Concentrating solar power plants for electricity and desalinated water production

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Abstract: Electricity and water are two commodities which are usually both required in arid countries having a high solar insolation. A number of technologies exists for both systems, which are briefly reviewed in this paper. Among the most matured and suitable concentrated solar power (CSP) plants for electricity generation are the solar tower (ST) and the parabolic trough collector (PTC) systems, whereas for desalination these are the multiple effects distillation (MED) type evaporator and the reverse osmosis (RO). The paper shows also the possibilities that exist and the ways that these technologies can be combined in order to produce simultaneously electricity and water. The equipment required to be used for these systems (steam cycle components, MED or RO) is usually very expensive therefore, the system is required to operate continuously without complete shut down during the night. Such a system would be very suitable for arid countries, which due to the water shortage problem they face, locate power plants in coastal areas in order to use the seawater for the cooling needs of the steam cycle system (condenser). Therefore, in this case it would be comparatively easy to combine the power system with desalination as the resource for such a system, i.e., seawater would be readily available.

Keywords: *Parabolic trough collectors, power tower, multiple effect boiling, reverse osmosis, desalination*

1. Introduction

Cyprus does not have at the moment any sources of energy and depends exclusively on imported oil for its energy needs. The only inexhaustible natural source of energy that Cyprus posses abundantly, is solar energy. It is well known that other forms of renewable energy, like the wind energy, wave energy and biomass have limited potential in Cyprus. Cyprus Government decided to erect a solar thermoelectric power generation station with a capacity of about 50 MW. The characteristics that need to be considered when selecting the right type of thermoelectric system are the cost of electricity produced and the land area that would be required to install the solar plant. The latter is very important as Cyprus has no desert land near the sea but on the contrary seaside areas are very expensive as they are used for touristic development. It should be noted that all existing power stations are located near the sea so the solar power station should also be located near to one of those stations to ease access to the grid and for the use of the seawater for the condenser.

2. Concentrating solar power

Concentrating solar power plants, use mirrors to generate high temperature heat that drives steam turbines traditionally powered from conventional fossil fuels. Some of these systems incorporate also heat storage which allows them to operate during cloudy weather and night-time. The main systems that are operational today in various countries are the parabolic trough collector (PTC) system and the central receiver or power tower system. More details about these systems can be found in [1].

2.1. Parabolic trough collector system

From the technologies available the most industrially matured is the parabolic trough system. This is mainly due to the nine large systems installed and operating in California, USA since 1985, which have a total installed capacity equal to 354 MWe. Mainly due to the plants operating in California for more than 20 years, parabolic trough is the most proven technology and today they produce electricity at about US$ 0.10/kWh. The success and durability of these plants has demonstrated the robustness and reliability of the parabolic trough technology. Compared to other technologies, this system has a high solar-to-electrical efficiency and low area per MWh requirement.

Parabolic trough collectors are the most mature solar technology to generate heat at temperatures up to 400°C for solar thermal electricity generation or process heat applications. Parabolic trough technology proved to be tough, dependable and proven. Today the second-generation parabolic troughs have more precise mirror curvature and alignment, which enables them to have higher efficiency than the first plants erected in California. Other improvements include the use of a small mirror on the backside of the receiver to capture and reflect any scattered sun rays back onto the receiver, the direct steam generation into the receiver tube to simplify the energy conversion and reduce heat losses, and the use of more advanced materials for the reflectors and selective coatings of the receiver.

2.2. Power tower systems

Power towers or central receiver systems use thousands of individual sun-tracking mirrors called "heliostats" to reflect solar energy onto a receiver located on top of a tall tower. The receiver collects the sun's heat in a heat-transfer fluid (molten salt) that flows through the receiver. This is then passed optionally to storage and finally to a power-conversion system which converts the thermal energy into electricity and supply it to the grid. In many solar power studies it has been observed that the collector represents the largest cost in the system, therefore, an efficient engine is justified to obtain maximum useful conversion of the collected energy. The power tower plants are quite large, generally 10 MWe or more, while the optimum sizes lie between 50-400 MW. It is estimated that power towers could generate electricity at around US$ 0.04/kWh by 2020 [2].

The heliostats should reflect solar radiation to the receiver at the desired flux density at minimum cost. A variety of receiver shapes has been considered, including cylindrical receivers and cavity receivers. The optimum shape of the receiver is a function of radiation intercepted and absorbed, thermal losses, cost and design of the heliostat field. For a large heliostat field a cylindrical receiver is best suited to be used with Rankine cycle engines. Another possibility is to use Brayton cycle turbines which require higher temperatures (of about 1000°C) for their operation and in this case cavity receivers with larger tower height to heliostat field area ratios are more suitable. For gas turbine operation, the air to be heated must pass through a pressurized receiver with a solar window. Combined cycle power plants using this method could require 30% less collector area than the equivalent steam cycles. Rankine cycle engines driven from steam generated in the receiver operate at 500 to 550°C.

2.3. Heat storage and hybridization

An interesting feature of parabolic troughs and power tower systems is that it is possible to store heat, which enables them to continue producing electricity during the night or cloudy days. For this purpose, concrete, molten salts, ceramics or phase-change media can be used. The parabolic trough and the power tower systems produce superheated steam which is used to drive the turbines of a conventional Rankine type power station or an Integrated Solar Combined Cycle System, i.e., they replace the conventional steam boiler with the solar collection system. It has been proved in a previous publication that a system with four hours of storage is the optimum for Cyprus [3]. Both systems can also be operated with fossil fuel (usually natural gas) so as to continue the production of electricity at low irradiation hours and during the night. This is due to the fact that the equipment involved is expensive and it is not viable to leave the systems to cool down and stay idle for a long time.

All existing power stations in Cyprus are located near the sea. Such a solar power system should also be located near the sea close to an existing power station to ease access to the grid and for the use of the seawater for the condenser. The erection of such a system inland is not possible due to the lack of water required for the condensation of the steam. This is because Cyprus suffers from a water shortage problem, so it has no adequate water supply inland and the proximity of the solar to an existing station means it will also be close to existing power lines and maintenance personnel form the station. Moreover, the location of the solar plant near the sea will enable it to be combined with solar desalination, for the production of fresh water which is also a required commodity for the island.

3. Desalination processes

Desalination can be achieved by using a number of techniques. Industrial desalination technologies use either phase change or thermal processes, or involve semipermeable membranes or single-phase processes to separate the salts from the seawater. All processes require a chemical pre-treatment of raw seawater to avoid scaling, foaming, corrosion, biological growth, and fouling and also require a chemical post-treatment. Here only two desalination methods are considered the multiple effect boiling system, falling in the first category, and the reverse osmosis system, falling in the second. These are the most suitable for the application considered as will be presented in the following sections.

3.1. The MED process

The multiple effect distillation (MED) process is composed of a number of elements, which are called effects. The steam from one effect is used as heating fluid in another effect, which while condensing, causes evaporation of a part of the salty solution. The produced steam goes through the following effect, where, while condensing, makes some of the other solution evaporate and so on. For this procedure to be possible, the heated effect must be kept at a pressure lower than that of the effect from which the heating steam originates. The solutions condensed by all effects are used to preheat the feed [4]. In this process, vapour is produced by flashing and by boiling, but the majority of the distillate is produced by boiling. The MED process usually operates as a once through system without a large mass of brine recirculating around the plant. This design reduces both pumping requirements and scaling tendencies [5].

Early plants were of the submerged tube design and used only two to three effects. In modern systems, the problem of low evaporation rate has been resolved by making use of the thin film designs with the feed liquid distributed on the heating surface in the form of a thin film instead of a deep pool of water. Such plants may have vertical or horizontal tubes.

Another type of MED evaporator is the Multiple Effect Stack (MES) type. This is the most appropriate type for solar energy application. It has a number of advantages, the most important of which are its stable operation between virtually zero and 100% output even when sudden changes are made and its ability to follow a varying steam supply without upset [4]. In Fig. 1, a four-effect MES evaporator is shown. Seawater is sprayed into the top of the evaporator and descends as a thin film over the horizontally arranged tube bundle in each effect. In the top (hottest) effect, steam from a steam boiler or from a solar collector system condenses inside the tubes. Because of the low pressure created in the plant by the vent-ejector system, the thin seawater film boils simultaneously on the outside of the tubes, thus creating new vapour at a lower temperature than the condensing steam.

The seawater falling to the floor of the first effect is cooled by flashing through nozzles into the second effect, which is at a lower pressure. The vapour made in the first effect is ducted into the inside of the tubes in the second effect, where it condenses to form part of the product. Furthermore, the condensing warm vapour causes the external cooler seawater film to boil at the reduced pressure. The evaporation-condensation process is repeated from effect to effect in the plant, creating an almost equal amount of product inside the tubes of each effect. The vapour made in the last effect is condensed on the outside of a tube bundle cooled by raw seawater. Most of the warmer seawater is then returned to the sea, but a small part is used as feedwater to the plant. After being treated with acid to destroy scale-forming compounds, the feedwater passes up the stack through a series of pre-heaters that use a little of the vapour from each effect to raise its temperature gradually, before it is sprayed into the top of the plant. The water produced from each effect is flashed in a cascade down the plant so that it can be withdrawn in a cool condition at the bottom of the stack. The concentrated brine is also withdrawn at the bottom of the stack.

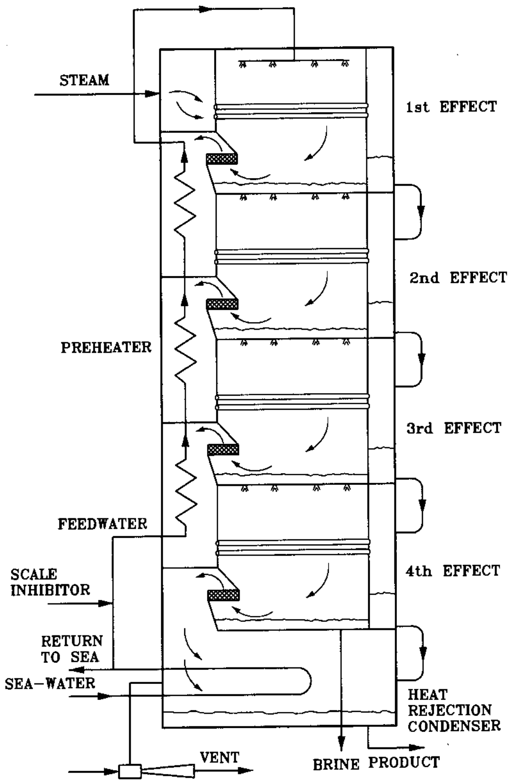

Fig. 1. Schematic of the MES evaporator.

The MES process is completely stable in operation and automatically adjusts to changing steam conditions even if they are suddenly applied, so it is suitable for load-following applications. It is a once-through process that minimises the risk of scale formation without incurring a large chemical scale dosing cost. The typical product purity is less than 5 ppm total dissolved solids (TDS) and does not deteriorate as the plant ages. Therefore, the MED process with the MES type evaporator appears to be the most suitable for use with solar energy.

3.2. The reverse osmosis process

The reverse osmosis (RO) system depends on the properties of semi-permeable membranes which, when used to separate water from a salt solution, allow fresh water to pass into the brine compartment under the influence of osmotic pressure. If a pressure in excess of this value is applied to the salty solution, fresh water will pass from the brine into the water compartment. Theoretically, the only energy requirement is to pump the feed water at a pressure above the osmotic pressure. In practice, higher pressures must be used, typically 50-80 atm, in order to have a sufficient amount of water pass through a unit area of membrane [4]. With reference to Fig. 2, the feed is pressurised by a high-pressure pump and made to flow across the membrane surface. Part of this feed passes through the membrane where the majority of the dissolved solids are removed. The remainder, together with the remaining salts, is rejected at high pressure. In larger plants, it is economically viable to recover the rejected brine energy with a suitable brine turbine. Such systems are called energy recovery reverse osmosis (ER-RO) systems.

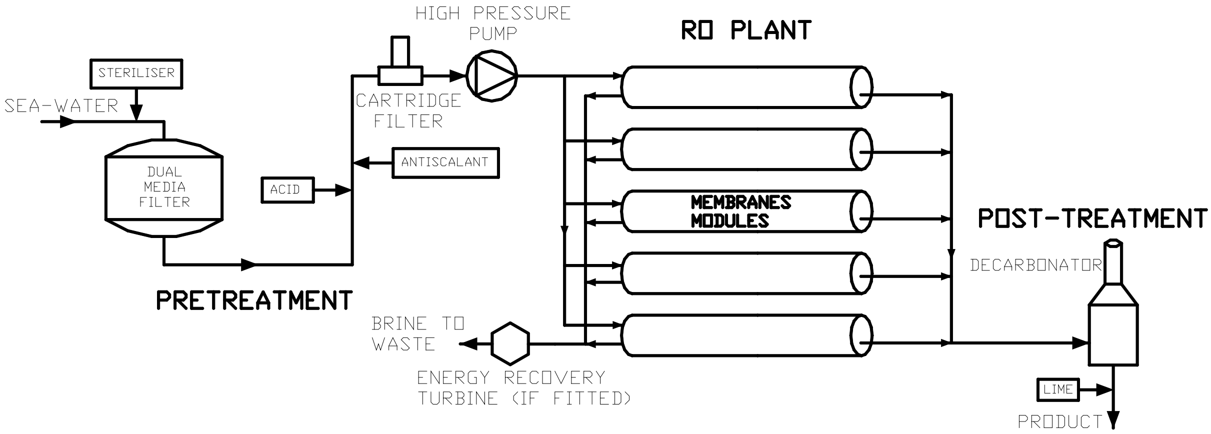

Fig. 2. Principle of operation of a reverse osmosis (RO) system.

Solar energy can be used with RO systems as a prime mover source driving the pumps or with the direct production of electricity through the use of photovoltaic panels. As the unit cost of the electricity produced from photovoltaic cells is high, photovoltaic-powered RO plants are not considered here. The membranes are in effect very fine filters, and are very sensitive to both biological and non-biological fouling. To avoid fouling, careful pre-treatment of the feed is necessary before it is allowed to come in contact with the membrane surface.

3.3. Characteristics of both processes

The identification and evaluation of the renewable energy resources (RES) in an area, is the primary step to be performed when designing a RES-driven desalination system. Such systems should be characterized by robustness, simplicity of operation, low maintenance, compact size, easy transportation to site, and simple pre-treatment and intake system [6].

The energy required for the two desalination processes considered, as obtained from a survey of manufacturers' data, is shown in Table 1 [4]. It can be seen from Table 1 that the process with the smallest energy requirement is RO-ER followed by RO and the MED.

Table 1. Energy consumption of desalination systems.

Process	Heat input (kJ/kg of product)	Mechanical power input (kWh/m^3 of product)	Prime energy consumption (kJ/kg of product)[1]
MED	123	2.2	149.4
RO	-	5-13 (10)	120
ER-RO	-	4-6 (5)	60

Notes: 1. Assumed conversion efficiency of electricity generation of 30%
2. Figure used for the prime energy consumption estimation shown in last column

A comparison of the desalination equipment cost and the seawater treatment requirement, as obtained from a survey of manufacturers' data, is shown in Table 2. The MED is the cheapest of all the indirect collection systems and also requires the simplest seawater treatment. RO although requiring a smaller amount of energy is expensive and requires a complex seawater treatment.

Table 2. Comparison of desalination plants.

ITEM	MED	RO
Scale of application	Small-medium	Small-large
Seawater treatment	Scale Inhibitor	Sterilizer, Coagulant Acid, Deoxidiser
Equipment price (Euro/m^3)	900-1700	900-2500 Membrane replacement every 5-6 yrs
Note: Low figures in equipment price refer to bigger size in range indicated and vice versa.		

4. Options considered

In this section, various options are considered to combine CSP with desalination. The first option considered is a thermal desalination system shown schematically in Fig. 3. In this option a solar field is used which provides thermal energy to a MED evaporator to produce fresh water. This solar heat can be given directly to the MED unit or in days with good irradiation the excess energy can be stored for use in periods of low sunshine and during the night. The system can also be hybridized using conventional fuel to run the desalination sub-system during the night. A very small quantity of electrical energy (compared to thermal) is required by the MED unit to drive the pumps. As the present RES system is thermal only, this quantity of electricity can be produced either from a PV system or obtained from the grid.

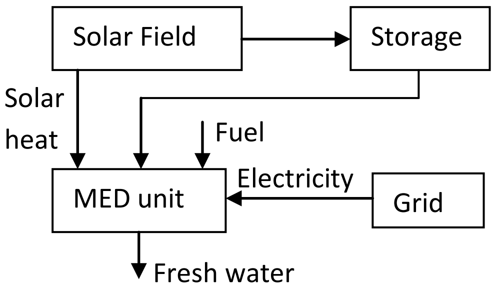

Fig. 3. Combination of a solar thermal system with MED for desalinated water production only.

The second option, shown in Fig. 4, concerns a solar thermoelectric system producing electricity with a CSP system. In this case some of the electricity produced can be used to drive a RO desalination system and the rest is supplied to the grid. This system has the advantage that the operators can decide according to the demand to produced either both, fresh water and electricity, or one of the two only. Any form of hybridization can go directly to the power plant as is normal to all such systems, when the storage is depleted a few hours after sunset, according to the size of the storage used.

The third option, shown in Fig. 5, is a combination of a normal solar thermoelectric power system with a MED unit to produce both electricity and fresh water. The MED requires thermal energy to operate in the form of high temperature hot water (>100°C) or low temperature steam. Therefore, this energy can be supplied either directly from the CSP system or from the waste heat of the power plant system, in the form of condensation heat. For this purpose the MED evaporator can be an integral part of the steam condenser of the Rankine power plant cycle. In this option the hybridization is done directly on the power plant as is normal to all CSP power systems. The small quantity of electricity required by the MED is taken from the power plant.

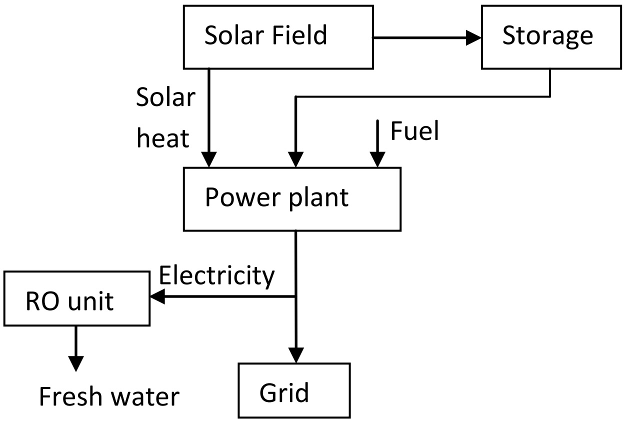

Fig. 4. Combination of a solar thermoelectric power system with RO to produce both electricity and fresh water.

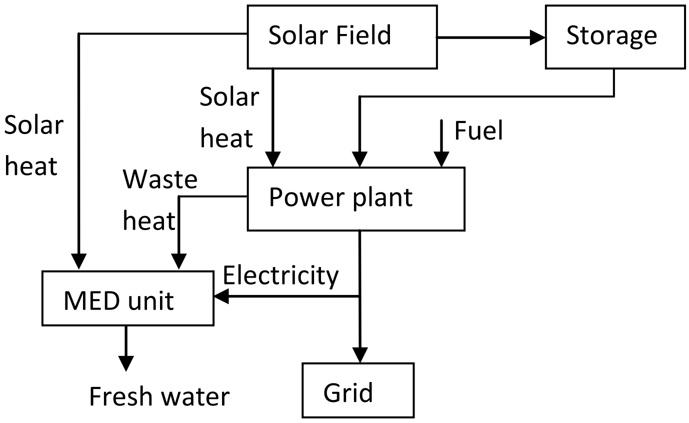

Fig. 5. Combination of a solar thermoelectric power system with MED, operated from solar and waste heat, to produce both electricity and fresh water.

The fourth option, shown in Fig. 6, is a combination of a solar thermoelectric power system with MED and RO systems for fresh water production. The RO unit operates as in the second option with the electricity produced by the CSP system, whereas the MED subsystem, which requires thermal energy to operate, can use either some of the thermal energy produced by the CSP system or the waste heat from the power plant, therefore the MED is part of the condensation system of the power plant. Again here the hybridization is done directly on the power plant as is normal to all CSP power systems. This option gives a larger number of operation options concerning the production of electricity and water according to the demand of each commodity however, it is a more expensive system as both MED and RO need to be purchased and installed.

All CSP systems shown in the above figures can use either a parabolic trough collector or a power tower system. As can be seen from the configurations presented above, there are a number of options to be considered when either only desalinated water or both electricity and fresh water are required. The choice of which system to apply for a particular case should depend on the particular requirements of each commodity and the characteristics of the load and water demand. Due to the high cost of the required equipment however, all systems needs to be hybridized so as to operate the plants round the clock to reduce the idle time, the energy required to bring the systems to their operating limit and the problems associated with the frequent starts and stops of the equipment and thermal cycling. Before considering any hybridization though, the optimum size of storage needs to be used to minimize the adverse effects of the burning of fossil fuels on the environment. For this purpose a less polluting fuel needs to be employed, like the natural gas.

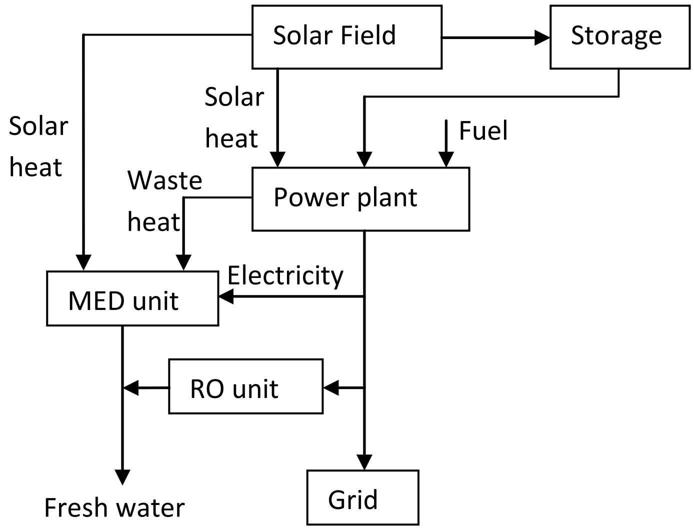

Fig. 6 Combination of a solar thermoelectric power system with RO and MED to produce both electricity and fresh water.

5. Conclusions

The parabolic trough and the power tower systems produce superheated steam which can be used to drive the turbines of the common Rankine cycle. Both systems can be supplied with conventional fuel (usually natural gas) so as to operate during hours of low irradiation and during night-time. For the reasons explained above such a solar plant need to be located near the sea. In such a case the solar plant can be combined with solar desalination to produce fresh water from seawater which is also a precious commodity for Cyprus. As shown in this paper a number of options exist for the combination of a CSP system with a desalination one to produce both electricity and water.

References

[1] S.A. Kalogirou, *Solar Energy Engineering: Processes and Systems*, Academic Press, New York, 2009, pp. 521-552.

[2] S. Taggart, Hot stuff: CSP and the power tower, *Renewable Energy Focus*, May/June issue, 2008, pp. 51-54.

[3] S.A. Kalogirou, Solar Thermoelectric Power Generation in Cyprus, Selection of the Best System, *Proceedings of the World Renewable Energy Congress XI on CD ROM*, Abu Dhabi, UAE, 2010.

[4] S.A. Kalogirou, Seawater Desalination Using Renewable Energy Sources, *Progress in Energy and Combustion Science*, 2005, Vol. 31, No. 3, pp. 242-281.

[5] S.A. Kalogirou, Survey of solar desalination systems and system selection, *Energy-The International Journal*, 1997, Vol. 22, No. 1, pp. 69-81.

[6] E. Tzen, R. Morris, Renewable Energy sources for desalination, *Solar Energy*,2003 Vol. 75, No. 5, pp. 375-379.