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Techno-Economic Analysis of Reverse Osmosis Desalination Plant Powered by Hybridized PV and CSP Systems for Irrigation Water

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Abstract. Large market opportunities exist for solar powered Reverse Osmosis (RO) desalination technologies in fertile but arid areas with large solar and sea water resources. A challenge to realizing these markets is the variable nature of solar resources, which for the desalination plant can lead to high water costs due to low capacity factors (CF) and increased maintenance costs due to repeated start-ups and shut-downs. A potential solution is to power RO plants using both PV and CSP with Thermal Energy Storage (TES) with an aim to reduce shut-downs, and increase CF. In this study, three solar energy systems to power RO are considered: 1) PV only; 2) CSP with central receiver (CR) and TES; 3) PV and CSP with CR and TES. Two RO operational strategies are considered: 1) nominal load only; 2) variable load between minimal and nominal. The performance of these systems is simulated for Mersin, Turkey, using TMY data. The PV and CSP with TES system and variable RO operation achieved the levelized cost of water (LCOW) 1.92 USD m^{-3} with an RO CF of 60.8%.

Keywords: PV CSP Hybridization, Reverse Osmosis, Desalination, Irrigation Water

1. Nomenclature

Q_{htf}	Thermal energy that can be transferred to heat transfer fluid in the receiver
P_{pv}	Electrical power output of PV plant
P_{csp}	Electrical power output of CSP plant, including using TES
$P_{csp,min}$	Minimum electrical power output of CSP plant
P_{cr}	Electrical power that can be generated using central receiver without TES
E_{tes}	Energy that can be generated only using TES
$t_{Q.htf,0}$	Number of consecutive hours in which Q_{htf} = 0
$P_{ro,n}$	Nominal power requirement of the reverse osmosis plant
$P_{ro,min}$	Minimum power requirement of the reverse osmosis plant

2. Introduction

Water and food security are becoming increasingly important global challenges due to decreasing freshwater resources and increasing population. 69% of the world water consumption is for agriculture [1] and by 2050, it is expected that agriculture will need to produce 60% more food globally [2], putting further stress on freshwater resources. Desalination technologies to produce irrigation water are a potential solution to these challenges, but have large energy requirements.

The co-location of large solar resources with fertile but arid areas near large bodies of seawater creates a vast potential for solar powered desalination while supporting the Paris Agreement. Among desalination technologies, Reverse Osmosis (RO) has one of the lowest Specific Electricity Consumption (SECs) and only requires electricity. Currently, photovoltaics (PV) generate low-cost electricity during the day, but lack an economic storage system to supply electricity at night. Therefore, only using PV to power a RO plant can lead to high Levelized Cost of Water (LCOW) due to small capacity factors (CFs) for the RO plant and increased RO maintenance costs due to increased number of stop / start occurrences. On the other hand, CSP, defined herein to explicitly include Thermal Energy Storage (TES), can deliver economically competitive dispatchable electricity, including at night.

The hybridization of PV with CSP ("PV+CSP") for RO desalination for the Canary Islands was previously investigated by Silvestre [3] where the RO plant was only allowed to operate at nominal load. It was found that PV+CSP powered RO can achieve lower LCOW than grid powered RO for this location. Even though the results of the study are already quite promising, it is expected that allowing the RO plant to operate at partial load can reduce LCOW further by increasing the RO plant's CF and reducing the number of train stop / start instances. Therefore, the objective of this study is to model, simulate, and assess a stand-alone desalination system where PV+CSP powers a variable load RO plant targeting the production of irrigation water for agriculture on Turkiye's Mediterranean coast.

3. Methodology

3.1 Reverse Osmosis Plant

A RO system with total capacity of 50 000 m^3 day^{-1} and with 5 or 20 trains is modeled. Each train can be turned on and off independently, and trains are allowed to operate either at nominal load only (termed *nominal load operation*) or at any load between their minimum and nominal loads (termed *variable load operation*). Toray DS2 is used to simulate the RO operation with the seawater composition of the Turkish Mediterranean Sea [4]. The RO configuration is single stage, single pass with no feed bypass. The specifications of the RO plant are presented in Table 1.

Table 1. The specifications of RO plant.

Parameter	20 Trains	5 Trains
Feedwater flow rate (m^3 day^{-1})	3 869 - 5 952	15 476 - 23 809
Permeate flow rate (m^3 day^{-1})	1 625 - 2 500	6 500 - 10 000
Recovery	42%	42%
Feedwater TDS (mg l^{-1})	37 100	37 100
Feedwater temperature (°C)	25	25
Element Type	TM820V-440	TM820V-440
Number of pressure vessels	20	80
Number of elements in each vessel	8	8
Pump Efficiency	80%	80%
ERD Efficiency	85%	85%

The RO is operated with a constant recovery flow rate rather than a constant concentrate or constant feed flow rate, as this provides a broader range of operation with a lower SEC and a more stable permeate quality [5]. The minimum load is fixed as 65% of the nominal load due to membrane and process limitations. The RO operational strategy for nominal load operation is to operate the maximum number of trains at nominal load at all hours and to turn off the remaining trains. In contrast, the broad operational strategy for variable load operation is to allow individual trains to operate at partial load to better match the RO load to variable solar resources, and therefore increase the RO's CF, and to prioritize operating a larger number of trains at partial load over operating a smaller number of trains at nominal load to decrease the number of stop / start instances. The operational strategy of RO plant with variable load operation is presented in detail in Figure 1.

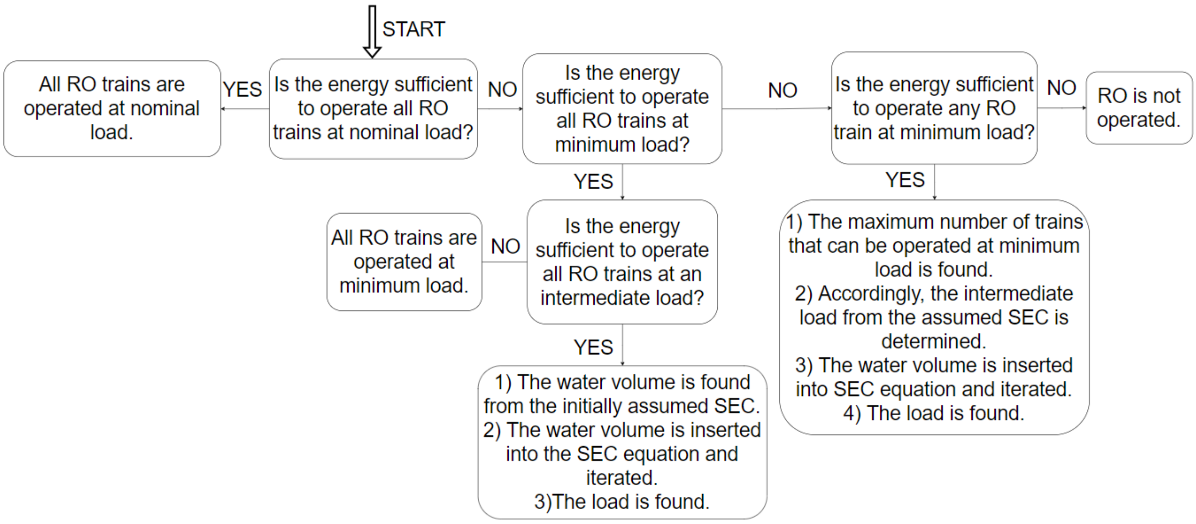

Figure 1. The operational strategy of RO plant with variable load operation.

3.2 Energy Systems

Three different grid-independent energy systems are analyzed: 1) PV; 2) CSP; and 3) PV+CSP. The CSP system is Central Receiver (CR) with TES.

The energy systems are simulated separately using SAM with the outputs being further processed with MATLAB. The models are run for Mersin, Turkiye (36.865° N, 34.61° E), which is on the Mediterranean coast, has a large agricultural sector and has a pilot 5 MW_{th} central receiver system (Greenway CSP). As a coastal location close to mountains, the simulated DNI data sets considered exhibited large variations over small distances. The micro-siting of the solar energy system is outside the scope of this study, and the simulated TMY data for the location of the pilot CR plant are used with an annual DNI of 1530 kWh m^{-2}.

3.2.1 PV System

The specifications of the PV system are presented in Table 2. The hourly electricity generation of the PV system is modeled using SAM.

Table 2. The specifications of PV plant.

Parameter	**Value**
Module type	LONGi Green Technology Co. Ltd. LR4-72HPH-420M
Inverter type	Sungrow Power Supply Co – Ltd : SC12000UD-US (480 V)
Capacity (MW)	8.5
Tracking	1 Axis (tilted N-S axis)
Tilt angle (°)	Latitude (36.865)
Surface azimuth angle (°)	180
Strings in parallel	749
Modules per string	27

Table 2. (*continued*)

Parameter	Value
Total numbers of modules	20 223
Number of inverters	6

3.2.2 CSP System: CR with TES

The specifications of the CSP system presented in Table 3.

Table 3. The specifications of CSP plant.

Parameter	Value
DNI design point (W m^{-2})	800
Solar multiple	3
Gross power of turbine (MW)	8.3
Turbine gross to net efficiency	85%
Turbine operating range	30%-100%
HTF fluid	60% $NaNO_3$, 40% KNO_3
Hot tank fluid temperature (℃)	575
Cold tank fluid temperature (℃)	290
Storage size (h)	12
Initial charged volume of hot tank	30%

Q_{htf} is exported to MATLAB and converted into electrical energy by multiplying by the efficiency factor, thermal efficiency and turbine gross to net efficiency of the CSP plant as suggested in [3]. The TES system is modeled based on conservation of mass and energy. A two-tank TES system is modeled and the hot tank is never discharged below 2%.

The operational strategy of the CSP plant for variable load operation of RO is presented in Figure 2. When Q_{htf} is zero and the TES is not fully discharged, $t_{Q.htf,0}$ is forecasted and the energy stored in the TES is distributed among those hours with an aim to maintain continuous operation of the maximum number of RO trains and minimum number of stop / start occurrences.

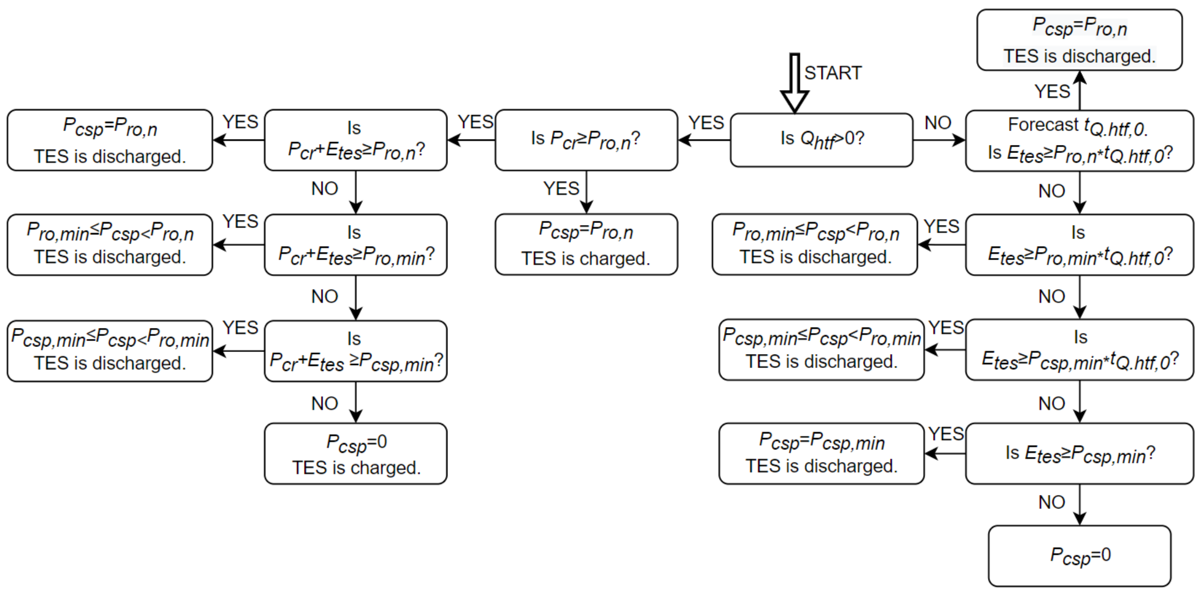

Figure 2. The operational strategy of CSP.

3.2.3 PV+CSP System

For PV+CSP systems, PV is always prioritized to power RO plant during the day. The CSP system prioritizes supporting the PV system when the PV output is insufficient to operate the RO plant in the operational range, and mainly stores energy in TES to power the RO system in the absence of solar resources. By doing so, it is aimed to increase the RO's operation time and reduce the effects of the variable nature of solar resources on the RO plant.

The operational strategy of the hybridized energy system for variable load operation of RO is presented in Figures 3 and 4. When Q_{htf} is zero but PV is operating (i.e., low DNI and high diffuse), $P_{ro,n}$ is aimed to be met. However, when there are no solar resources and the TES is at least partially charged, the TES is discharged following the operational strategy of the CSP plant.

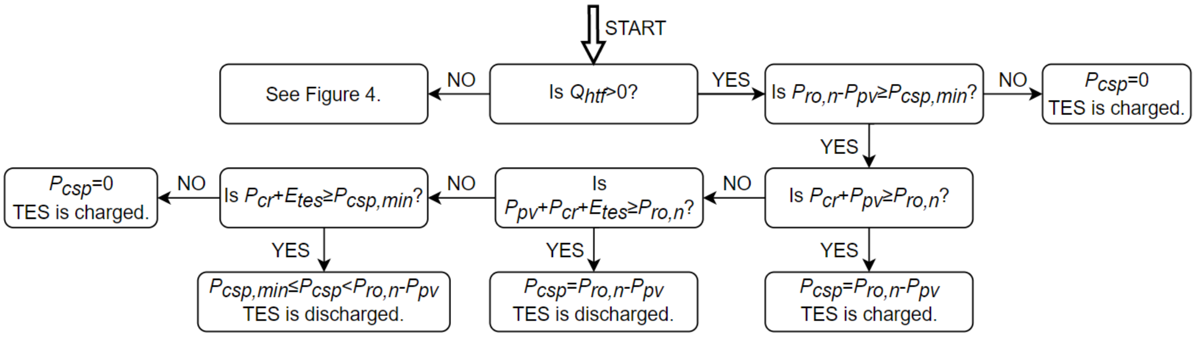

Figure 3. The operational strategy of PV+CSP system when Q_{htf} > 0.

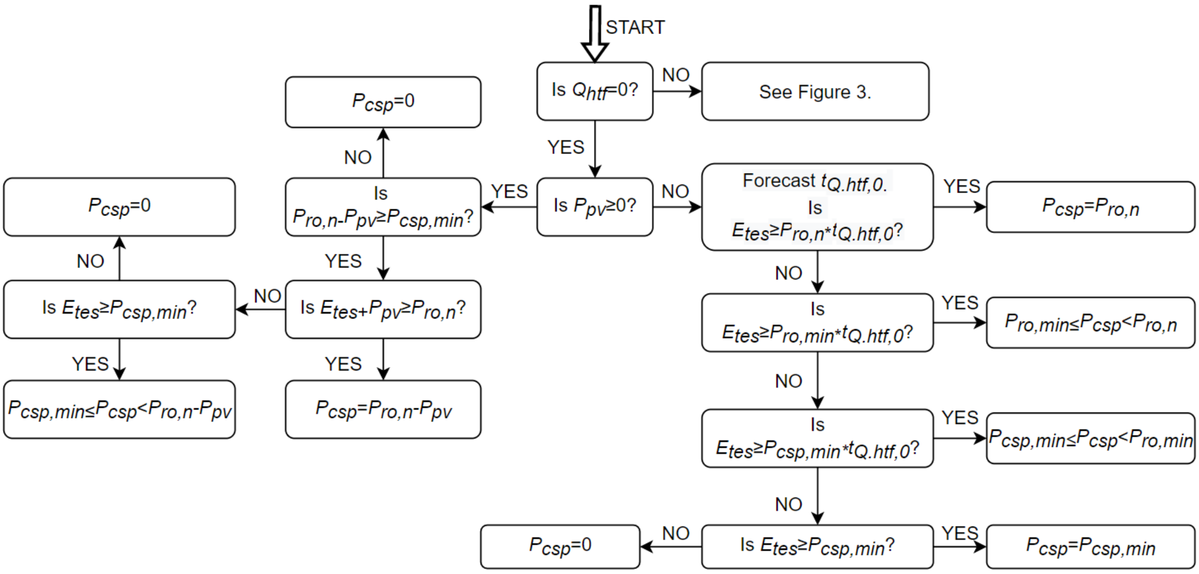

Figure 4. The operational strategy of PV+CSP system when Q_{htf} = 0.

3.3 Economic Analysis

The LCOW is calculated using the Net Present Value (NPV) method to compare different energy systems and operational strategies. The economical inputs of the PV, CSP and RO systems are taken from [6], [7], [8]. The discount rate and the lifetime of the plants are assumed as 10% and 25 years, respectively.

4. Results

The RO plant is simulated for design permeate flow rates varying from 65% to 100% of the design flow rate in 5% increments. The SEC of the RO system analyzed in this study is found to be 2.18 kWh m^{-3} and 2.41 kWh m^{-3} for the minimum load and nominal load, respectively. However, it is reported in [9] that RO constitutes only 71% of the total energy consumption of a desalination plant with the remaining 29% due to non-RO loads; therefore, the estimated SECs for RO are divided by 71% to estimate the SEC of the complete desalination plant. The simulated permeate flow rates and the corresponding overall energy consumptions are fitted to a function to be used in the model for the variable operation of RO plant and presented in Fig. 5 (a) and (b) for 2 500 m^3 day^{-1} and 10 000 m^3 day^{-1} train capacities, respectively.

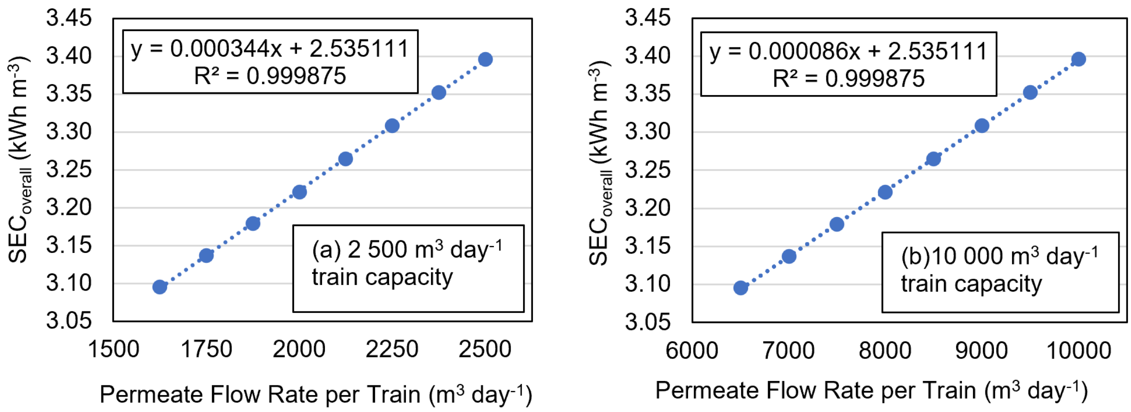

Figure 5. The overall SEC of RO plant in the determined operational range with (a) 2 500 m^3 day^{-1} and (b) 10 000 m^3 day^{-1} train capacities.

The CF and LCOW of PV, CSP and PV+CSP system with 2 500 m^3 day^{-1} and 10 000 m^3 day^{-1} train capacities with nominal and variable load operation of RO are presented in Figure 6. The PV system for the nominal load operation of RO with 10 000 m^3 day^{-1} train capacity results in the highest LCOW, 2.33 USD m^{-3}, as the low CF of the PV leads to a large RO plant with large capital costs and low CF. However, with the PV+CSP system powered RO with variable load operation with 2 500 m^3 day^{-1} train capacity, the LCOW is found almost as same with the PV powered RO, 1.92 USD m^{-3}, due to the lowered LCOE of CSP with PV integration and increased CF of RO.

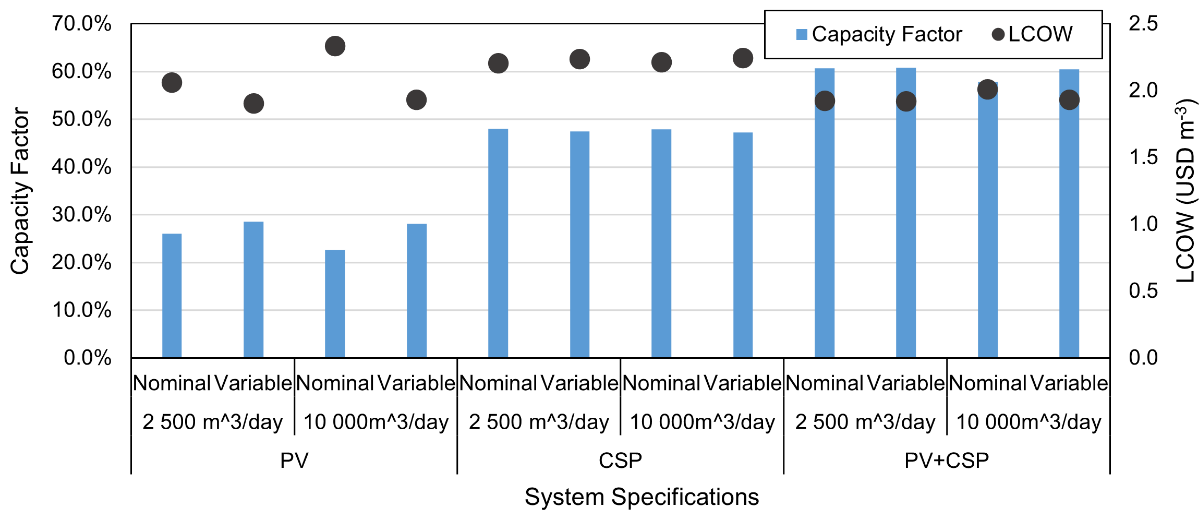

Figure 6. The CF of RO plant and LCOW of PV, CSP and PV+CSP system with 2 500 and 10 000 m^3 day^{-1} unit capacities with nominal and variable load operation.

Figure 7 presents the Utilization Factor (UF) and Stop Start Ratio (SSR) of RO powered by PV, CSP and PV+CSP system with 2 500 m^3 day^{-1} and 10 000 m^3 day^{-1} train capacities with nominal and variable load operation of RO. The UF is the ratio of the sum of hours each train is operated to the product of number of trains and total number of hours over the year; whereas, the SSR is defined as the ratio of the total number of stop/start instances to the number of trains of RO, 5 or 20. The variable operation of RO with PV increases the CF and UF up to 23.8% and 50.2%, respectively; however, as PV lacks a storage system to adjust the power output, the SSR also increases by 19.7%. With the energy schemes including CSP, in addition to the increase in UF, SSR decreases significantly. Specifically, with PV+CSP and variable load operation of RO with 2 500 m^3 day^{-1} train capacity, the SSR decreases by 50.5% with an 20.6% increase in UF. Therefore, it is concluded that variable load operation is advantageous for PV to increase CF whereas it is advantageous for CSP systems to reduce the number of stop/start instances.

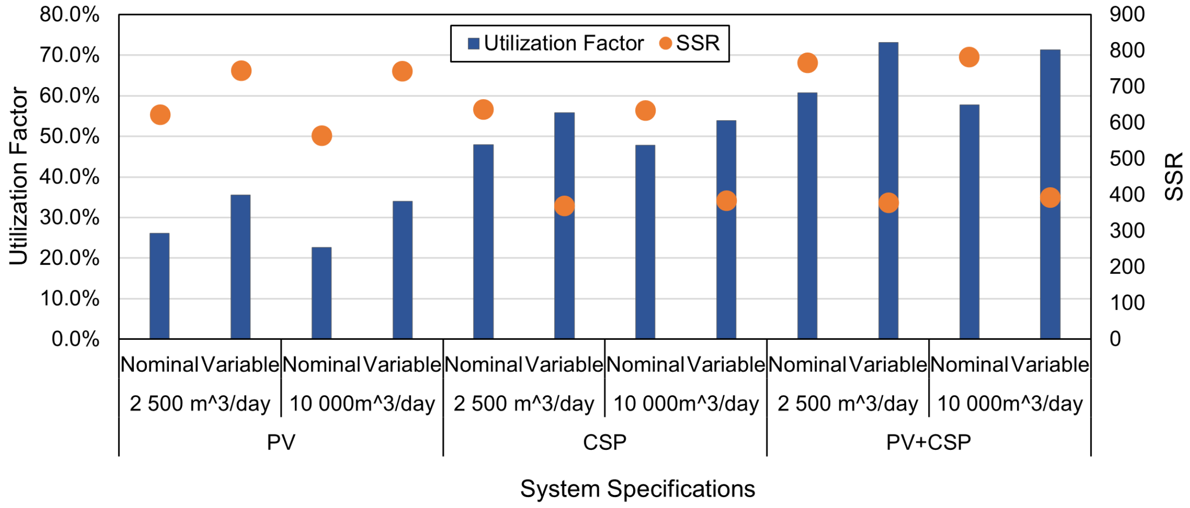

Figure 7. The UF and SSR of RO plant of PV, CSP and PV+CSP system with 2 500 and 10 000 m^3 day^{-1} unit capacities with nominal and variable load operation.

5. Conclusions

A grid-independent desalination system consisting of one or both of PV and CSP powering a RO plant is investigated, where the CSP system includes TES. The RO plant consists of multiple trains. Two operating strategies are considered for each RO train: nominal load and variable load. The model is run for Mersin, Turkiye, on the Mediterranean coast. It is concluded that switching from nominal to variable load operation for the RO trains is most advantageous in terms of capacity factors for the PV only case as it allows the RO load to better match the variable PV output. Separately, the systems with CSP significantly reduces the number of stop / start instances. The LCOW of 1.92 USD m^{-3} is obtained for PV+CSP for the variable load operation of RO with 2 500 m^3 day^{-1} train capacity. Finally, with the PV+CSP scheme, the CF of RO plant of 60.8% is achieved and with the variable load operation, 50.5% reduction in SSR is reached compared to the nominal load operation.

Data availability statement

The data supporting the results of this article can be accessed through https://hdl.handle.net/11511/98560.

Author contributions

Eylül Gedik: Methodology, Formal analysis, Writing - original draft;

Diego-César Alarcón-Padilla: Conceptualization, Methodology, Supervision;

Derek Baker: Supervision, Writing – review & editing, Funding Acquisition, Project administration;

Competing interests

The authors declare no competing interests.

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