INTEGRATING DESALINATION WITH CSP: LARGE SCALE COGENERATION OF WATER AND ELECTRICITY

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Abstract

The demand for fresh water is a growing concern that is shared globally. Finite fresh water resources, accompanied by an exponential population growth will demand the need for additional installed desalination plants worldwide. However, desalination is extremely energy intensive with the costs thereof depending on the availability of local energy resources (coal, oil, gas, etc.). Fortunately, most arid regions generally also have high solar energy resources that could be utilized instead of conventional fossil fuel resources.

This is a theoretical case study, within the context of Namibia, in Southern Africa, investigating the possible benefits and concerns of integrating a multiple-effect desalination (MED) plant with a 100MW$_e$ concentrating solar power (CSP) tower plant for the large scale cogeneration of electricity and water (CSP+D). The results of the CSP+D plant are compared to a more conventional CSP and reverse osmosis (RO) configuration. The main disadvantage of the CSP+D plant is the pumping requirements of the seawater inland to the plant location.

Keywords: cogeneration; CSP; desalination; MED; MES;

1. Background

Namibia has a relatively low peak electricity demand of approximately 524MW$_e$. In 2015, more than 60% of the nation's annual electricity consumption was imported from the Southern African Power Pool (SAPP) [1]. Large scale desalination with CSP (CSP+D) could be an attractive option to secure Namibia's future water and electricity demands. Especially, due to the country's excellent direct normal irradiation (DNI) resources as illustrated in Figure 1.

The Trekkoppje RO plant was built in 2010 in order to support the water requirements for the uranium mining industry in the Erongo region. Additionally, the concern that the increased water extraction could potentially damage the Omdel aquifer is a key driver for seawater desalination in this region. The plant has the ability to deliver 20 million cubic meters of desalinated water annually, which is pumped 50km's inland at an elevation of 500m above sea level for use by various industries [2]. Namibia is the fourth largest uranium producer in the world, with its production expected to triple by 2017 after the completion of the Husab mine [3].

In 2015 NamPower had set out a tender document of an environmental feasibility study for the development of a 125MW$_e$ CSP plant in Arandis [4]. Arandis is a small town in the Erongo region within relative close proximity to the Trekkoppje, Rössing, Husab and Langer Heinrich uranium mines.

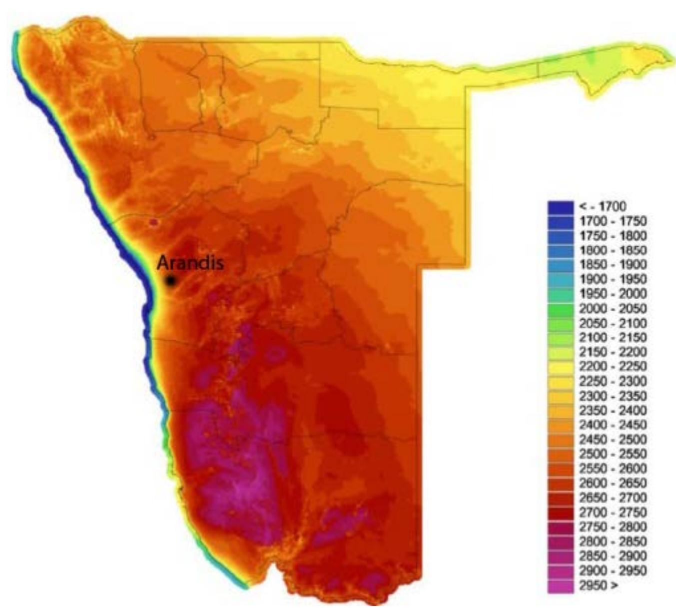

Figure 1: DNI solar resource map of Namibia, [5]

2. Approach

2.1 Case study setup

Given Namibia's present electricity and water circumstances, the following hypothetical scenario is investigated near Arandis:

A low temperature thermal desalination plant is integrated with a $100MW_e$ CSP plant for the cogeneration of water and electricity. Seawater is pumped to Arandis and desalinated, delivering water for the surrounding mines. The thermal energy requirement of the desalination plant will be provided from the condensing steam exiting the low pressure turbine. Three CSP+D cases are investigated varying the top brine temperature (TBT) in each case. TBT's between 70-55°C are considered. Handling of the reject brine is excluded in this study.

The more conventional option would be to provide the existing RO plant with electricity from the CSP plant in Arandis. Therefore, a dry-cooled CSP plant will be modelled to serve as the reference case for comparing the energy requirements for each configuration.

2.2 Technology selection

Multiple-effect distillation is progressively gaining commercial market acceptance as a more efficient desalination technology when compared to conventional multiple-effect flashing (MSF). The multiple-effect stacked (MES) configuration is an alternative arrangement of the MED process with effects stacked vertically on top of one another. The advantage of MES is that pumping requirements of the distillate and brine are significantly reduced. Such a plant can also operate more reliably under transient conditions, making it the most suitable for solar energy applications [6].

A CSP tower type configuration is currently the most commercial CSP technology that is able to produce electricity using molten salt as the heat transfer fluid (HTF). The ability of molten salt to reach higher temperatures than most other commercial HTF's is attractive for increasing the power plant efficiency.

2.2 Evaluation of MES vs. RO scenario

The pumping power required for each unit of distillate produced in kWh/m^3 is calculated with the aim to compare the electricity usage of the investigated MES plant configuration with that of the existing RO plant. The pumping power of the CSP+D case excludes the electricity consumption required for pumping the distillate inland. This assumption is made based on the fact that in any case the distillate of the RO plant would have to be pumped inland to Arandis, where it is further distributed or consumed. The auxiliary power of the MES plant is assumed to be $1kWh/m^3$ [7].

3. CSP power tower plant model

3.1 Heliostats, receiver and storage

The CSP modeling methodology from Gauché et al. [8] has been followed and focuses on the optical-to-thermal conversion of energy. This simplified modeling approach has the ability to give results with minimal computational time and with acceptable levels of accuracy.

The power tower plant with two-tank molten salt storage has been modeled in MS Excel with the following approximations:

- Steady-state operating conditions
- Cosine, shading and blocking heliostat efficiencies are a function of the zenith angle only
- Start-up periods are accounted for by "dumping" the first hour of electricity production after each start-up

3.1 Power block

The method of Gauché et al. excludes a suitable power block model; therefore a reheat Rankine cycle has been modeled in Engineering Equation Solver (EES) to investigate the effect of integrating a thermal desalination plant (MES) into the power block as a condenser for the Rankine-cycle steam. The power tower plant has been modeled assuming the following conditions:

- Pressure losses in the Rankine cycle are excluded
- Isentropic efficiency of turbine to be 85%
- Isentropic efficiency of pumps to be 75%
- Feed-water heaters are 100% effective

The live steam temperature and pressure specifications were chosen to be that of the Siemens SST-600 turbine [9]. The condensing steam at point 10 in Figure 2 is dependent on the ambient dry-bulb temperature for the dry-cooled reference case. An initial temperature difference (ITD) of 24°C was assumed [10].

In the three CSP+D cases, the top brine temperature determines the condensing steam conditions. The outlet pressure of the high pressure turbine (HPT) (point 8) as well as the bleeding pressure locations for the four closed feed-water heaters (points a,b,d,e) are optimized for each power plant configuration to deliver the maximum Rankine cycle efficiency.

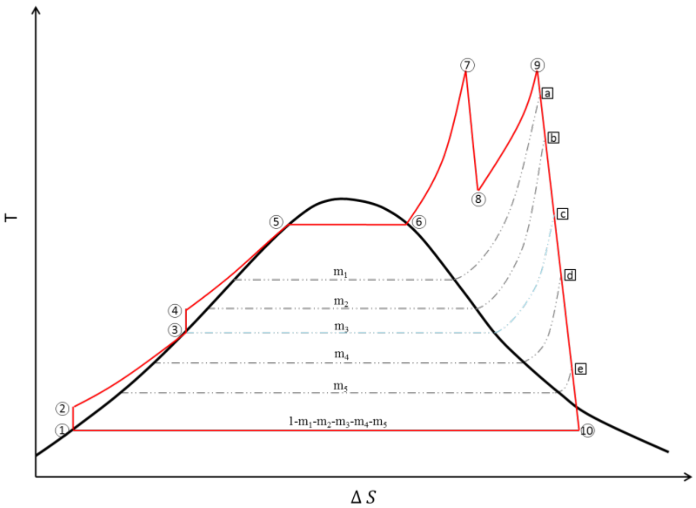

Figure 2: Rankine cycle T-S diagram

4. MES desalination plant model

The MES modelling approach from Mistry et al. [11] is followed closely and also modelled in EES. A segmental method is used in which each subcomponent (effect) is modelled individually and then integrated with one another to assemble the entire plant model. Each subcomponent, or process, is handled as a control volume and solved by continuity and energy balance equations. The dashed-line and numbered control volume boxes are illustrated in Figures 3, 4 and 5. The MES plant has been modeled with the following assumptions:

- Steady-state operation
- Seawater properties are only a function of temperature and salt content
- Seawater temperature remains constant (15°C)
- Energy losses to the environment are negligible
- Salt content of distillate produced is negligible
- The boiling point elevation (BPE) is not constant in each effect
- The distillate vapor generated via boiling and via flashing of the brine is slightly superheated by the amount equal to that effect's BPE

Preheated feed-water enters the top of the first effect (Figure 3) and boils at the specified top brine temperature producing distillate vapour as well as brine with a slighty increased salinity. The steam exiting the low pressure turbine (LPT) acts as the heating source for the first effect and transfers all of its latent heat, returning to the steam generator as saturated fluid.

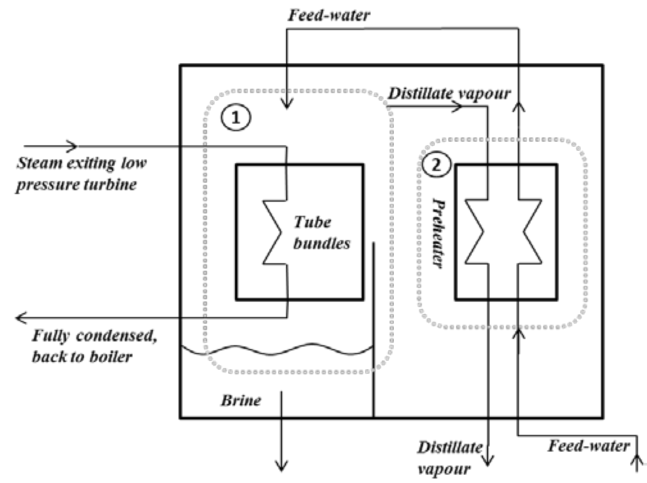

Figure 3: MES plant, first effect

The distillate vapour created in the i^{th} effect slightly preheats the feed-water of the MES in a preheater before moving on to the $i^{th}+1$ effect acting as the heating steam. The brine from i^{th} effect flows over to the $i^{th}+1$ effect and due to a small reduction in pressure, partially flash-evaporates. The "un-flashed" brine then boils over the evaporator tubes as in the 1^{st} effect.

After a distillate vapour stream has fully condensed it is collected in what is called a flash-box. The pressure inside the i^{th} flash-box corresponds to the pressure inside the i^{th} effect. Further partial flash-evaporation occurs when the incoming condensed distillate enters the i^{th} flash-box due to the small reduction in pressure. This process is repeated until the n^{th} effect is reached.

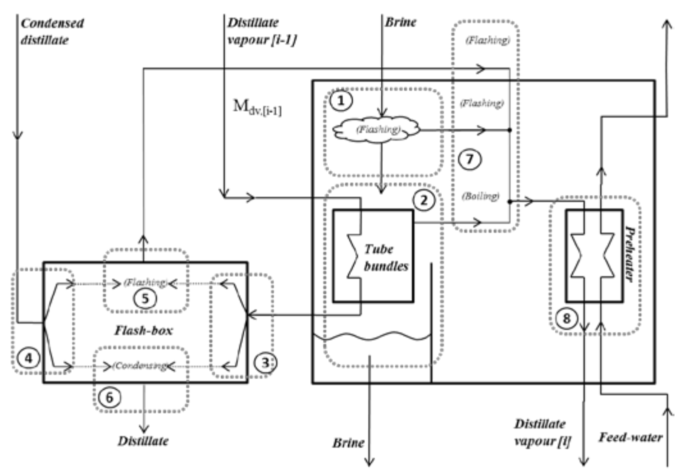

Figure 4: MES plant, i^{th} effect

The distillate produced in the n^{th} effect flows through a condenser and then accumulates with the rest of the distillate from the n^{th} flash-box. The cooling seawater exiting the condenser serves as the feed-water flowing up through a series of preheaters until entering the first effect. There is typically some excess seawater needed to condense all the n^{th}-effect distillate, which is rejected together with the brine back to the ocean or a designated evaporation pond.

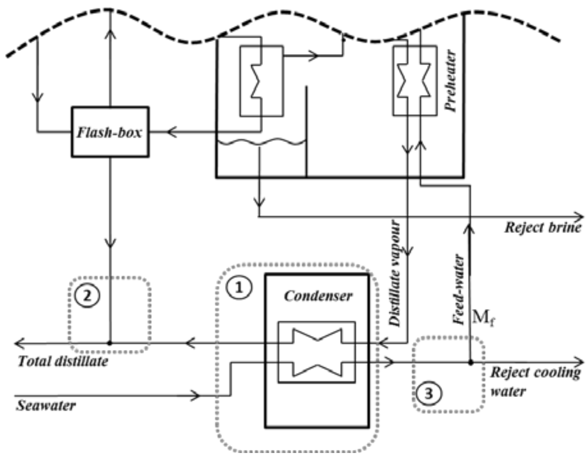

Figure 5: MES plant, condenser

4.2. Performance parameters

The system performance of an MES plant is most significantly influenced by the number of effects added in the system. Carrying out a parametric analysis by varying the number of effects, the performance ratio (PR) and the specific heat transfer area (SA) of the plant can be evaluated.

The mass flow rate of distillate produced over the mass flow rate of input heating steam supplied is called the performance ratio (eq. 1). Figure 6 illustrates how the performance ratio improves with the addition of effects as well as how this model compares to other models in the literature.

$$PR = \frac{\dot{m}_{distillate}}{\dot{m}_{steam}} \qquad (1)$$

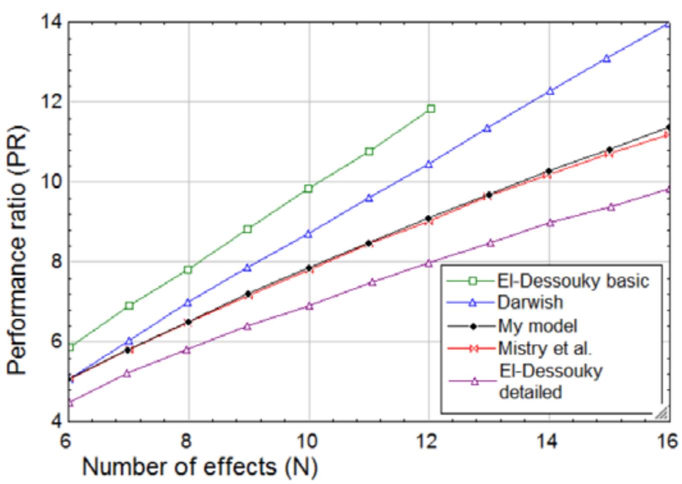

Figure 6: Performance ratio comparison, (TBT = 70°C)

Another consequence of increasing the number of effects is the reduction of the driving temperature difference over each effect. Adding more effects increases the SA of the plant as well as the capital investment. When lowering the TBT, the increase in SA gradually becomes more exponential when adding effects as seen in Figure 7. Calculating the SA includes the area of the effects, preheaters and final condenser as calculated by equation 2 with units given in $m^2/(kg/s)$.

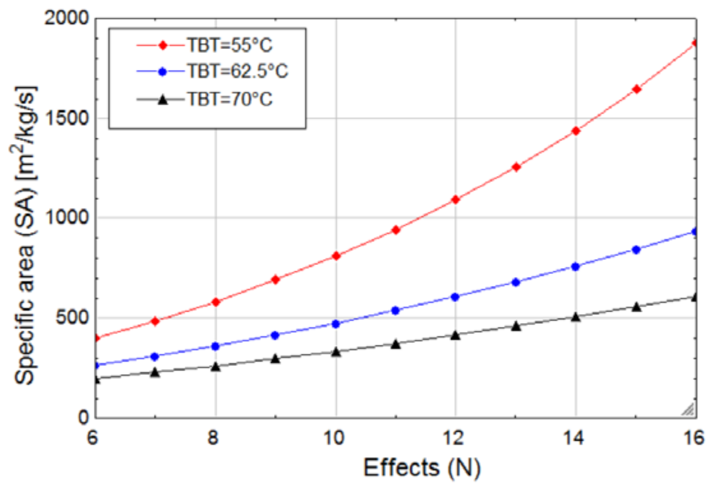

Figure 7: Specific heat transfer area requirements at various TBT's

$$SA = \frac{\sum A_{effects} + \sum A_{preheaters} + A_{condenser}}{\dot{m}_{distillate}} \qquad (2)$$

5. Economics

In literature, the capital investment costs of MED desalination plants are generally a function of installed plant capacity. In this study it seems more appropriate that the capital costs be a function of total heat transfer area. Equation 4 is a correlation from Hall [12] for titanium-stainless steel shell-in-tube heat exchangers. It is a function of heat transfer area and calculates the capital investment in USD. This aids in understanding the economic implications of reducing the TBT and is shown in Figure 8. The results for the three CSP+D configurations, using Hall's correlation, has been normalized to be compared to the correlations of Wittholtz et al. [13], Loutatidou , Hammond et al and El-Nashar.

$$C_{invest} = 3800 + 3749A^{0.81} \qquad (3)$$

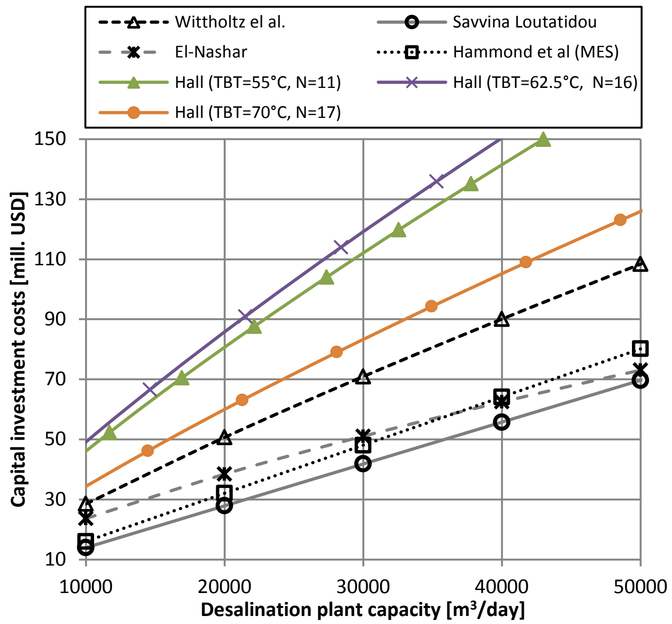

Figure 8: Capital investment cost comparison of MED plant technologies

5. Results and discussion

The design point (DP) for the dry-cooled power plant had been chosen to be at noon on the 20th of March. Notice in Table 1 that the average Rankine cycle efficiency is somewhat higher than that of the DP conditions. This is attributed to the fluctuation in ambient temperature conditions, especially after sunset. A solar multiple (SM) of 3.3 with 14hours of full-load thermal energy storage (TES) allows the dry-cooled plant to reach a capacity factor (CF) of approximately 91%.

Parameter	Value
Rankine efficiency, design point [%]	43.49
Rankine efficiency, year average [%]	45.26
Steam mass flow rate [kg/s]	89.26
Number of heliostats required (12m×12m) [-]	10354
Thermal energy storage [MWh_{th}]	3218.5
Electricity generated [GWh/annum]	803

Table 1: Dry-cooled CSP tower plant outputs

In Table 2 the three different cogeneration power plant case results are tabulated. Similar to the reference case, a SM of 3.3 and 14hours of TES are used. However a reduced CF of approximately 89% is obtained in all cases. The increase in condensing temperature decreases the Rankine cycle efficiency and requires a greater thermal energy input to generate the same net-amount of electricity ($100MW_e$).

Parameter	Case 1	Case 2	Case 3
Condensing temperature [°C]	57.5	65	72.5
Rankine efficiency	43.68	42.73	41.78
Steam mass flow rate [kg/s]	87.43	89.41	91.13
Number of heliostats required (12m×12m) [-]	10313	10542	10785
Thermal energy storage [MW_{th}]	3205.4	3275.9	3350.7
Electricity generated [GWh/annum]	784	784	784

Table 2: CSP-MED power plant outputs

The MES desalination plant results are presented in Table 3 for each configuration. The maximum number of effects in each configuration is constrained by assuming a minimum temperature difference of 1.5°C across each effect. Due to bleeding off steam at various points between the HPT and LPT for feed-water heating, not all of the steam exits the LPT in the Rankine cycle. This reduces the amount of steam sent to be condensed in the first effect of the MES plant.

From the desalination plant perspective, case 3 seems to be the most economical option because of its high performance ratio and its low specific heat transfer area. Additionally it has the lowest total electricity consumption due to its excellent seawater usability score. The total electricity consumption includes the auxiliary power of the plant needed to run the vacuum pumps, etc.

The electricity consumption of the Trekkoppje RO plant at the Namibian coast is in the range of 4.1 to 4.5kWh/m^3 [2]. The electricity consumption of the MES in case 3 falls in the range of the RO plant usage. However, the additional thermal energy input required for thermal desalination reduces the Rankine cycle efficiency and the annual generated electricity.

Parameter	Case 1	Case 2	Case 3
Top brine temperature [°C]	55	62.5	70
Effects [-]	11	16	17
Heating steam [kg/s]	54.3	57.1	60.1
Performance ratio (PR)	7.39	9.3	9.57
Specific heat transfer area (SA) [m^2/kg/s]	966.6	945.5	669
Sea water usability [%]	62.5	90.5	95.7
Pumping electricity consumption [kWh/m^3]	6.0	3.5	3.2
Total electricity consumption [kWh/m^3]	7.0	4.5	4.2
Water produced (million) [m^3/annum]	11.3	15.0	16.2

Table 3: MED plant configuration specifics

6. Conclusion

The capital cost approximations made using Hall's correlation seems to overestimate the capital costs for MES systems as seen in Figure 8. Nonetheless, if the capital costs are assumed to be a function of the total heat transfer area of the desalination plant; then the escalated trend that occurs when lowering the TBT will still be relatively similar.

Integrating a low-temperature thermal desalination plant with a CSP plant does affect the power block performance unfavorably. When compared to the dry-cooled reference case; the Rankine efficiency of case 3 drops approximately 3.5% and the annual electricity production drops 2.4%. The Rankine cycle efficiency impacts the number of heliostats required as well as the size of the TES, which in turn will affect the levelized cost of electricity. However, this marginal decline in electricity production may be justified, depending on the electricity and water tariffs available. There is currently no official tariff structure for CSP in Namibia. In order to keep levelized costs of water to a minimum, base load operation is recommended for a CSP+D plant.

In comparison to the results of the thermal desalination alternatives, the CSP+RO combination appears to be the most feasible option in the context of this case study. The distance which the seawater needs to be pumped to the desalination plant is a major drawback for the CSP+MES scenario. Moving the desalination plant closer inland could solve this problem, however the DNI diminishes as one moves closer to the coast as can be seen in Figure 1. Taking rust corrosion into consideration might also be required when planning a CSP plant relatively close to the coast of Namibia.

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