Concentrating solar power multi-effect desalination in Al Khobar, Saudi Arabia

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Abstract. As about two-thirds of the thermal energy to the power cycle of a concentrated solar power plant is dumped to the condenser, typically air or evaporative cooling, there is the opportunity to achieve energy savings by using a multi-effect distillation system to condensate the steam and at the same time produce desalinized water. Preliminary design considerations and computations for a concentrated solar power plant located in Al Khobar, Saudi Arabia, are here proposed. The solar field has an aperture of 1,230,000 m², it uses oil as the receiver fluid, it uses a six hours’ thermal energy storage by molten salt, and it features a 140 MW turbine. It is expected production of up to 413 GWh of electricity annually, for a capacity factor of 0.36, by using an air-cooled condenser. Adoption of a glass enclosure and a multi-effect distillation plant replacing the air-cooled condenser may permit the same electricity production plus the production of desalinized water in an environment protected by sand and dust.

1. Introduction

Energy and water supply will be two of the major issues humanity will face during this century. With the projected growth of concentrated solar power (CSP) around the world, the integration of CSP with desalination (CSP+D) has great potential. Often, where there is high solar radiation to support CSP, clean water is even more precious than energy.

Desalination is steam-driven (for example multi-effect distillation, MED) or electricity-driven (for example pressure forced reverse osmosis, RO). Where water conditions give MED an advantage versus RO, and there are the right conditions for CSP, then MED may be conveniently integrated with CSP plants. Regarding CSP, the most promising opportunity lies in the Parabolic Trough (PT) design.

Thermal energy storage (TES) by molten salt (MS) introduces the added value of dispatchability but at an increased cost and complexity. CSP with TES is the only renewable energy plant that can deliver power when the resource is not available (wind and solar photovoltaic or CSP without TES need external energy storage by batteries or pumped hydro). CSP with TES features oil as the receiver fluid, then a two tanks TES with MS as the thermal energy storage fluid, and water/steam as the power cycle fluid. The condenser of the Rankine power cycle is air-cooled or evaporative for in-land, arid, desert areas. While there are no examples so far of CSP in coastal locations, it may be convenient to use saltwater once-through condensers. Solar field temperatures are typically 293 K/393 K, and pressure and temperature of the steam to turbine 393 K and 100 bar. This is the design of the 250 MW Solana, in Gila Bend, AZ, the most successful CSP plant presently operated, delivering annual average capacity factors of 36.40% with the opportunity to extend production up to 6 hours after the sunset thanks to the 6 hours of TES. This is also the design of the 250 MW Genesis and Mojave, respectively close to Blythe,
CA and close to Barstow, CA, that do not have TES, and thus only produce electricity during the day. Genesis and Mojave have the latest annual average capacity factors of 28.11% and 24.45%. While the 12 months moving average of the monthly capacity factors is still growing for Solana, this parameter is stable for Genesis and has been recently decreasing for Mojave. Since the start of the operation, the maximum 12 months moving average of the monthly capacity factors was 36.40% in Solana, 29.20% in Genesis, and 28.72% in Mojave.

In areas such as Al Khobar, due to sand, dust, humidity, and proximity to the sea, all the plant equipment has to be enclosed in a glass room. Additionally, the condenser of the power cycle, usually air-cooled or evaporative for the in-land CSP can be made once-through saltwater condenser. Here we examine the integration of a MED plant with a CSP PT without TES, with the MED being feed by partially expanded steam. Presently, there are in Al Khobar two desalination plants both featuring multi-stage flash distillation (MSF). MSF distills seawater by flashing part of the water into steam in multiple stages of countercurrent heat exchangers. MSF was popular in the past but recently suffers from the competition of RO due to much lower energy consumption. MED has in principle advantages versus MSF, but not an energy consumption advantage compared to RO. The availability of steam from a PT solar field may turn MED into the preferred candidate.

2. MED plants

In desalination, seawater is separated into a freshwater stream with a low concentration of salts and a brine with a high concentration of salts. The most relevant technologies are thermal desalination and membrane desalination. Thermal desalination utilizes heat to change the phase of the seawater from liquid to vapor. Membrane desalination uses pressure to force water through a semi-permeable membrane. While membrane desalination needs the energy to run a pump, that may be produced with any mean, thermal desalination utilizes heat, often in the form of steam, that may be conveniently produced by a CSP plant. MED thermal desalination systems may be competitive with seawater RO under specific water conditions [1]. MED systems are designed with multiple evaporator stages, which evaporate seawater to produce desalinated water.

Normally, in large desalination plants, the number of stages or effects varies between 8 and 16 due to the low-temperature drop per effect. Seawater is heated to approximately 70 °C by a steam supply. Boiling occurs in the sequence of effect vessels, each held at a lower pressure than the last. Because the boiling point of water decreases as pressure decreases, the vapor boiled off in one vessel can be used to heat the next. Only the first vessel (at the highest pressure) requires an external source of heat. The seawater and external steam source both enter the MED system in the first effect on opposite sides of the heat exchanger tubes. Steam is fed to the inside of the tubes, and seawater is sprayed over the outside of the tubes in a typical effect. The seawater, upon contacting the heat exchanger tubes, begins to boil. The vapor produced is collected and is transported to the second effect on the inside of the second effect’s heat exchanger tubes. The heating steam from the first effect condenses inside the first effect’s heat exchanger tubes and is returned to the power plant as condensate. Concentrated seawater brine in the first effect is collected in trays and transported across the outside of the heat exchanger tubes in the second effect, where again it boils by heating and the pressure change. This process continues throughout the series of effects. After the final effect, the vaporized water that has collected on the inside of the effect heat exchanger tubes is cooled and condensed with seawater in a final heat exchanger.

Most MED designs include a thermal vapor compressor (TVC) to increase system efficiency. A TVC recycles some of the vapor produced in the desalination process to reduce the total amount of steam required to drive the process. A TVC is a steam ejector that entrains low-pressure vapor from a downstream effect with motive steam and discharges the mixture into the first effect. MED plants are generally built-in units of about 100 m²/day up to 36,400 m²/day (0.03 to 8 mgd), allowing this design to be utilized in smaller volume applications. Multiple units may be combined in one plant to further increase capacity. The system produces very high-quality product water from the sea or brackish water with a total dissolved solids (TDS) concentration of 25 mg/l or less.

3. CSP plants

A PT is made up of a linear parabolic reflector concentrating the sunlight onto a tubular receiver located along the focal line of the reflector [2]. The tubular receiver is filled with a working fluid that is often
oil, molten salt, or even water/steam. The reflector follows the sun. The tracking operates along a single axis. The working fluid is usually heated to 390 to 500 °C, depending on the fluid, oil or molten salt flowing through the receiver. If oil or MS, this fluid is then used in a heat exchanger to produce steam for the power cycle. The shaped mirrors of a PT focus the sunlight on a tube running along the focus line with typically an 80x concentration. The sunlight is absorbed by the tube in a glass vacuum and delivered to the receiver fluid. While PT may be less efficient than a solar tower (ST), where a huge number of two-axis tracking heliostats focus the solar energy on a small receiver atop of a tall tower, they are much simpler and less expensive to build and operate. Reference PT specifications change if the fluid is water/steam, oil, or MS as follows, ref. [2] to [8].

For oil as the receiver fluid, the receiver temperature is 390 °C. The peak flux on the receiver is 25 kW/m². The hot storage temperature if any is 390 °C, the cold storage temperature is 290 °C, and the condenser temperature is 40 °C for heat rejection. This is the configuration used for example in the CSP PT plant of Solana, Genesis, and Mojave.

For MS as the receiver fluid, the receiver temperature may go up to 500 °C, the peak flux on the receiver is 25 kW/m², the hot storage temperature is 500 °C, and the cold storage temperature is 300 °C. The condenser temperature is unchanged. There is no large CSP PT plant presently featuring this opportunity.

In the case of water/steam as the receiver fluid, the receiver temperature may also go up to 500 °C, the peak flux on the receiver is 25 kW/m². The hot and cold storage tanks are not available in this case, all the other parameters being unchanged. Similarly, there is no large CSP PT plant presently featuring this opportunity.

Supercritical steam power cycles and supercritical carbon dioxide power cycles are also being considered to improve the conversion efficiency thermal-electric. Higher temperature receiver fluids, and materials and manufacturing improvements to reduce costs are also the major area of concern for CSP PT.

Enclosed troughs are used to protect the plant equipment from high winds and blowing sand and dust [9]. Glass Point solar steam generators [9] house thin curved mirrors inside a greenhouse. The mirrors track the sun throughout the day, focusing the heat on pipes containing water. The concentrated sunlight boils the water to generate steam. The greenhouse has an automated washing machine to maintain optimal performance even in harsh conditions. The Glass Point PT system is only used to produce steam then used in the oil fields.

In Saudi Arabia, in coastal areas such as Al Khobar, sand, and dust, plus humidity and salinity for the proximity to the sea, suggest enclosing all the plants in a glass room. In the case of a plant producing electricity, it is also important to adopt a once-through seawater condenser. In this case, the most reliable technology is oil as the receiver fluid, then one heat exchanger oil to steam/vapor. If the production of electricity is the main focus of the plant, the best opportunity is then to adopt thermal energy storage by molten salt. If the main focus of the plant is to produce desalinized water, then the best option is to use water as the receiver fluid and then MED. If the focus of the plant is to produce both electricity and desalinized water, then the best option is again to use water as the receiver fluid, with then part of the steam to the turbine diverted to the MED, or also adopt the classic scheme with oil as the receiver fluid, a heat exchanger to produce steam, and then use part of the steam to the turbine diverted to the MED.

4. Electricity plus desalination

A key issue with deploying renewable energy conversion systems is their intermittent nature. Solar photovoltaics (PV) generate power only when the sun shines. CSP, if fitted with TES, may theoretically produce electricity 24/7, even if in practice CSP plants with TES have about the same capacity factors of CSP plants without TES, much higher costs, and reduced reliability, as the technology is everything but mature. The 6 hours of thermal energy storage in Solana permit power generation after sunset during the summer months, up to the early hours of the following morning, as it is otherwise impossible without TES. The benefits of energy storage are invaluable in improving grid stability, power quality, and the continuity of supply. However, TES is difficult to be implemented.

Combining CSP with desalination has an energy storage advantage. Many solar fields for CSP are designed to match an average insolation flux. In the summer and during peak daylight hours, there is excess heat produced by the solar field. In the absence of TES, some of the solar collectors or mirrors
must be defocused (energy dumping). This excess heat may be used in the desalination plant. In principle, as the power demand seasonally changes, a combination of solar power generation and desalination may allow some additional degree of discretionary allocation of the heat input to the production of power or water desalination. CSP plants usually have a steam power cycle where expansion in the turbine is limited by the conditions to the air-cooled or evaporative condenser. In hot locations, a once-through seawater condenser provides better efficiencies of the power cycle than an air-cooled or evaporative condenser. In the specific area, an air-cooled or evaporative condenser is difficult to be used also for other reasons, from the salt to the sand and dust to the humidity. Using a MED as condenser may also provide advantages vs. an air-cooled or evaporative condenser.

A CSP plant without TES plus a steam/water power cycle coupled to a switchable MED desalination plant/once trough seawater condenser may give advantages vs. a traditional CSP plant without TES with an air-cooled/evaporative condenser, producing desalination in addition to more electricity.

A CSP plant without TES coupled to MED is shown in ref. [10]. The Thermoflex [11] model describes a plant in the coastal Surt region of Libya producing up to 15,000 m³ per day of potable water while also delivering electricity up to 15 MW of power. The receiver fluid is water/steam. The plant, which also features a natural gas combustor to support the solar field in the production of steam, has no air-cooled or evaporative or once-through saltwater condenser, but only the MED plant. The hybrid design fossil fuel – solar can produce power and water 24/7 without thermal energy or other external storage such as batteries or pumped hydro. The MED plant replaces the condenser to also produce potable water from seawater. The solar field uses Linear Fresnel Collectors (LFC) with direct steam generation (DSG) rather than the parabolic trough. Turbine inlet steam conditions are 55 bar and 400 °C. The MED design has a nominal performance ratio of 10.4 by using 12 effects over a temperature range of 30 °C.

Thermoflow/thermoflex is the preferred software for this kind of modeling, permitting the accurate representation of the turbine sections, the condenser, and the many heat exchangers involved in the plant design.

Many other options are certainly possible. Solar field plus a natural gas burner in parallel, or solar field only, or solar field plus thermal energy storage to produce steam, and then one traditional condenser once trough saltwater, one condenser once trough saltwater and the MED, or the MED only, to condense the steam. In between these other alternatives, a purely theoretical CSP plant with TES coupled to MED is shown in ref. [12]. The model is based on Transient System Simulation Tool (trsys) [13], which is based on what concerns the CSP on SAM [14]. The receiver fluid is oil. The heat storage fluid is MS. Then, there is a heat exchanger for the MS and a heat exchanger for the water/steam. The plant does not feature a boiler to support the solar field in the production of steam. It has no air-cooled or evaporative or once-through saltwater condenser, but only the MED plant to serve as condenser.

5. Preliminary simulations

A SAM [14] model was developed for half of the Solana plant in Gila Bend, with experimental and computational capacity factors compared in the validation exercise. Solana has 6 hours of molten salt thermal energy storage and air-cooled condenser. As the real plant still suffers from maturity issues with 12 months moving average of the capacity factor always increasing (latest 36.4%), operation of many components is overrated in SAM that is proposing a 41% annual average capacity factor over the typical year. Fig.1 presents a comparison of the computed and measured capacity factor for Solana, Gila Bend, AZ. Fig.2 then presents the computed capacity factors for a plant the same as one half of Solana, except a 10% larger specific solar field, located in Al Khobar, Saudi Arabia. Fig. 3 finally presents the power of collecting energy in the solar field, the power to and from the storage, and finally the power to the steam power cycle. As the rated efficiency of the power cycle is about 36%, about 2/3 of the thermal energy from the power cycle gets dumped to the condenser.

Unfortunately, SAM has a very crude representation of the turbine and condenser, and it does not permit to model once-through saltwater condensers or MED plants. The SAM condenser pressure is dependent on ambient air temperature, cooling technology, and cooling load through simplified relations. The only two cooling technologies available are wet cooling and dry cooling. Both wet and dry cooling use ambient air as the cold thermal reservoir. Wet cooling uses the wet-bulb air temperature. Dry cooling uses the dry-bulb temperature of the air.
Figure 1. The experimental and computational capacity factor for Solana, Gila Bend, AZ. Computations were performed using SAM.

Figure 2. The computational capacity factor for a plant like ½ of Solana, with the specific solar field, increased 10%, located in Al Khobar, Saudi Arabia. Computations were performed using SAM.

Figure 3. Computational thermal energy from the solar field and to/from the storage, and thermal power to the power cycle, over the 24 hours of a typical day of every month for the Al Khobar plant. Computations were performed using SAM. About 2/3 of the energy to the power cycle is then dumped to the condenser. This energy may be used for MED.
The dry-bulb temperature can be significantly higher than the wet-bulb temperature. With a once trough seawater condenser, the temperature of the cold thermal reservoir is otherwise the water temperature, that especially daytime during the summer is much lower than the dry-bulb air temperature. With MED distillation, the temperature of the cold thermal reservoir is larger than the water temperature but difficult to say if there are gains or losses versus the air-cooled condenser without performing appropriate simulations with better software tools such as thermoflow.

6. Conclusions

In coastal locations, where sand, dust, humidity, and salt also play a major role in concentrated solar power plants operation, there is the convenience to adopt a glass enclosure for the parabolic trough plant components, as well as to use a once trough saltwater condenser in place of traditional air-cooled or evaporative cooling condensers. As two-thirds of the thermal energy to the power cycle gets dumped at the condenser, an interesting opportunity is to use a multi-effect distillation plant as the condenser of the steam power cycle. This way, the plant produces both electricity and desalinized water. Following this preliminary exercise, better simulations are needed to determine the feasibility of such a plant in terms of costs and performance. For a 24/7 operation, a natural gas or oil burner can be conveniently added to the basic concentrated solar plant design.

7. References

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