The operation of large-scale reverse osmosis units in combination with different solar power plants, both, Concentrating Solar Power (CSP) and Photovoltaics (PV) has been evaluated under variable load conditions. In the case of the Reverse Osmosis (RO) unit, configurations with and without an energy recovery device have been considered. In the case of the CSP plant, a thermal storage system with several capacities (8–14 h) covers the periods with low solar radiation and no storage has been taken into account for the PV plant due to the prohibitively high cost of batteries at large scale. Two scenarios and different strategies within each scenario have been proposed to adapt the operation of the RO unit at partial load in order to assure a stable operation. In the first scenario, the RO unit is represented as a whole unit with variable performance according to the power availability. In the second scenario, the RO unit is composed of 10 sub-units that are switched on/off depending on the power availability. The analysis has been done for a specific location in Algeria and the dynamic performance of the RO unit has been presented for each scenario, together with an economic analysis.

Introduction

The development of industrial and agricultural activities together with the increasing population has led to the massive exploitation and contamination of water resources, leading to an alarming shortage of fresh water. Middle East and North Africa (MENA) is one of the regions suffering more and more from serious problems of freshwater availability [1]. Such water scarcity leads to the use of seawater desalination technologies that can alleviate this problem [2]. Algeria is one of the countries in MENA region that has included seawater desalination. The strategy of Algeria until 2030 is to have 1 billion m^3/year of water produced by seawater desalination [3]. The exploitation of renewable energy sources (solar or wind) to produce electricity and fresh water is commonly considered as a very promising way to reduce the pollution and the environmental impact. Algeria has this great solar potential and the climatic conditions are favorable for the implantation of solar plants. Therefore, it seems logical that solar desalination will be one of the solutions to obtain freshwater in many regions of the country.

There are several works in the scientific literature about the combination of RO plants with Photovoltaics (PV) or wind energy and with CSP, which give promising economic results when it is compared with the operation of Reverse Osmosis (RO) driven by fossil energy. However, some of them have been done for a design point or don't consider the operation of the desalination plant under intermittent power due to the nature of the source of energy. Manolakos et al. [4] presented a technical and economic comparison between a PV-RO system and a RO-Solar Rankine system with a capacity of 0.1 m^3/h and 0.3 m^3/h of fresh water, respectively. The study was carried out in Thirasia Island (Greece). The cost of desalination using the PV-RO system resulted 7.77 €/m^3 while that of the RO-Solar Rankine system was as high as 12.53 €/m^3. The authors concluded that the PV-RO cost is very close to that of water transport cost, thus the PV-RO system could be a realistic solution for the problem of water scarcity in this region. Triki et al. [5] studied the feasibility of using 1MW_e wind turbine to power a brackish water RO unit including pressure exchanger recovery system for three southern locations in Algeria (Adrar, Timimoun and Tindouf), in which storage batteries were used to cover the intermittence and fluctuation of the wind power. The authors revealed that the daily nominal water production based on the annual electricity production delivered by the wind turbine was 3720 m^3/day in Adrar, 3315.36 m^3/day in Timimoun and 2843.52 m^3/day in Tindouf. Moreover, the levelized water costs were found to be 0.66 \$/m^3 at Adrar, 0.7 \$/m^3 at Timimoun, and 0.75 \$/m^3 in Tindouf, with the RO unit operating only under design point. Nafey et al. [6] performed an energy, exergy, and cost analysis for a combined solar organic Rankine cycle (ORC) and a RO desalination unit. The study was carried out taking the same specifications as Sharm El-Shiekh RO desalination plant (Egypt). Several solar thermal collectors (Flat Plate, Parabolic Trough and Compound Parabolic Concentrator) were investigated for the heat input required in the ORC where different working fluids were examined for such cycle. The results showed that Parabolic Trough collectors are the best choice for the thermal energy supply. Dehmas et al. [7] presented an analysis of a 5000 m^3/day SWRO system powered by a wind power plant with a nominal capacity of 10 MW_e in the region of Tenes (Algeria). An economic analysis of the environmental benefits was done but the operation of the desalination plant under intermittence and fluctuated wind power was not presented. Finally, Caldera et al. [8] did a global estimation of the seawater desalination cost based on solar PV and wind energy for 2030. The authors concluded that the levelized water cost for regions with a desalination demand in 2030 is found to lie between 0.59 €/m^3-2.81 €/m^3, which are very similar to those of today in the case of powered fossil seawater RO (SWRO) plants (price between 0.60 €/m^3-1.90 €/m^3).

There are only few works in the literature that consider the intermittent power source. Wenyu Lai et al. [9] presented the different solutions and strategies used to adapt the wind power fluctuation to a RO desalination process. Three types of strategies were applied; the first is the storage technology to maintain the energy supply constant. The second is the hybridization to smooth out the wind fluctuation and intermittence. The third strategy, called self-adjusting RO unit, consisted in adapting the operation with the variable energy input as follows: firstly, adjusting the operating conditions of the RO unit within a safe operational window (SOW), secondly, adjusting the RO using the gradual capacity strategy. Ntavou et al. [10] presented an experimental evaluation of a small-scale multi-skid RO unit (an RO unit composed of several RO sub-units) with a capacity of 2.1 m^3/day that operate with fluctuating power, considering different seawater temperatures. The authors proved the flexibility of the use of the multi-skid RO unit configuration, especially when the power input derives from a fluctuating renewable energy source. Peñate et al. [11] presented the assessment of a stand-alone wind powered RO desalination plant with isobaric energy recovery device applying the gradual capacity strategy to adapt the fresh water production to the wind power availability. The nominal production of this plant was 1000 m^3/day with a fixed recovery ratio of 35%, and it was compared to a conventional fixed capacity desalination plant with a recovery ratio varying between 34% and 40%. The authors concluded that the fixed capacity plant allows the production of a greater amount of water per year in comparison with the gradual capacity strategy, but the desalination unit does work more hours in the year in the latter case.

Regarding the combination of RO units with solar thermal plants, Palenzuela et al. [12], [13], [14] investigated several configurations of the coupling between multi-effect distillation (MED) units and parabolic trough concentrating solar power (CSP) plants and compared them to the combined CSP-RO system. In all the configurations studied, the net electric power was 50 MW_e. A detailed techno-economic analysis was carried out for two locations, Almeria (southern Spain) as Mediterranean region and Abu Dhabi (UAE) in Arabian Gulf. The work was performed considering three different conventional refrigeration processes for the power cycle in the CSP plant (dry cooling, once through cooling, and evaporative cooling). It was found that for Mediterranean region, the combined CSP-RO system using the evaporative cooling technology is better from a thermodynamic and economic point of view, being the electricity and water costs in this case 18.79 c€/kWh and 1.01 €/m^3, respectively.

This paper covers the research gaps in the literature presenting a techno-economic comparison between two stand-alone solar desalination systems (i.e. the RO plants operate only with the electricity provided from the solar plants) at variable load conditions: a 50,000 m^3/day RO plant directly powered by a CSP plant with central receiver tower technology, and the same RO plant directly driven by the electricity produced by a PV plant without batteries. In the first case, different thermal storage capacities have been investigated. Three options have been studied for the RO plant: an RO plant without energy recovery device (ERD) and an RO with two types of ERD (a Pelton wheel turbine recovery (WTR) and a pressure exchanger (PEX)). The study has been performed for a specific location in Algeria: TENES, one of the Algerian coastal regions at the Mediterranean area. On one hand, it has been considered that the CSP plant is located 60 km far from the coast to avoid corrosion problems in the mirrors and the possible reduction in the Direct Normal Irradiation (DNI) and, on the other hand, the PV plant has been located at 5 km far from the coast also to avoid corrosion in the solar panels. In the two solar desalination systems analyzed, the RO plant will be located at 2.5 km from the shore. In both cases (CSP or PV plants), the RO unit will operate according to the available power coming from the solar plant, adapting its operation following the most suitable strategies developed to assure acceptable fresh water production without affecting the membrane.