STRATEGIES FOR ENHANCING THE USE OF SOLAR ENERGY IN UTILITY-SCALE DESALINATION PLANTS

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ABSTRACT

The current expansion of desalination faces the challenge of the amount of energy required to operate the plants. The extra pressure of the electricity consumption of reverse osmosis (RO) plants running 24 hours a day at a certain location is not always met by the existing electric grids. In addition, for the sustainability of desalination, the new sources of energy that must be incorporated into the grid to meet the demand for RO should be renewable, and renewable energy sources are variable. Photovoltaic (PV) plants are proposed as the first option since they produce the cheapest renewable electricity, and solar radiation is highly available where desalination plants are required. However, without using batteries that are expensive, PV can only supply a reduced fraction of the total energy needed. Concentrated Solar Power (CSP) plants generate electricity that may not be as cheap as PV. Still, it is more manageable because thermal energy storage is much more feasible and cheaper than batteries, so CSP electricity can be produced during a much larger fraction of the day (even at night) compared to PV electricity. In this work, we analyze how the hybridization of PV with CSP technologies can significantly increase the total fraction of solar electricity that can be effectively supplied to the grid to meet the demand of RO plants. Several scenarios are compared and discussed considering a typical RO plant and a discussion on cost implications is used to suggest the most favorable case.

Keywords: Desalination, Sustainability, Solar energy, Photovoltaic, Concentrated Solar Power.

I. INTRODUCTION

Water scarcity is one of the main problems for the immediate future worldwide. Among the 17 Sustainable Development Goals defined by the United Nations [1], Goal 6 aims to ensure availability and sustainable management of water and sanitation for all. This makes desalination the most viable technological solution for guaranteeing the freshwater supply in order to mitigate the availability problem. Due to several factors such as climate change, population growth, increasing industrialization and contamination of existing resources, worldwide desalination capacity has risen significantly. It has gone from 35 million m^3/d in 2005 to approximately 100 million m^3/d in 2021, with an expected increase to 150 million m^3/d by 2025 [2].

Reverse Osmosis (RO) is the prevailing desalination technology, with 70% of the desalination capacity installed [3]. In addition, the significant cost reductions and increasing energy efficiency that this technology has experienced in recent years suggests that practically all future large-scale desalination plants will be based on RO.

The main disadvantage of desalination is the energy demand, which increases significantly the electric grid load and, in many cases, requires an extension on the existing grid for implementation. This is why the water scarcity problem can become an energy and environmental problem. The use of fossil fuels to desalinate water has a considerable impact on CO_2 emissions. The carbon footprint for RO desalination of seawater has been calculated between 0.4–6.7 kg CO_2eq/m^3 [4], which means that desalinating 1000 cubic meters of seawater could potentially release to the environment as much as 6.7 tons of CO_2. This fact jeopardizes the sustainability of this technological solution, which leads to the need of decarbonizing the desalination industry by replacing fossil fuels with renewable energies. In this context, the incorporation of solar energy is being considered to facilitate the expansion of the desalination capacity in the world, given that the regions that require desalination tend to be those that have high levels of solar irradiation.

Solar Photovoltaic (PV) electricity is the cheapest amongst all the renewable energy technologies. Levelized Cost of Electricity (LCOE) reported for utility-scale PV projects commissioned in 2019 was an average of 68 USD/MWh, with an expected decrease to a third in 2050 [7], and the minimum cost reported is 20 USD/MWh (at Mohammed bin Rashid Al Maktoum Solar Park, Dubai). However, the relative movement of the Sun in the sky means that the solar radiation is not constant and follows a (predictable) curve during the day, with the peak at the highest solar altitude each day. In addition, cloud covering, fog and dust reduce the solar irradiance in a less predictable way, augmenting the variability of the PV energy produced and reducing its capacity factor (CF), which is the ratio between the actual energy produced by the solar plant and the total energy demand (the peak power assumed constant during the whole day). In the best conditions, the capacity factor of PV energy is rarely above 30% [8].

To enhance the capacity factor, the PV plant can be dimensioned with a peak power above that of the demand. This means that there will be times when the instantaneous energy production will be above that consumed. If that excess energy is stored in batteries, it can be used at other times when the PV is not able to supply the full power required. This enhances the operating time that the solar energy is available but increases the CAPEX of the solar facility, not only by the increase of the size of the PV field but by adding the cost of batteries, which has an impact on the cost of electricity.

On the other hand, concentrated solar radiation can also be used to generate solar thermal electricity by the so-called Concentrating Solar Power (CSP) plants. In this case, the solar collectors are used to produce heat, from which electricity is generated through a thermodynamic cycle (i.e. Rankine, Brayton Cycle). Parabolic trough (PT) and central receiver (CR) are the two dominant CSP technologies. Parabolic trough systems dominate the current global market in CSP plants. However, the trend is drifting towards CR since this technology has a higher potential to reduce costs and increase efficiency [9]. The possibility of storing heat in molten salts at 400-550 ºC to operate the turbine when there is no solar irradiance, makes CSP the only dispatchable renewable energy. The electricity can be produced on demand from molten salts, which are a more affordable and sustainable means of energy storage than batteries for electricity (and they do not use critical materials with environmental and geopolitical limitations) [10]. CSP is, therefore, a very attractive supplement to PV energy, which otherwise must be coupled to a non-renewable source of energy to supply the desalination plant for stable operation.

The costs of CSP are higher than those of PV but on a descending trend, and the cheapest plant awarded has an LCOE of 74 USD/MWh, which is amongst the range projected for utility-scale PV with batteries. Deployment policies have significantly reduced the cost of CSP in the last decade, with further decreases expected if further investments in new power plant capacities are undertaken. Furthermore, there is room in CSP to increase the efficiency, as is the case of using Brayton cycles based on air (or even supercritical CO_2) in high-temperature central receivers (>700 ºC) using air or falling particles, and this can lead to significant cost decreases in the LCOE of CSP [11].

Several studies existing in the literature have revealed interesting results about the combination of CSP and PV plants. In all cases, the operation of the PV plant is prioritised during the day and the CSP plant acts as buffer. In a study carried out by Platzer [12] it was concluded that the combination of a 50 MW PV plant and a 50 MW CSP plant may enhance the dispatchability and reduce the size of the solar field needed in the CSP plant. It was found that the LCOE could be reduced from 0.152 €/kWh to 0.124 €/kWh with the hybrid CSP-PV plant in comparison to only a CSP plant. Another study done in Atacama Desert (Chile) by Green et at. [13] showed that the capacity factor (CF) could be increased from 80 % to 90 % with the combination of CSP and PV. In the case of the techno-economic evaluation performed by Zurita et al. [14], apart from the molten salt storage in the CSP plant, batteries were considered in the PV plant. The system was supposed to deliver a constant power of 100 MW for 24 h a day. The CSP plant was set to run on minimum capacity (30 %) when the production from the PV plant would exceed 65 MW and turn off when it would exceed 95 MW, with the aim of reducing the shutdown sequences of the power block in the CSP plant. In addition, it was established that the excess power from the PV plant would be stored in the battery system during these operation modes or dumped if the batteries were full. The batteries would discharge when the thermal energy storage system (TES) could not meet the demand. It was obtained that the lowest LCOE (77.2 USD/MWh) and a CF of 82.2 % were achieved with no battery storage and the following conditions: 14 h TES, a solar multiple (SM, which is the ratio between the thermal power output of the solar field during design conditions and the thermal power required for the power block to operate at nominal capacity), of 2.2, and 130 MW PV. The highest CF (90.3 %) was reached with 14 h TES, SM of 2, 190 MW PV and 400 MWh of battery storage. However, in this case the LCOE was 87.5 USD/MWh. Therefore, a cost reduction of 90 % for the battery storage would be needed for a hybrid system with batteries to reach a LCOE as low as one without batteries.

In the case of hybrid CSP+PV for desalination, only studies with Multi-Effect Distillation (MED) can be found in the literature, such as those performed in northern Chile [15-17]. In all cases, the MED plant is driven by exhaust steam from the CSP plant and it is connected in parallel with the condenser of the power block. The CSP plant is controlled to prioritise the power output from the PV plant, so that both plants deliver a total power of 100 MW. In this case, the MED only functions when the electrical power output from the CSP plant exceeds 50 MW. Otherwise, all excess heat from the CSP is dumped through the condenser. As example, in the study performed by Valenzuela et al. [15], it was found that the hybridisation with CSP + PV + MED resulted in a 7.6 % reduction of CF and an increase of 12.7 % in LCOE compared to CSP + PV.

To the best of the authors' knowledge, there are no studies in the scientific literature considering a hybrid CSP+PV system to meet the electricity demand of a RO plant. This work presents a techno-economic study of the hybridization of PV with CSP to significantly increase the total fraction of solar electricity that can be effectively supplied to a RO plant. Several scenarios have been established in terms of thermal storage capacity of the CSP system, considering a typical RO plant and the location in Palomares (Almería, in the Southeast of Spain). Simulations have been performed for a typical metrological year of this location and a discussion on cost implications has been used to suggest the most favourable case.

II. RESEARCH

Fig. 1 shows the layout of the system studied. The cheaper electricity generated from the PV system is prioritized during daytime, which allows the thermal energy from the receiver of the CSP system to be stored in the molten salt tanks and be used to generate electricity when not enough solar radiation is available (from the sunset onwards), thus favouring the continuous operation of the RO plant. In the case of the PV, state-of-the-art collectors with 1-axis tracking of the Sun have been considered, without using batteries. In the CSP case, the Central Receiver technology with a thermal storage system based on molten salts and a Rankine Cycle has been considered. For the refrigeration of the power cycle, an air cooling system has been selected in order to avoid the high water consumption required by wet cooling systems.

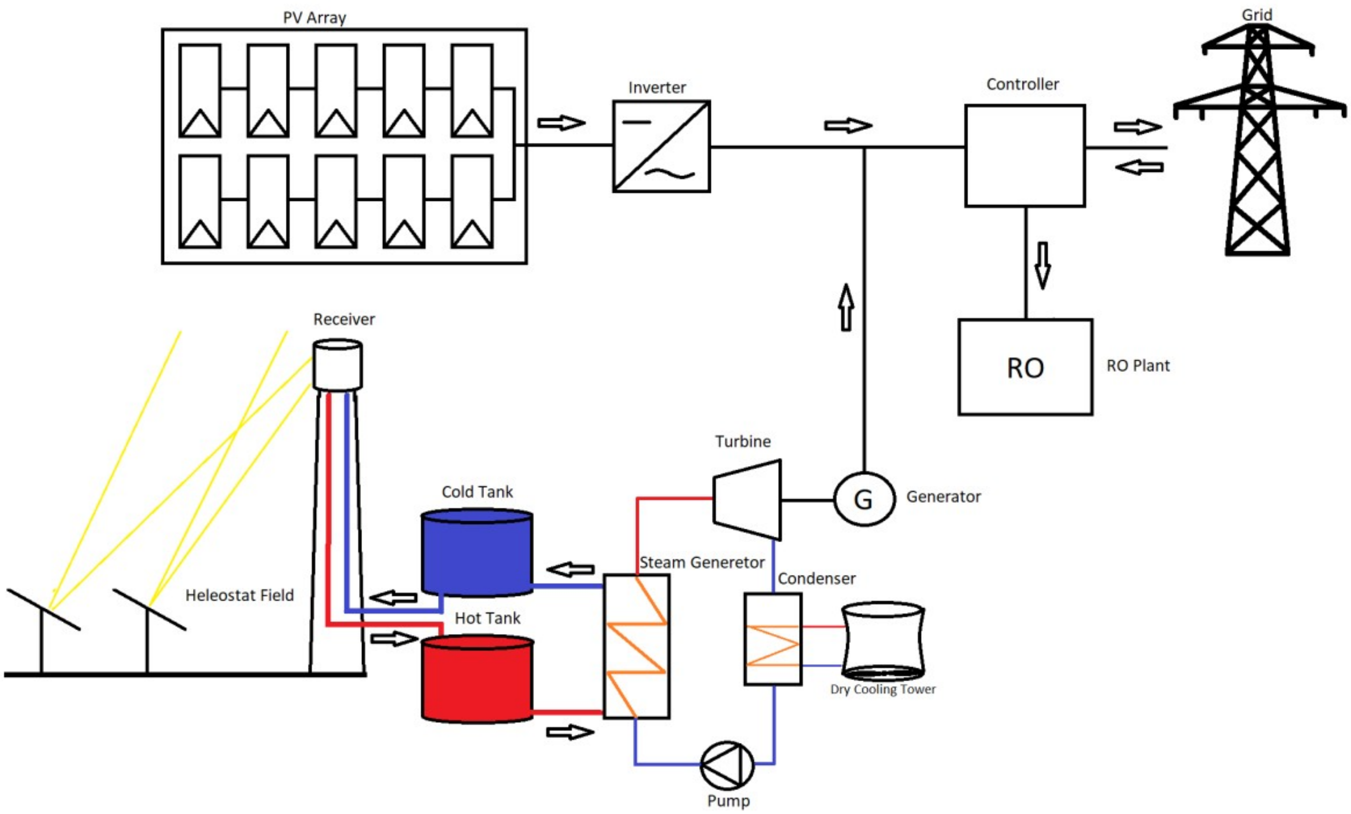


Fig. 1. General layout of the CSP+PV+RO system

Both power systems have been designed to produce the electric power needed for the RO plant to produce 4 Hm^3/day of desalinated water at nominal conditions, which is a figure that can be expected for the total seawater desalination capacity of Spain in few years. The average consumption of a RO plant for seawater desalination (SWRO) has been taken as 3 kWh/m^3, which is a figure in the low end of the current state of the art [18], as can be expected considering new or retrofitted plants for high efficiency. This gives roughly a total power required for the RO plant of 500 MW_e.

A 500 MW_e PV power plant was designed and simulated in SAM and the hourly net power output from the PV plant was then imported into Python, to be used in a tailor-made model. The CSP plant, a 500 MW_e power tower molten salt facility with a solar multiple of 2.5, was also simulated in SAM. The heliostat field, tower dimension and receiver were optimized for a nominal output of 500 MW_e using SAM optimization capabilities. The hourly thermal output received by the heat transfer fluid was then exported to be used as input in the mentioned Python model. In such model, the thermal energy has been managed either to be stored or to be sent to the power block to produce electricity depending on the available electricity provided by the PV model. The power cycle nominal efficiency, provided by SAM, is 41.2%. The power produced by the power block has been simulated using this nominal efficiency multiplied by the efficiency fraction at partial load, which is calculated using the following equation:

$$EF = -0.4774 \cdot LF^3 + 0.8606 \cdot LF^2 - 0.2437 \cdot LF + 0.8596 \qquad (1)$$

where EF is the efficiency fraction at partial load (LF being load fraction). This equation was obtained by simulations performed in a model previously developed in Engineering Equation Solver by the authors of this paper. Additionally, parasitic load is estimated to represent a 10% of the turbine gross output.

A parametric study has been done considering different thermal storage capacities for the CSP plant: 8, 17, 24 h, determining for each case the Levelized Cost of Electricity (LCOE), the capacity factor and the total land footprint of PV and CSP power plants. Note that the LCOE and the land footprint have been determined by SAM. As mentioned before, the location considered is Palomares, a village near the sea in Almería, SE Spain with the following geographical coordinates: 37.241, -1.790.

III. RESULTS

To illustrate the intrinsic variability of solar energy supply, Figure 2 shows the total power generated during a day (summer solstice) by a 500 MW_e installation of PV solar energy. It can be seen that the total power required by the RO plant is only reached at about solar midday (around 14:20 local time considering GMT+1 time zone and daylight-saving time, as corresponding to the location suggested for the study). The options are then to increase the size of the PV system and store in batteries the excess energy generated above the nominal power required, or to hybridize with a CSP system that can store heat and produce electricity during the rest of the day.

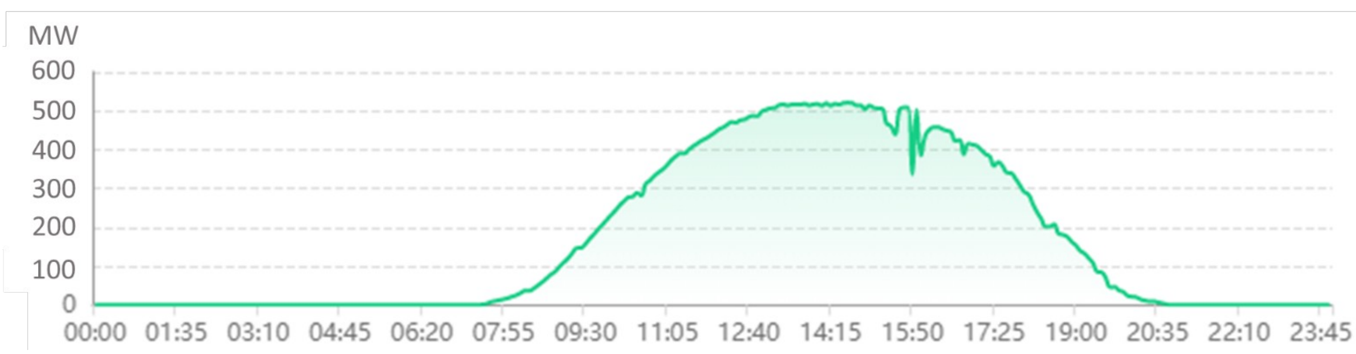
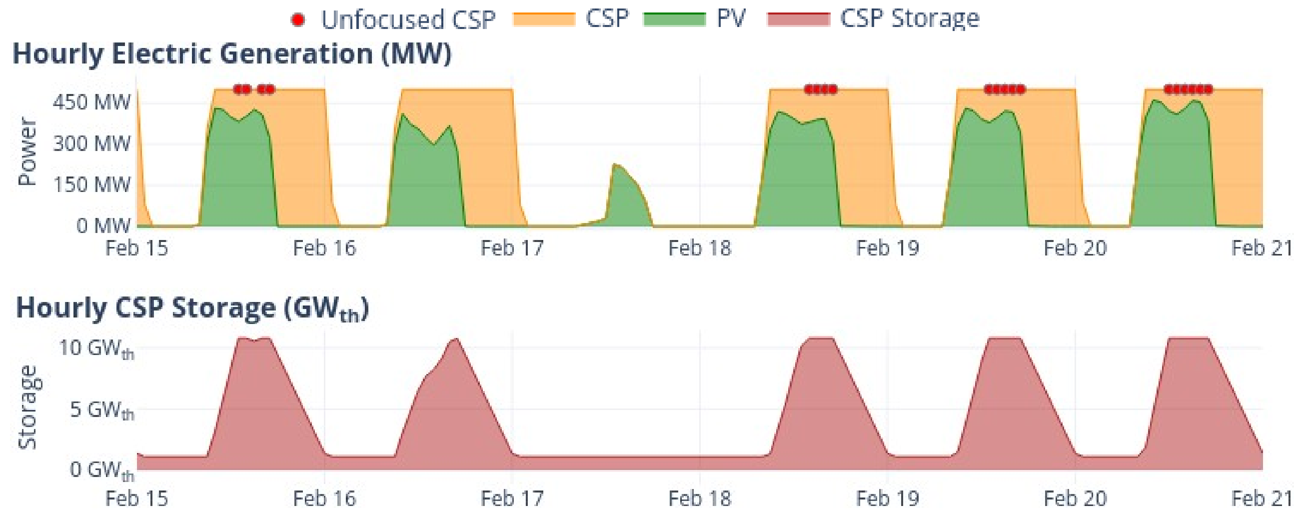
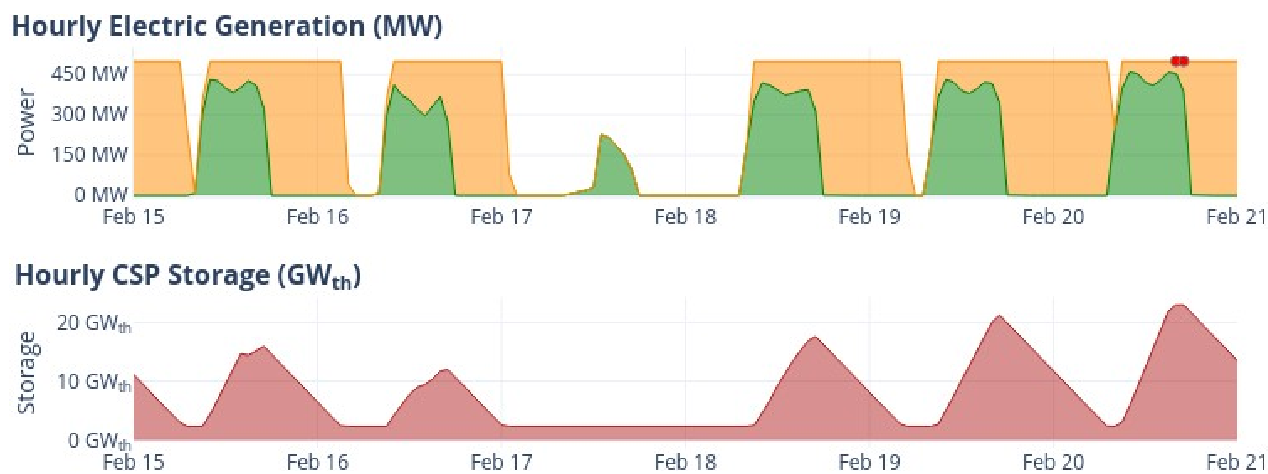


Fig. 2. Effective power supplied along a summer day (solstice) by a PV 500 MW_e system.

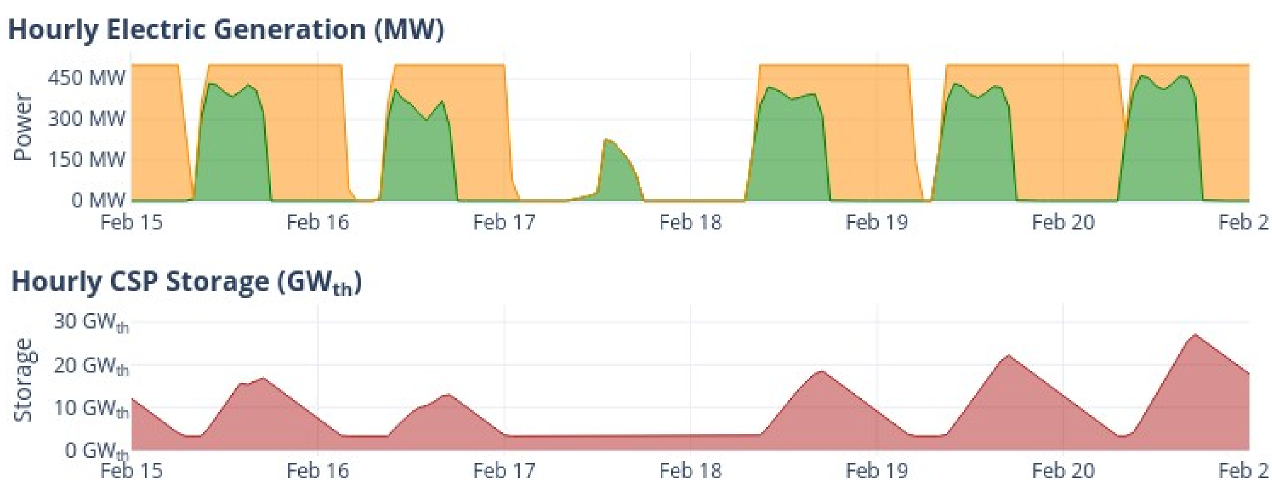
The relative monthly contribution of each solar power technology (PV and CSP) has been determined, and a simulation representative for summer and winter performed in order to understand the operation strategy of the hybridization. Figure 3 shows the hourly electricity generation with each configuration (8, 17 and 24 hours) for winter (from 15th to 21st of February), and Figure 4 for summer (between 2th and 8th of August). The figures also show the hourly available thermal storage for each configuration. As observed, when the required output power coming from the hybrid PV + CSP system is 500 MW_e and the thermal storage of the CSP is full, the solar field must be defocused or the CSP power must be shut down, since there is no means to store this energy surplus (see red dots in Figure 3 and 4).



a) 8 hours of thermal storage

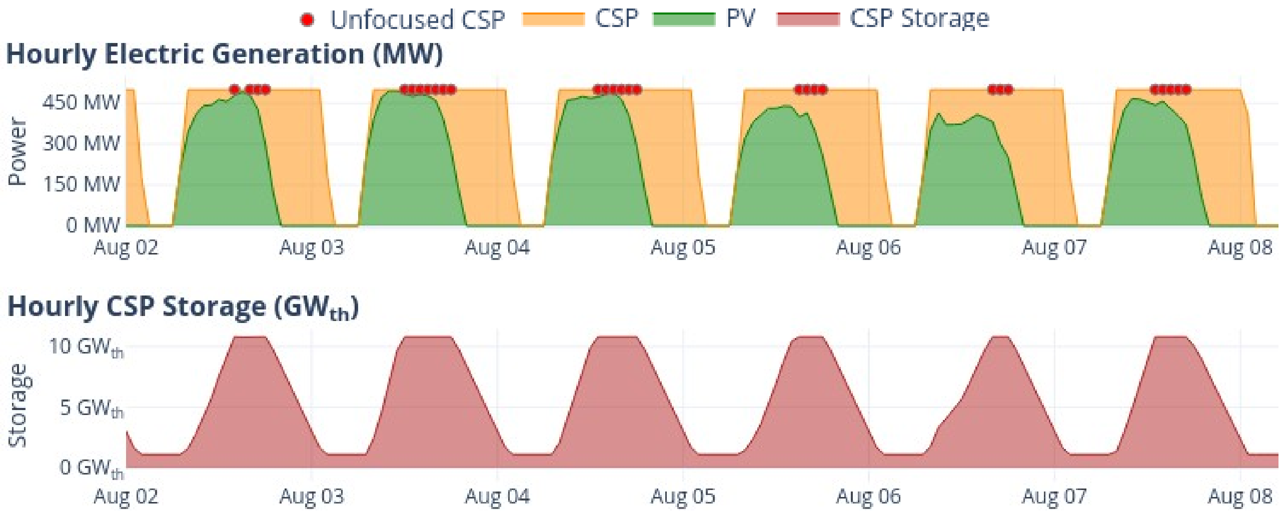


b) 17 hours of thermal storage

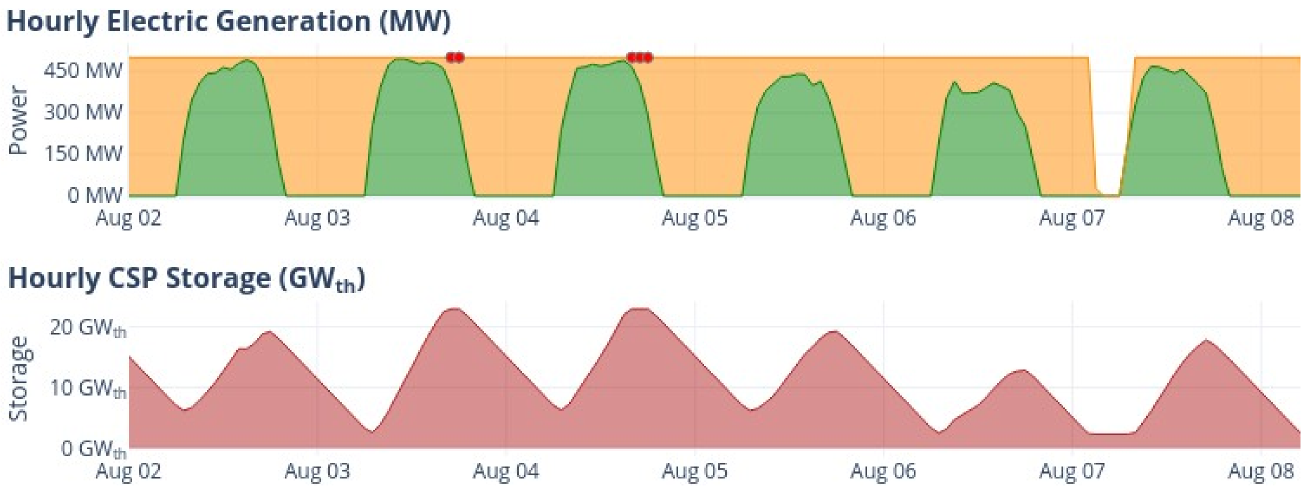


c) 24 hours of thermal storage

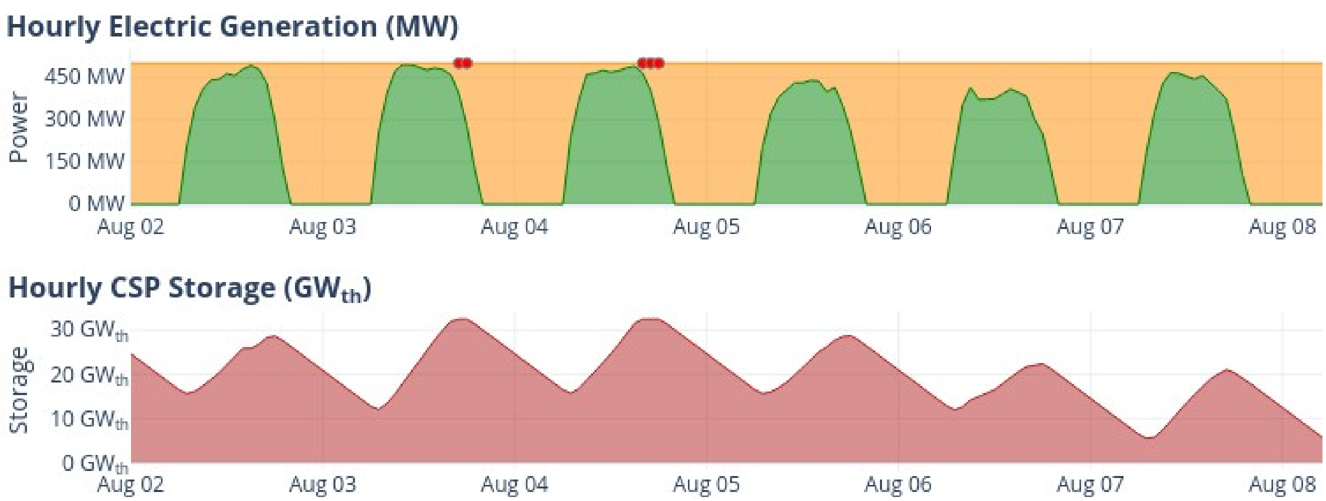
Fig. 3. Hourly electricity generation and available CSP thermal storage from March 15 to 21



a) 8 hours of thermal storage



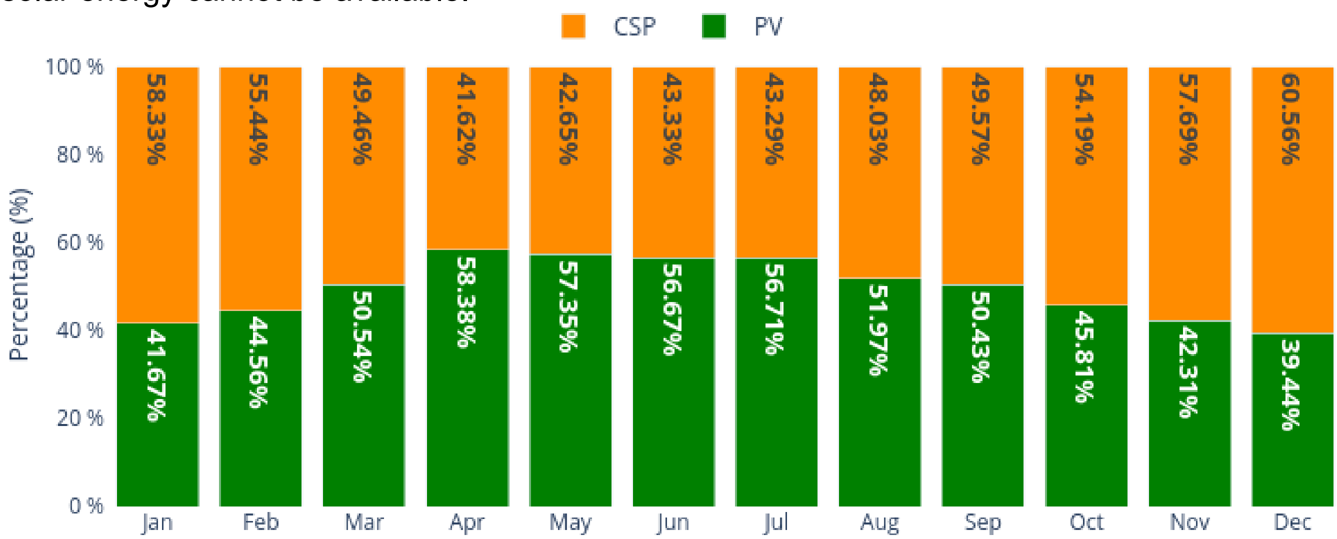
b) 17 hours of thermal storage



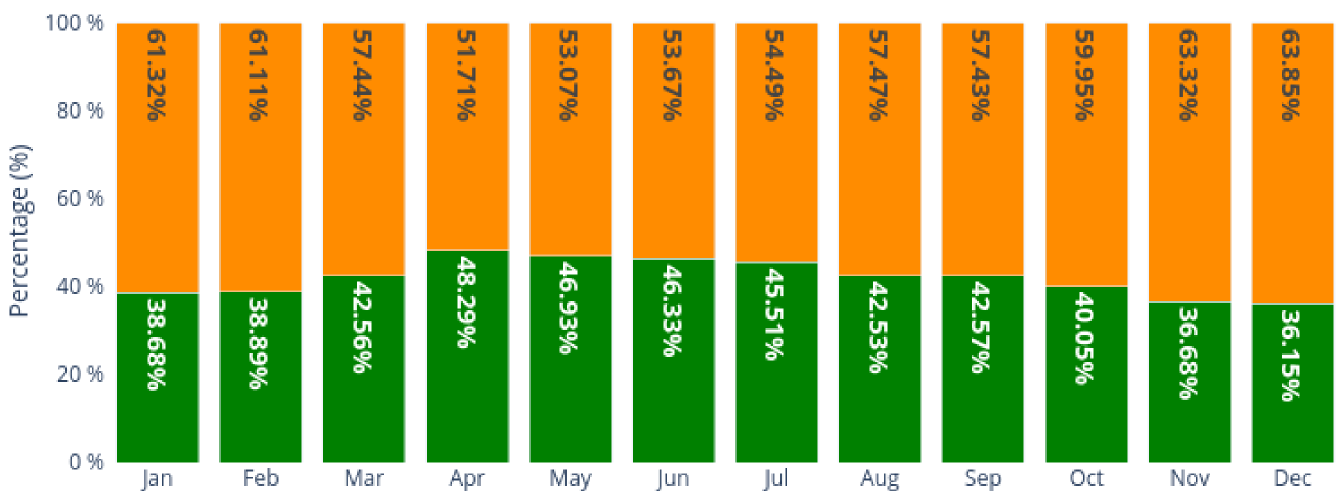
c) 24 hours of thermal storage

Fig. 4. Hourly electricity generation and available CSP thermal storage from August 1 to 7

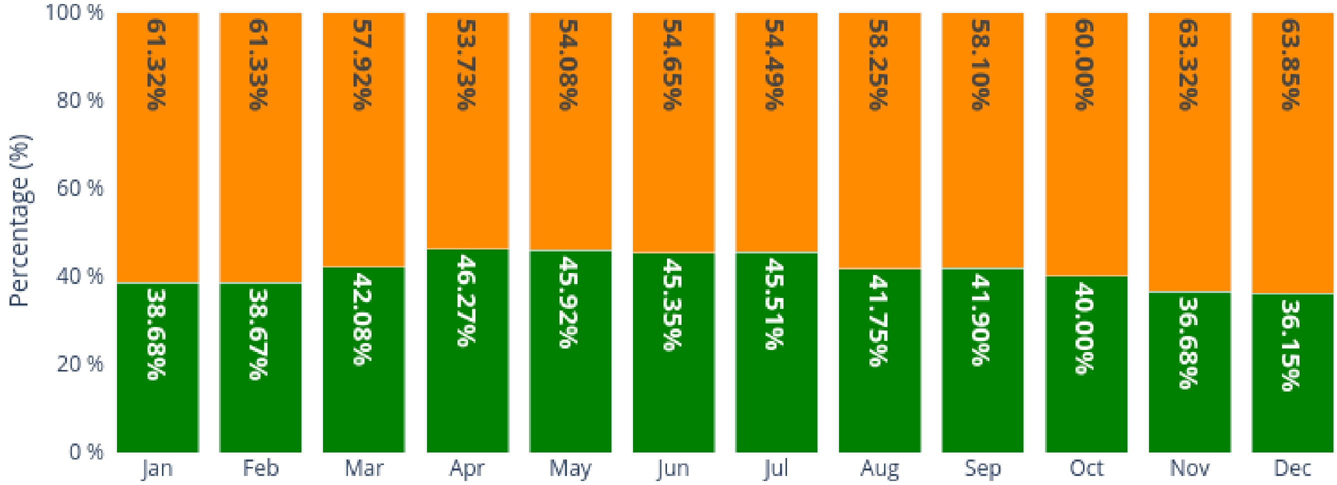
The relative contribution to the total electricity generation from each solar power technology each month is shown in Figure 5. Enhancing the CSP thermal storage allows to store more energy and increase the contribution of CSP to the electricity generation. However, reaching full coverage of the total electricity demand with solar energy is not possible, especially during the winter. Figure 6 represents the monthly capacity factor, that is, the fraction of the month that the solar energy can supply the total electricity needed to produce 4 Hm^3/day with RO plant. As it can be observed, adding CSP energy to the PV increases significantly the capacity factor each month, but it can only reach close to 100% during the summer months. Increasing the total power installed, instead of 500 MW_e for each plant as considered in this study, could enhance the capacity factor during the winter months, but at the expense of having excessive power during the summer, which would mean that solar energy would not be used, with the subsequent impact on the CAPEX of the power plants. In the months when the capacity factor is below 100%, additional electricity from the grid (most likely non-renewable) would be needed during the night. However, in many cases the water demand during the winter months is less than in the summer, so the RO plant could be stopped for some hours at night when solar energy cannot be available.



a) 8 hours of thermal storage



b) 17 hours of thermal storage



c) 24 hours of thermal storage

Fig. 5. Monthly relative contribution of each solar power technology

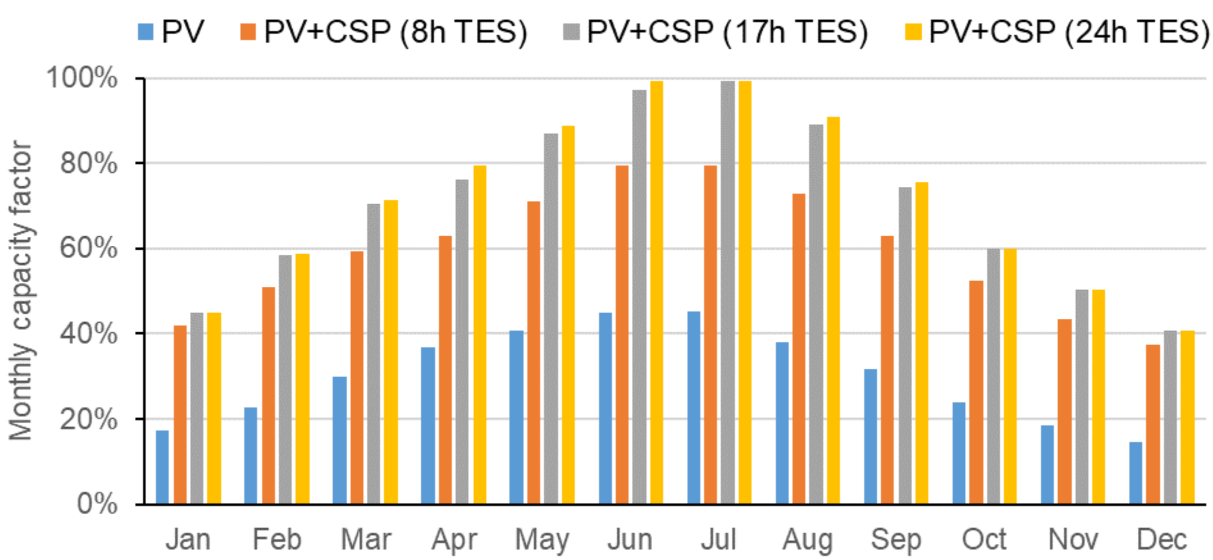


Fig. 6. Capacity factor for each month of the PV system alone and hybridized with CSP with different scenarios of thermal energy storage (8, 17 and 24 hours).

Table 1 summarizes the results, showing LCOE, capacity factor and land use for each solar power technology considering the three different scenarios of CSP with TES: 8, 17 and 24 hours. Table 2 shows the results obtained for a hybrid PV+CSP system. The total capacity factor is the sum of the capacity factors obtained by the PV and the CSP-TES in each case. The total LCOE has been determined considering the respective LCOE weighted by the capacity factors of each PV and CSP technology. Using 17 h thermal storage does not make a big difference with respect to using 24 h thermal storage. In this case, the total capacity factor of solar energy would be about 71% and the costs of electricity about 4.56 c$/kWh for PV, and 14.62 c$/kWh for CSP, which result in total electricity cost of 10.30 c$/kWh, competitive compared with the predicted costs of PV+Batteries (with a medium technological development), that are around 27 c$/kWh [21].

Table 1: Results of each solar power technology for supplying electricity to a 4 Hm^3/day SWRO operation

	500 MW PV	500 MW CSP – Solar Tower		
Storage (Hours)		8	17	24
LCOE (c$/kWh)	4.56	13.51	14.62	15.59
Capacity factor (%)	30.42	29.16	40.30	41.25
Total land use (Ha)	1760.8	4459.9	4459.9	4459.9

Table 2: Results for a hybridization of PV + CSP with different TES capacities for supplying solar electricity to a 4 Hm^3/day SWRO operation

	500 MW PV + 500 MW CSP (8 h TES)	500 MW PV + 500 MW CSP (17 h TES)	500 MW PV + 500 MW CSP (24 h TES)
Total LCOE (c$/kWh)	8.94	10.30	10.91
Total Capacity factor (%)	59.58	70.72	71.67

IV. CONCLUSIONS

From the results of this work, it can be concluded that by adding CSP to PV, the use of solar energy in desalination can be significantly enhanced. With hybrid plants combining PV and CSP with thermal energy storage, it is possible to increase the total capacity factor, allowing the RO plant to operate continuously with solar energy during a much larger fraction of the time (above 70%), in comparison to only PV, which would provide just 30% of the total energy. Thus, CSP with thermal storage is demonstrated as a good supplement to PV for incorporating solar energy towards the decarbonization of desalination. Combining 500 MW of PV and 500 MW of CSP with 17 hours of thermal storage would produce in SE Spain a total amount of solar energy closer to that required by RO plants to produce a total of 4 Hm^3 of SWRO desalinated water per day. For this case the total electricity cost of 10.30 c$/kWh would be competitive with the predicted cost of PV using batteries, and even the price of grid electricity in many cases. These results should be taken as a reference, since it is not very likely that 500 MW solar power plants are built, but instead a series of distributed plants with smaller capacity. However, for what concerns the hybridization of PV and CSP, the conclusions are valid and roughly scalable. Future research should investigate the optimization of the size of the different solar systems to maximize the capacity factor while keeping the minimum LCOE.

V. REFERENCES

1. https://sdgs.un.org/goals
2. I. Ihsanullah, M.A. Atieh, M. Sajid, M. K. Nazal, Desalination and environment: A critical analysis of impacts, mitigation strategies, and greener desalination technologies, Science of the Total Environment 780 (2021) 146585.
3. J. Ríos-Arriola, N. Velázquez, J. Armando Aguilar-Jiménez, G.E. Dévora-Isiordia, C.A. Cásares-de la Torre, J. Armando Corona-Sánchez and S. Islas, State of the Art of Desalination in Mexico, Energies 15 (2022) 8434
4. A. Tal, Addressing Desalination's Carbon Footprint: The Israeli Experience, Water 10 (2018) 197
5. UNESCO; World Water Assessment Programme. The United Nations World Water Development Report 2014: Water and Energy;
6. UNESCO: Paris, France, 2014. The Glasgow Climate Pact—UN Climate Change Conference (COP26) at the SEC—Glasgow 2021. Available online: https://ukcop26.org/the-glasgow-climate-pact/ (accessed on 9 February 2023).
7. IRENA. (2020). Renewable power generation costs in 2019. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Jun/IRENA_Power_Generation_Costs_2019.pdf
8. A. Boretti and S. Catelleto, Trends in performance factors of large photovoltaic solar plants, Journal of Energy Storage 30 (2020) 101506.
9. F. Trieb, H. Müller-Steinhagen, J. Kern, J. Scharfe, M. Kabariti, A. Al Taher, Technologies for Large Scale Seawater Desalination Using Concentrated Solar Radiation, Desalination 235 (2009) 33–43.
10. The value of solar thermal electricity. Cost vs. value approach, Published by ESTELA (European Solar Thermal Electricity Association), Brussels, Belgium, 2016 https://estelasolar.org/our-activities/communication-and-media/publications/
11. G. Zhu and C. Libby, Review and future perspective of central receiver design and performance, AIP Conference Proceedings 1850 (2017) 030052.
12. W. Platzer, "PV-Enhanced Solar Thermal Power," Energy Procedia 57 (2014) 477-486
13. A. Green, C. Diep, R. Dunn and J. Dent, High capacity factor CSP-PV hybrid systems, Energy Procedia 69 (2015) 2049-2059
14. A. Zurita, C. Mata-Torres, C. Valenzuela, C. Felbol, J. M. Cardemil, A. M. Guzmán and R. A. Escobar, Techno-economic evaluation of a hybrid CSP + PV plant integrated with thermal energy storage and a large-scale battery energy storage system for base generation, Solar Energy 173 (2018) 1262-1277
15. C. Valenzuela, C. Mata-Torres, J. M. Cardemil and R. A. Escobar, CSP + PV hybrid solar plants for power and water cogeneration in northern Chile, Solar Energy 157 (2017) 713-726
16. C. Mata-Torres, P. Palenzuela, A. Zurita, J.M. Cardemil, D.C. Alarcón-Padilla, R.A. Escobar, Annual thermoeconomic analysis of a Concentrating Solar Power + Photovoltaic + Multi-Effect Distillation plant in northern Chile, Energy Conversion and Management 213 (2020) 112852
17. C. Mata-Torres, P. Palenzuela, D.C Alarcón-Padilla, A. Zurita, J.M. Cardemil, R.A. Escobar, Multi-objective optimization of a Concentrating Solar Power + Photovoltaic + Multi-Effect Distillation plant: Understanding the impact of the solar irradiation and the plant location, Energy Conversion and Management X 11 (2021) 100088

18. D. Zarzo and D. Prats, Desalination and energy consumption. What can we expect in the near future?, Desalination 427 (2018) 1-9
19. https://sam.nrel.gov/
20. G. Van Rossum, FL. Drake, Python 3 Reference Manual. Scotts Valley, CA: CreateSpace; (2009)
21. F. Schönigera, R. Thonigb, G. Rescha, and J. Lilliestam, Making the sun shine at night: comparing the cost of dispatchable concentrating solar power and photovoltaics with storage, Energy Sources, Part B: Economics, Planning, and Policy 16 (2021) 55–74