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Research of the best desalination technologies with renewable energy for freshwater production: the case of two cities in France

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Nomenclature:

E_{d/m^2} : average daily PV out per m2 of installation (kWh/day)

E_d : Average daily energy production from 1 kWh of installation (kWh/day)

$\mathrm{P_{sp}}$: Power of the panel per m² (kW_p/m^2)

V_{fw_RO} : Volume of fresh water produce by the reverse osmosis plant (l)

V_{fw_MSF} : Volume of fresh water produce by the multistage flash desalination plant (l)

P_{RO} : Production of volume of fresh water per kWh (l/kWh)

S_{PV_RO} : Size of the solar panel installation with the reverse osmosis plant (m^2)

S_{PV_MSF} : Size of the solar panel installation with the multistage flash desalination plant (m^2)

V_m : monthly volume demand of a city (m^3)

nb_d : number of days during a specific month

Q_i : Energy gained due to sun irradiation. (W)

$G(n)$: Irradiance (W/m^2)

A_0 : Aperture Area. (m^2)

η_O : Optical efficiency of the mirror.

Q_r : Reflective energy (W)

ρ : Reflectance

α : absorbance

τ : Transmittance

Q_{conv} : Convective losses (W)

h_c : Convective heat transfer coefficient

A_t : Surface area of the receiver tube exposed to the environment (m^2)

T_{tube} : Temperature of the tube (K°)

$T_{ambient}$: Ambient temperature (K°)

Q_{rad} : Radiation losses (W)

ϵ : Emittance

σ : Stefan-Boltzmann constant

$\dot{m}_{PTC}$: Flow of the liquid in the first loop (kg/s)

C_{water} : Specific heat capacity of water

ΔT_1 : Difference of the input temperature and output temperature of the loop 1

ϕ_1 : energy transfer

η_e : Efficiency of the exchanger

Glossary

Fresh water: is water without salty but it is not always drinkable. From rivers and streams or even glaciers [1].

Drinking water (Or potable water): unlike fresh water, drinking water has received some additional treatments to be drinkable [1].

Abstract

The lack of water affecting human activity and the household, is a real problem even in France, accelerated by the increase of the drought periods cause by the global warming. The shortage risks therefore to increase in the future, so some solutions need to be implemented to fight against this problem. During this paper we are going to study two technologies of desalinization powered by various solar sources in two cities in France. The goal is to determine which combinations is the best for each city and finding the size of installation required for each project. The demand of the fresh water will be focused on the direct consumption of the household on drinkable water.

Introduction

Drinking water is a very important resource for the human population. The quantity of fresh water has a direct impact on the human activities, and it is used in many fields such as agriculture, industry, and household consumption. The access to drinking water is an essential need, indeed, the hydration is one of the main factors at the survival of the human body. Agriculture also needs a large amount of water to irrigate the plantations and get drink the animals. For the industry, the fresh water is use in many processes such as cleaning or cooling.

Worldwide, the total supply of freshwater amounts to 35 million cubic kilometres[2], mainly found in glaciers, rivers, lakes, groundwater, or artificial reservoirs. In France, fresh water comes from multiple sources. For example, they treat the water of the rivers to get drinkable water. They also extract water from groundwater. Groundwater and rivers are the main source of water in France. The amount of water in these reserves change trough the water cycle [3], which makes it possible to recharge the available water stock. The rivers are supplied partially by the melting of the glaciers which are supplied by the snowing. The groundwater is supplied by the rain which go through the ground before filled the groundwater cave. The recharge of nature reserves such as the water table is therefore an important issue because two-thirds of the water intended for human consumption comes from underground sources in France [4].

France is a country with a varied climate but mainly oceanic and continental. Temperatures vary throughout the year between -5°C and 30°C with the hot season in summer and a cold season in winter and two middle seasons, lasting four months each. There are many raining days in winter season, the reserves accumulate water in the period, in contrast, the summer is a dry season with few raining days, so the global reserves have difficulties to refill in this season.

The global warming has increased the difficulty to refill the reserve of fresh water in the world and it creates many regions with freshwater problem. This phenomenon is going to be worse in the future. According to OECD, in 2050 40% of the global population will be living in water-stressed regions [5]. In the case of France, the temperature has risen a lot, leading to an increase of the strong dryness which create difficulties in recharging groundwater. The average temperature have increase of 1.1°C compared to the pre-industrial era [6].

The droughts have also affected the lakes and the rivers, which have a very low levels during the period of dryness. The article form Euro news [7] estimate that 90% of glaciers in the Alps could disappear by 2100 due to the global warming. Water reserves have therefore fallen drastically and there have been increasing shortages [4].

In addition, the consumption of drinking water by human has also increased and will continue to increase in the future. Water demand has risen significantly and is expected to exceed global supply by 40% by 2030 [8]. The causes of these change are population growth, the industrial development of the world and especially climate change. The drinkable water is now overexploited and there are shortages

of this essential resource in different regions of the world which are a real threat for the humanity. The demand increase pushes the humanity to exploit more the reserve and create even more shortage. To complete the water demand in France, 32 billion cubic meters of fresh water [4] were extracted in 2017 from various fresh water sources. This amount represents 0,84% of the Mondial consumption of fresh water, with a Mondial consumption around 3 800 km^3. Only 17% of this amount was used to produce drinkable water [4]. This percentage will increase in the future due to the rise of the demand.

Today, the consumption is very different from a world region to another. In France, the average daily consumption of water in a household is 146 litres per inhabitant [4]. This is equivalent to an average of 53 cubic meters per year. For the metropolitan region of France, if we also take the indirect consumption, like the industrial and the agriculture, the annual volume of water per inhabitant is 82 cubic meters [9] (around 224 litres per day per inhabitant). To compare in UAE the consumption is one the highest in the world with a consumption between 525 and 600 litres per capita per day in 2007 [10]. This is equivalent to a consumption over 190 cubic metres per year per inhabitant. The excessive consumption of UAE is explained by various things such as the very dry climate which produce a high evaporation rate and an uncontrolled use of water for irrigation [11].

The household water consumption is linked to many different uses as drinking, washing clothes and dishes, cleaning and outdoor activities like garden and swimming pool.

The consumption of water changes a bit during the year. The study carried out by Olivier Gerin et al. (2014) [12], show the seasonal variation of hot and cold water consumption of an household in Belgium. This study will help us to estimate the water consumption in the cities. We can report these results because the Belgium is next to France and the climate is quite the same especially for the norther part.

Shortage happens when the resources of water are not enough to supply the population. There are many shortages each year mostly during the summer months. In 2022, more than 100 French cities were running of water due to the low precipitation and the high temperature [13]. The shortage creates many different risks for the population in various area. For example, they can create health problems due to a bad hydration and disease development. Shortage also affects the economic part, by lack of water to irrigate plantation, so the food production will be less efficient. And it creates problems in the environment, by affecting the biodiversity. The low levels of lakes and river kill many species and some species can disappear, it is the desertification of field due to the lack of water.

Desalinisation:

To compensate the lack of water, the society have developed diverse ways to produce drinkable water. Today in the world, countries mainly extract the fresh water from different natural sources, and they treat it to produce drinkable water. However, there are other ways to produce drinkable water such as the desalination of sea water. The principle is to extract water from the sea and with different processes removing the salt for the sea water to produce fresh water. Based on the International Desalination Association (IDA) and Global Water Intelligence, the number of desalinisation plants worldwide is 19,372 in 2017, with a total capacity of water production of 92.5 million cubic meter per day, [14]. The actual desalination production in the world represents 0,29 % of the France consumption.

Today in France, they produce drinkable water by extracting the fresh water from different natural sources, and by treating it with different processes of filtration. There is no desalination plant active today in France, however, we can see some projects appear that show the interest and maybe the implementation in the future. There is a project for a desalination plant in the Vendee region using reverse osmosis technology to produce fresh water [15]. However, the project has not been completed because the project has no economic viability today. In fact, there is no desalination in France because it is less expensive to treat the fresh water from the natural sources. France is not using desalination also because the reserve still stays high, but with the global warming, it's possible to see new projects

of desalination plant due to the lack of fresh water natural reserve. The neighbours of France have developed some project such as Spain which have the biggest desalinisation plant in Barcelona. The capacity of production of 200 million litres of water per day (equivalent to 200,000 m^3 per day), the production represents 24% of the consumption of Barcelona [16]. This plant also uses the reverse osmosis technology.

There are several methods of desalination of the water. And especially two types of method, the thermal desalinisation with the distillation process and the filtration desalination with different membranes to filter the salt and other waste of the seawater by put pressure to the water to pass through the filter. For the filtration desalination, the Reverse Osmosis (RO) is the most use and it represents 65% of the market [17]. For the thermal desalination, the main technology is the Multistage Flash Distillation (MSF) which represents 21% of the market, follow by the Multi Effect Distillation (MED) with 7% [17]. Today the most mature technology of thermal desalinisation is the Multistage Flash desalination (MSF)[18].

The study carried out by John Feria et al. (2021) [19], shows the different technology of thermal desalinisation used in the world. In this review, the multistage flash desalinisation (MSF) is present, and two others popular technologies such as the multi effect distillation (MED) and the vapor compression (VCD). The study concludes with a review on the water desalinization with renewable energy. Also in the study carried out by García-Rodríguez et al. (2002) [18], write on the different technologies of renewable energy link to the different desalinisation technologies, especially the thermal desalinisation such as the MSF and the MED and the membrane such as the RO. The MSF with the PTC have been successfully installing in Kuwait [18] with a production of 100 m^3/day, the project is a special MSF technology call MSF auto regulated. And a 20 m^3/day for the RO. This study regroups many projects of solar desalination in the world and the water production of each project. That show the interest for the solar desalination in the world.

The choice of desalination technology changes between the different area of the world. As the graph below we can see that the choice of the technology is completely different, with mainly RO in United States (69%) and mainly MSF in UAE (86,7%).

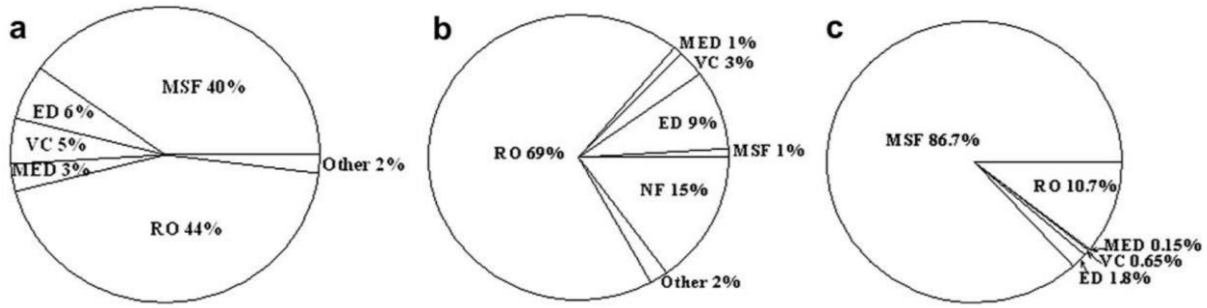


Fig 1: Distribution of desalination production capacity by process technology. For (a) the World, (b) the United States, and (c) The Middle East. [20]

After the reading of many papers, we will choose to study the MSF technology for his popularity and his capacity to be apply to large scale and the RO which are popular also and has the best energy efficiency, as we can see on the table below:

Desalination Technology	Specific Energy Requirements
Multi-Effect Distillation	14–21 kWh/m^3
Multi-Stage Flash	20–27 kWh/m^3
Mechanical Vapor Compression	7–12 kWh/m^3
Thermal Vapor Compression	16.26 kWh/m^3
Seawater Reverse Osmosis	4–6 kWh/m^3

Fig 2: Typical total electrical energy consumption in different desalination technologies. [19]

Most of desalinisation plant are power by electricity from the national grid today. Depending on the country, the electricity can be very polluted to produce. A solution to reduce the impact on the planet is to use renewable energy technologies to power the desalinisation plant. There are few projects that have been developed in the world. The most used source is solar energy, with 70% of the market (43% of photovoltaic panel (PV) and 27% of solar thermal), follow by the wind energy with 20% [17]. These sources of renewable energy are linked to different desalinisation technologies where the most common is PV with RO, which represents 32% of the market [21].

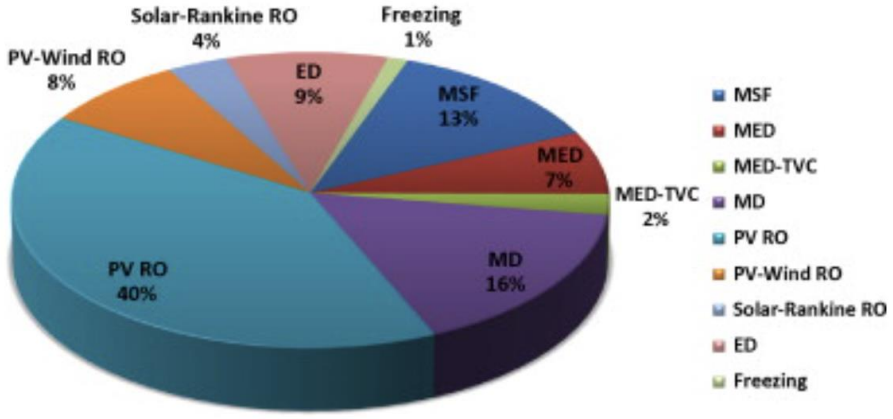


Fig 3: Share of desalination Technologies in indirect solar desalination plants installed worldwide. [22]

Solar desalinisation:

Solar desalination is a potential solution to freshwater shortages around the world. There are many studies done on solar desalination. Most studies and simulation models are carried out in countries with ideal weather conditions for solar exploitation. The United Arab Emirates is one of the countries with the most studies carried out.

The research on solar desalination focuses mainly on two systems:

- Thermal desalination link with a thermal solar system such as the parabolic thermal concentrator.

- Membrane desalination power by electricity from a PV system which is the most combo use in the solar desalination in the world.

For the thermal desalinisation there are many studies which use the Parabolic Trough Collector (PTC) to power a desalinisation system. For example, Fadi Ghaith (2018) studied the performance of a solar parabolic trough collector to power a desalination system in United Arab Emirates [23]. In this study, he discovered that the total production of drinking water is 67308 kg/year for a 60 m² installation. However, in this study he doesn't use a multistage flash desalinisation plant, but he directly evaporates the seawater in the PTC pipe. He uses a flushing system, to eliminate the salt and maintaining an optimal productivity. He compares the system with a preheating system to improve the result.

The study carried out by Al-Othman et al. (2018) [24], experiment and simulate an installation of solar desalinisation drive by PTC link to MSF desalinisation. The simulation has been done in UAE, and the system is capable to produce 1880 m^3/day of desalinated water, out of 40,000 m^3/day of seawater. The total aperture of the PTC is 3160 m^2. So, we can calculate that the production is around 0,59 m^3/day/m^2. In this paper, a solar pond (SP) has been used to improve the results of the simulation. The solar pond has been already implemented in some project; it has a very low cost. The principle is stoking water outside and get energy from the sun by heating the water surface. The solar pond is used to preheat the seawater in this study.

Both previous studies [e.g. 23,25] try to improve the performance of the system by combining the technologies to maximize the freshwater production. Different technologies such as the preheating or the solar pond bring an advantage with a cheap production heating system which will preheat the water at the beginning of the process. However, the cheap production heating system cannot reach the high temperature needed due to the technology limitations.

For the membrane desalinisation there are many studies which use the solar panel to power a desalinisation system. In the study of Mohamed Abdelgaied et al. (2021) [25], the principle is to use photovoltaic panels to operate a desalination plant using reverse osmosis. In this study, the desalinisation system combines a Humidification-Dehumidification (HDH) and Reverse Osmosis (RO) processes, to improve the performance of the water production. The energy use to produce fresh water is ranged between 1.22 and 1.24 kWh/m^3. The data used from the Metronome program for the Cairo city, in Egypt.

Moreover, there are much others research on solar desalination which try to use new solar system to get better result. Such as the study carried out by Mohamed Omri et al. (2022) [26], where it study an installation with the Concentrator Photovoltaics link to a MED desalination system. The idea of this study is to use the overheat of the Concentrator Photovoltaics to heat the water for a MED desalination. The study resulted by showing that this system could preheat the water for the MED, but it is not enough to power all the plant. However, this technology can reduce the cost of the desalination water and avoid a wate of energy.

The study carried out by Muhammad Tauha Ali et al. (2011) [22], This study gives a global review of the indirect solar desalination. It looks at different combo of technologies such as the PV-RO or the PTC-MSF and regroup the result from many projects. This study helps to understand the different types of solar desalinisations and see the different process which are used to power desalination plant from the solar sources.

Cost of seawater desalination:

The cost of the fresh water is often link to the energy needed to produce it. The lakes and rivers water have the lowest energy cost to produce drinkable water follow by the groundwater with a consumption of 0.37 kWh per cubic meter of fresh water and 0.48 kWh per cubic meter for the groundwater [27]. The wastewater treatment has also very low energy cost, around 0.62 to 0.87 kWh per cubic meter of fresh water [27]. This is why France choose this method today. In another hand, the desalinisation of seawater has a high energy cost which depends on the method (around 2.58 - 8,5 kWh/m3 [27]). The method with the lowest energy cost is the reverse osmosis which spend between 4 and 6 kWh per cubic meter of fresh water [17]. The Multistage Flash Distillation spends around 20-27 kWh per cubic meter of fresh water produced [19]. However, The MSF plant is still used a lot because the installation of this plant is easier to build for big freshwater production. Despite the high energy cost, this type of installation offers various advantages that allow it to be easily combined with renewable energy production technologies. In particular, the solar energy production technologies, where energy losses can be limited by reducing the number of different losses and using only thermal energy without passing by other form of energy as electricity for example. This is why there are some studies which

are still using MSF [e.g. 22, 24]. Also, another reason it is due to the water production results which are attractive in sunny area.

The study carried out by Caldera et al. (2016) [5], look at the local cost of reverse osmosis desalinisation with solar PV. The study also estimates the price of the fresh water with an installation hybrid PV and wind. And found that the price will be between 0.59 €/m^3–2.81 €/m^3 depending on which technology has been used. This study shows the amount of money that will be necessary to pay to get fresh water from renewable with reverse osmosis desalination plants. Another study made by Li Junwen et al. (2019) [28], compare the price of fresh water for each desalination technique. The results are 1.92 \$/m^3 (~1.76 €/m^3) for the MSF and 1.06 \$/m^3 (~0.97 €/m^3) for the RO. The study shows that the reverse osmosis is the cheapest way to produce fresh water.

Environmental impact of the desalination:

The study carried out by Saleh et al. (2019) [29], it studies the CO2 emissions produce by a the desalinisation plant in UAE. Moreover, in this study, they estimate the potential CO2 emissions from the desalinisation plan in 2030. They found that the CO2 emissions will be around 139.252 billion tons in 2030 the supply the UAE in fresh water. This massive amount of pollution is due to the used of petrol to power the desalination plant. This result on CO2 emission will help us to compare with the number that we will get in this study.

Aims

The goal of this paper is to find the best combination of technologies for two French cities and understand why the final combination is the best. The lack of water for the plantation and the hold house, is today a real problem in France, accelerated by the increase of the drought periods cause by the global warming. This study will give first research for these two locations. And also, a beginning for the studies on desalination of seawater in France.

Research Proposal:

My research aims to compare the two combined technologies and find out which one performs better in the two regions studied. In addition, this study will provide information on the freshwater production capacities for each technology in the two cities. It will also determine the dimensions of the installations required for each solar technology. Furthermore, the CO2 impact of each project will be calculated and compare to fossil desalinisation plant.

Toulon and Le Havre have almost the same number of inhabitants but are located in different locations with different climates. During this research exercise, the two locations will be analysed, and the objective is to discover the potentials of freshwater production in the two different locations with two methods using solar resources. The first method of using photovoltaic panels to generate electricity to power the RO desalination plant. And a second method that uses the concentration of solar energy to produce hot steam which will give his energy to the Multistage flash desalination plant. Finally, the calculations will be carried out to determine the best technology for each location and the CO2 impact of the installation.

Research questions:

During this paper, we are going to try to answer the following questions:

The water needs.

- What is the consumption of the household for both city?
- What is the variation of the need during a year?

The water production.

- How many litres of fresh water can we produce with the different solar technologies in one days per m² of solar installation? The goal is to determine the production of fresh water in the two different area.
- What the best technology for each region?

The goal of this studies is to better understand the solar desalination and see the best technologies that can be used in France.

Limit of the previous studies:

Today, there are few research on desalination and no research on the solar desalination in France. It can be explained because the treatment of dirty water is cheaper than the desalination in France. But with the global warming the importance of water will be higher, and the lack of resource will push the society to develop the desalination solution. Moreover, the desalination will be also necessary to fight against the drought.

In most of the paper on solar desalinisation, the study use combines technologies to improve the result, as we saw before with an addition of a preheating system to the desalination plant in previous studies [e.g. 23, 24].

However, during this paper, we are going to calculate the freshwater production without any improvement. I choose to not do the calculation with additional technologies because we want to get data on the fresh water production with just the desalination plant and the solar energy production system.

Methodology

For the calculation, there are two main parts for each solar technology. The PV with the reverse osmosis, and the Parabolic Trough Collectors (PTC) with the multistage flash desalinisation process (MSF). In order to compare the two methods of drinking water production, we will study the production of drinking water for each month of the year. The objective will be therefore to compare the quantitative production and the variation during the year.

The demand of the cities:

First of all, we are going to look at the variation of the demand of the cities. During this paper we are going to focus on the consumption of the household in fresh water.

We have to calculate the demand of fresh water for each city during the year.

Toulon: The population is 180 452 inhabitants in 2021 [30]. The consumption of fresh water in the area is 54,61 m^3 per inhabitants and per year [31]. The total demand will be:

$$Total\ demand = population \times comsumption = \ 9\,854\,483{,}72\ m^3$$

Le Havre: The population is 166 058 inhabitants in 2021 [32]. The consumption of fresh water in the area is 47,94 m^3 per inhabitants and per year [31]. The total demand will be:

$$Total\ demand = population \times comsumption = \ 7\,960\,820{,}52\ m^3$$

Toulon consume 21,8% more fresh water than Le Havre. This is due to the difference of the population and especially the consumption of fresh water which is higher in the South in France.

A study done on the consumption of household in Belgium [12] give us the data on a typical variation of freshwater consumption during the year. This data show that the consumption is a little bit higher

in winter than in summer with the lowest month which is July. This data is quite surprising because in summer the temperature is higher, and it look more logic to have a higher consumption. However, the Belgium is in the around the same latitude (49°) as the city of Le Havre and far from 300 km, so we can estimate that the consumption is the same.

Nevertheless, Toulon is not in the same latitude and the climate is a bit different so the variation of freshwater consumption should be different. One of the points is that the summer is a bit hotter in the South than in the North. However, they are no data for the consumption of this area, so we are going to suppose that the consumption is the same in the two cities study in this paper, it will be easier to compare the results between both cities.

The variations are very small, nevertheless, we are going to consider it in the calculations.

We used this data to calculate the consumption of each month by multiplying the total consumption by the percentage of consumption of each month. This percentage of the total water production is not directly given in the seasonal variation study [12]. However, I used one of the graphs from the study to estimate precisely the demand monthly variation (V_m).

$$V_m = average\ consumption \times monthly\ variation\ percentage$$

The graphs bellow shows the result of the freshwater consumption for both city during the year:

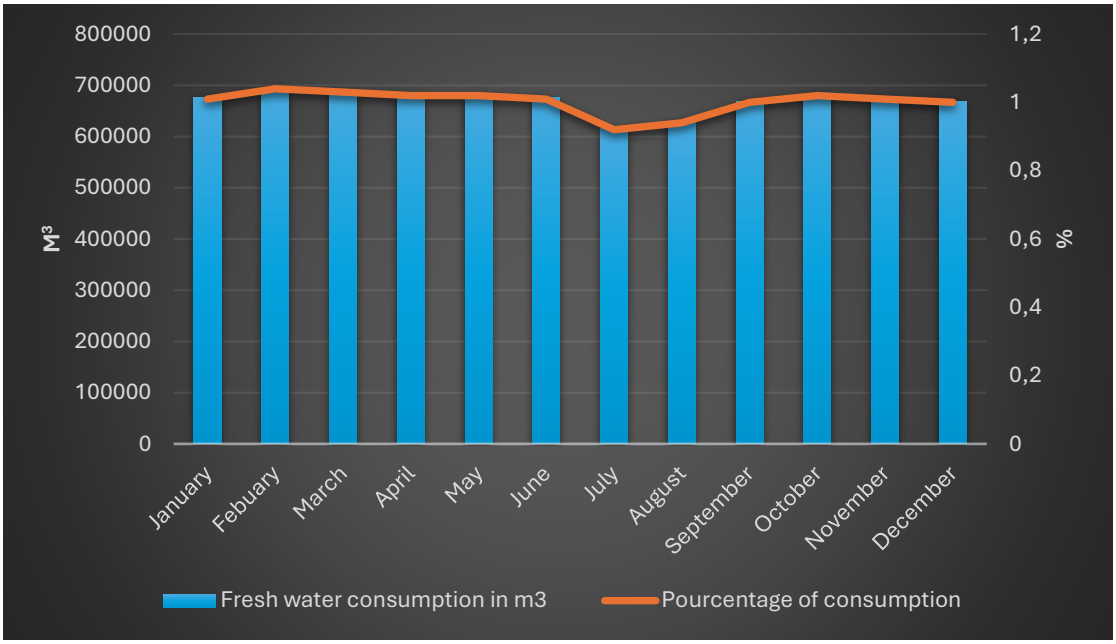


Fig 4: Water demand of the household (m^3) in Le Havre

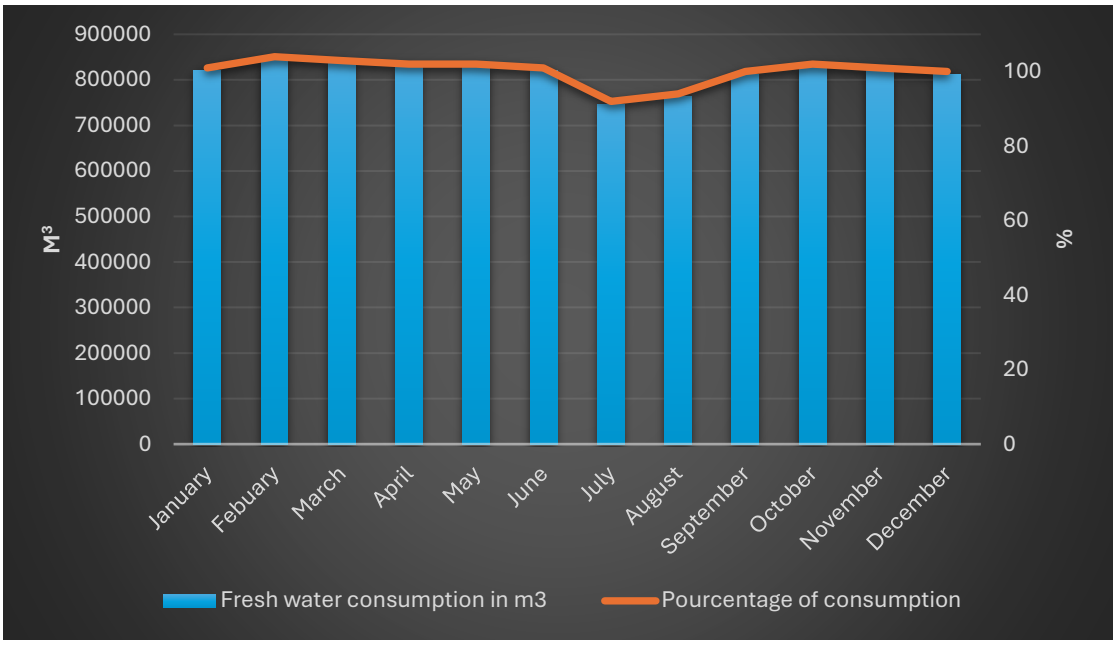


Fig 5: Water demand of the household (m^3) in Toulon

We can see on the graph that the freshwater consumption is near constant during the year in the household.

Methodology PV-RO and PV-MSF

In the following part, we are going to calculate the freshwater production with solar panel for Both technology (PV-RO and PV-MSF). The goal is to determine the best one between these two combos.

PV with the Reverse Osmosis (RO) and the Multi-Stage Flash desalination (MSF):

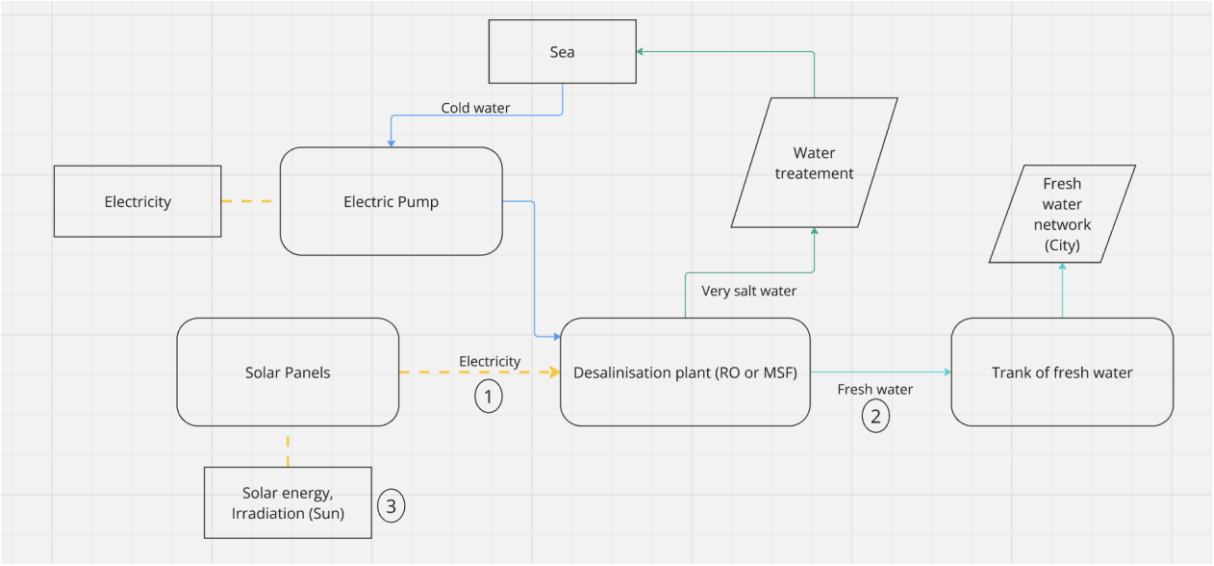


Fig 6: Models simplify of the system PV + RO / PV + MSF

The graph above represents the cycle of the system. First, the water is extracted from the sea by a electric pump and filter before going to the desalination plant. The desalination plant produces fresh water which go after in a tank to be stock or is distributed in the water network of the city. In another and the brine produce by the plant is treated before being release in the sea.

The first calculation will focus on how much energy we can get with one meter square of PV, the number 1 on the graph. Then, we will look how much fresh water we can get from this one-meter square of this PV installation (number 2). Finally, the number 3 correspond at the last calculation for this system: determine the size of the PV installation needed to complete the demand of the cities.

Calculations:

First, we will do the calculations related to the photovoltaic panels. We retrieved the data from the PVgis website [33]. Indeed, this site gives precise data on the electricity production of a solar panel installation. We have the possibility to enter precise parameters on the panel used, such as the type of photovoltaic panel technology (for our crystalline silicon study), the inclination of the solar panels (35°), as well as the system losses (14%). Then, the site provides us with different data to operate, including average daily energy production from a given system (kWh/day). The given system is a system of 1 kW_p, because the PVgis do calculation on a system with a minimum size of 1kW_p. So, to get the production per square meter we need to start by the first calculation as describe bellow.

Photovoltaic panel feature (used for the simulation):

- Power: 360 W_p
- Area: 1,94 m²
- Power per m² of the solar panel used (P_{sp}): 185,6 W_p/m^2

1) Calculation of the average daily energy per m^2 of installation (kWh/day):

To obtain the average daily energy per m^2 of installation (E_{d/m^2}), we need to multiply the data of average daily energy production from 1 kW_p of installation (E_d) by the power of the panel per m² of the solar panel used (P_{sp}) divided by 1kW_p. We will use this formula for each month.

$$E_{d/m^2} = E_d \times P_{sp}/1000$$

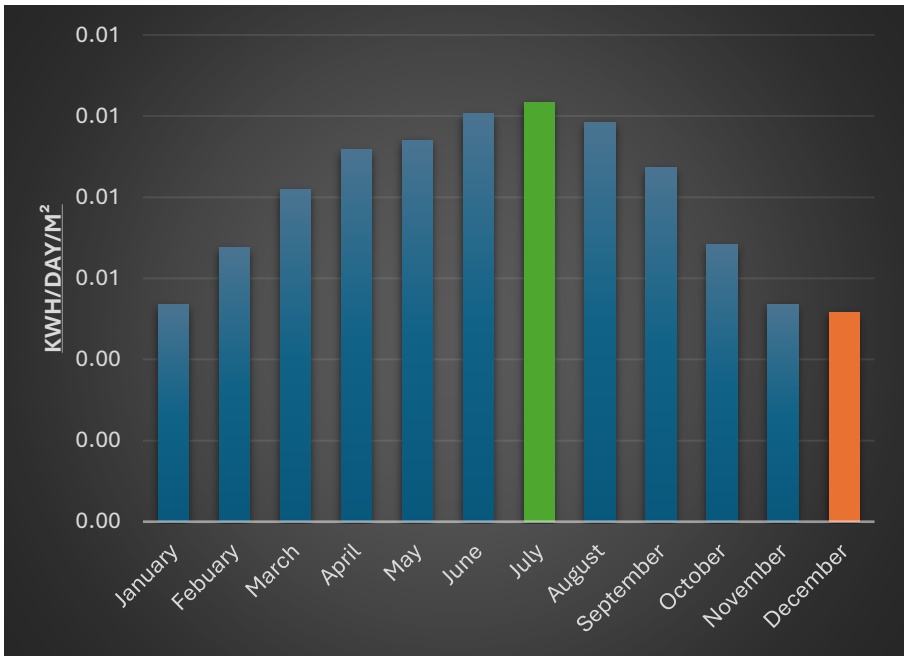


Fig 7: Average daily energy production per m² of PV panel (kWh/day/m²)

After calculating the electricity production per square metre, we will calculate the drinking water production of each technology. To do this, we use the table below, the data of which come from a

study by [19]. The first line of the table come from the study and the following ones is a simple conversion to get the litre per kWh for each technology.

Unit	RO	MSF
kWh/m3	6	27
m3/kWh	0,166666667	0,037037037
L/kWh	166,6666667	37,03703704

To find the average daily production of each month in drinking water per square metre (V_{fw}), we must multiply the average daily energy production of each month (E_{d/m^2}) by the production value of volume of fresh water per kWh (P_{RO} or P_{MSF}).

2) Calculation of the daily volume of fresh water produced by the reverse osmosis:

$$V_{fw_RO} = E_{d/m^2} \times P_{RO}$$

2) Calculation of the daily volume of fresh water produced by the multistage flash desalinisation (MSF):

$$V_{fw_MSF} = E_{d/m^2} \times P_{MSF}$$

Now, let's calculate the size of the PV installation to supply the demand. To get the total size of the installation (S_{PV_RO} and S_{PV_MSF}) which will supply one hundred percent of the demand, we need find the worst month of the year, where the PV installation is the biggest. For that, we are going to calculate the size of installation needed for each month. For the calculation of one month, we divide the total volume of freshwater demand for this month (V_m; previously calculated) by the sum of the daily production of this month ($nb_d \times V_{fw_{RO}}$).

3) Calculation of the size of the PV system with the reverse osmosis:

$$S_{PV_RO} = \frac{V_m}{nb_d \times V_{fw_{RO}}}$$

3) Calculation of the size of the PV system with the multistage flash desalinisation:

$$S_{PV_MSF} = \frac{V_m}{nb_d \times V_{fw_{MSF}}}$$

Result of PV-RO and PV-MSF

All the calculations have been done on Excel. We get the amount of fresh water produced every day for each month per m² of PV installation from the daily energy production and the formula seen previously. After calculating all the values, we plot the graphs of the freshwater production per m² on average day for each month. In Figure 8 and 9, the blue line is for reverse osmosis production and the orange line for the multistage flash desalination production.

For the city of Le Havre, the lowest value of freshwater production is during the winter where the energy production is the lowest, with an average production of 41,8 kg per day for the reverse osmosis and 9,3 kg for the multistage flash desalination. The highest value is in June, but the production seems to be stable between April and July where the value of production of fresh water is around 130 kg (between 129,9 kg and 135,5 kg).

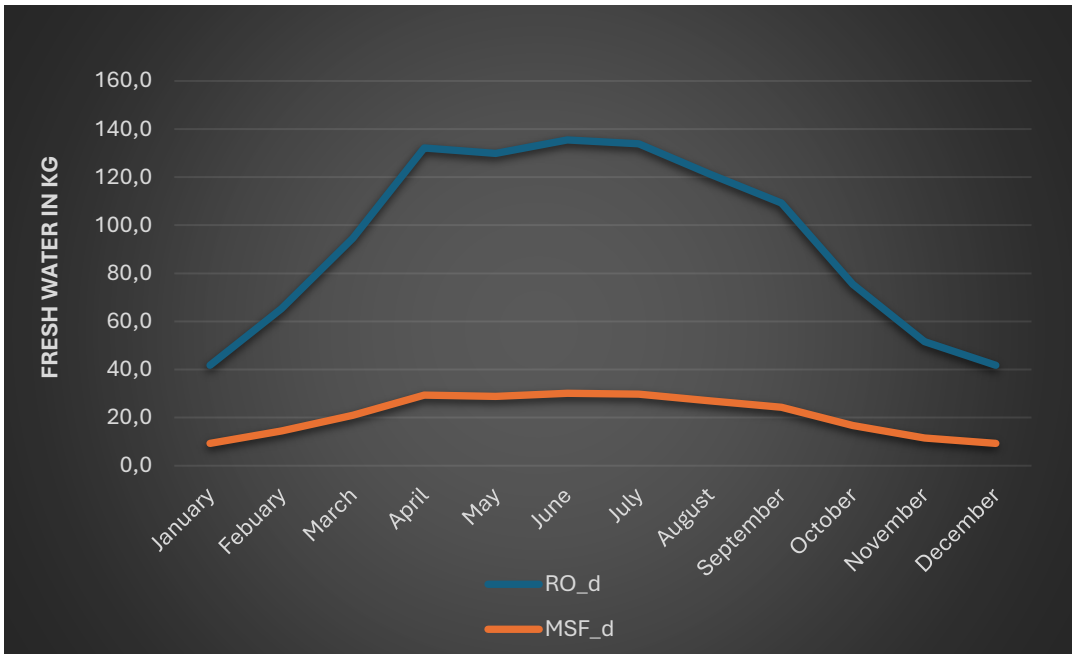


Fig 8: Water production per m² on average day of each month in Le Havre

The total production per m² of PV installation during the year in Le Havre is 34 482,4 kg for the reverse osmosis and 7 662,7 kg for the MSF.

For the city of Toulon, the lowest value of freshwater production is also during the winter, but the result is higher than the city of Le Havre. This difference seems logic because the energy production from solar panel in Toulon are higher than Le Havre. The energy production is the lowest in December with an average production of 86 kg per day for the reverse osmosis and 19,1 kg for the multistage flash desalination. This time the highest value is in July with 172,3 kg/d/m² for the RO and 38,3 kg/d/m² for the MSF. The freshwater production increase progressively until July, then they decrease until December before going up again.

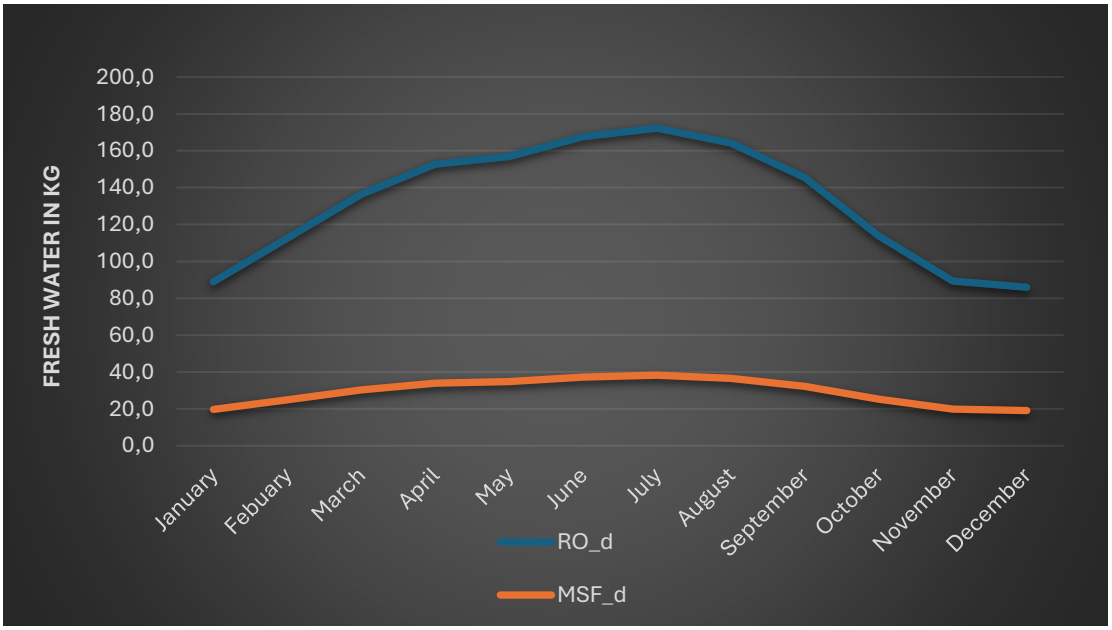


Fig 9: Water production per m² on average day of each month in Toulon.

The total production per m² of PV installation during the year in Toulon is 48 289,2 kg for the reverse osmosis and 10 730,9 kg for the MSF.

Finally, we found that with the PV system, the reverse osmosis is the best technology to use in both cities. The freshwater production is 4.5 times more productive with the RO than the MSF. The result make sense because the reverse osmosis needs less energies to produce fresh water from seawater.

Then we can compare both cities in the same graph for each technology. The following graphs highlight the difference between the two cities for each combo of technology. For the combo PV and RO, there are a huge difference in December, indeed, the freshwater production per m² is more than two times higher in Toulon (89,1 kg) than Le Havre (41,8 kg). However, the freshwater production during the summer is more closely between the two cities with a difference around 19% in June. The most similar month production is April with a difference of production around 13,5%.

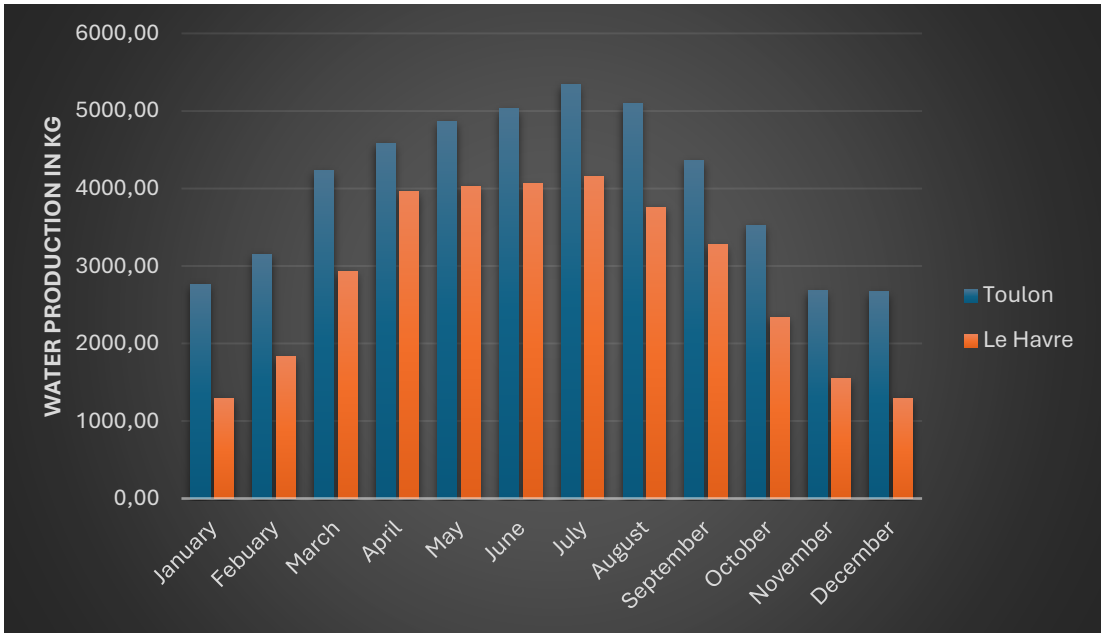


Fig 10: PV + RO process results of water production (in kg) for each city

Then, for the combo PV and MSF, the differences are similar because the solar data are the same, however, the value are much lower than the reverse osmosis due to the difference of efficiency of the two technologies.

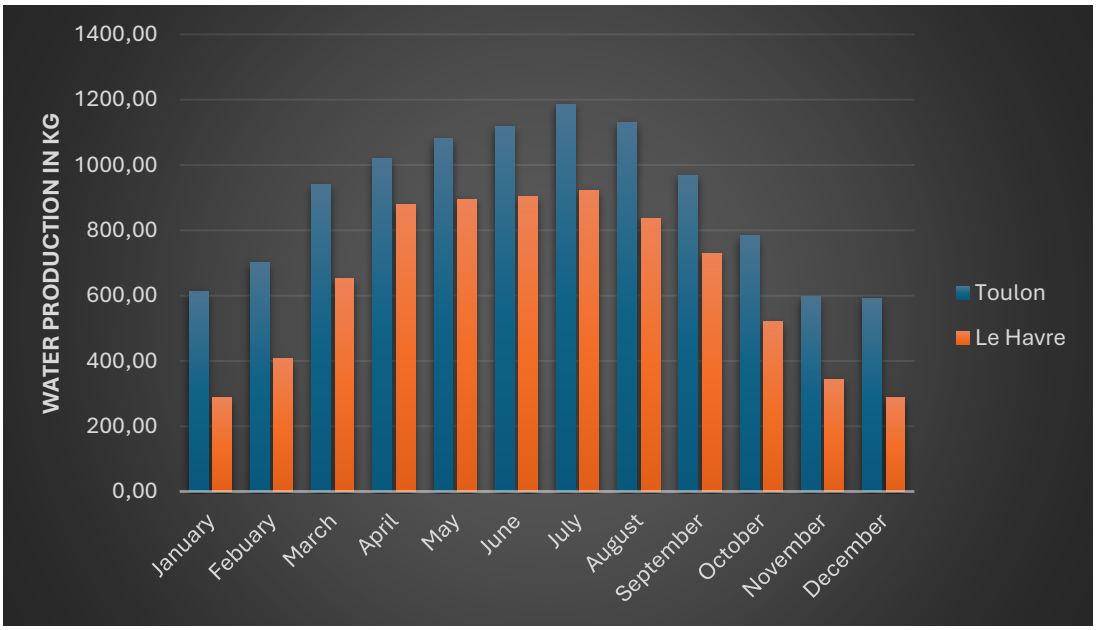


Fig 11: PV + MSF process result of water production (in kg) for each city

Afterwards, the freshwater production per m² data will help to calculate the size of the installation necessary to supply the demand of the city. To complete the demand, we must find the worst month, that mean where the difference between the supply and demand are the most spread.

In Toulon and for the combo PV and RO, it's in November where the surface of PV is 305 365 m² to supply all the demand of the city. Moreover, the combo PV and MSF needs a surface of 1 374 142 m² to supply 100% of the demand. For the city of Le Havre with the combo PV and RO, the worst month is January where the surface of PV is 521 920 m² to supply 100% of the demand. In another hand, the combo PV and MSF needs a surface of 2 348 638 m² to supply all the demand.

The result of the size of the solar panel installation looks especially high. It is due to the demand of fresh water of the city which are also high. The city could decide in the future to produce just a percentage of the demand and get the other part from other sources like the treatment of dirty water which are often use nowadays in France. The two graphs below show the size of the PV installation needed depending on the percentage of the demand completed.

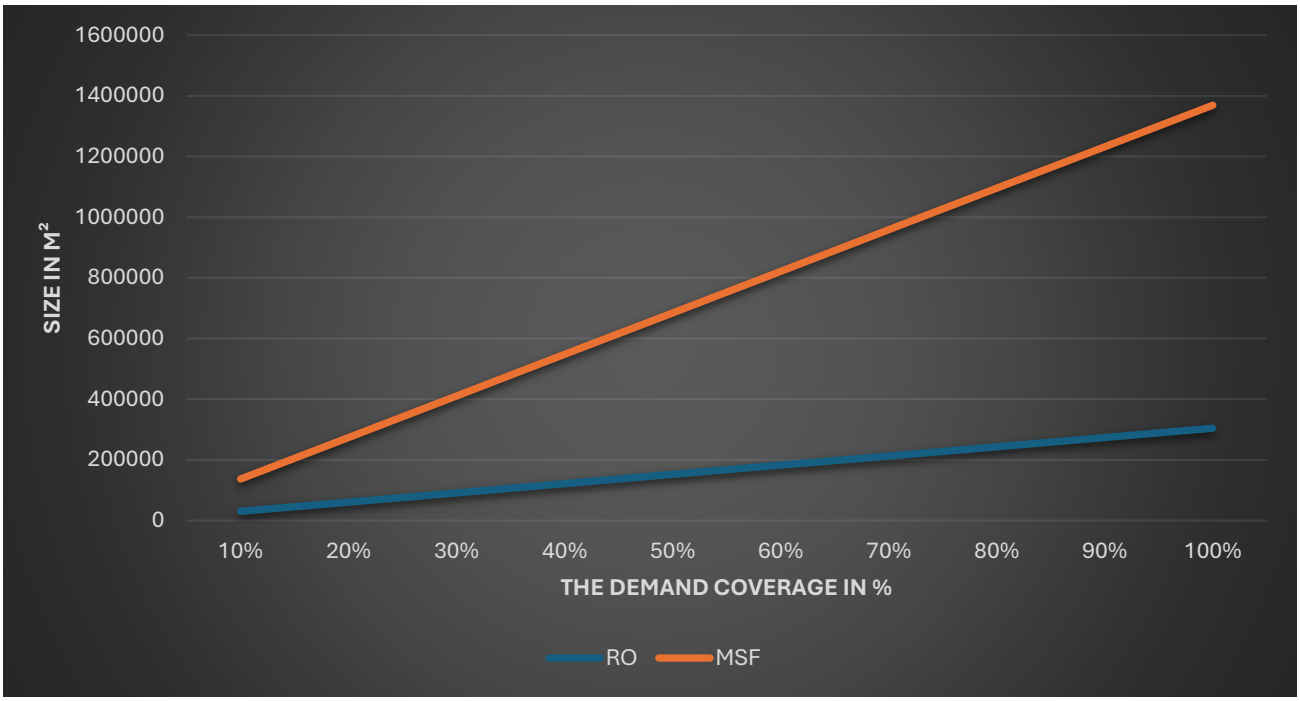


Fig 12: Size of the PV installation in m² depending on the demand coverage in Toulon

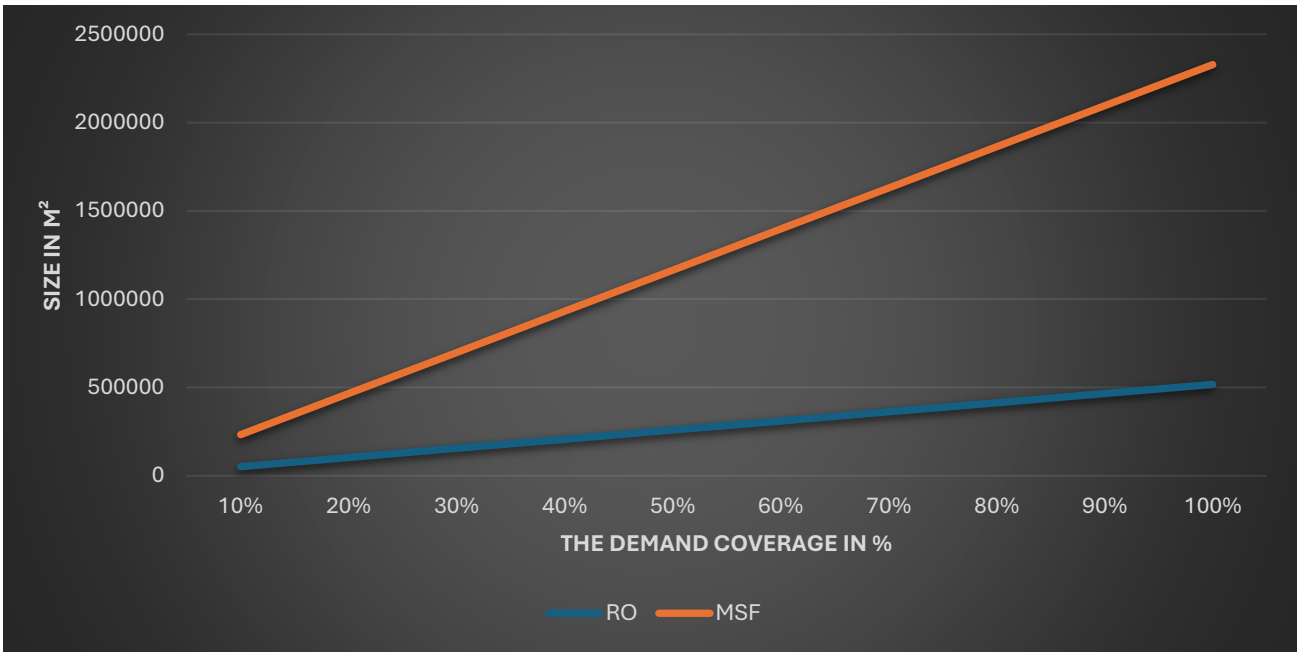


Fig 13: Size of the PV installation in m² depending on the demand coverage in Le Havre

Methodology PTC-MSF

In a second step, we carried out the calculations of the solar concentrators with the MSF. The idea is to calculate the daily production of a typical day of each month in order to find the total freshwater production of each month.

The installation is composed by two separated loops with different flow and temperature. In the first loop, there are a special liquid. This liquid circulates across the PTC, where its temperature increases until 250°C. Then the liquid goes into the exchanger, where it gives its energy to the other loop. The second loop start in the sea, where we extract the seawater and put pressure in it to avoid vaporisation in the exchanger (because we want to bring the salt in the MSF system). The exchanger heats the seawater until it reaches a temperature of 120°C and with the pressure the seawater stays liquid. Then the hot seawater goes on the MSF system where the seawater vaporising by the decrease of the pressure. The MSF system separate the fresh water from the brine.

The goal of using two loops is to use a better liquid with a higher efficiency (η_O) in the PTC loop. And avoid the circulation of the seawater in the PTC system which can worn quickly the tube in the time.

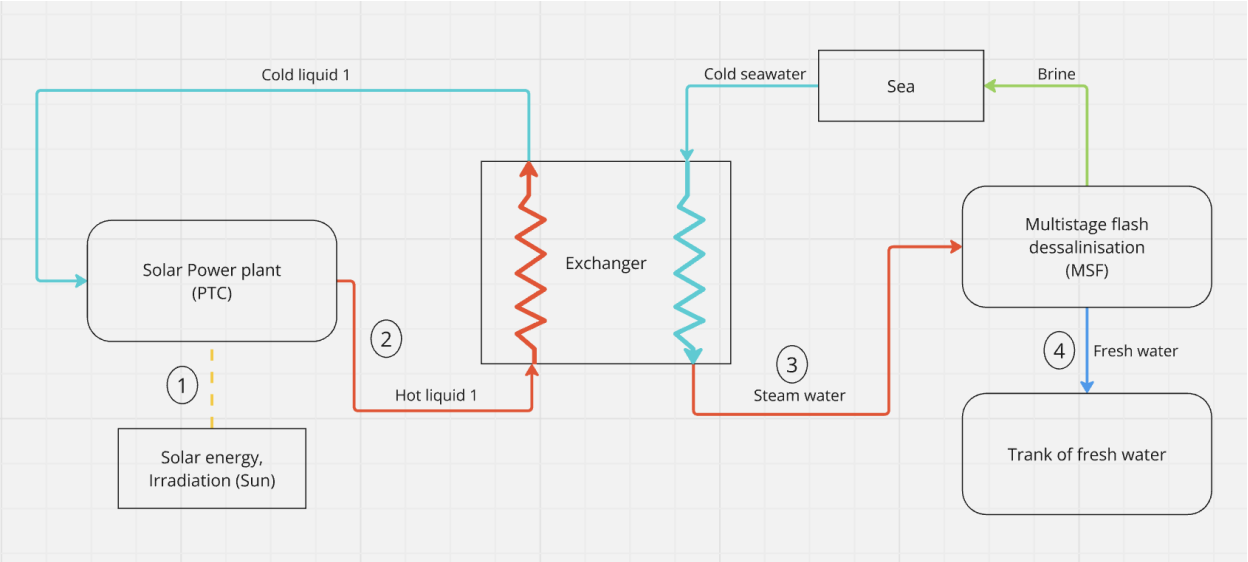


Fig 14: Models simplify of the system PTC + MSF

The goal of the calculation is to determine the flow of the fresh water (calculation number 4). To find this result we need to calculate the flow of the two loops (number 2 and 3). And we need to begin to find the energy collected by the PTC (number 1).

1) Energy collected by the PTC:

To simulate the parabolic trough collector and do the calculation on the steam production, we need to size the different parts of the PTC, such as the tube, the aperture, and all the other characteristics of the system. The following tables give values on real PTC used on previous study [e.g. 23, 24].

Parameters	Value
η_o	0.55
ρ	0.80
τ	0.91
α	0.90
γ	0.85

Fig 15: The optical efficiency and the geometric parameters of the PTC (Source : [24])

CHARACTERISTICS	
Maximum operating Temperature	320 °C
Area of Aperture	78.1 m²
Width of Aperture	2.13 m
Length	36.7 m
Focal length	0.53 m
Tube diameter of absorber	31.8 mm
Tube diameter of cover	54 mm
Thickness of reflector glass	0.8 mm
Rim angle	90°
Acceptance angle	1.7°
Ratio of geometric concentration	21.3
Peak optical efficiency	0.83
Reflectance	0.94
Transmittance	0.95
Absorbance	0.94
Emittance	0.2

Fig 16: Tabs of the value used in previous study (Source : [23])

During the next calculations, we are going to take the values and used the formula given by two studies done with PTC system [e.g. 23, 24].

Calculation of PTC with the MSF desalinisation process:

We recover the solar irradiation of each hour of the typical day with PVgis: $G(n)$. We have made a first calculation to find the energy gained by the irradiation, which we will call Q_i. We will take the aperture area (A_0) that will be equal to one square meter so that our calculation is made per square meter. Optical efficiency (η_O) will be found in the formula.

$$Q_i = G(n) * A_0 * \eta_O$$

Then, we have to take into account the losses related to the reflectivity of the tube (Q_r) with ρ the reflectance of the tube.

$$Q_r = \rho \times Q_i$$

Now, we need to calculate the energy absorbed by the tube Q_{ab}. For that, we need to multiply the reflectance power (Q_r) with the coefficient of absorbance (α) and the transmittance (τ).

$$Q_{ab} = \alpha \times \tau \times Q_r$$

There are also the convective losses (Q_{conv}) and the radiation losses (Q_{rad}). The convective losses can be calculated by multiplying the convective heat transfer coefficient (h_c) with the surface area of the tube (A_t) and with the difference between the temperature of the tube (T_{tube}) and the ambient temperature ($T_{ambient}$).

$$Q_{conv} = h_c * A_t * (T_{tube} - T_{ambient})$$

For the radiation losses, we need to multiply the emittance (ϵ) with the Stefan-Boltzmann constant (σ) and with the surface area of the receiver tube exposed to the environment (A_t), and also with the difference of the temperature of the tube to the power of four and the ambient temperature to the power of four.

$$Q_{rad} = \epsilon \cdot \sigma \cdot A_t \cdot (T_{tube}^4 - T_{ambient}^4)$$

Finally, the useful energy (Q_a) can be calculated by the following formula:

$$Q_a = Q_{ab} - (Q_{conv} + Q_{rad})$$

2) Flow of loop 1:

In a second part, we are looking for the flow of the liquid in the first loop ($\dot{m}_{PTC}$). We need to divide the useful energy (Q_a) previously calculated by the multiplication of the specific heat capacity of water (C_{water}) with the difference of the input temperature and output temperature (ΔT).

$$\dot{m}_{PTC} = \frac{Q_a}{C_{water} \times \Delta T_1}$$

$\dot{m}_{PTC}$ is in kg/s, so we have to multiply by 3600 to get the kg/h.

3) Exchanger and the flow of loop 2:

Now, we are looking to determine the flow of the second liquid in the second loop. The thermic power of the second liquid (ϕ_2) is equal to the flow of the first (ϕ_1) multiply by the efficiency of the exchanger (η_e).

$$\phi_2 = \phi_1 \times \eta_e$$

In addition, the thermic power (ϕ) is equal to the mass flow of the liquid ($\dot{m}$) multiply by the specific heat capacity of liquid (C_{liquid}) and also multiply by the difference of the temperature between the entrance and the exit of the exchanger ($\Delta T = |\, T_{out} - T_{in}\,|$).

$$\phi = \dot{m} \times C_{liquid} \times \Delta T$$

We can replace the terms, and we get the following formula:

$$\dot{m}_{MSF} \times C_{seawater} \times \Delta T_2 = \dot{m}_{PTC} \times C_{water} \times \Delta T_1 \times \eta_e$$

So, we reorganize the equation: $\dot{m}_{MSF} = \frac{\dot{m}_{PTC} \times C_{water} \times \Delta T_1}{C_{seawater} \times \Delta T_2} \times \eta_e$

For the temperature use we are going to use a previous simulation done in a study. The temperature used to evaporate the seawater in 120°C [24], so $T_{in_{MSF}} = 120°C$.

4) Volume of freshwater production

In a previous study made by Al-Othman et al. [24], the multistage flash desalinisation plant transforms 40,000 m^3 of seawater into 1,880 m^3 of fresh water. The efficiency of the MSF (η_{MSF}) is 4,7% in this example. We take the same value for this paper.

$$V_{fw_MSF_PTC} = \dot{m}_{MSF} \times \eta_{MSF}$$

Result of PTC-MSF

Loop 1:

The first loop calculation consists of to get the value corresponding to the steam produce by the PTC installation per m². The water enters the PTC with a temperature of 20°C and go out of the solar system with a temperature of 250°C. We are looking how much water we can heat at this temperature during a day and get the flow of this loop the flow will increase when we add more surface of PTC.

PVgis give hourly irradiation data from an average day of each month. So, with the formulas seen previously and these data, we have calculated the production of the steam in the PTC for each hour of a days.

Toulon results and analysis

In Toulon, the typical day of January will produce 4,57 kg of steam at 250°C per m² (orange line), and 9,69 kg in June (blue line). The graph below shows the result of the production during a typical day of the month. There are the lines which represent the accumulation of the water production during a typical day and the column which show the steam flow for each hour of the day.

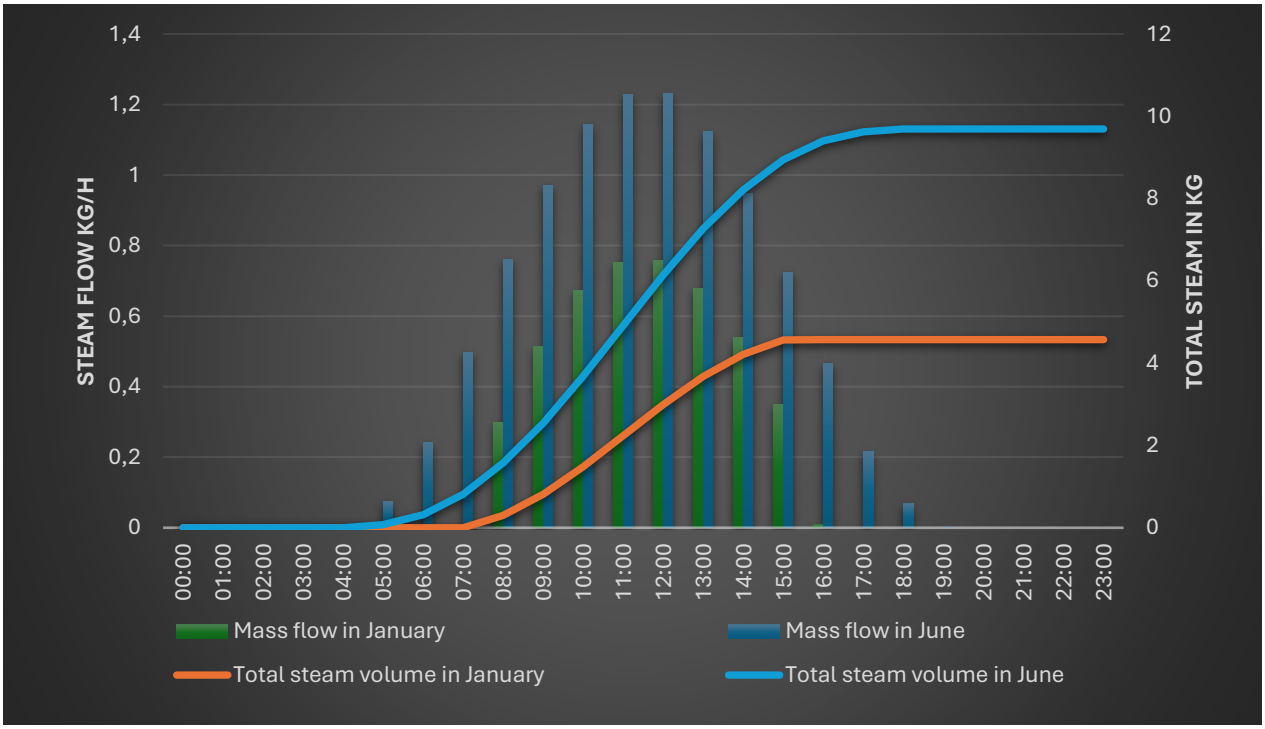


Fig 17: Steam production in kg during a typical day of June and of January in Toulon; and the accumulation of steam production during the day

On the January, we saw that the day is short, starting a 7am and ending at 4pm. In another hand the June production graph show that the day is longer, starting at 5am to 7pm. The direct solar irradiation is also higher in summer so there is more production in June than January. The production of fresh water is more than 3 times higher in June than January for the same size of installation.

Le Havre results and analysis

In Le Havre, the parameter of the PTC is the same, but the solar irradiation is different. The temperature in and out are the same and the calculation are also done on one meter square of installation. However, the results are lower, with a production of 2,12 kg of steam per day in January and 7,56 kg per day in June.

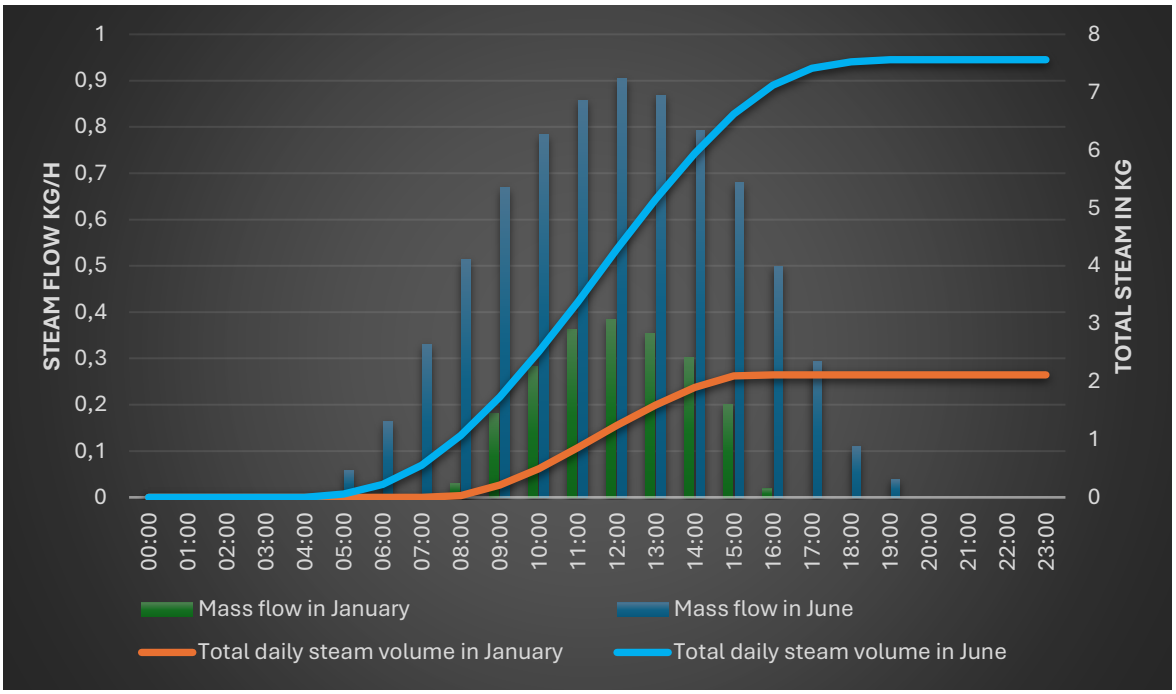


Fig 18: Steam production in kg during a typical day of June and of January in Le Havre; and the accumulation of steam production during the day

As well as Toulon the daytime is different between winter and summer in Le Havre. The production is also more than 3 times higher in June than January.

The steam production in Toulon is more than 2 times higher in term of volume than the steam produce in Le Havre. The two simulations look quite similar but the variation of production across the hour is different. Indeed, we notice a difference of increasing of steam production during the day. This difference explained by the solar irradiation data which are progressing differently between the two cities.

Exchanger part:

The hot steam goes from the PTC to the exchanger, where the loop 1 give its energy to the loop 2 by heating the seawater from the second loop. The specific heat capacity of the seawater is 3850 J/kg/K which is lower than the specific heat capacity of the water in the loop 1 (4184 J/kg/K). In addition, the temperature needed to operate the MSF is lower than the temperature of hot water which is going out of the PTC. This difference participates to have a higher flow in the second loop. The flow and the efficiency of the MSF explained in the previous method, give us the final production of fresh water.

In Toulon, the freshwater production for one average day is 0,43 kg in January and 1,33 kg in June. The value is much lower than the steam production because there are many losses, such as, the exchanger losses (η_e=80%) and the multistage flash desalination plant losses (η_{MSF}=4,7%).

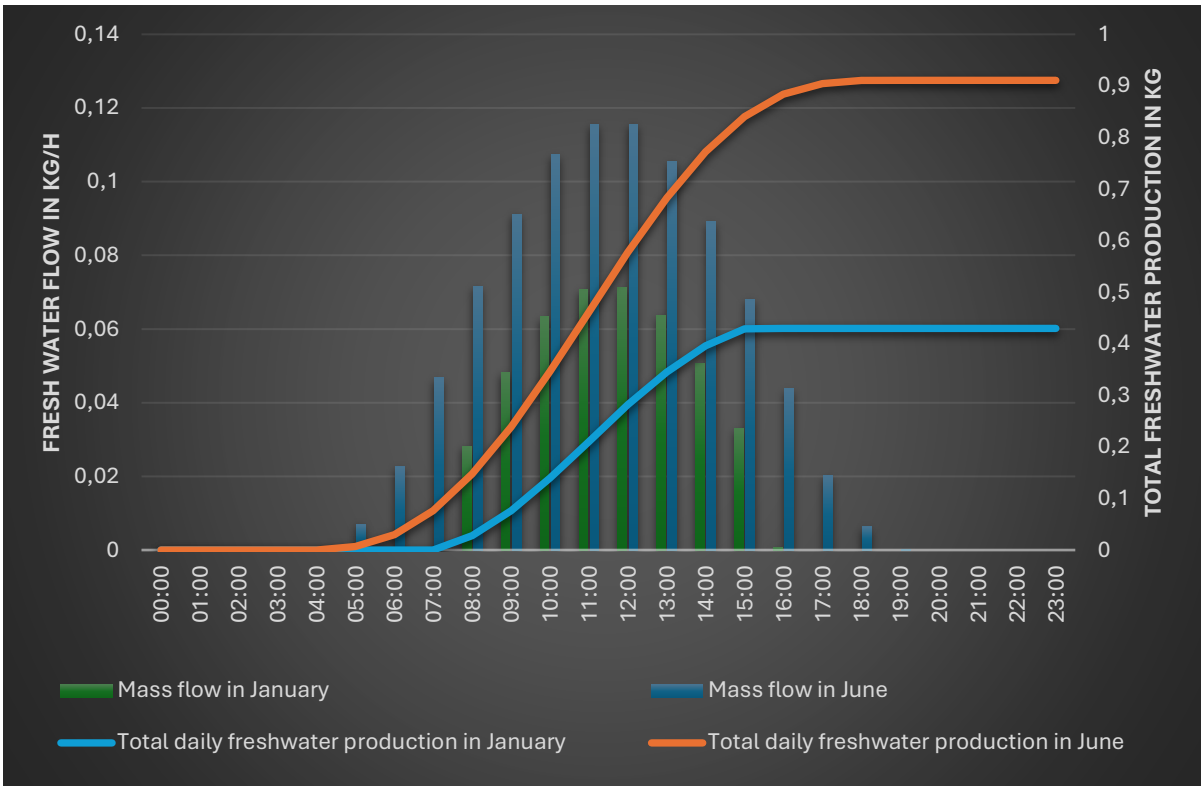


Fig 19: Freshwater production in kg during a typical day of June and of January in Toulon; and the accumulation of fresh water during the day

In Le Havre, the freshwater production for one average day is 0,19 kg in January and 0,71 kg in June.

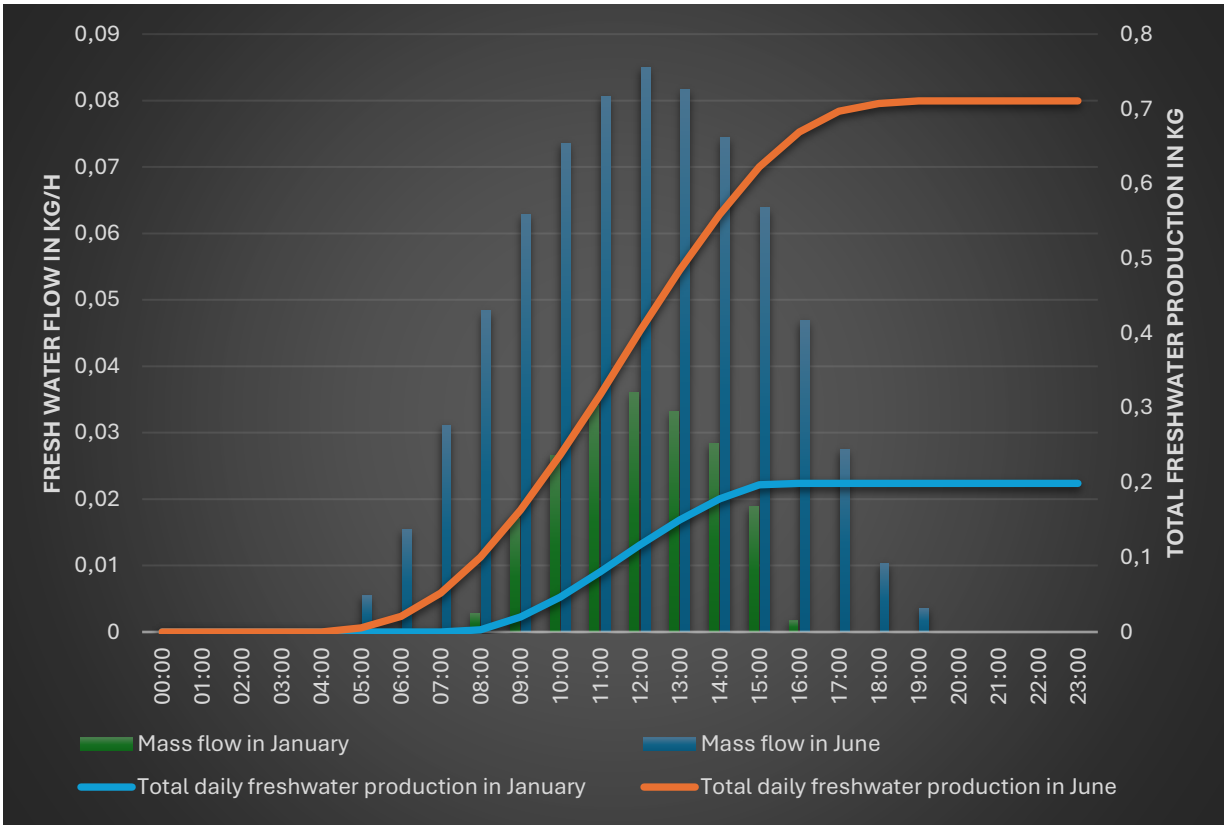


Fig 20: Freshwater production in kg during a typical day of June and of January in Le Havre; and the accumulation of fresh water during the day

The production of fresh water in Toulon is around twice higher than the freshwater production in Le Havre for the same settings with the different solar irradiance due to the localisation of the project.

Then, there are the total production of each month. That basically calculates the average day result by the number of the day of each month, to get the graph below.

In the graph, there is the best months in July and the worst in December, which seems confirm the expectation. The freshwater production graph is quite similar as the solar irradiance receive by the PTC. Its result can be explained because the solar resource is the leader variable of the freshwater production.

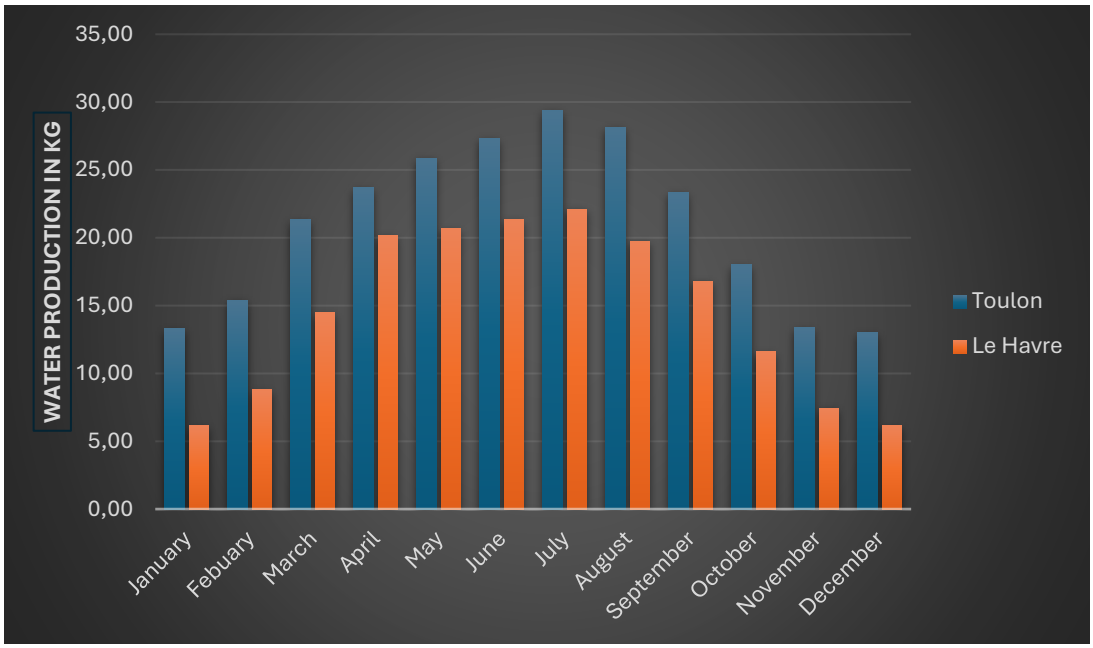


Fig 21: Total freshwater production per m² of installation for each month and for both city

The total production per m² of installation during the year is 252,24 kg for Toulon and 175,39 kg for Le Havre.

After the calculation of the production of fresh water per m², we can calculate the size of the installation of the combo PTC and MSF. As the same method as the previous combo, we have to select the worst month to answer the demand where the size of the installation is the biggest. For the city of Toulon, it is in December, and the total area of PTC will be 65 869 037m² to answer 100% of the demand. And for Le Havre, it's in January with a size of 118 820 582 m² of PTC to power the MSF and produce enough water to answer the demand of the city.

Discussion

Analysis of the results

During this paper we have done calculations on two different combinations of technologies. The results show that the PV link with RO desalination system is the best for both cities. The result shows that for the same area the combo PV and RO will produce between 180 and 200 times more than the combo PTC and MSF in Toulon and, between 200 and 215 times more in Le Havre.

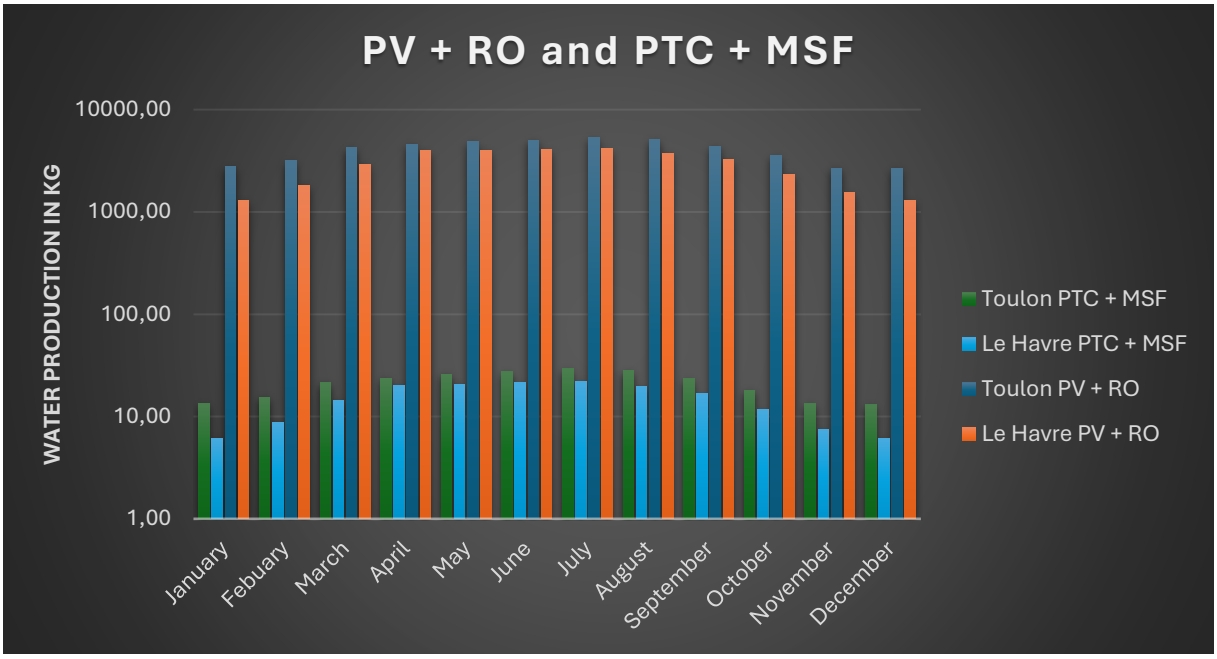


Fig 22: Freshwater production in kg depending on the combo technologies and the location

In this graph, we used the logarithmic on the vertical axis to show the huge difference between the results of PTC + MSF and PV + RO. The result of this paper seems to make sense because the reverse osmosis is the most energy efficient and the irradiation data for the PV are better due to the method to collect the sun energy. Indeed, the PTC need direct solar irradiation to collect energy and operate correctly. In another hand, solar PV need sun light to be powered, it can collect the direct and also the diffuse energy of the sun to produce electricity. So, the PV are more efficient to produce energy in cloudy days, where the direct irradiation is low, and the diffuse energy is more prevalent. In Toulon and in Le Havre, there are more than 15% and 25% respectively of the time with cloudy weather during the year that give an advantage to the PV on the PTC in this area [e.g. 34, 35]

Moreover, most of the project in Europe are based on reverse osmosis process, so this choice made by the previous projects confirms the potential of RO in the area.

However, the combo PTC with the MSF could have better result in an area with more direct solar irradiation. Many projects in the middle east use the combo of PTC with MSF, which show that the solar irradiance can be more favourable to the thermal desalinisation. In UAE, most of the desalination is thermal with 86.7% of desalinisation are from MSF plant[20]. It could be interesting to compare both combos of technology in UAE and another country with great direct solar irradiation to see if the result are different in this area.

Comparison of the freshwater production with the results of previous studies:

In order to compare the result of this study with previous studies, we need to take into account the maintenance in the calculation. In the previous study wrote by Fadi Ghaith et al. (2018), it estimates that the maintenance of a PTC installation is around 12 days per year, that represent around 3,3% of a year. So, we are going to take the same amount of maintenance for both locations. The installation will work 353 days per year, that we are going to consider in the final result.

For the PTC with the multistage desalinisation process, we get a production during the year between 0,2 and 0,71 kg/day/m² for the city of Le Havre and 0,42 to 1,4 kg/day/m² for Toulon. Compared to the study from Fadi G done in UAE, the result of this paper should be lower.

Indeed, this is the case. We can calculate form UAE study the average of freshwater production per square meter per day which is between 2,33 and 3,57 kg/m^2/day.

Comparison of the freshwater production with the solar irradiation data:

Global solar atlas gives the data of the energy that the installation can get from the global tilted irradiation at optimum angle. This data can help to compare the results of previous studies with this paper and estimate if the result of this study is satisfactory or not.

For the UAE we take the city of Abu Dhabi for our calculation. The global tilted irradiation at optimum angle in UAE is around 2345,1 kWh/m²/year, in another hand, the irradiation are 1933,5 kWh/m²/year and 1385,6 kWh/m²/year for Toulon and Le Havre respectively. The water production in the UAE project is 67308/60 = 1121,8 kg/m²/year. For Toulon and Le Havre, it's approximately 278,9 kg/m²/year and 175,4 kg/m²/year. With the maintenance taking in count, the freshwater production is 269,7 kg/m²/year and 169,6 kg/m²/year respectively.

A study made by Mohamed Abdelgaied et al. (2021) [25] in Egypt, worked on a PV + RO project and found a production of freshwater between 70 080 and 73 000 kg/year/m².

Location	Average energy from the solar irradiation per day (kWh/d) (data on global solar atlas)	Result of the study for thermal desalinisation per m^2 (kg/year)	Result of the study for PV + RO desalinisation per m^2 (kg/year)
UAE	2345,1	1121,8	X
Egypt	2299,5	X	70 080-73 000
Toulon	1933,5	269,7	48 282,1
Le Havre	1385,6	175,4	34 476,2

Between Toulon and Le Havre, the result corresponds to the average energy from solar irradiance. In another hand, the result from UAE is much better. It can be explained because the method is a bit different with the seawater which are directly going inside the PTC, which is more efficient. The total loss of the installation is higher in our system in this paper due to the exchanger which produce additional losses.

For the PV + RO, in Egypt, with the result of this study we expect a production of 57 000 kg/year/m². The result of the study done in Egypt is 23% higher than the result expected. This difference can be explained by the Humidification-Dehumidification (HDH) system which improve the efficiency of the installation.

Limits of my study and what could be do in a:

This study will give information for just two locations Le Havre and Toulon. It could be interesting to add some calculations on other locations in France. It could be also interesting to produce a map of France with all the potential freshwater production data, with the same method of calculation of this paper. This idea can be studied in a further paper.

Moreover, in this study with have done calculations on average days of a particular month. It could be interesting to do calculation with the exact daily weather conditions variation. Sometimes there are some cloudy days in a row. During this period the desalination system will work partially and will influence the freshwater supply. In further research it could be interesting to analyse these types of variation and propose some solutions to avoid some shortage on short-term periods. Some solution could be to add freshwater storage capacity for example.

During this dissertation, the calculation of production of the fresh water has been done during all the year. However, the need of fresh water in France varied during the year. The context in France shows

that the need is not the same during all the year due to the speed of the refill of the reserves which are not the same in winter and in summer. The level of the reserves is often high during the winter, so the treatment of the water is less needed. Indeed, during this period the collect of the water from the river and from the water table is enough to supply the population. The use of the desalination may be useless during periods when there is no lack of water.

In further research, it could be interesting to get real data about the water consumption of the cities. The variation should be studied more in details, as example the daily freshwater consumption.

This paper has looked at the efficiency of production depending on the technology and try to find the one with the smallest size of installation. We assume that it will give the lowest cost of installation. But the final cost of fresh water depends on the combo technologies (PV + RO and PTC + MSF) global costs. These estimations are necessary to develop a project and do the final choice.

Conclusion

During this paper, we saw that the problem of fresh water in France comes mainly from the availability of the resource in the nature that the direct variation of the consumption. Today the fresh water is extracted mainly from natural sources, but sometimes it's not enough to supply the population. So, the desalination should be developed to complete the lake of fresh water.

The consumption of fresh water for the cities of Toulon and Le Havre is counting in millions of m^3 per year. It represents a huge amount of fresh water, and as we saw in this paper, it requires significant infrastructures to complete all the demand with renewable energy technologies (around hundreds of thousands of meter square of PV).

We saw that the solar desalination production is lower during the winter due to the lack of sun irradiation. However, during this period, the naturel resources are very high. The solar desalination is especially good to complete the demand during the summer where the reserves are low, and the freshwater production is the best.

During this paper, we have looked at three different combos of technologies, which are the PV + RO, PV + MSF and PTC + MSF. We didn't look at the PTC + RO because the reverse osmosis needs electricity to be powered and the PTC produce less electricity than the PV in both localisations. However, we decided to study the PTC + MSF which didn't convert the energy in electricity and stay in thermal energy.

During this study, we have looked to the thermal losses of the PTC + MSF in order to determine if this combo could be better to produce fresh water than the PV + RO. We discovered that the PTC + MSF have a production around 200 times lower than the PV + RO in France. The freshwater production with the PV + RO is between 86 and 172,3 L per day per m^2 of solar installation in Toulon and 41,8 and 135,5 L per day per m^2 of solar installation in Le Havre depending on the month.

The combo PV + RO is the best for both locations, this is due mainly to the irradiation data and the losses of the PTC+MSF which are too high in France to offer a serious concurrence to the PV + RO. However, the results of the study proved that the differences between PTC + MSF and PV+ RO decrease when the project is further in the south.

The result make sense, indeed, it is currently the reverse osmosis projects which are the most used in Europe and the PV are more used in France than the PTC due to the low direct irradiation. There is currently no PTC plant in France, but we can find many solar panels. The PTC are more used in the south countries like Morrocco or Spain which are not too far from France.

In further research it could be interesting to study the combo PTC + MSF compared to the PV + RO in hotter area for example in UAE where the technologies of PTC and the MSF plant are used. Indeed, the MSF desalination is the most used in this area, then the RO desalination as we saw before. There are also European countries which use the PTC such as Spain. It could be also interesting to choose other locations to do the study in South of Europe area.

In the future, the global warming is going to change the weather conditions which will lead to an increase of the demand for the fresh water. The desalination with renewable technologies will bring a key solution to fight against the lack of water while limiting the carbon impact.

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