Renewable Energy For Sea Water Reverse Osmosis Desalination Plants : Worldwide Screening For Implementation Potential

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Cet article porte sur l'identification de différentes régions, par l'utilisation d'un logiciel d'information géographique (Geographical Information System - GIS), où l'on peut satisfaire la demande en eau par une installation de dessalement d'eau de mer de taille moyenne par le principe de l'osmose inverse (50-100 MLD), le tout alimenté électriquement par des énergies renouvelables (par exemple l'énergie solaire et éolienne). À travers différents scénarios, le coût global de l'eau sera comparé pour déterminer si cette installation constitue un investissement valable. Ce coût regroupe les coûts de l'installation, des énergies renouvelables, du terrain et des interconnexions.

Mots-clefs : SIG, cartographie, SWRO, eau, coût, énergie renouvelable

This article focuses on the idea to identify different locations, by using a Geographical Information System (GIS), where the demand for water could be met by mid-size sea water by reverse osmosis (SWRO) desalination plant (50-100 MLD) running on renewable energy (for example solar and wind energy). Through different scenarios, the global water cost will be compared to determine if this installation is worth the investment. This cost regroups the plant costs, the renewable energy costs, the land, and the interconnections.

Keywords : GIS, mapping, SWRO, water, cost, renewable energy

1. Introduction

1.1. Water desalination

Water represents approximately 60% of the human body and the human body needs roughly 2,4 litres per day.
To produce drinking water, fresh water is mostly used. However, in some regions, the access to fresh water is more complicated. Therefore, other techniques have been invented. The most known technique is water desalination. As the ocean covers about 70% of the earth, many techniques exist :

- Reverse Osmosis (RO)
- Multi Stage Flash (MSF)
- Electrodialysis Reversal (ED)
- Ion eXchanges (IX)
- Distillation

Choosing one technique above another strongly depends on the salinity of the water, as shown in figure 1. The technique of reverse osmosis is considered nowadays as the most efficient and reliable. It can be used with either brackish water (mix of fresh and salt water) or sea water.

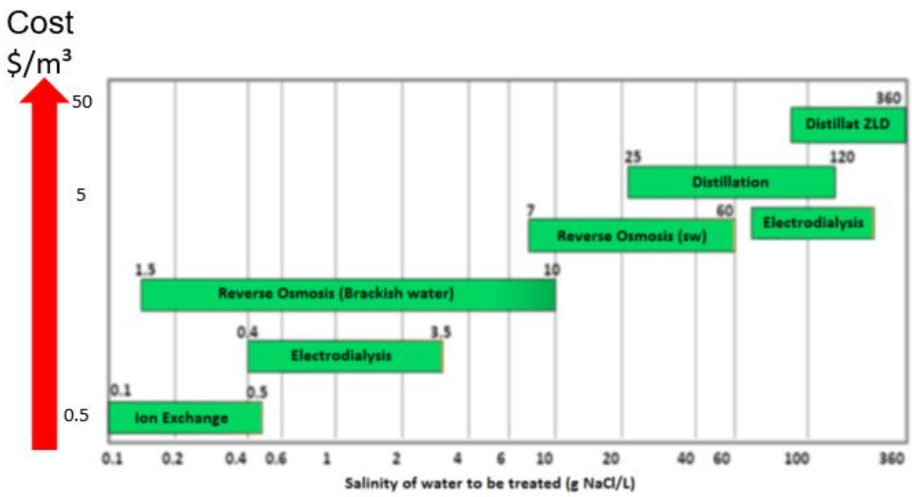

Figure 1 : Price of the water according to its salinity[1]

1.2. Sea Water Reverse Osmosis (SWRO) desalination plant

The principle of reverse osmosis is to force a hypertonic solution to cross a semi-permeable membrane to a hypotonic solution, using a pump or a plunger. The pressure needed is higher than the osmotic pressure
[1].

A SWRO desalination plant consists of four main parts, as shown in figure 2 :

- Pre-treatment : used as a first chemical treatment of the sea water;
- High Pressure Pump (HPP) : used to raise the pressure of the treated water above the osmotic pressure;
- Membranes : used to apply the reverse osmosis principle;
- Post-treatment : depending on the use of the water, it will be treated to match the requirements of the application.

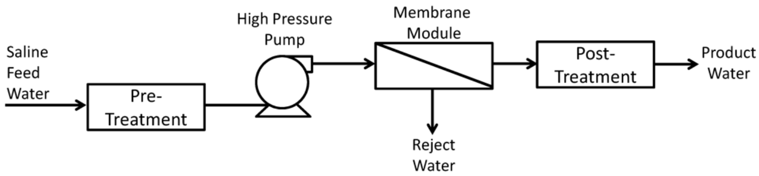

Figure 2 : Sea Water Reverse Osmosis (SWRO) desalination plant schematics[10]

2. Power supply

The power supply analyzed in this study will focus on the Photo Voltaic (PV) solar panels and wind turbines.
The technology used for the solar panels will be Cadmium-Telluride for their lower carbon footprint compared to the Carbon-Silicon technology.
For this study, a 2 MWp (Mega Watt peak) wind turbine technology has been desiced, since it is a classical value for today’s technology.

1. The osmotic pressure is the equilibrium pressure necessary to cancel the exchange between the clean water and the concentrated solution.

3. Approach

3.1. The preparation

First we identify the key technical parameters of the renewable-powered desalination plant impacting the cost of the water.
Then these parameters are derived for a location screening and gather maps in Geographical Information Software (GIS).

3.2. Screening for a reference scenario

The different target ranges for the screening parameters corresponding to the target water cost will be defined in the reference scenario.
By using ArcGIS, we will screen for locations where all the parameters are in the target range :

- Macro screening : water salinity, solar/wind resources, etc., i.e. reducing the screening domain ;
- Micro screening : cities size, unconstructed land proximity & area, etc.

3.3. scenarios

For alternative scenarios, the previous point will be repeated. This will lead to a sensitivity analysis.

4. Key parameters

There are 2 kinds of key parameters : those depending on the region of the world where the plant will be installed and those depending on the plant itself.

4.1. Region

The location influences the following parameters :

- Annual irradiation : stands for the irradiation over 1 year. This parameter is important for the installation of solar panels. Therefore the values of the irradiation will be for an optimal tilt angle and an azimuth of $0[°C]$ (oriented South).
- Annual wind speed
- Interest rate : is important to calculate the different costs. We will assume in the study that the interest rate does not vary.
- Electricity grid : represents the cost and percentage of electricity needed from

the grid.
- Total Dissolved Solids (TDS) : stands for the salinity of the water (its ion composition). A sea water with a high TDS will require a large amount of energy and pre-treatment (+ post-treatment) than a lower composition. An example of the composition of different types of sea water can be found in appendix A.

4.2. Desalination plant

For the desalination plant, these following parameters are important :
- Nominal power : the power required to supply the desalination plant;
- Annual energy consumption.

5. Location screening

The location screening will be carried out in 2 stages : first on a world scale, and then on a local scale (country map).
To determine the different locations, a GIS (Geographical Information System) software will be used, Arcmap, owned by esri®. This software combines layers to create a map. For this study, the maps that inform about wind (onshore), solar, water crisis, and sea water salinity conditions have been used.
By using this software, it is possible to visualize the data of the different maps and adapt them (ranges values, visibility, colors, etc.).

5.1. World map

A world map will be used to gather maps to determine the countries where there is a need for desalination/water treatment, the regions where solar or wind (onshore and/or offshore) energy is sufficient, and the global ocean salinity.

5.2. Country map

To select a country, the parameters of the world scale will have to be met first. The best countries will be those that meet all the criteria of the world scale. Once a country meets the parameters, the same analysis will be carried out but on a national scale : determine the cities where the demand matches the range of production of the desalination plant, determine where the desalination plant could be installed (unconstructed space) close to the city, determine an area for a solar farm within 10 km.

6. Reference scenario

The reference scenario will analyse the screening parameters to target the water cost. These different parameters are the access to water, the salinity of the water, the power required, the power generation plant, the area range of the desalination plant, the range of the acceptable water cost, and the range of the acceptable electric cost.

6.1. Access to water

According to the 2011 report of the World Health Organization (W.H.O.)[12], one person should have access to 20 litres per day. This study will focus on the water consumption for an optimal access of water per person, which is, according to W.H.O., i.e. 100-200 L/capita/day [12]. For a desalination plant of 50 MLD, it is possible to determine the target population :

- 50 Mega liters per Day (MLD) = 50.000 m^3/day
- 100 L/capita/day = 0,1 m^3/day
- The city population will be $\frac{50.000}{0,1} = 500.000$ persons

Therefore the target retained will be a population of 0,5 to 1 million people.

6.2. Salinity of the water

A sea water with a high ion composition will require a larger amount of energy and pre-treatment (+ post-treatment) than a lower composition. This is why treating river water requires less energy than sea water. The table in Annex A represents the average composition of the sea water. The regions in the Middle East are known for having more salty seawater than the worldwide average composition of sea water.
Since the region of installation has not been determined, this study will focus on a TDS value of the typical sea water, i.e. 34.483 mg/L[5].

6.3. Power requirement

The desalination plant's power will not only vary on the output but also on its input. These input values are :

- Ion composition : TDS = 34.483 mg/L
- Feed temperature : $T_{feed} = 25[°C]$C
- pH = 8
- Recovery : v = 43%
- Stages in pass : 1
- Flow factor : 0,85
- Membranes : BW30-440i

Figure 3 represents the configuration for one membrane used in this study. To determine the power required, the ROSA [2] software has been used.
To calculate the power consumption, the input values for the software are the values discussed previously.

The output values indicated by the software corresponds to an energy consumption of 3,96 kWh/m³ for a typical seawater value. This means that for a 50 MLD desalination plant, the energy required should be about 198 MWh/day.

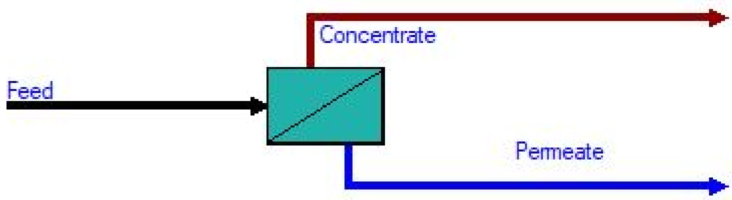

Figure 3 : ROSA System configuration

6.4. Power generation plant

This study focuses on the sustainability of the energy used to power the desalination plant. Nowadays, different technologies exist to create sustainable energy, such as solar, wind, hydropower, etc.

This study will focus on only 2 of these technologies, the solar and wind energy. The main advantage of using these 2 technologies is their maturity and their cost. As represented by Table 1, the levelized cost of electricity (LCOE) and the installation cost are one of the lowest in comparison to other technologies.

2. ROSA is a software developped by the american company Dow Water & Process Solutions

	CSP	PV solar	Wind turbine	Hydro	Geothermal
Advantages	- Can use the thermal storage to better match supply with demand - High efficiency	- Low operating cost - Decreasing prices	- The wind blows almost all the time - Land can still be used for farming	- Only uses a small fraction of the available resources - Can help improve environmental quality	- Constant energy source - Mostly underground
Disadvantages	- Ground space - Transmission lines	- Fragile materials - Storage or grid connection for a continuous use	- Not always steady and predictable - Bird lives	- Destruction of natural habitats - High installation costs	- Can cause Earthquakes - Location specific
Installation cost ($/kW)	$6050 - $12600	$1200	$1477	$1535	$2000 - $5000
LCOE [3] ($/kWh)	$0,14 - $0,35	$0,07 - $0,31	$0,06 - $ 0,10	$0,02 - $30	$0,04 - $0,14
Efficiency (%)	18%	15%	35%	90%	15%

Tableau 1 : Comparison of renewable power generation technology

6.5. Area range

The area ranges depend strongly on the scenario. However, based on a similar project realized by Engie Laborelec, the average area is estimated about 0,25 $m^2/(m^3/day)$. In this study, it has been decided to focus on mid-size installation : between 50 and 100 mega litres per day (MLD).
With these parameters set, we can approximately determine the area range :

- For a 50 MLD, the area range would be about 12.500 m^2 or 1,25 ha ;
- For a 100 MLD, the area range would be about 25.000 m^2 or 2,5 ha.

These areas correspond to the physical area of the plant.
In this study, the availability of land will be based on satellite images (non-constructed zones).

6.6. Range of the water and electrical cost

The water price depends on multiple factors such as the drinking demand, the type of desalination technology used, the power required, etc. All these parameters are influenced by the region where the desalination plant is installed. For reverse osmosis technology, the water is usually tried to be kept under 2$/$m^3$.
To determine whenever the electrical cost is interesting or not, it must be compared with the electrical cost of the grid. If the electrical cost of the combination of renewable energy with the grid is more expensive than buying it from the grid, it means that it is not interesting to use this combination.

7. Different scenarios

For this study, some possible scenarios will be analyzed :

- Sizing a solar farm to meet the maximum power required by the desalination plant (scenario 1a)
- Sizing a wind farm to meet the maximum power required by the desalination plant (scenario 1b)
- Sizing a solar farm to meet 50% of the annual consumption of the desalination plant (scenario 2a)
- Sizing a wind farm to meet 50% of the annual consumption of the desalination plant (scenario 2b)

For the scenario 2 (2a & 2b), batteries might be needed since the solar farm will be oversized regarding the maximum power required by the desalination plant. The addition of the batteries will only be interesting if the cost permits it. Figure 4 regroups all the scenarios analyzed in this study.

Scenario	Grid	Battery Storage	Solar panels	Wind turbines
1a	Yes	No	Yes (CdTe)	No
1b	Yes	No	No	Yes (2MW)
2a	Yes	Yes	Yes (CdTe)	No
2b	Yes	Yes	No	Yes (2MW)

Figure 4 : Different scenario configuration

8. Results Summary

With the choice of Sao Paulo in Brazil as the reference scenario, a map can be made in Arcmap to determine the regions where the wind speed and the solar irradiation are greater than the reference scenario, as shown in the figures 5 and 6.

The target regions identified are :

- South America : Peru and Chile
- Caribbean Sea : Jamaica
- Africa : Morocco and South Africa
- Asia : Middle East (Red Sea)

Figure 5 : Different scenario configurations - Wind

Figure 6 : Different scenario configurations - Solar

8.1. Sao Paulo, Brazil

The region of Sao Paulo will be considered as the reference scenario.
Figure 7 represents the results for the different scenarios.
The best scenario seems to be the scenario 2b. However, for the scenarios 2a & 2b installing batteries were analyzed to be too expensive.
The analysis over the year 2016 has shown that the wind speed was not sufficient to recharge the batteries while supplying the desalination plant. In short, for scenario 2b, installing batteries will rise the overall cost and recover the cost of the batteries will not be possible. The same problem has been realized for the scenario 2a (solar). Therefore it has been decided to keep the sizing of the installation to provide 50% of the desalination plant consumption but without installing batteries. The excess of production will be sent to the grid without any cost.

	Reference
Location	Brazil, Sao Paulo
GHI	1686 kWh/m²
Utilization factor wind turbines	20%
Grid electricity price	0.14 $/kWh
Water TDS	34.403 mg/l
Interest rate	6,5%
SWRO specific consumption Nominal power Yearly consumption	50 MLD 3.96 kWh/m³ 8.25 MW 72.27 GWh/y

Reference	1a	1b	2a	2b
RES installed	Solar PV (CdTe)	Wind	Solar PV (CdTe)	Wind
RES capacity	8,25 MW	8,25 MW	18,88 MW	18,63 MW
RES generation & share	15.793 MWh/y 22%	16.000 MWh/y 22%	36.135 MWh/y 50%	36.135 MWh/y 50%
RES electricity cost	0,055 $/kWh	0,057 $/kWh	0,071 $/kWh	0,057 $/kWh
RES CAPEX	8.25 M$	8,25 M$	18,88 M$	18,63 M$
SWRO CAPEX	83.05 M$	83,05 M$	83.05 M$	83,05 M$
SWRO OPEX (53% power)	16.6 M$/y	16,6 M$/y	14,4 M$/y	13,4 M$/y
Water cost	1.36 $/m³	1.36 $/m³	1,28 $/m³	1,24 $/m³

Figure 7 : Summary results for Sao Paulo, Brazil

8.2. Peru

Figure 8 represents the results for another region in the world where a possible installation could be possible.

Compared to the reference scenario, we can see that the irradiation is 6% higher and that the wind speed is over 10% higher than the reference scenarios. This will result in a lower cost since the required renewable energy installation will be lower.

As we can see in the Figure 8, the cost of the water for every scenario is lower than the reference scenario ! However, the interest rate and the cost of electricity are lower than those of the reference scenario. These parameters have a bigger influence on the variation of the water cost, as the TDS value.

	Peru	(compared to reference)
Location Population	Peru – Callao ~800,000 p.	
GHI (Callao)	1779 kWh/m²	+93 kWh/m² (+6%)
Wind speed (Chiclayo)	6,59 m/s	0,89 m/s (+13,5%)
Grid electricity price	0.12 $/kWh	-0,02 $/kWh
Water TDS	34.992 mg/l	+588 mg/l (+1,7%)
Interest rate	3%	-3,5% (-54%)
SWRO specific consumption Nominal power Yearly consumption	50 MLD 3.96 kWh/m³ 8.25 MW 72.27 GWh/y	50 MLD 3,93 kWh/m³

Reference	1a	1b	2a	2b
RES installed	Solar PV (CdTe)	Wind	Solar PV (CdTe)	Wind
RES capacity	8,19 MW	8,19 MW	17,75 MW	18,35 MW
RES generation & share	16.538 MWh/y 23%	16.000 MWh/y 22%	35.861 MWh/y 50%	35.861 MWh/y 50%
RES electricity cost	0,041 $/kWh	0,057 $/kWh	0,052 $/kWh	0,057 $/kWh
RES CAPEX	8.19 M$	8,19 M$	17,75 M$	18,35 M$
SWRO CAPEX	83.05 M$	83.05 M$	83.05 M$	83.05 M$
SWRO OPEX (53% power)	13,77 M$/y	14,33 M$/y	11,64 M$/y	11,95 M$/y
Water cost	1.09 $/m³	1,24 $/m³	0,99 $/m³	1,14 $/m³

Figure 8 : Summary Results Peru

Table 2 represents the influence of each parameter of the water cost analysis. The most influencing one will be the interest rate.
The influence of the wind speed and the irradiation do not have that big of an influence compared to the interest rate. However, this does not mean that the installation of a desalination plant can be done everywhere, but that it is important to discuss with the local authorities about the interest rate to lower the country.
As shown in the maps in the Figures 5 and 6, there are some regions where an installation could be realized but it is not everywhere (compared to the reference scenario).

	Interest rate	**Electricity grid cost**	**TDS**	**GHI**	**Wind speed**
Water cost 1a (\$/m^3)	10%	8%	<1%	1%	N/A
Water cost 1b (\$/m^3)	10%	8%	<1%	N/A	<1%
Water cost 2a (\$/m^3)	15%	6%	1%	2%	N/A
Water cost 2b (\$/m^3)	14%	6%	1%	N/A	<1%

Tableau 2 : Influencing terms

9. Conclusion

The combination of renewable energy with sea water desalination by reverse osmosis is known to be possible since it already exists. Therefore this study set out to determine what the costs are when combining renewable energy with a mid-size SWRO desalination plant (50.000m³/day over drinking water).

The world population is growing and the accessibility to drinking water becomes more and more crucial in certain regions in the world. Desalination plants are being constructed to answer this crisis. Desalinating water can be done by different methods, such as the reverse osmosis, ion exchanges, distillation, and many more. In this study, it has been decided to focus only on the reverse osmosis technique because it is the most common technique, the most reliable, and has the largest range of the salinity of water that it is suited to treat (up to 60.000 mg/L). The reverse osmosis technique was also chosen because this analysis is in partnership with the company Suez which is specialized in reverse osmosis desalination.

The renewable energy market is growing every year and renewable energy installations are more and more built around the world. This is because their costs are reduced every year while their performance is improving.
Nowadays, solar panels and onshore wind turbines are considered as the most mature technology in the renewable sector. The total capacity installed in growing every year, which results in cost reductions. However, the performances of other technologies, such as the concentration solar power (CSP), are also reaching performances and maturity every year.

The combination between renewable energy and SWRO desalination plant results in a competitive water cost. However, oversizing the renewable energy installation and installing batteries to store the overproduction and reduce the dependency of the grid might result in higher costs, because of the cost of the batteries. The reduction of the dependency might be reached, but if the equivalent cost of electricity from the batteries is more expensive than the electricity cost from the grid, there is no interest in installing batteries. Furthermore, installing batteries would only be interesting if selling the overproduced energy to the grid is not interesting (e.g. it costs more to buy from the grid than selling to the grid).

The scenarios analyzed in this study do not represent all the existing possibilities that combine renewable energy with water desalination plants.

With the scenarios that have been studied, some changes may be done to adapt the cost prices, such as selling the overproduction of energy to the grid (which means that it is interesting to sell the overproduction to the grid), or reducing the sizes of the batteries to avoid the over cost and still reduce the grid dependency.

However, other scenarios can also be possible. In these scenarios, installing other renewable energy technologies such as the CSP are also a possibility, since their cost becomes as interesting as solar panels.

In this study, the solar panels used were Cadmium-Telluride panels. But this study could be realized with crystalline-Silicon (cSi) panels. To go even further, an analysis could be realized where the electricity is produced off-grid by combining multiple renewable energy technologies (and adding batteries to provide constant energy to the plant). All the possible combinations ensure that there are a lot of choices to supply desalination plants.

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Appendices

A Addition information

	Typical Seawater	Eastern Mediterra-nean	Arabian Gulf of Kuwait	Red Sea at Jeddah
Chloride (Cl^-)	18.980	21.200	23.000	22.219
Sodium (Na^+)	10.556	11.800	15.850	14.255
Sulfate (SO_4^{2-})	2.649	2.950	3.200	3.078
Magnesium (Mg^{2+})	1.262	1.403	1.765	742
Calcium (Ca^{2+})	400	423	500	225
Potassium (K^+)	380	463	460	210
Biocarbonate (HCO_3^-)	140	-	142	146
Strontium (Sr^{2+})	13	-	-	-
Bromide (Br^-)	65	155	80	72
Borate (BO_3^{3-})	26	72	-	-
Fluoride (F^-)	1	-	-	-
Silicate (SiO_3^{2-})	1	-	1,5	-
Iodide (I^-)	<1	2	-	-
Total Dissolved Solids (TDS)	**34.483**	**38.600**	**45.000**	**41.000**

Tableau 3 : Major ion composition of Seawater [mg/L][5]