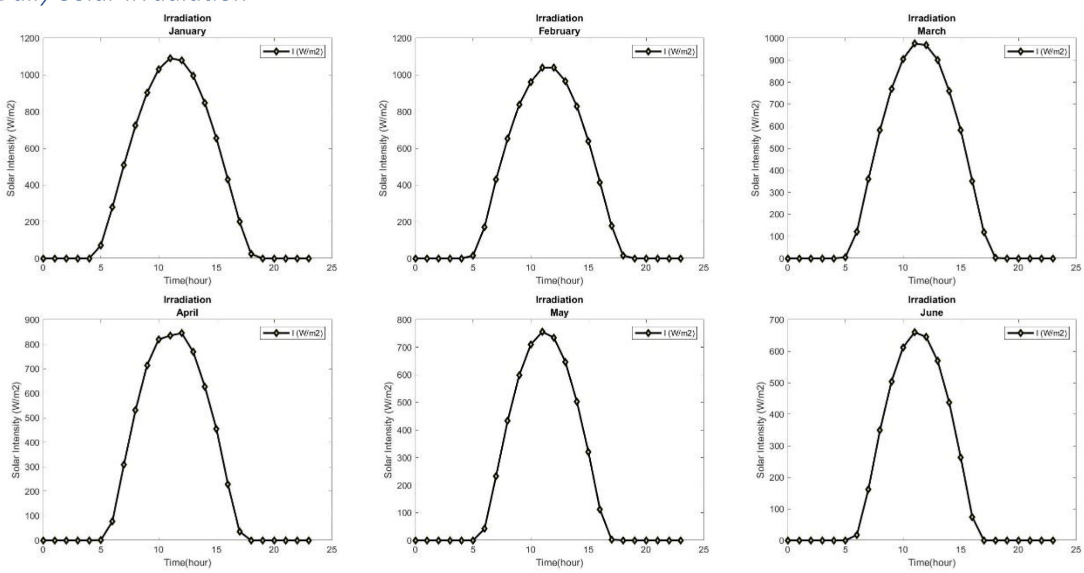


Figure 53 Daily water production - Best case

Daily Solar Irradiation



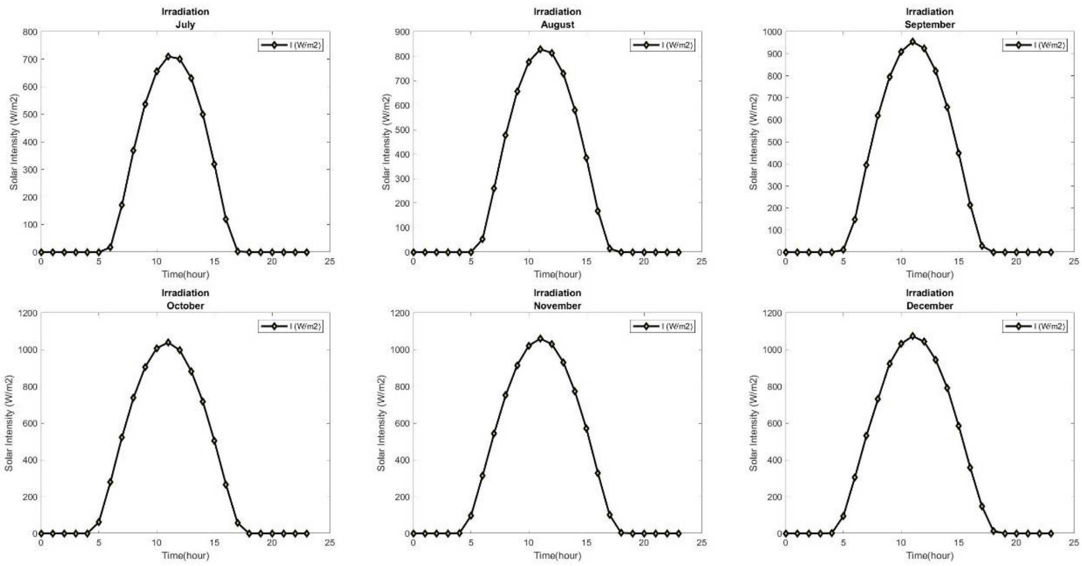
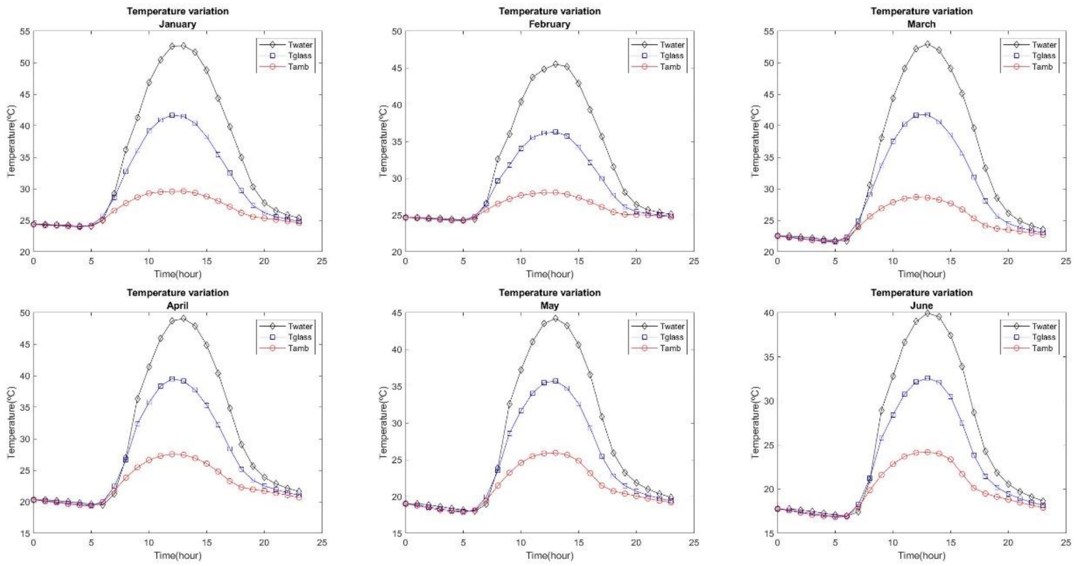


Figure 54 Daily solar irradiation - Best case

Average case scenario

Temperature Variation



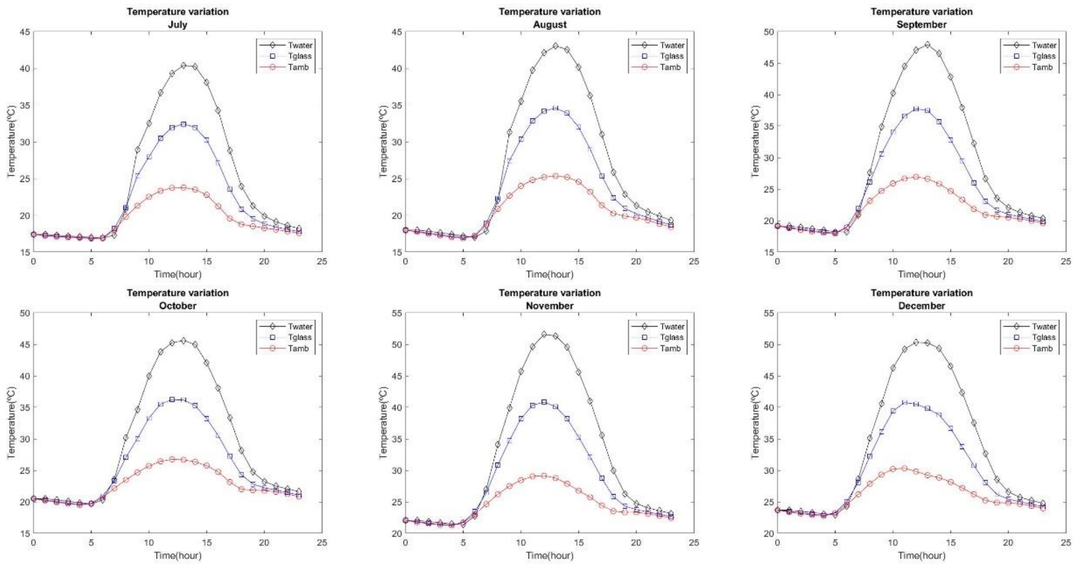


Figure 55 Temperature variation - Avg case

Daily Water Production

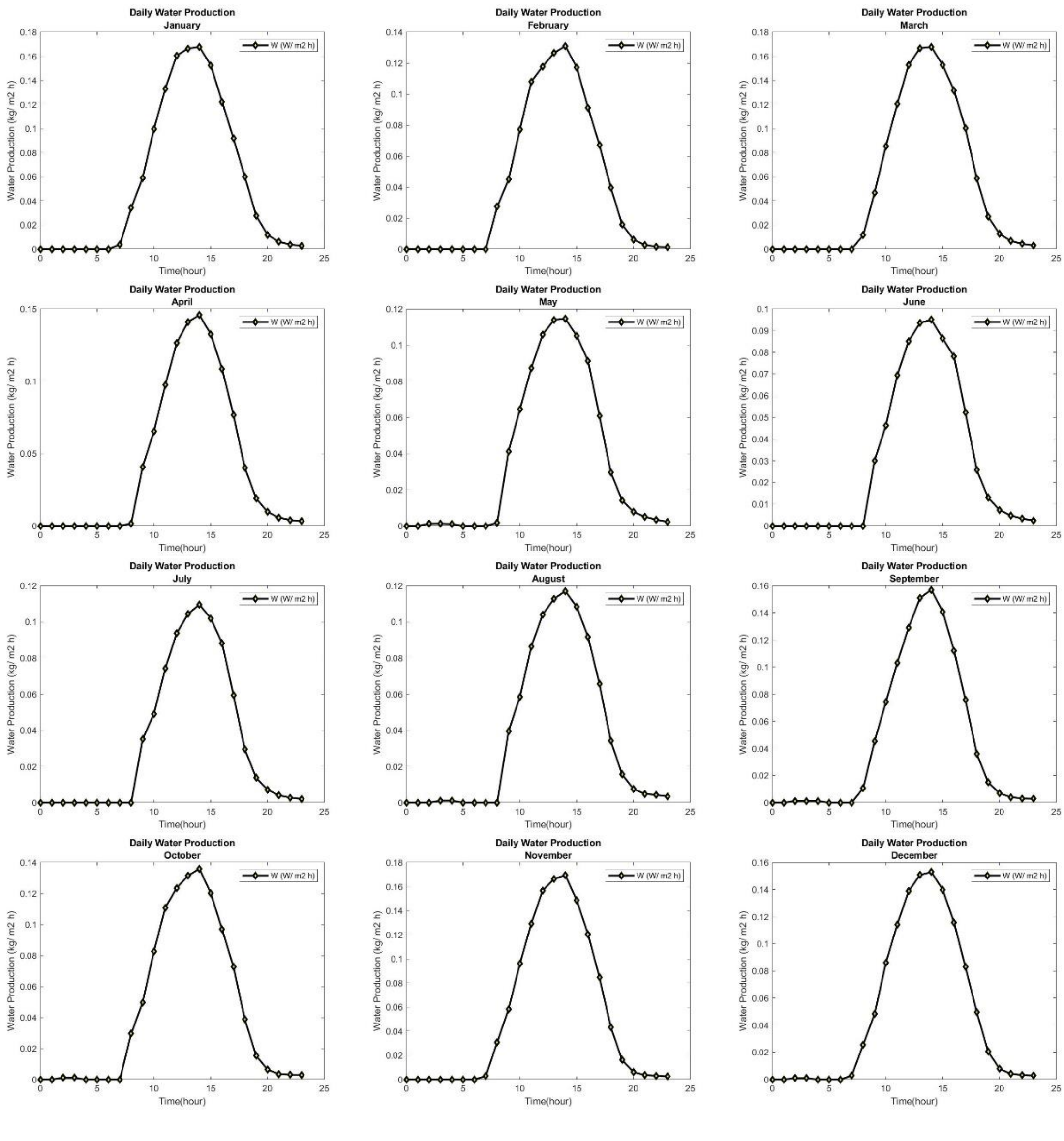


Figure 56 Daily water production - Avg case

Daily Solar Irradiation

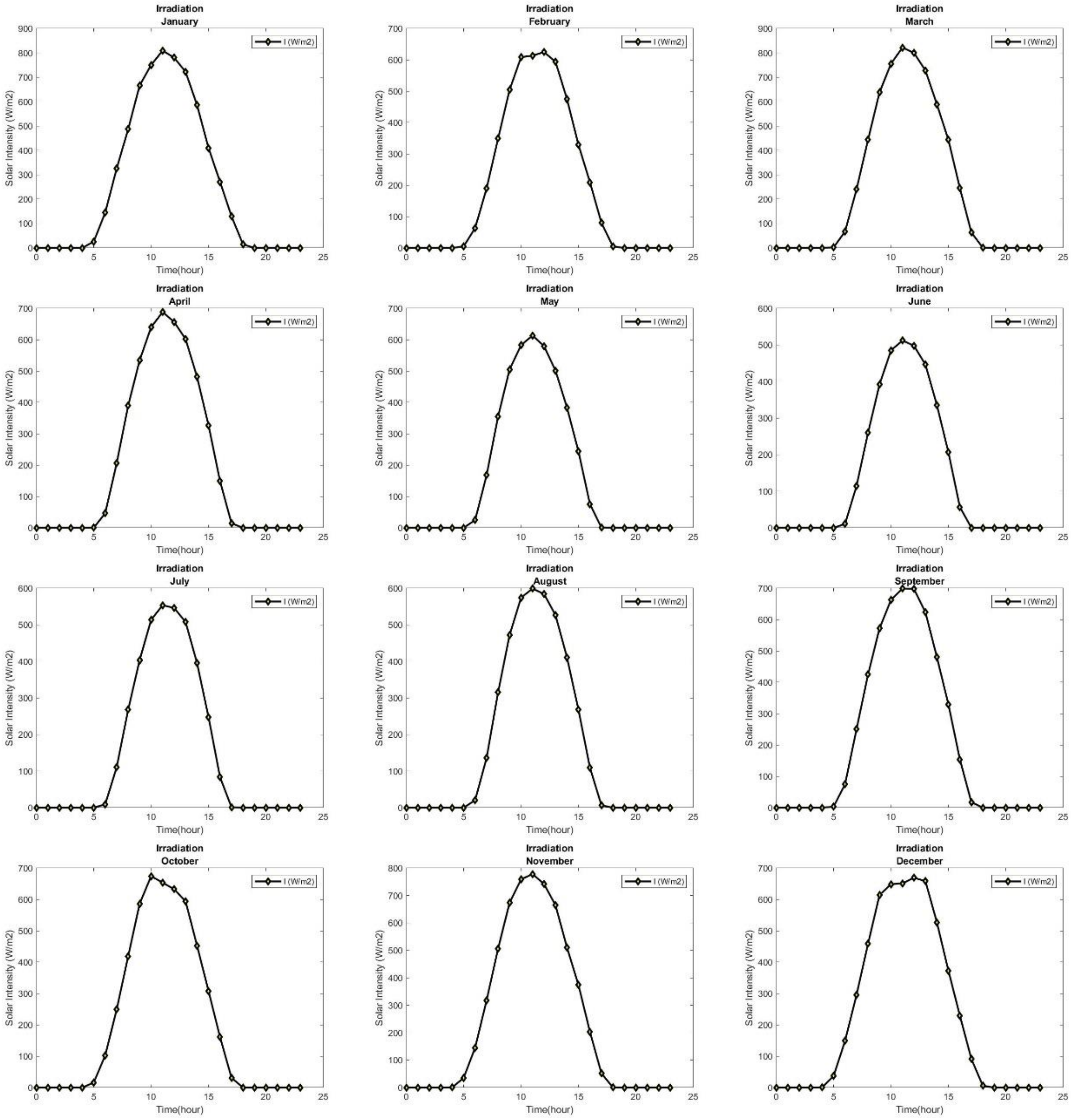


Figure 57 Daily solar irradiation - Avg case

Worst case scenario

Temperature Variation

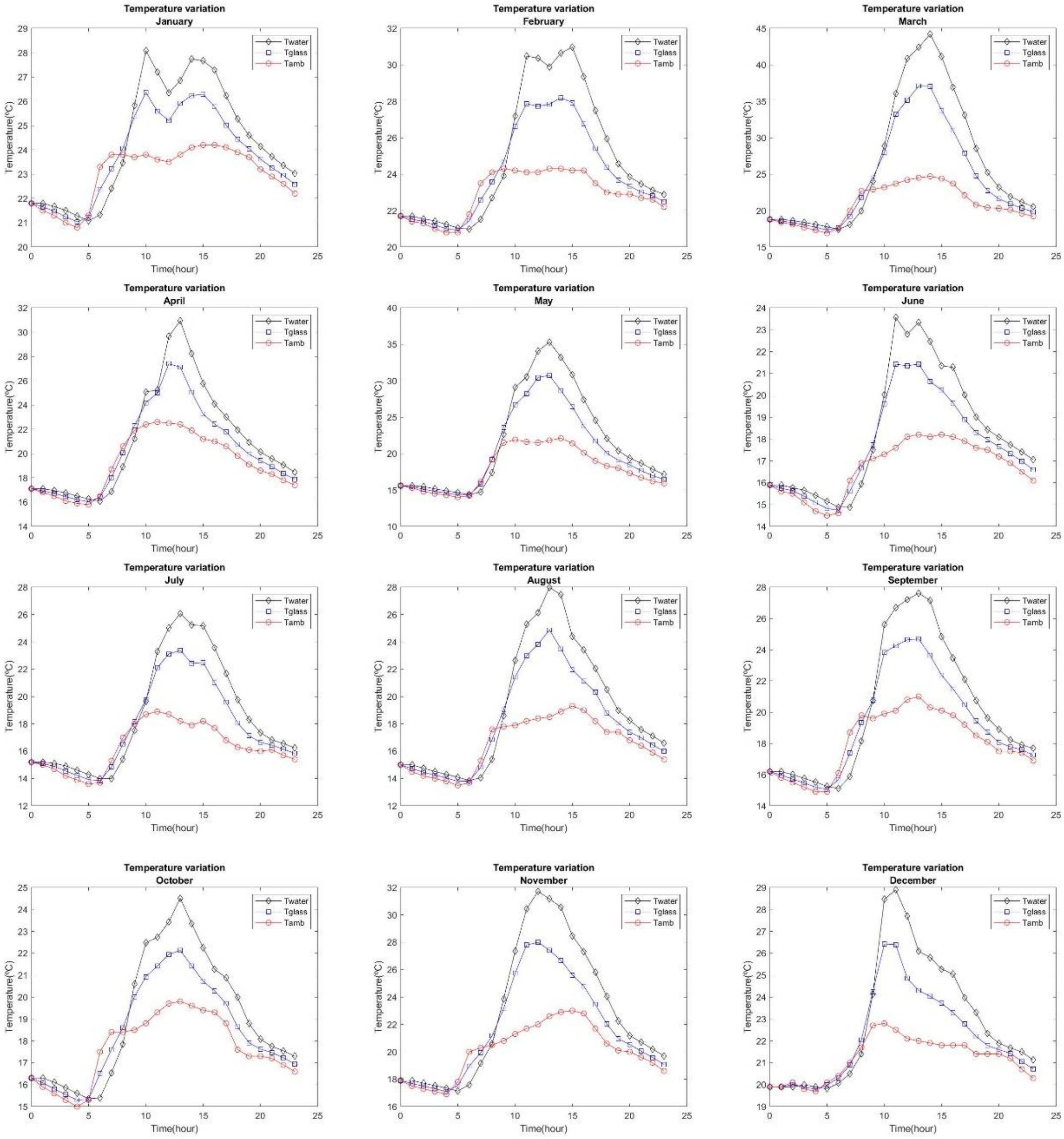


Figure 58 Temperature variation – Worst case

Daily Water Production

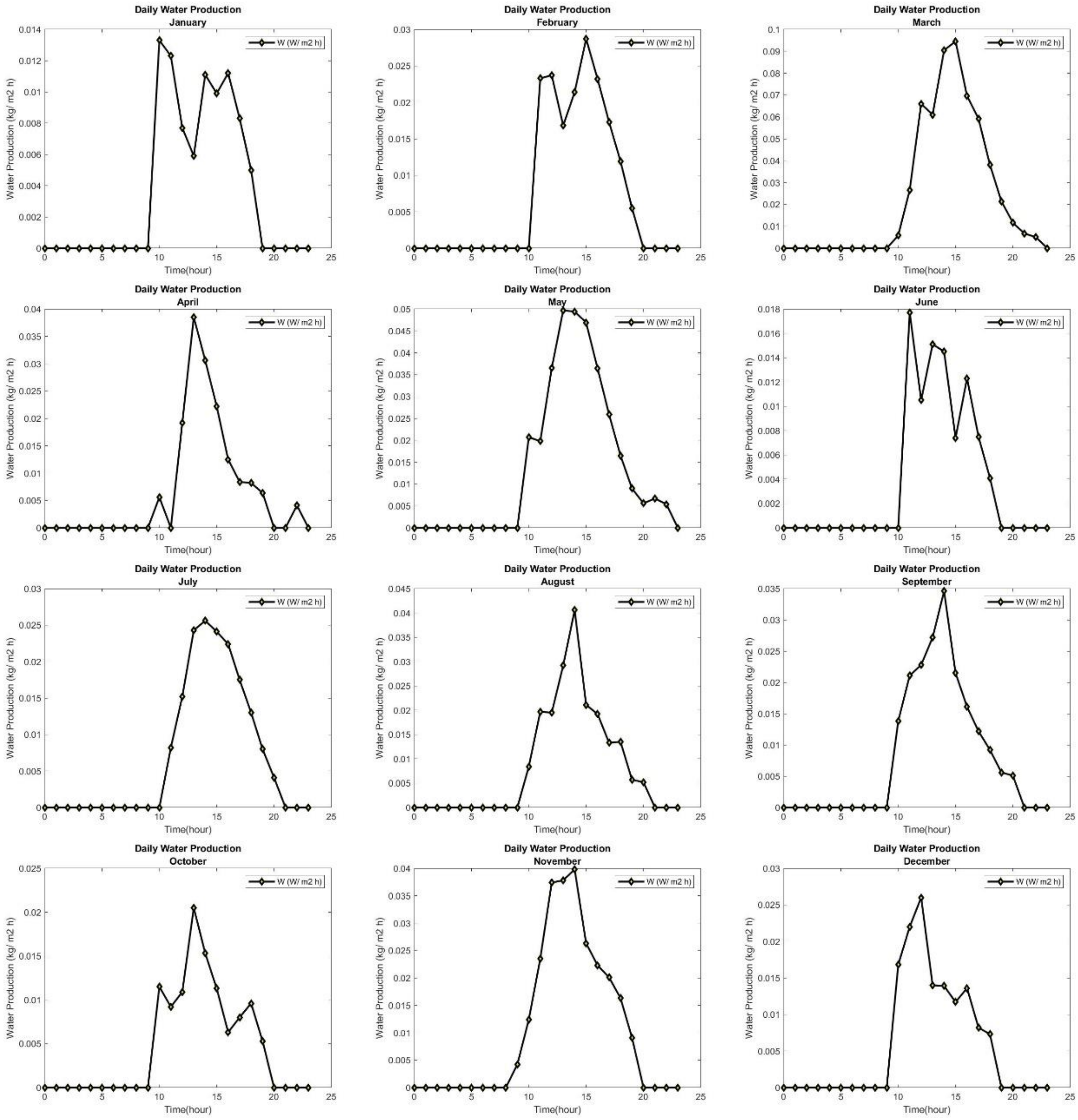


Figure 59 Daily water production – Worst case

Daily Solar Irradiation

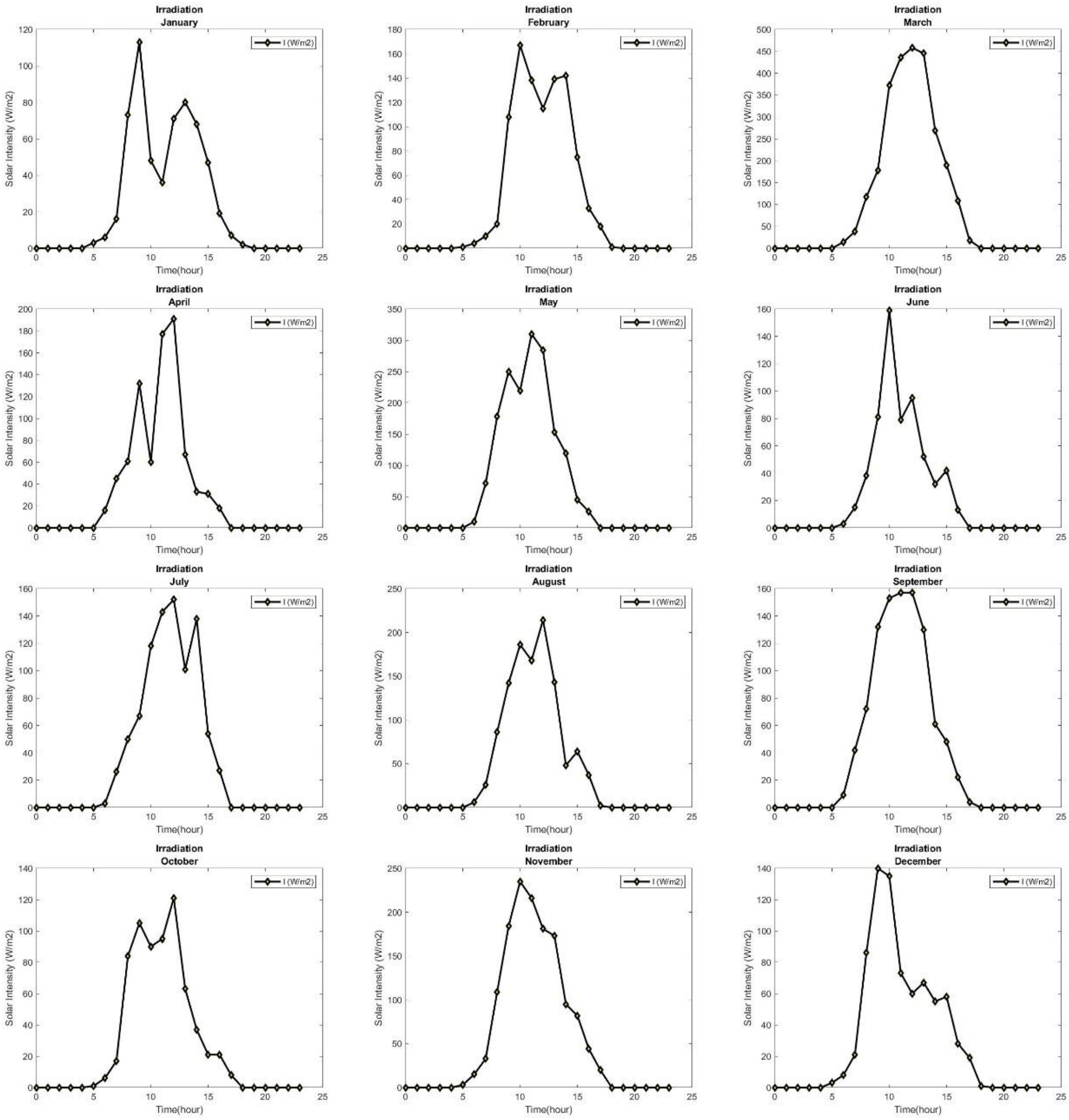


Figure 60 Daily solar irradiation – Worst case

Best case scenario with 300W resistance

Temperature Variation

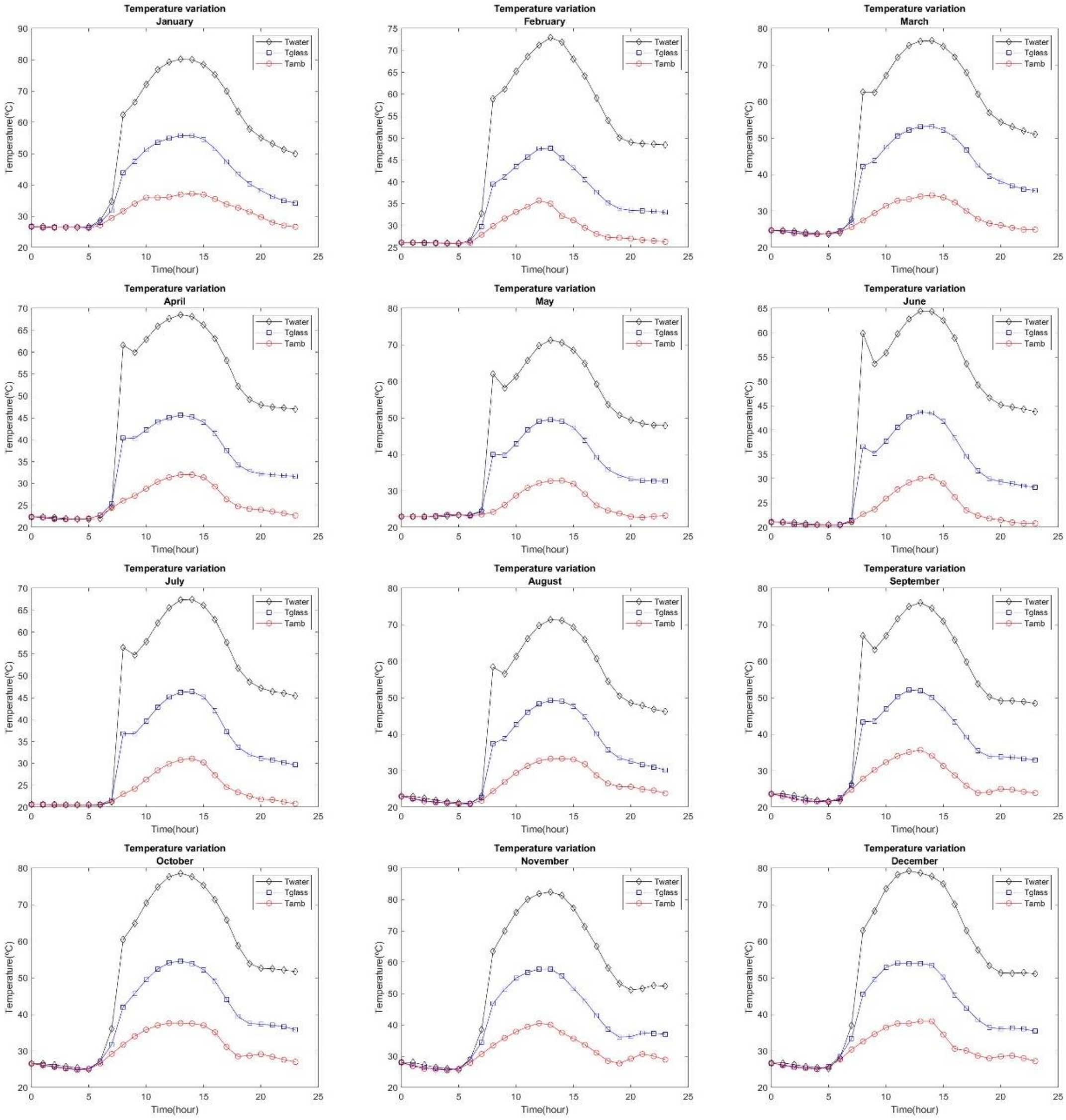


Figure 61 Temperature variation – Best case with resistance

Daily Water Production

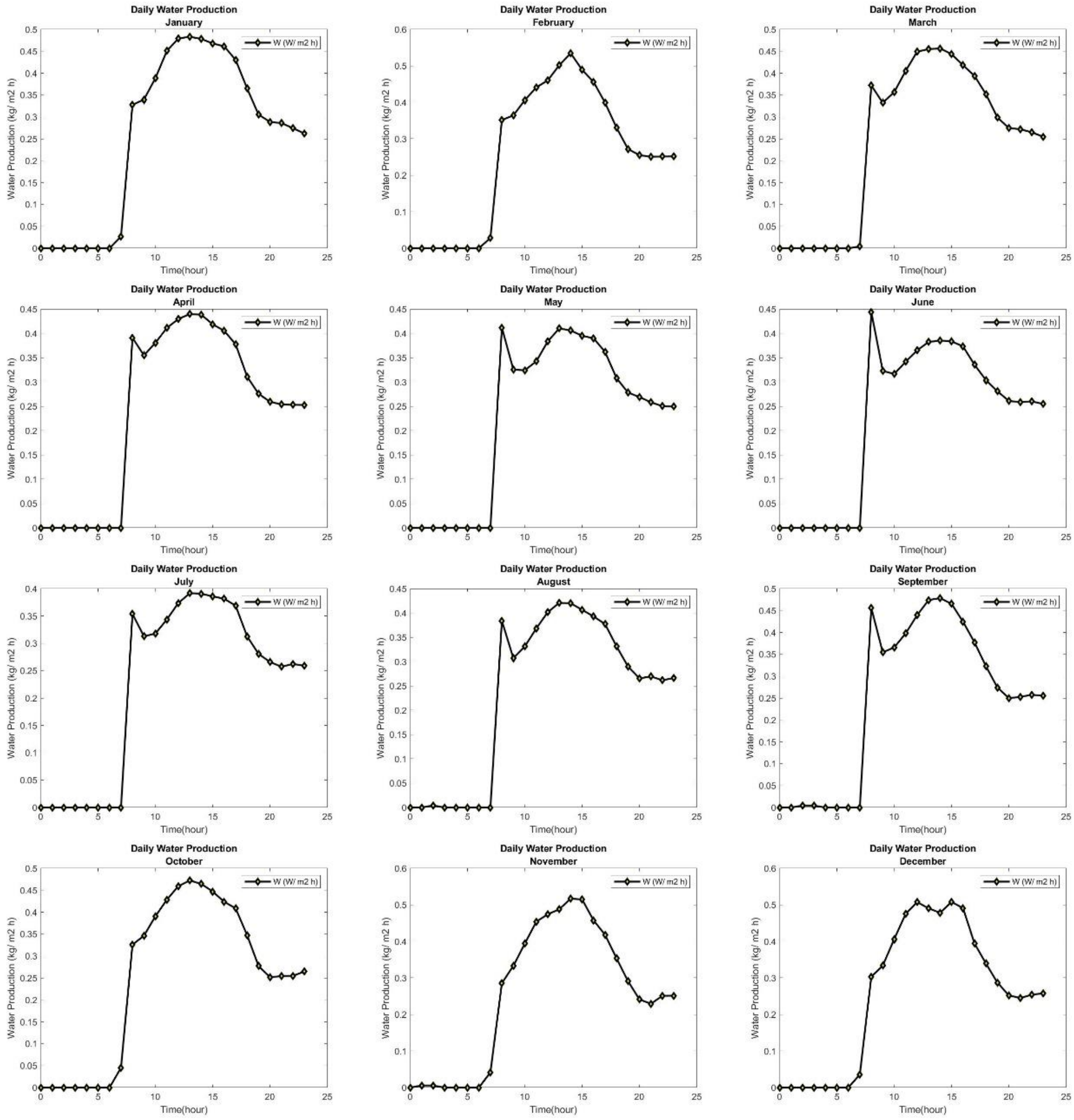


Figure 62 Daily water production – Best case with resistance

Daily Solar Irradiation

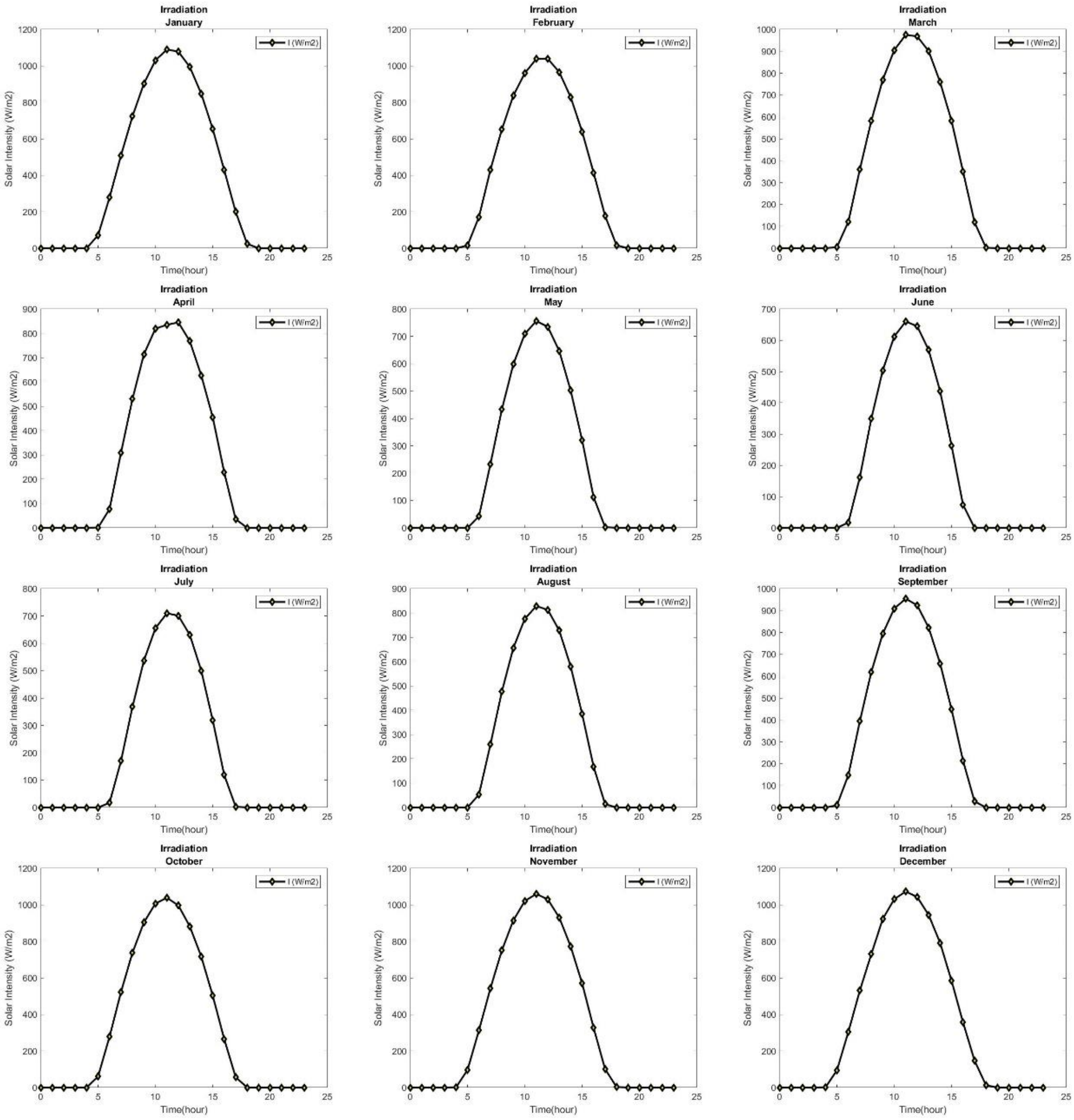


Figure 63 Daily solar Irradiation – Best case with resistance

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