Combined concentrated solar power plant with low-temperature multi-effect distillation

Mohammad Al-Addous, Mustafa Jaradat, Mathhar Bdour, Zakariya Dalala and Johannes Wellmann

Abstract
This study analyzes a technological concept for simultaneously generating power and desalinating water in a Middle East and North Africa country. An innovative, low-temperature, multi-effect desalination (LT-MED) process integrated with a concentrating solar power (CSP) plant was assessed and analyzed. A combined power and seawater desalination plant was modeled for the city of Aqaba by the Red Sea in Jordan. Parabolic-trough collectors using indirect steam generation with thermal energy storage connected with power and desalination blocks were designed. The designed plant was modeled and simulated using EBSILON Professional, a discrete energy balance simulation software, under several operating conditions, to analyze the results. An economic feasibility analysis of the combined CSP+LT-MED plant was also conducted. The simulation results showed the broad variability of the cogeneration system in terms of electricity generation and water production. The output power of the CSP plant without water production reached 58.7 MWel in June. The output power accompanied with distilled-water production with a mass flow rate of 170 m³/h was approximately 49.5 MWel. Furthermore, the number of desalination stages had the strongest influence on distillate production but limited the operational flexibility of the power plant due to the temperature gradients within the desalination stages. The distilled-water mass flow reached 498 m³/h for 10 stages. The research showed that the design successfully worked with up to €78.84 million, earned from selling the produced electricity.

1Energy Engineering Department, School of Natural Resources Engineering and Management, German Jordanian University, Amman, Jordan
2Department of Environmental Technology, Technische Universität Berlin, Berlin, Germany

Corresponding author:
Mohammad Al-Addous, Energy Engineering Department, German Jordanian University, P.O.Box 35247, Amman 11180, Jordan.
Email: mohammad.addous@gju.edu.jo

Creative Commons CC BY: This article is distributed under the terms of the Creative Commons Attribution 4.0 License (https://creativecommons.org/licenses/by/4.0/) which permits any use, reproduction and distribution of the work without further permission provided the original work is attributed as specified on the SAGE and Open Access pages (https://us.sagepub.com/en-us/nam/open-access-at-sage).
However, owing to highly subsidized water tariffs in Jordan (80% less than the actual cost), the integration of water desalination into the CSP plant was not economically feasible.

**Keywords**
Solar energy, Middle East and North Africa region, multi-effect desalination, solar distillation, concentrated solar power

**Introduction**
Forty-seven percent of the world’s population are expected to be living in areas of high water stress by 2030 (Organisation for Economic Co-operation and Development, 2010). One area that is already severely affected is the Middle East and North Africa (MENA) region, in which, according to the World Bank (2017), 5% of the world’s population currently lives; however, unfortunately, this region has less than 1% of the world’s renewable freshwater.

The most water-scarce region in the world is the MENA. Figure 1 shows a world map of physical water stress. It is readily apparent that the MENA region lies in the red zone with a level of physical water stress exceeding 70% according to the United Nations world water development report 2019 (World Water Assessment Programme, 2019).

Water resources have declined considerably in recent years, estimated now as being at one-third the level in 1960 and forecast to halve again by 2050 if current consumption trends continue. As an MENA country, Jordan is already experiencing a situation of acute water scarcity. Jordan is ranked as the world’s second-poorest country for water with an annual per capita water availability of 147 m³/year, which is far below the international water poverty line of 500 m³/year. This issue is deteriorating because of rapid population increase, changes in living standards, increased economic activities, and pollution (World Bank, 2017).

![Figure 1. World map with physical water stress in 2018 (World Water Assessment Programme, 2019).](image-url)
Seawater desalination offers an innovative solution to the water issue and is of particular interest to MENA given that most of its countries have access to seawater. Desalination is not exactly a new technique, but a few drawbacks have always been associated with its conventional systems, such being cost-ineffective, being intensively energy consuming, and (unsurprisingly) emissions of greenhouse gases (Trieb et al., 2007). These concerns have inspired the concept of combining renewable energy (RE) sources with seawater desalination techniques.

Many research activities are focused on using RE to solve world problems, with water scarcity being among the most important. Many researchers have reviewed the different combinations of RE with desalination processes worldwide and have analyzed the performance of existing RE desalination plants (Ghaffour et al., 2015; Xevgenos et al., 2016). Goosen et al. (2014) studied the challenges in applying RE technologies to desalination while accounting for current and future challenges. However, the low-temperature, multi-effect desalination (LT-MED) systems have rarely been addressed and discussed in the literature. The cogeneration of power and water in large concentrating solar power (CSP) plants with thermal storage can have significant energy and economic benefits to supply regions with high direct solar radiation and good seawater access. Owing to increasing water scarcity, the MENA region has a high demand for desalinated water and a sharply increasing energy demand, which cannot be completely covered using fossil fuels.

Several researchers have promoted RE desalination in the MENA region. Many have shown the potential of integrating solar energy, specifically concentrated solar power (CSP) technologies, with desalination in the Mediterranean countries (Al-Addous et al., 2017; Cipollone et al., 2016; Moser et al., 2011; Sharon and Reddy, 2015).

Solar desalination has been studied, particularly where CSP plants are attached to electrically driven (i.e., reverse osmosis (RO)) and thermally driven desalination units (i.e., multi-effect distillation (MED) and multi-stage flash (MSF)). However, some discussed technologies such as the RO process are not among the most preferable ones in Jordan and the Gulf countries. The use of RO is limited in the Gulf countries as a result of the harsh regional conditions. The narrowed water body of the Gulf is often highly saline depending on the seasonal temperature. Furthermore, the summer season extends over a long period from April to October with high temperature averages of 40°C and 30°C for the air and water, respectively. The RO process used in the United States, Japan, and other countries experience much milder conditions and much lower open sea water salinity, and the summer temperature averages for air and water are below 25°C (El-Dessouky and Ettouney, 2002). Furthermore, most of the thermal desalination systems that have been discussed use direct generation using water or air as a working fluid. Direct generation systems have better efficiency and cost-saving advantages over conventional indirect methods for steam generation. However, such systems also have drawbacks, including difficulties in application, mainly instability of steam and water pressure and temperature, and difficulties in controlling flow and steam parameters due to two-phase flow in solar radiation absorber tubes.

Research on MED units is expanding continuously. Some studies have shown that this technology could be improved by coupling basic MED with a thermal vapor compression (MED-TVC) unit to manage the energy consumption of the plant, thereby attaining a higher water output (Al-Mutaz and Wazeer, 2015; Mistry et al., 2013).

Techno-economic studies have been widely conducted. For example, Fylaktos et al. (2015) presented a techno-economic study of Cyprus in which the financial performance of three different 4-MW<sub>e</sub> CSP plants was compared, namely, (i) an electricity-only
generating CSP plant, (ii) an electricity-and-water generating CSP plant using RO, and (iii) an electricity-and-water generating CSP plant using MED with the same RO capacity. Although the electricity-only CSP plant was most suitable economically, solar desalination could be performed efficiently as well.

Darwish et al. (2016) simulated different solar desalination possibilities and discussed them in the context of investment cost as a viable option for Gulf region countries. The solar desalination plants examined included technologies such as RO, MED, MSF, and MED-TVC desalination units. RO was simulated when attached to a photovoltaic (PV) plant, a CSP plant, and a CSP plant combined with MSF. As for the thermally driven units (i.e., MSF, MED, and MED-TVC), they were attached to a CSP plant. The results showed that driving RO using PV was very expensive compared with other alternatives. The lowest specific capital cost (in the range of $2200–$3200/m³/d) was achieved when solar energy was used to operate a solar power plant attached to RO and MSF units. However, MEDs need less thermal energy. This is due to the lower boiling point elevation, i.e., the difference between the boiling point of seawater and that of pure water (Wellmann et al., 2018).

In the present paper, an integrated solar combined cycle of a CSP plant and a thermal seawater desalination unit was simulated for the coastal city of Aqaba by the Red Sea in Jordan. The solar part of the plant was a CSP plant to be combined with LT-MED thermal seawater distillation. The LT-MED was to be driven by the waste steam from the steam turbine. This configuration could be beneficial as it not only generates electricity from green energy but also produces water to contribute to solving major water and energy concerns in the MENA region.

There are many outstanding features of the combined CSP and LT-MED process, including:

- Low corrosion and scaling as a result of low operation temperature (top brine temperature below 75°C), thus allowing for use of inexpensive aluminum alloys.
- It is more suitable for the examined region, Aqaba and the Gulf region, compared with the RO process in view of the high salinity of the relevant water body. Membrane lifetimes vary from three to five years, strongly depending on intake water pre-treatment and its associated costs (El-Dessouky and Ettouney, 2002).
- The low operating temperature allows for reduced heat loss and a minimal requirement for thermal insulation.
- As mentioned, not only do thermal desalination technologies need thermal energy, they also need electrical energy for the operation of the pumps. This is also an advantage for MEDs, as they require less pumping power.

Seawater desalination systems

Seawater desalination is defined as the process of separating seawater from its salt content, thus transforming it into freshwater. Desalination techniques differ by energy input and the separation process applied. One option is membrane-based technologies that need only electrical energy as input, such as RO and electrodialysis (ED). Generally, RO can be considered currently as the most commercially used membrane technology, with the highest share of desalination plants installed worldwide according to the World Bank (2012).

Other technologies such as MSF and MED require mainly thermal energy for the evaporation and condensation of seawater (distillation) and have been applied since the early
1960s. All thermal desalination plants require electrical energy to pump the different media (Micale et al., 2009). The dominant thermal desalination technologies are MSF and MED (Ghaffour et al., 2015; Trieb et al., 2007; Wellmann et al., 2018). Figure 2 shows the various seawater desalination technologies and their shares worldwide (Wellmann et al., 2018).

**MED technology**

MED units use the concept of evaporation chambers, called effects. Feed water is introduced to the effects by spraying it through nozzles found at the top of each effect to a tube-bundle row located in the effect. In the tubes, only the first effect carries steam coming from external sources, such as steam turbines or waste heat from power plants. Some of the water evaporates, and this steam flows into the tubes of the next effect, heating and evaporating more water; the remainder is left behind as concentrated brine. Each stage essentially reuses the energy from the previous one, with successively lower temperatures and pressures after each stage.

Different researchers use different methods to estimate the distilled-water mass flow rate ($\dot{m}_d$) that is produced. Equation (1) calculates $\dot{m}_d$ from the steam mass flow rate ($\dot{m}_s$) from external resources and the number of effects of the MED unit ($n$), (Gebel, 2008)

$$\dot{m}_d = \dot{m}_s \ n^{0.85}$$

This formula is general and applicable without the need to consider the MED-unit specific parameters such as intake seawater (brine) temperature, brine concentration, temperature effect, brine feed configuration type, and heat transfer area.
The \( m_s \) entering the first effect produces the initial vapor that is the driving “steam” of the second effect, etc. This means that increasing \( n \) increases the possibility of more vaporization, thereby increasing the amount of distilled water that is produced, assuming the same amount of feed water fed by the nozzles per effect. Consequently, the driving temperature difference in each effect is lowered (Al-Addous et al., 2017). From an economic perspective, the larger the MED unit (higher \( n \)), the higher the fixed cost, but the lower the operating costs as less energy is consumed (El-Dessouky and Ettouney, 2002).

The system discussed in this paper operated at a top brine temperature of 70°C, which was considered a low temperature known as LT-MED (Khawaji et al., 2008), the maximum temperature of a single-stage/effect to reduce corrosion problems and heat transfer coefficients and avoid scaling (i.e., increased solubility limits of mineral substances due to elevated temperature). Maintaining a lower top brine temperature leads to lower risk of scale formation. Because LT-MED units operate at low temperature, they are strong candidates for operation using waste heat from steam turbines. In addition, the requirements of chemical pre-treatments to decrease scaling problems are less sophisticated than those of MSF and RO units.

System description

Figure 3 shows the plant concept considered for analysis in this paper. The plant was split into three subsystems, namely, the solar block, power block, and the desalination block. Parabolic-trough collectors (PTCs) were chosen in this paper instead of a central receiver tower owing to their low cost of capital investment. PTCs focused the direct normal irradiance (DNI) into a focal tubular receiver. A working fluid (thermal oil in this study) absorbed the concentrated solar energy and transferred it to the power block \( Q_{SG} \). Part of the converted solar energy was stored in the thermal energy storage (TES) system.

Solar power plant

Parabolic-trough concentrator. PTCs focused the DNI into a focal tubular absorber. The solar field was designed to be suitable for base-load power generation using direct storage of the solar heat while allowing for high operating temperatures for optimized thermodynamic efficiency. The DNI was the main power source of this plant. 900 W/m² was used for the design point, which resulted in thermal power generation being transferred to the TES system. A sun position tracking system was employed to intercept as much solar radiation
as possible. For linear concentration, sun tracking was performed on a single axis of tracking either azimuth angle, where the concentrators were aligned in the north–south position. Table 1 shows the design parameters of the PTC field.

The PTC field was used to concentrate the incoming DNI onto the receiver focal line. The output was a heat flux (useful energy) distributed over the area of the receiver pipe and was calculated per Duffie and Beckman (2013), Ghaffour et al. (2015), and Xevgenos et al. (2016)

\[ Q_u = F_R A_a \left[ S - \frac{A_r}{A_a} U_L (T_i - T_a) \right] \]  

(2)

where \( F_R \) is the collector heat removal factor, which equals the collector efficiency factor \( (F') \) multiplied by the collector flow factor \( (F'') \) and is given as

\[ F_R = F' F'' \]  

(3)

\[ F' = \frac{1}{U_L} + \frac{D_o}{h_f D_i} + \left( \frac{D_o}{2k} \ln \frac{D_o}{D_i} \right) \]  

(4)

\[ F'' = \frac{\dot{m} C_p}{A_r U_L F'} \left[ 1 - \exp \left( - \frac{A_r U_L F'}{\dot{m} C_p} \right) \right] \]  

(5)

where \( A_a \) is the aperture area, \( A_r \) is the receiver area, \( U_L \) is the overall loss coefficient, \( D_o \) and \( D_i \) are the receiver tube outside and inside diameters, respectively, \( k \) is the cover thermal conductivity, \( h_f \) is the fluid-to-tube heat transfer coefficient, and \( \dot{m} \) and \( C_p \) are the mass flow rate and specific heat, respectively. The term \( S \) is the absorbed radiation per unit area of the unshaded aperture and is given as

\[ S = I_b \rho (\gamma \tau z)_n K_{\gamma \tau z} \]  

(6)
where the effective incident radiation $I_b$ measured on the plane of the aperture includes only the beam radiation, and $\rho$ is the diffuse reflectance of the concentrator. The factors $\gamma$, $\tau$, and $\alpha$ are functions of the angle of incidence of the radiation on the aperture, and $K_{\gamma \tau \alpha}$ is the incidence-angle modifier used to account for deviations from the normal angle of incidence.

The solar receiver transferred the incoming heat flux to the thermal oil and increased the fluid temperature. The receiver model considered optical and thermal losses during the heat transfer. Thermal losses could have been conduction, radiation, and convection losses and also depended on the ambient temperature. Equation (7) defines the internal calculations of EBSILON

$$Q_{\text{loss}} = A_r h_w (T_r - T_a) + A_r \varepsilon \sigma (T_r^4 - T_{\text{sky}}^4) + A_r U_{\text{cond}} (T_r - T_a)$$

where $h_w$ is the wind heat transfer coefficient, $\varepsilon$ is the emissivity of the receiver, and $\sigma$ is the Stefan–Boltzmann constant ($5.67 \times 10^{-8}$ W m$^{-2}$ K$^{-4}$).

Radiational losses depended on sky temperature, which, in turn, was a function of the dry bulb and dew point temperatures. Heat transfer by convection between the receiver and the cover was suppressed as the annulus was assumed to be evacuated so that convection was suppressed at very low pressures.

---

**Figure 4.** Flow diagram of the solar block with simulation results of an exemplary day (June 21, 2019) for the city of Aqaba. DNI: direct normal irradiance.
The PTC field generated much more heat than that consumed by the power cycle during the day. The direct TES system was directly loaded with surplus heat and unloaded during the night. Because the calculation was based on a steady-state simulation, the TES system operation was characterized by the mass flow difference between input and output. Figure 4 shows the flow diagram of the solar block with simulation results of an exemplary day. The simulation was performed for noon on the summer and winter solstices (June 21 and December 21) and the approximate vernal and autumnal equinoxes (March 21 and September 21).

**Thermal energy storage.** In CSP technology, one way to produce steam is direct steam generation in which steam is generated directly in tubes exposed to heat from focused solar radiation (solar radiation absorber tubes). Direct steam generation has better efficiency and cost-saving advantages. However, it also has drawbacks, including difficulties in application mainly owing to instabilities of steam and water pressure and temperature, and difficulties in controlling flow and steam parameters due to two-phase flow in solar radiation absorber tubes.

The working fluid consisted of a thermal oil, which is commonly used in PTC plants. The direct storage system consisted of two isolated tanks filled with hot and cold thermal oil. Owing to the high stability of the thermal oil, this could be achieved at ambient pressures. The solar thermal energy generated in the absorber was directly stored in the hot tank at 384°C. After cooling to 300°C, the thermal oil was stored in the cold tank. During diurnal operation, the thermal oil inside the cold tank was pumped through the receiver, absorbing up to 164.8 MWth depending on solar radiation. There were two pumps required to supply the absorber and the steam generator with the thermal oil. Table 2 summarizes the design parameters for the thermal storage system.

**Power block**

Figure 5 shows the modeled power block, which was based on the Rankine cycle. The power block consisted of four turbines combined with an alternator to generate power from the received thermal energy. The first turbine was coupled with a gas turbine as a backup for continuous operation, and the gas turbine was coupled to the system in bypass. The TES system was a two-tank system with molten salt as the storage medium.

The thermal fluid leaving the PTC field entered the steam generator, which was the connecting component between the solar and the steam cycles. The steam generator for the power cycle consumed 164.8 MWth during operation. The power block consisted of the standard components of a steam generator (economizer, evaporator, super heater, and

| Parameter                  | Value/setting                  | Unit |
|----------------------------|--------------------------------|------|
| Working fluid              | Thermal oil (Therminol VP-1)   | –    |
| Maximum level              | 28,500                         | t    |
| Minimum level              | 815                            | t    |
| Pressure in storage        | 1                              | bar  |
| Temperature in storage (hot tank) | 384                          | °C   |
| Temperature in storage (cold tank) | 292                           | °C   |
reheat) and a steam turbine with an electrical generator. The steam turbine was modeled in three stages with high, medium, and low pressure expanding the generated steam from 129.6 to 0.4 bars while reducing the temperature from 377°C to 75°C. The steam mass flow was set to 33.7 t/h, which resulted in an electrical power generation of 49.6 MW<sub>el</sub>.

As shown in Figure 3, the gas turbine was connected with three pressure-dependent turbine sections, namely, the high-, medium-, and low-pressure sections. The gas turbine operated as a steam generator at low-steam production from a solar PTC power plant at low DNI. The steam left the high-pressure section and entered the medium-pressure turbine and low-pressure turbine. The last stage led directly to the final condenser, which also acted as the interface with the desalination unit. All the turbine stages were connected to a single shaft that was connected to the electric generator.

The power cycle for a CSP plant is the Rankine cycle. A classical Rankine cycle consists of a boiler, a steam turbine, a condenser, and a pump. Clearly, a classical Rankine cycle is less efficient than the reheat-and-regeneration ones that are used commercially. In the reheat Rankine cycle, steam is extracted from an intermediate stage of the turbine, reheated in the boiler, and then expanded back again into the turbine. In the regeneration Rankine cycle, steam is extracted from the turbine and used to pre-heat the liquid at the outlet of the pump. In principle, the Rankine cycle for CSP is the same as the conventional one, except that the boiler is replaced with a heat exchanger. This is where the water absorbs latent heat to vaporize and turn to steam, and this latent heat of vaporization comes when the heat-

Figure 5. Power block with simulation results of an exemplary day (June 21, 2019) for the city of Aqaba. HEX: heat exchanger.
transfer fluid exchanges its latent heat in the heat exchanger. The formed steam flows next to a steam turbine where it is extracted and mechanically drives a generator to generate electricity.

There are two classifications of steam turbines, namely, condensing (extraction) and noncondensing (back-pressure). Extraction steam turbines offer a high amount of electricity generation, which is not desired in the CSP-MED plant because its electricity consumption is not relatively high. Because of the low desalination demand, back-pressure steam turbines are considered the better alternative. In addition, they are simple, relatively inexpensive and more efficient.

Using back-pressure turbines means that the process acts as a condenser, applicable for MED because the feeding steam condenses from the first effect, ideally keeping its flow rate and saturated temperature. The turbines can be distinguished by different pressure sections, which can be divided into high-, medium-, and low-pressure stages.

Our system used four turbine stages, which consisted of one high, one medium, and two low-pressure sections. After the high-pressure section, the steam was reheated in the second super heater before entering the medium pressure stages. Table 3 summarizes the design parameters for the four-staged turbines.

**Table 3.** Design parameters of the four-staged turbines.

| Parameter                  | Inlet conditions | Outlet conditions |
|---------------------------|------------------|-------------------|
| High-pressure turbine     |                  |                   |
| Pressure, bar             | 129.6            | 39.8              |
| Temperature, °C           | 376              | 250               |
| Medium-pressure turbine   |                  |                   |
| Pressure, bar             | 39.8             | 4.8               |
| Temperature, °C           | 260.4            | 150.3             |
| Low-pressure turbine      |                  |                   |
| Pressure, bar             | 4.8              | 1.0               |
| Temperature, °C           | 150.3            | 99.6              |
| Low-pressure turbine      |                  |                   |
| Pressure, bar             | 1.0              | 0.4               |
| Temperature, °C           | 99.6             | 75.9              |

Al-Addous et al. 1841

In the presented MED desalination unit, heat transfer from condensing vapor to evaporating brine was achieved through tube-bundle heat exchangers. The horizontal tube evaporator is commonly used for desalination plants, and thus it was applied in the current research. The steam was condensed inside of the heat exchanger tubes while the intake feed water was distributed by spraying nozzles over the tubes, which fell through gravity. Figure 6 shows the complete process and some exemplary values.

In this study, the low-temperature desalination was modeled as a four-stage system with four heat exchangers HEX1 to HEX4 for heat recovery. Seawater with a mass flow rate of 751 kg/s, an inlet temperature of 20°C, a mass fraction of 35 g/kg, and a pressure of 5 bar recovered heat from the rejected brine. The low-temperature desalination acted as a power-plant condenser by using the condensation heat from the power block for the desalination process.
The seawater entered a series of evaporators and condensers through which the temperature and pressure decreased while the salinity increased from stage to stage. Meanwhile, the auxiliary power consumption for the condenser pumps increased. Consequently, the desalination unit had been limited to four stages despite reducing the possible water production; this was due to the increased operational flexibility of the power plant and desalination unit.

The MED thermal demand was assumed to be 80 kWh\textsubscript{th}/m\textsuperscript{3} based on the literature (International Renewable Energy Agency (IRENA), 2012). In addition to heat, MED systems also require electricity to power the pumps. However, this electrical energy demand is minimal in comparison to the heat demand and lies in the range of 1.5 to 2.5 kWh\textsubscript{el}/m\textsuperscript{3} (DeFelice and MacDonald Gibson, 2013).

The steam to drive the MED was set to a temperature of 75.9°C and a pressure of 0.4 bars. The steam mass flow rate was set to three different values in the range of 25 to 70 kg/s to study how the flow rate affected both the output electrical power and distilled water. Table 3 summarizes the parameters related to the LT-MED unit simulation. The most important initial parameters for the desalination unit are summarized in Table 4.

**Table 4.** Design parameters of the desalination unit.

| Parameter                              | Value/setting | Unit          |
|----------------------------------------|---------------|---------------|
| Heat input HEX                         | 80            | kW\textsubscript{th}/m\textsuperscript{3}          |
| Temperature, hot in                    | 75.9          | °C            |
| Mean log temperature difference        | 12.7–3.2 (stage 1–4) | °C          |
| Steam mass flow rate                   | 25–70 (variable) | kg/s         |
| Stages                                 | 4             |               |
| Intake and cooling temperature         | 20            | °C            |
| Intake and cooling mass flow           | 1500          | t/h           |
| Pressure in cooling suction line       | 5             | bar           |

HEX: heat exchanger.

The seawater entered a series of evaporators and condensers through which the temperature and pressure decreased while the salinity increased from stage to stage. Meanwhile, the auxiliary power consumption for the condenser pumps increased. Consequently, the desalination unit had been limited to four stages despite reducing the possible water production; this was due to the increased operational flexibility of the power plant and desalination unit.

**Figure 6.** Flow diagram of the desalination block with simulation results of an exemplary day (June 21, 2019) for the city of Aqaba. HEX: heat exchanger.
Methodology

Simulation environment

The complete system was modeled using the software EBSILON Professional V13.02, particularly the solar library. EBSILON was developed to perform detailed simulation for the design and engineering of power plants. The integration of a library for fluid properties allowed for calculation of saltwater mixtures and heat transfer fluids.

The program uses a one-dimensional numerical routine according to Newton–Raphson which allows only steady-state simulations. The technical model of the CSP plant was derived from known projects using the solar library “EbsSolar,” incorporating several designs from CSP manufacturers and other simulation environments (STEAG Energy Services GmbH, 2020).

Furthermore, EBSILON Professional allowed the use of our own environmental data. Owing to the extensive measurement of the ambient conditions at the selected site, it was possible to use our own meteorological data for the selected site in Aqaba, Red Sea, Jordan, for performance calculations. The power block simulation focused on the influence of flexible condensation pressures as well as optimized part-load behavior. Owing to the thermal storage system, the power block could operate independently from the solar radiation.

In this simulation, the PTC field component calculated the total incident power $Q_{\text{inc}}$ using measured DNI values given by the sun positions for azimuth angle and solar height. The attached absorber component transferred the reflected solar radiation into the fluid (here, thermal oil) while calculating heat and pressure losses at a constant receiver temperature.

The receiver converted the incident power $Q_{\text{inc}}$ to the effective heat $Q_{\text{eff}}$ absorbed by the heat transfer thermal oil, i.e., the receiver was simulated as a heat exchanger for the concentrated solar heat by a given outlet temperature of the thermal oil fluid (set value). The heat flux at nominal load condition was set to 900 W/m², and the receiver mass flow $\dot{m}_R$ was calculated according to the effective heat flux $Q_{\text{eff}}$ absorbed by the fluid. The enthalpies of the thermal oil before and after the heat supply were noted with $h_1$ and $h_2$, respectively

$$Q_{\text{eff}} = Q_{\text{inc}} - Q_{\text{loss}} = \dot{m}_R(h_2 - h_1)$$ (8)

The energy stored $\dot{Q}_{\text{sto}}$ in the storage tank, assuming constant specific heat $c_p$, is given by the following equation

$$\dot{Q}_{\text{sto}} = \dot{m}_{\text{sto}}c_p(T_{\text{sto,h}} - T_{\text{sto,c}})$$ (9)

where $\dot{m}_{\text{sto}}$ is the mass flow rate of the thermal oil, and $T_{\text{sto,h}}$ and $T_{\text{sto,c}}$ are the hot and cold thermal storage tank temperatures, respectively.

The total mass and specific heat coefficient used in the thermal storage system were defined as $M_{\text{sto}}$ and $c_p$, respectively To ensure a design capacity for full-load operation to supply thermal energy $\dot{Q}_{\text{PB}}$ the power block, the storage system needed to be dimensioned for a maximal duration $t_{\text{sto}}$. The total mass of molten salt $M_{\text{sto}}$ required for this operation could be calculated by

$$M_{\text{sto}} = \frac{\dot{Q}_{\text{PB}}t_{\text{sto}}}{c_p(T_{\text{sto,h}} - T_{\text{sto,c}})}$$ (10)
The maximal storage time was determined by certain mass limits of upper and lower storage level. Owing to the state depended density $\rho_{\text{th, oil}}$ of the thermal oil, the resulting maximal volumes required consideration for the tank design. They were strongly influenced by the temperature. Therefore, the density $\rho_{\text{th, oil}}$ required calculation according to the actual storage temperature at the beginning of the time interval.

To perform a time series analysis, the mass balance of each tank needed to be defined. This requires the definition of a time interval $t_i$ which was set to 1 h. During this interval, the loading $\dot{m}_+$ and unloading $\dot{m}_-$ mass flows were constant. Now, the new mass $M_{\text{sto,}n}$ of the hot and cold tank after each time interval could be calculated using the actual storage level $M_{\text{sto,}a}$

$$M_{\text{sto,}n} = M_{\text{sto,}a} + (\dot{m}_+ t_i) - (\dot{m}_- t_i)$$  \hspace{1cm} (11)

Cost analysis

Cost analysis of the plant was performed according to the levelized cost of electricity (LCOE) and the levelized cost of water (LCOW) following

$$\text{LCOE} = \frac{(\text{FCR} \times \text{CAPEX}) + \text{FOM}}{\text{CF} \times 8760} + \text{VOM}$$  \hspace{1cm} (12)

where FCR is the fixed charge rate, CAPEX is the capital expenditures, FOM is the fixed operation and maintenance cost, CF is the capacity factor, 8760 is the number of hours in a year, and VOM is the variable operation and maintenance cost. The assumed values of the cost parameters in Equation (8) are given in Table 5.

Unfortunately, there is limited to almost no available financial information for low-temperature desalination units. Nevertheless, a practical model for parametric cost estimation was applied in this study. Known as the power-sizing model, it is used most commonly for obtaining preliminary cost estimates of industrial plants and equipment.

Table 5. Assumptions related to cost analysis.

| Variable                      | Value   | Unit   |
|-------------------------------|---------|--------|
| CAPEX for CSP with 6-h storage| 7495    | €/kW   |
| FOM for CSP+D                 | 70.26   | €/kW   |
| VOM for CSP+D                 | 0.03    | €/kWh  |
| FOM for MED                   | 0.22    | €/m³   |
| VOM for MED                   | 0.28    | €/m³   |
| Electricity selling price^a   | 15      | cents/kWh |
| Water selling price^b         | 50      | cents/m³ |

CAPEX: capital expenditure; CSP: concentrating solar power; FOM: fixed operation and maintenance cost; VOM: variable operation and maintenance cost; MED: multi-effect desalination.

^aAccording to Jordanian National Electric Power Company.

^bAccording to Water Authority of Jordan.
The power-sizing model relates the cost of a plant to its capacity or size and uses the following relationship for a cost estimate

\[
\frac{C_A}{C_B} = \left(\frac{S_A}{S_B}\right)^X
\]

(13)

where \(C_A\) and \(C_B\) are the capital expenditures of the MED plant in this study and a reference plant, respectively, and \(S_A\) and \(S_B\) are the distilled-water capacities of the MED plant in this study and a reference plant, respectively. The reference MED plant was selected from the literature (Palenzuela et al., 2015) with costs of 1119.7 €/m³ for a capacity of 35,607 m³/d.

**Results and discussion**

The performance of the cogeneration plant was analyzed for its electrical power generation in the CSP plant and its distillate production as a function of the DNI, number of stages, condensation pressure, and waste steam mass flow rate.

Figure 7 shows the simulation results for the hourly data of electrical output without seawater desalination on the selected days in the field for the proposed CSP+D plant in Aqaba. The average power output in the field was found to be 58.7 MW on June 21, 53.8 MW on March 21 and September 21, and 33.4 MW on December 21.

The net capacity factor (CF) of the designed 100 MWc CSP plant is given by (IRENA, 2012)

![Figure 7. Power-scheme simulation results for the solar power plant with thermal desalination combined with equivalent electrical power for storage without water desalination.](image-url)
\[
\text{CF} = \frac{P_{\text{net}}}{8760 \times \text{Plant power capacity}}
\]  \hspace{1cm} (14)

The annual energy yield from the proposed PTC plant design with 6 h of full-load TES was 317.7 GWh with a CF of 40.8\% and 195.84 GWh with a CF of 22.6\% without storage.

The generated power depends on the incident radiation and the cycle thermal power input to the turbines. Hourly weather data recorded from a weather station in Aqaba were used to study the DNI from for the plant. Figure 8 shows the monthly variations of average DNI in Aqaba. As shown in Figure 8, Aqaba has high radiation levels exceeding 6 kWh/m²/d during the year except for the months of January, February, November, and December. The maximum DNI of 8.34 kWh/m²/d is recorded during the month of June, while the minimum value of 3.58 kWh/m²/d is received during December.

Figure 9 shows the simulation results of the hourly data of electrical output with seawater desalination on the selected days in the field for the proposed CSP+D plant in Aqaba. The average power output in the field was found to be 49.5 MW on June 21, 44.13 MW on March 21 and September 21, and 28.11 MW on December 21. As shown in Figure 9, the output power was decreased for the plant with desalination compared with output power without desalination.

Figure 10(a) to (d) shows the reduction in the output power as a function of steam mass flow rate. For the selected simulation days, the reduction in the output power from the power plant, as a result of desalination of the seawater, was 16.1\% for March, June, and September and 15.6\% for December.

The main influences were the condensing steam pressure in the first heat exchanger of the CSP plant and the circulation mass flow of the desalination unit. The results showed that the

![Figure 8](image-url)

**Figure 8.** Average DNI per month for the city of Aqaba. DNI: direct normal irradiance.
Figure 9. Power-scheme simulation results for CSP+D plant combined with equivalent electrical power for storage with seawater desalination.

Figure 10. Electrical power output as a function of steam mass flow rate for the selected simulation days: (a) March 21; (b) June 21; (c) September 21; (d) December 21.
low number of stages had a positive influence on the cogeneration system and offered more flexibility in power and water generation.

The waste steam is re-used for desalination at mass flow rates of 25, 38, and 57 kg/s. The electrical output as a function of steam mass flow rate encountered slight reductions of 0.80% absolute (in June) to 1.43% absolute (in December).

Figure 11 shows the optimized curve of the electrical power output and the temperature entering the desalination unit as a function of condensation pressure. The calculations were based on optimized mass flows for maximizing the distillate production. This required a special design of the heat exchanger to allow for lowered condensation pressures of 0.3 bar. However, the heat exchanger areas were required to be substantially increased. Condensation pressure varied from 0.32 to 1 bar. Lowering the condensation pressure directly increased the power generation but at the same time decreased the steam temperature entering the desalination system. As shown in Figure 11, a condenser pressure of 0.45 bar represented the optimal pressure for power and distilled-water generation.

CSP condensation pressure was the only influence on the available heat in the first heat exchanger. An increased heat supply should result in increased water production. Considering that the heat was supplied by the CSP steam condenser, complete condensation was required under all operating conditions. Setting the evaporator mass flow to sufficiently high values could ensure complete steam condensation but was not favorable for the distillate output.

Figure 12 shows the model results for the distilled-water mass flow rate as a function of the number of stages. More stages in the desalination unit increased the distillate production due to the reuse of heat in the stages. Here, the number of desalination stages varied from 4 to 10. Design conditions were calculated with \( n = 4 \) stages to keep flexibility in condensation pressures and power generation. The necessary mass flows through the evaporators ensured complete steam condensation. As the required mass flows increased with the number of
desalination stages, the temperature gradients in each stage decreased. To allow for the examination of influence, the mass flows were kept at constant values allowing for complete condensation. The condensation pressure was fixed to 0.6 bar to ensure a sufficient heat supply. As shown, the distilled-water mass flow rate increased with the number of stages, that being 170 t/h for four stages and up to 498 t/h for 10 stages. The power generation shown previously represented the results for four stages despite reducing the possible water production, owing to the increased operational flexibility of the power plant and desalination unit.

In comparison to other solar power technologies, CSP is still considered an expensive technology. The LCOE of the power-plant configuration with desalination was calculated to be 0.13 €/kWh. Meanwhile, the LCOW was equal to 0.15 €/m³. For a selling price of 0.5 €/m³ in Jordan (Water Authority of Jordan, 2017), the annual income from the sold water as a function of the number of stages is shown in Figure 13.

As shown in Figure 13, the annual income for desalination unit varies from €0.74 million for a four-stage unit to €2.18 million for a 10-stage unit. However, the increase in the sold-water income is accompanied by a sharp decrease in the annual income from sold electricity as a result of there being more stages.

The annual income from selling the electricity for the standard configuration of the CSP plant without desalination was €78.84 million, according to the electricity tariff in Jordan (National Electric Power Company of Jordan, 2018). This was €10.74 million higher than its annual cost. However, the annual income was €52.56 million for the plant with desalination. Figure 14 shows the annual income from selling electricity.

Based on selling prices of 0.50 €/m³ and 0.15 €/kWh for water and electricity, respectively, the annual income was up to €2.18 million from selling distilled water and up to €78.84 million from selling electricity. The output power decreased by approximately 15% for the plant with desalination compared with that without desalination. This reduction in
electricity production at the expense of produced water resulted in a decrease in the annual income of approximately €26.3 million compared with the increased income of up to €2.2 million from the water sold. However, the subsidies of the Jordanian government for water prices in Jordan are very high. One cubic meter costs the Jordanian Ministry of Water and Irrigation 1.80 Jordanian dinars (€2.4), while the selling price for the average citizen is approximately 0.5 €/m³, according to Water Authority of Jordan.
Conclusions

Worldwide population growth and climate change have harshly reduced water supplies. Furthermore, tapping freshwater for the MENA region has become more difficult. For Jordan, a MENA country, desalination could be a sustainable option to address water scarcity in Aqaba, the Kingdom’s only coastal city. In an attempt to solve the water scarcity problem, a thermal seawater desalination unit, LT-MED, powered by an integrated solar energy power plant, has been simulated. The working fluid of the LT-MED unit was the waste steam from the power block turbines. Performance and cost analyses of a CSP applying PTC with TES were carried out, and EBSILON software was used to evaluate the performance of the designed CSP plant with an annual average DNI exceeding 5.5 kWh/m²/d. The waste steam was extracted at different mass flow rates and the performance of the plant was compared with that of a standard CSP plant with an electrical output capacity of 59 MW. Compressing the steam to fit the requirements of the LT-MED and condensing it back to the power plant showed an increase in the gross electrical power output. However, owing to the electrical demand of the desalination unit, the net electricity decreased. According to the performed analysis, the output power from the suggested CSP plant reached 58.7 MWel in June. The output power for the CSP system with seawater desalination was approximately 49.5 MWel accompanied by a distilled-water mass flow rate of 170 m³/h. Furthermore, the distilled-water mass flow rate increased with the number of desalination stages, which reached 498 m³/h for 10 stages. Furthermore, the condenser pressure of 0.45 bar was found to be the optimal pressure for power and distilled-water generation.

Based on selling prices of 0.50 €/m³ and 0.15 €/kWh for water and electricity, respectively, the annual income was up to €2.18 million from selling distilled water and €78.84 million from selling electricity. The output power decreased by approximately 15% for the plant with desalination compared with that without desalination. This reduction in the produced electricity at the expense of the produced water resulted in a decrease in annual income of approximately €26.3 million compared with the increased income of up to €2.2 million from the water sold. However, highly subsidized water tariffs in Jordan make the integration of water desalination into CSP plant economically ineffective. The water selling price is 80% less than the actual cost. Action needs to be taken to cope with the very limited water supply in the MENA region, especially in Jordan, with millions of refugees from neighboring countries who have added additional strains on water resources.

Acknowledgements

The authors would like to thank the Higher Council for Science and Technology (HCST) and the Institut National des Sciences Appliquées de Lyon in France for their continuous support throughout the lifetime of the project.

Author Contributions

MA-A and MJ: conceptualization; MJ and JW: methodology; MJ: software; MA-A and MB: formal analysis; MB and JW: investigation; MA-A, ZD, and JW: resources; MA-A: data curation; MJ: writing—original draft; JW, ZD and MA-A: writing—review and editing; and MA-A: supervision.
Declaration of conflicting interests
The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding
The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work has been supported by The Higher Council for Science and Technology (HCST) in Jordan and the deanship of graduate studies and research at the German Jordanian University under a project called “Development and demonstration of a hybrid CSP-biomass gasification boiler system (BIOSOL, ERANETMED).

ORCID iD
Mohammad Al-Addous https://orcid.org/0000-0001-6963-9062

References
Al-Addous M, Dalala Z, Class CB, et al. (2017) Performance analysis of off-grid PV systems in the Jordan Valley. Renewable Energy 113: 930–941.
Al-Mutaz IS and Wazeer I (2015) Current status and future directions of MED-TVC desalination technology. Desalination and Water Treatment 55(1): 1–9.
Cipollone R, Cinocca A and Talebbeydokhti P (2016) Integration between concentrated solar power plant and desalination. Desalination and Water Treatment 57(58): 28086–28099.
Darwish MA, Abdulrahim HK, Hassan AS, et al. (2016) PV and CSP solar technologies & desalination: Economic analysis. Desalination and Water Treatment 57: 16679–16702.
DeFelice NB and MacDonald Gibson J (2013) Effect of domestic water use on air pollutant emissions in Abu Dhabi, United Arab Emirates. International Journal of Energy and Environmental Engineering 4(1): 33.
Duffie JA and Beckman WA (2013) Solar Engineering of Thermal Processes. 4th ed. Hoboken: John Wiley.
El-Dessouky HT and Ettouney HM (2002) Fundamentals of Salt Water Desalination. 1st ed. New York: Elsevier.
Fylaktos N, Mitra I, Tzamtzis G, et al. (2015) Economic analysis of an electricity and desalinated water cogeneration plant in Cyprus. Desalination and Water Treatment 55(9): 2453–2470.
Gebel J (2008) An Engineer’s Guide to Desalination. Essen: Vgb Powertech.
Ghaffour N, Bundschuh J, Mahmoudi H, et al. (2015) Renewable energy-driven desalination technologies: A comprehensive review on challenges and potential applications of integrated systems. Desalination 356: 94–114.
Goosen MFA, Mahmoudi H and Ghaffour N (2014) Today’s and future challenges in applications of renewable energy technologies for desalination. Critical Reviews in Environmental Science and Technology 44(9): 929–999.
International Renewable Energy Agency (2012) Renewable Energy Technologies: Cost Analysis Series 1, Concentrating Solar Power (Issue 2/5). Available at: www.irena.org/publications/re_technologies_cost_analysis-csp.pdf (accessed 30 November 2019).
Khawaji AD, Kutubkhanah IK and Wie J-M (2008) Advances in seawater desalination technologies. Desalination 221(1–3): 47–69.
Micale G, Cipollina A and Rizzuti L (2009) Seawater desalination for freshwater production. In: Micale G, Rizzuti L and Cipollina A (eds) Seawater Desalination. Berlin: Springer, pp. 1–15.
Mistry KH, Antar MA and Lienhard VJ (2013) An improved model for multiple effect distillation. Desalination and Water Treatment 51(4–6): 807–821.
Moser M, Trieb F, Kern J, et al. (2011) The MED-CSD project: Potential for concentrating solar power desalination development in Mediterranean countries. *Journal of Solar Energy Engineering* 133(3): 031012.

National Electric Power Company of Jordan (2018) Annual report. Available at: www.nepco.com.jo/store/docs/web/2018_en.pdf (accessed 6 March 2019).

Organisation for Economic Co-operation and Development (2010) *Sustainable Management of Water Resources in Agriculture. OECD Studies on Water*. Paris: OECD.

Palenzuela P, Alarcón-Padilla DC, and Zaragoza G (2015) *Concentrating Solar Power and Desalination Plants*. Springer International Publishing: Cham-Switzerland.

Sharon H and Reddy KS (2015) A review of solar energy driven desalination technologies. *Renewable and Sustainable Energy Reviews* 41: 1080–1118.

STEAG Energy Services GmbH (2020). *EBSILON Professional Online Help*. EBSILON®Professional. STEAG Energy Services GmbH. Division System Technologies, Rüttenscheider Str. 1-3, 45128 Essen-Germany. Available at: http://www.steag-systemtechnologies.com

Trieb F, Kabariti M, Shahin W, et al. (2007) *Concentrating Solar Power for Seawater Desalination*. Stuttgart: German Aerospace Center. [Mismatch]

Water Authority of Jordan (2017) Available at: www.waj.gov.jo/sites/en-us/default.aspx (accessed 6 January 2019).

Wellmann J, Meyer-Kahlen B and Morosuk T (2018) Exergoeconomic evaluation of a CSP plant in combination with a desalination unit. *Renewable Energy* 128: 586–602.

World Bank (2012) *Renewable energy desalination: an emerging solution to close the water gap in the Middle East and North Africa* (English). Water Partnership Program (WPP). Washington, DC: World Bank.

World Bank (2017) *Beyond Scarcity: Water Security in the Middle East and North Africa*. Washington, DC: The World Bank.

World Water Assessment Programme. (2019). *The United Nations World Water Development Report 2019*. New York: United Nations Educational, Scientific and Cultural Organization.

Xevgenos D, Moustakas K, Malamis D, et al. (2016) An overview on desalination & sustainability: Renewable energy-driven desalination and brine management. *Desalination and Water Treatment* 57(5): 2304–2314.