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THERMODYNAMIC ANALYSIS OF COMBINED PARABOLIC TROUGH SOLAR POWER AND DESALINATION PLANT IN THE NORTHEAST REGION OF BRAZIL

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Abstract. *An increase in demand for water, resulting from population growth and the need to augment food production, puts pressure on the limited available water resources, especially in areas of physical water scarcity. One alternative to offset the water demand and many of the negative impacts of running desalination plants is to combine Concentrating Solar Power (CSP) and desalination technologies. Thus, different models were combined aiming the thermodynamic analysis of a CSP system in cogeneration with MED and RO plants, under different conditions it would find throughout the year in the Northeast region of Brazil. The MED thermal model developed to provide an accurate description of the process was solved using a simultaneous equation solver. Detailed information about the brine and distillate flow rates and various temperature profiles were calculated. CSP and RO processes were solved using software packages. The results of the study show that the MED and RO desalination processes powered by CSP can present excellent performances, and the RO option would be more efficient in some cases.*

Keywords: *Solar energy, desalination, cogeneration, thermodynamic analysis, CSP.*

1. INTRODUCTION

Every continent is already facing water stress. In consequence of the high population density of cities and increasing urbanization, urban water supply is endangered. It is estimated that by 2050, 685 million people will face an additional decline in freshwater availability of at least 10 %, due to climate change (UNESCO, 2020). In terms of water resources, Brazil is renowned as one of the most water abundant countries, although this natural resource is unequally distributed in the territory. In 2019, around 22 million people were affected by drought in Brazil, and 94 % of those live in the Northeast region. The most critical drought conditions normally occur in December in the Northeast (ANA, 2020).

A way to reduce water scarcity is the seawater or brackish water desalination, a climate-independent source of fresh water in rural or urban areas. According to Cherif and Belhadj (2018), in 2014 there were approximately 17000 desalination plants worldwide and about 1 % of all fresh water consumed globally was produced by desalination plants, but this percentage is growing year-on-year. The reverse osmosis (RO) method has the highest market share, with a reported production of 65.5 million m³/day, accounting for 69 % of the volume of desalinated water produced (Jones *et al.*, 2019). Other desalination technology that is receiving considerable attention as a strong competitor is the multi-effect distillation with thermal vapor compression (MED-TVC). The MED-TVC process is characterized by lower energy consumption (≈ 2 kWh/m³) (Mistry *et al.*, 2012) compared to the RO process (≈ 2.5 - 4 kWh/m³) (Voutchkov, 2018). Unfortunately, due to the high energy and economic costs, desalination is currently concentrated in regions like the Middle East and North Africa (MENA) where there is an abundant supply of natural gas and oil.

In the past few decades, the combination of renewable energy, energy recovery devices and improvement of technology, reduced the cost of desalinated fresh water. According to Blanco *et al.* (2013), solar energy is the first candidate to overcome the desalination process dependence on the fossil fuels, due to its very high potential in most water-stressed regions. Concentrated solar power (CSP) has the highest potential, among different solar energy technologies, its cost is already lower than world market prices of fuel oil and rapidly decreasing with further market expansion (Trieb, 2007).

A series of theoretical studies dealing with the coupling of desalination units with CSP plants can be found in the literature. Works have demonstrated the desalination powered by CSP potential in specific locations, such as south-east Spain (Palenzuela *et al*., 2011), Gaza Strip (Hamdan *et al*., 2008), New Mexico (Téllez *et al*., 2009), and Oman (Gastli *et al*., 2010). Recently, an experimental co-generative power cycle with a MED applied as the steam condenser unit was installed in Borg El Arab – Egypt. The plant produces 1 MWe power with 250 m³/day of desalinated water, and allows individual testing of the components and their connection on a relevant scale (Hassan *et al*.,2018).

This work shows the results of different models combined to simulate power generation and desalination, regarding the operation of RO and MED-TVC systems powered by CSP, located in the Northeast region of Brazil. This work was conducted using as the main simulation tool the System Advisor Model (SAM), developed by the US National Renewable Energy Laboratory (NREL, 2020), the Reverse Osmosis System Analysis (ROSA), developed by the Dow Chemical Company (DOW, 2016), and a detailed model of MED system.

2. SOLAR POWER AND DESALINATION CONSIDERED MODELS

When multi-purpose plants are analyzed, MED and RO systems are considered the most suitable ones, as they present the best performances within the commercial technologies operating in the desalination market. The integration between power and RO plants does not represent a real problem, since the RO system simply uses the produced electricity of the power plant to feed the desalination unit. Also, in this case the plant does not need to be physically close to the power plant, a fact that could be considered as an advantage against the lower direct normal irradiation (DNI) at the areas close to the sea.

In challenging ambient conditions with seasonal high seawater temperatures and saline concentrations, the MED system is a very attractive against the RO option, which is normally penalized when high salinity water is treated, from both the energy and maintenance points of view. The MED option provides advantages such as reducing or replacing of the cooling system of the power cycle, although this means that the MED unit needs to be located close to the steam turbine of the power plant. This dependency might cause a problem due to the limited availability of lands near the sea.

The model used to describe the MED system is an adaptation of the models made by Mistry *et al.* (2012) and El-Dessouky and Ettouney (2002). The following approximations are made in this study:

- Steady state operation.
- Salinity of product desalinated water is 0 g/kg.
- Heat exchangers in the effects are large enough to condense vapor to saturated liquid.
- Seawater is an incompressible liquid and the properties are only a function of temperature and salinity.
- Energy losses to the environment are negligible.
- Non-equilibrium allowance (NEA) is negligible.
- Brine (liquid) and distillate (vapor) streams leave each effect on that effect's temperature.
- Distillate vapor is slightly superheated.
- The overall heat transfer coefficient is averaged over the length of an exchanger.
- The overall heat transfer coefficient in each effect, feed heater, and condenser are a function of temperature only.

2.1 Validation of MED-TVC model

The MED-TVC model is validated through comparing the results against field data of a two different MED-TVC plants. One is a plant located in Ashdod, Israel, a 6-effect desalination plant design to produce around 17450 m³/day of fresh water and coupled to a 50 MW$_e$ power plant (Fisher *et al.*, 1985). The other plant has a total of 12 effects and it is located in Trapani, southern Italy, producing in total 36000 m³/day, as it is powered by a set of boilers using natural gas (Casimiro, 2015). A very good agreement is shown in Table 1 and Table 2 between the model and field data. The distillate $\dot{m}_D$, brine $\dot{m}_B$ and feed water $\dot{m}_F$ mass flows and maximum brine salinity X_B simulated results when compared to real data shows a deviation between 0.2 % and 0.4 %. In comparison to the Ashdod plant the main differences lie in the temperature into the effects, up to 4.6 °C for the fourth effect.

Table 1 - Comparison with field data of Ashdod plant for a MED-TVC system.

Parameter	Ashdod	Present model
$\dot{m}_D$	201.4 kg/s	201.4 kg/s
$\dot{m}_F$	611.1 kg/s	608.4 kg/s
T_1	50-54 °C	58.5 °C
T_2	46-50 °C	54.0 °C
T_3	41-45 °C	49.6 °C
T_4	38-40 °C	45.2 °C
T_5	36-38 °C	40.7 °C
T_6	34-37 °C	36.3 °C

Table 2 - Validation of the main outputs from the MED process using field data of Trapani plant.

Parameter	Trapani	Present model	Deviation
$\dot{m}_D$	104.17 kg/s	104.17 kg/s	-
$\dot{m}_B$	209.72 kg/s	210.50 kg/s	0.4 %
$\dot{m}_F$	314.00 kg/s	314.70 kg/s	0.2 %
X_B	59.90 g/kg	59.79 g/kg	0.2 %

2.2 Main parameters used for the simulation

For this study the steam Rankine power cycle for parabolic trough CSP plants was chosen. The thermodynamic model of the power cycle was developed using a simultaneous equation solver, and correlations describing a Rankine cycle with intermediate steam extractions. Figure 1 and Figure 2 show the systems CSP-MED-TVC and CSP-RO considered in this work. In both RO and MED-TVC configurations, the cogeneration system was designed considering 30 MW_e of gross electric installed capacity and 380 m^3/h of distillate production. The CSP was solved using the SAM empirical model, that uses a set of curve-fit equations derived from regression analysis of data measured from real projects. The solar field configuration set in SAM consisted in an aperture area of 188000 m^2, the Therminol VP-1 as the solar field heat transfer fluid (HTF) and the Luz LS-2 as the solar collector assembly. The receiver selected was the Luz Cermet Vacuum, responsible for collecting the solar radiation and transferring it in the form of thermal energy to the HTF. No thermal storage is considered in the solar field, but the CSP plant has an auxiliary natural gas HTF heater to provide thermal power.

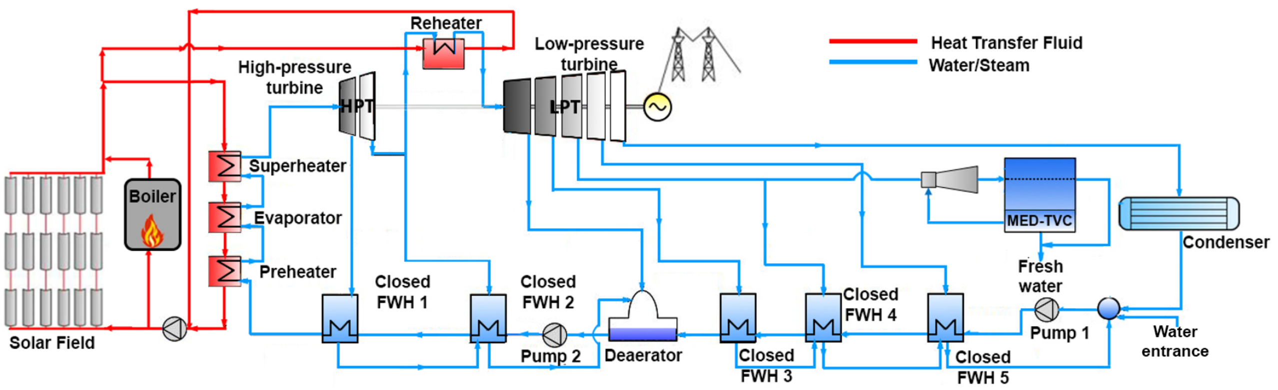

Figure 1. Diagram of the CSP+MED-TVC system analyzed in this study.

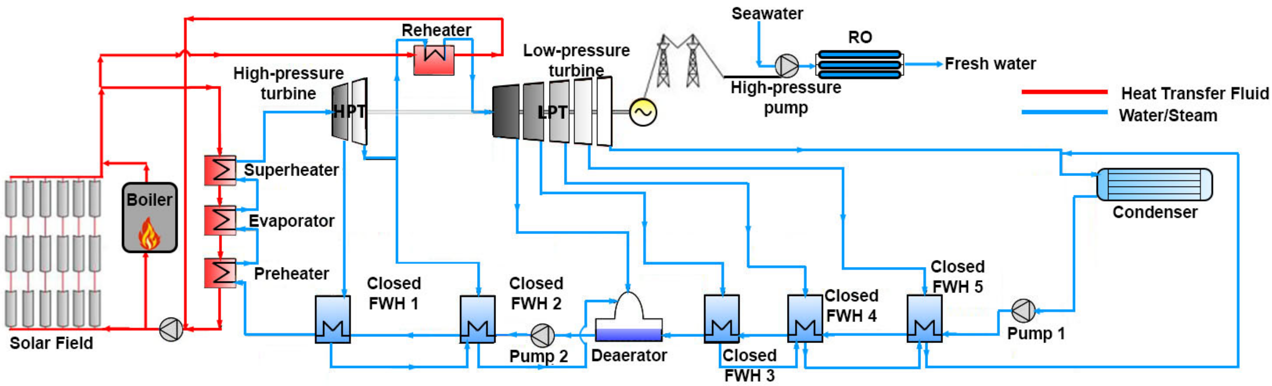

Figure 2. Diagram of the CSP+RO system analyzed in this study.

The MED-TVC system is modelled in a modular method in which each of the subcomponents are modelled separately and then instantiated the necessary number of times with additional equations to connect the various components, in order to piece together the complete model.

The MED-TVC configuration has been considered, due to the increase in the system performance ratio and the reduction in the specific flow rate of cooling water over the stand-alone MED system. The MED-TVC plant is assumed to have 12 effects, since it is observed that the performance ratio increases with increasing number of effects. The main inputs used to simulate the MED-TVC are described in Table 3.

Table 3 - Main simulation inputs for the MED-TVC model.

MED-TVC	**Value**	**Units**
Total number of effects	12	-
Seawater temperature	27	°C
Salinity concentration of the feed water	40	g/kg
Temperature of vapor in the last effect	40	°C
Ejector compression ratio	4	-
Boiling point elevation	1	ºC
Terminal temperature difference in the feed heater	5	ºC
Steam temperature	70.2	ºC
Motive steam pressure	100	kPa
Recovery Ratio	0.4	-

The configuration showed in Figure 2 consists of a Reverse Osmosis plant integrated into a parabolic trough concentrating solar power plant (PT-CSP). To simulate the complete system the selected tools were ROSA and SAM. It is assumed that all the remaining net electricity produced by the CSP plant that is not consumed by the RO system is available to be injected into the electrical grid. It is important to note that the CSP+RO model neglects the feed water pre- and post-treatment, and the minimum start-up and shut down time. The simulation was performed using ROSA to calculate the outputs from the RO plant, and the main inputs in ROSA include seawater quality and temperature, the number of membranes, and type of membrane. Rosa assumes steady-state operation and can only simulate single point operation, which is then considered hourly values in the simulation. Table 4 shows the list of inputs used for the RO simulations in ROSA software.

Table 4 – List of inputs used for the RO simulations in ROSA.

RO	**Value**	**Units**
Pre-stage ΔP	34.5	kPa
Total dissolved solids	40149	mg/l
Pump efficiency	85	%
Flow factor	1	-
Recovery ratio	45	%
Membrane type	SW30HRLE-440i	-
Elements in each vessel	7	-
Pressure vessels in each stage	88	-
pH	7.2	-
Seawater temperature	27	°C

The starting point to define the site project was the basic requirements of good value of the DNI and locations with access to seawater. The greatest potential for solar thermal energy in Brazil is located in the Northeast close to the equator, with a DNI on the order of 6 kWh/m². Fortaleza is the state capital of Ceará, located in the Northeast region of Brazil and a coastal city with a population above one million that could benefit from power and fresh water production. The weather data used for the simulations in Fortaleza was gathered from National Solar Radiation Database (NSRDB). As stated by NSRDB the original solar radiation and meteorological set of data for the years 1998 to 2017 is condensed into one year's worth of the most usual conditions. Moreover, the method used to calculate the one year of hourly data that best represents median weather conditions considers many factors beyond a simple calculation of median values, including solar radiation and other data such as wind speed and ambient temperature (NREL, 2017).

The overall efficiency of the cogeneration plants is given by Eq. (1).

$$\eta_{th} = \frac{P_{net}}{P_{th}} \tag{1}$$

where P_{net} is the gross power production in the turbines minus the power consumed by the desalination plant P_{desal}, cooling system P_{cool} and the pumps P_{pumps}, and P_{th} is the cycle thermal input. The electrical consumption demanded by the desalination plant P_{desal} is determined by Eq. (2).

$$P_{desal} = SEC \times M_d \tag{2}$$

where SEC is the specific electricity consumption required by desalination plant and M_d the total fresh water production from the desalination plant.

3. RESULTS AND DISCUSSION

The simulations of configurations CSP+MED-TVC and CSP+RO returned an equivalent production profile for water and power throughout the year as shown in Figure 3. The solar resource is more accessible in the second half of the year in the Northeast of Brazil, when average DNI values increase. It is possible to verify from Figure 3 that from a production perspective the CSP+RO system would return a slightly better performance. In addition, for both configurations the capacity factors for the CSP and the desalination plants are low (below 15 %) in the first four months of the year. This is due to the fact that the plants do not include heat storage systems, what could be used to increase the operating hours of CSP plants beyond the hours where the sun shines over the plant.

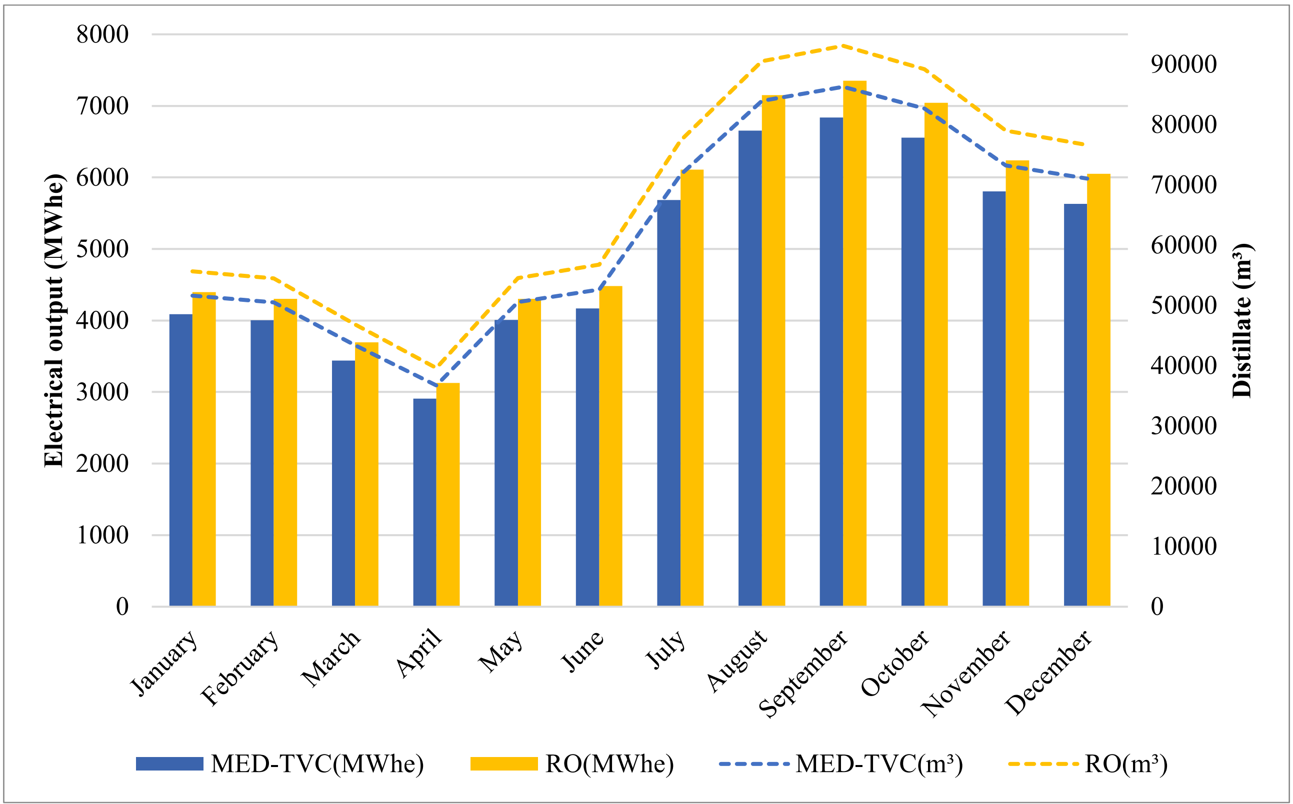

Figure 3. Comparison of freshwater and electric power production between CSP+MED-TVC and CSP+RO configurations, for the city of Fortaleza in Northeast of Brazil.

The results for annual fresh water and net electrical production in Table 5 show a percentage difference of 7 %, between CSP+MED-TVC and CSP+RO configurations. Part of the feed seawater in the MED-TVC plant is used to remove the excess heat added to the system, because of that a larger amount of seawater is needed in the MED-TVC in comparison to RO system. Moreover, the CSP+MED-TVC configuration uses steam from the turbine's third extraction, thus impacting in the plant's electricity generation. To compensate these losses in electrical production the turbine has to produce an additional amount of electricity, and an extra quantity of thermal energy is demanded as shown in Table 5. Throughout the year both configurations operated for 6 h approximately per day, and a higher mean electrical output is observed for the CSP+RO system.

Table 5 – General performance characteristics of the CSP+RO and CSP+MED-TVC plants for the case study in Fortaleza.

Parameter	**CSP+MED-TVC**	**CSP+RO**	**Units**
Total output of fresh water produced	753423.6	813749.2	m^3/year
Mean distillate flow rate	324.2	349.7	m^3/h
Mean feed seawater flow rate	1422.4	775.3	m^3/h
Net electrical production	59707.3	64243.4	MWh_e/year
Mean CSP electrical output	25.7	27.6	MW_e
Design power cycle thermal input	97.1	89.9	MW_t

The overall efficiency of the cogeneration systems CSP+RO and CSP+MED-TVC was obtained considering different specific electricity consumptions (SEC) values. The SEC of the MED-TVC plant was varied in a range of 1.2 to 2.2 kWh/m^3, while the RO plant was varied in a range of 3 to 5.5 kWh/m^3. Table 6 shows the simulated results for the thermal overall efficiency η_{th} varied as a function of the SEC, of the CSP+RO and CSP+MED-TVC systems considered.

Table 6 – Overall thermal efficiency of the configurations CSP+RO and CSP+MED-TVC with wet cooling system.

SEC (RO), kWh/m³	**3**	**3.5**	**4**	**4.5**	**5**	**5.5**
Overall efficiency η_{th} (%)	35.7	35.5	35.3	35.1	34.9	34.7
SEC (MED-TVC), kWh/m³	**1.2**	**1.4**	**1.6**	**1.8**	**2.0**	**2.2**
Overall efficiency η_{th} (%)	33.7	33.6	33.6	33.5	33.4	33.3

The simulations performed to compare the overall efficiency showed that the values were slightly more favorable for the CSP+RO system. Although the RO process has the higher specific electricity consumption as a consequence of higher pumping requirements, the utilization of the steam extracted from the low-pressure turbine result in a significant impact on the gross power production of the MED-TVC system.

4. CONCLUSION

The results of the simulations performed in this work for the Northeast of Brazil case study in Fortaleza indicate that solar desalination is thermodynamically feasible in locations with similar conditions as Fortaleza. Production peaks during the month of September and decreases between the months of January and May. In addition, the simulations show that there is a small advantage of using the CSP+RO configuration in comparison to the CSP+MED-TVC option, throughout the year, a performance ≈ 7 % higher is observed with the CSP+RO system considering the total amount of net electricity produced. Both configurations would benefit from a thermal storage system, allowing the systems to extend their 6 h operation, and consequently increase the capacity factor. Finally, the develop of a detailed economic model would validate the CSP+RO and CSP+MED-TVC feasibility in the Northeast of Brazil, and help determine the financial investments of these projects.

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