# Design and economic evaluation of solar-powered hybrid multi effect and reverse osmosis system for seawater desalination

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## Abstract

Reducing the cost of fresh water has always been a major concern in the desalination industry. A solar powered hybrid multi-effect distillation and reverse osmosis desalination plant (MED+RO) has been designed and optimised from an economical point of view in a previous work by the same authors. In the present study, the possibility of coupling the desalination plant with a photovoltaic (PV) solar farm is investigated, with the aim of generating electricity at low cost and in a sustainable way. A detailed mathematical model for the PV system has been implemented from the literature. Interestingly, the model can predict the cost of the PV system in terms of capital cost and electricity cost per kWh considering the input data of solar irradiation, duration of daylight and technical specification of a real solar module. Consequently, the solar PV model has been combined with the desalination model, which enables to estimate the cost of fresh water per cubic meter. Data about four locations, namely Isola di Pantelleria (IT), Las Palmas (ES), Abu Dhabi (UAE), and Perth (AUS), have been used to economically test the feasibility of installing the proposed plant, and especially of the PV solar farm.

***Keywords:*** Seawater desalination, MED+RO+PV photovoltaic hybrid system, Economic cost modeling, Cost estimation, Fresh water production cost.

## Introduction

Seawater desalination is and will be a fundamental process to deal with fresh water shortage in many regions of the world. However, every desalination technology is energy intensive. The use of traditional energy sources is raising more and more concern not only because of an increase in cost, but also because of the pollution problems derived from the burning of fossil fuels (Khan et al., 2018). Fortunately, areas where desalination is required often have a good potential for renewable energy usage. Wind, geothermal and solar are getting a lot of attention as possible alternatives for energy production and much research has been done on the use of these energy sources in combination with desalination technologies. Especially, solar energy has been studied for decades to reduce the cost of solar panels while increasing their efficiency and is nowadays a very convenient renewable source. Having said this, the use of photovoltaics is particularly convenient in regions with a high amount of solar irradiation, such as the Gulf Cooperation Council Countries. It is noteworthy to mention that PV renewable energy source has been utilised by Espino et al. (2003) as a stand-alone process to supply an adequate energy for RO process. More importantly, Azevedo Santos Moniz (2014) demonstrated a share of 43% for PV in water desalination compared to 27%, 20%, and 10% for solar thermal, wind, and hybrid, respectively. This can address that PV is the dominant renewable energy source. Moreover, several researches can be found in the literature that presented the use of concentrating solar power (CSP) in conjunction with a desalination plant. In this respect, Khan et al. (2018) have reviewed several technologies used for the desalination of water using renewable sources of energy in large and small desalination plants. This include a thorough analysis of the trends and technical developments of PV-RO, wind-RO, and hybrid PV-wind-RO. Some of the successful research on the use of solar energy in hybrid desalination plants are reported in the following.

Mohamed et al. (2004, 2006) carried out a simulation of a simplified hybrid wind-PV-RO desalination plant based on a techno-economic analysis. This in turn elaborated an outstanding water production cost of 5.21 €/m$^3$.

Koutroulis and Kolokotsa (2010) affirmed a lower overall production cost of hybrid desalination system of PV/wind compared to an individual process of PV or wind. The study is occurred via an optimisation of process performance in such desalination systems.

Palenzuela et al. (2011) investigated the potential of low temperature (LT) MED and MED_TVC desalination systems coupled with a concentrating solar power (CSP) plant, considering also a reverse osmosis (RO) unit connected to the same power plant. The simulation was carried out using hourly irradiation data from Almeria in Spain and showed that the combination of solar energy with LT-MED is more efficient thermodynamically than the configuration with MED_TVC. Moreover, the CSP plant coupled with MED_TVC is more cost-effective with respect to the independent processes due to the requirements of a smaller solar field.

Calise et al. (2014) designed a solar trigeneration system integrating photovoltaic/thermal collectors (PVT) and multi-effect seawater desalination. The solar system was able to produce both heat and electrical energy for the desalination unit, achieving good performance on both energetic and economic point of view. The system was modelled and dynamically simulated and a thermo-economic analysis was conducted, aiming to determining the optimal values of the most important design variables.

Weiner et al. (2015) investigated the design of a CSP+MED+RO system to be installed in California’s Central Valley. The study highlighted the economic benefits of using a hybrid system with respect to stand-alone processes, as well as the benefits of using CSP as energy source instead of grid electricity.

Smaoui et al. (2015) designed an optimal photovoltaic (PV) system to supply a reverse osmosis desalination unit. The methodology used aimed to find the optimal technical-economic configuration, considering meteorological data and desalination power requirement of Kerkennah island in Tunisia. As a result, the installation of a PV system combined with wind turbines resulted in the best configuration to minimise the fresh water production cost.

Novosel et al. (2015) modelled a RO seawater desalination system coupled with wind and PV plants to be installed in Jordan, a region in need of fresh water and at the same time rich in potential for renewables. In this study, six scenarios for the development of the Jordanian energy system were investigated. The results showed that the proposed system can increase the share of renewables in the production of electricity with a consequent reduction in fuel consumption, costs and pollution.

Khan et al. (2018) indicated that extensive experimental and theoretical researches have been carried out on coupling PV and wind energy to power RO systems. Up to the authors' knowledge, the economic analysis for the coupling of photovoltaic system with a hybrid desalination plant that uses RO process and a thermal process of multi-effect distillation, has not been thoroughly discussed in the literature. This is basically true for the feasibility assessment to construct such proposed hybrid desalination plant in several locations around the world based on actual data. In fact, concentrated solar power is often the preferred technology to simultaneously produce electricity for the membrane process and secondarily for the thermal process, and heat for the thermal process. However, considering the recent remarkable decrease in the cost of energy produced with PV, together with the fact that the estimated cost of low temperature, low pressure steam for the LT-MED process is much lower than the cost of electricity for the entire system (Al-Obaidi et al., 2019), using PV alone can be a plausible alternative from an economic point of view for the proposed plant. In order to test the model with actual data related to real locations, four sites have been chosen for theoretical installation of the system and the criterion of judgement is an economic one.

## 2. Description of proposed hybrid MED+RO desalination system

Multi effect distillation (MED) is a thermal process mainly used for seawater desalination. The process consists of many stages called *effects*. In each of these effects, seawater is sprayed on a horizontal tubular heat exchanger where steam flows inside, and it is partially evaporated. The vapor is then partially used to pre-heat the feed, and the rest is sent to the next effect. Pressure and temperature decrease among the effects to ensure the driving force for the heat exchange. In the literature, the economic and energetic competitiveness of low-temperature MED process compared to the thermal process of multi stage flashing (MSF) has been clearly highlighted (Ophir et al., 2005; Al-Sahali et al., 2007).

Reverse osmosis (RO) process is used in several industrial applications like seawater desalination, food and beverage processing and wastewater treatment (Al-Obaidi et al., 2017). RO process is counted as one of the prominent separation methods due to its ability to separate solids and pollutants effectively and in an environmentally friendly way, while maintaining low energy consumption (Ang et al., 2017; Hilal and Wright, 2018). Seawater reverse osmosis is a pressure driven process in which two mediums of different solute concentration are separated using a semi-permeable membrane. This process uses higher pressure than the osmotic pressure, thereby water and a little fraction of some ions can pass over the membrane from the high concentration side towards the low concentration side, while most of the salts are rejected. Seawater desalination plants using RO technology are usually designed as a multi-stage process in a way to fulfil high quality water at high recoveries.

In Fig. 1, a complete hybridization of MED and RO process is represented from a previous research of the same authors (Filippini et al., 2018). In this respect, RO process is placed upstream to maximize the recovery ratio of the plant and receives the seawater feed from the seawater storage tank. The RO retentate is mixed with a by-pass stream and fed to the MED process. The distillate of the thermal process and the permeate of the membrane process are blended to obtain a fresh water with a salinity lower than 200 ppm. The detailed mathematical model of the whole hybrid MED+RO system is summarised in Tables A.1 and A.2 in Appendix A. The economic model to evaluate the cost of fresh water is given in Table A.3 in Appendix A.

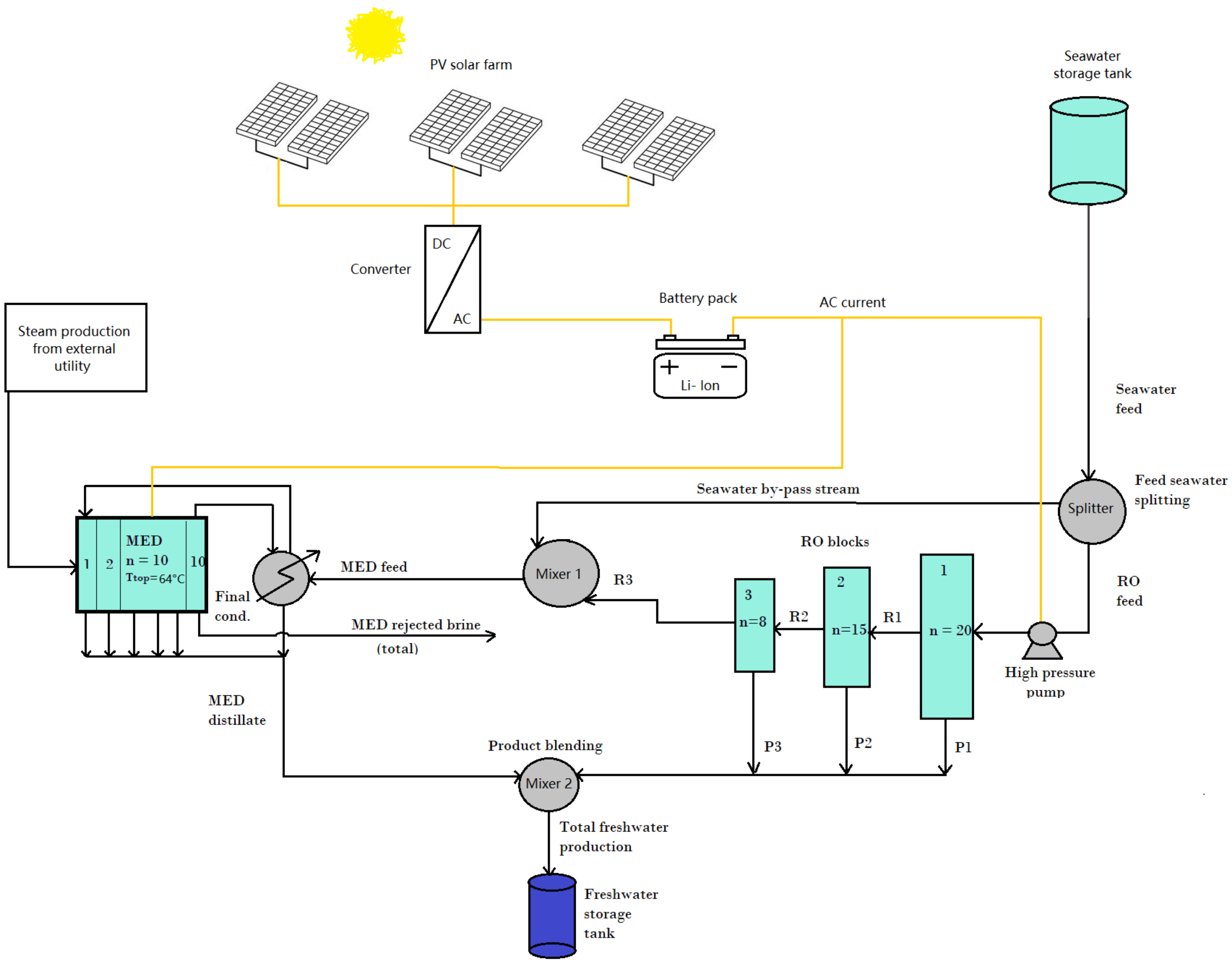


**Fig. 1**. Schematic representation of the complete plant (MED+RO+PV).

The whole hybrid plant of MED+RO has been optimised with respect to some relevant operating parameters, using the final cost of fresh water as a single objective function to be minimised (Al-Obaidi et al., 2019). Table A.4 in Appendix A shows the optimised operating conditions in addition to other parameters required for the simulation, both for Med and RO. Additionally, Table A.5 in Appendix A presents the economic variables used in the economic model.

Few limitations of the economic model used in the study can be identified. First, the cost related to the disposal of the rejected brine, which can be non-negligible especially when considering isolated locations, is not included. Secondly, the lack of evaluation of the cost associated with the import of steam to power the MED section of desalination plant, since the PV system can provide electricity only to the RO plant. However, the cost of steam is considered in the economic model, while only the transport cost was not very relevant. However, the authors believe that those limitation do not undermine the validity of the model, since the non-considered cost are expected to be negligible with respect to, for example, the cost of electricity.

Fig. 2 shows the results of the optimised simulation for the MED+RO system without PV carried out by Al-Obaidi at. al (2019), in terms of fresh water cost and annual operating costs as a function of electrical energy price. The output of this economic optimisation is a substantial increase in the productivity of RO process besides an increase of its electrical energy consumption. More importantly, a strong relationship is confirmed between the fresh water cost, annual operating cost and electricity price. Therefore, finding a way to produce a cheap electricity would serve the reduction the cost of fresh water and increase the environmental stainability of the plant. In this respect, a photovoltaic solar farm has been designed and connected to the desalination MED+RO plant to generate the required electrical energy both for the thermal and the membrane process (Fig. 1). A detailed explanation of the PV system and the mathematical model are illustrated in the next section.

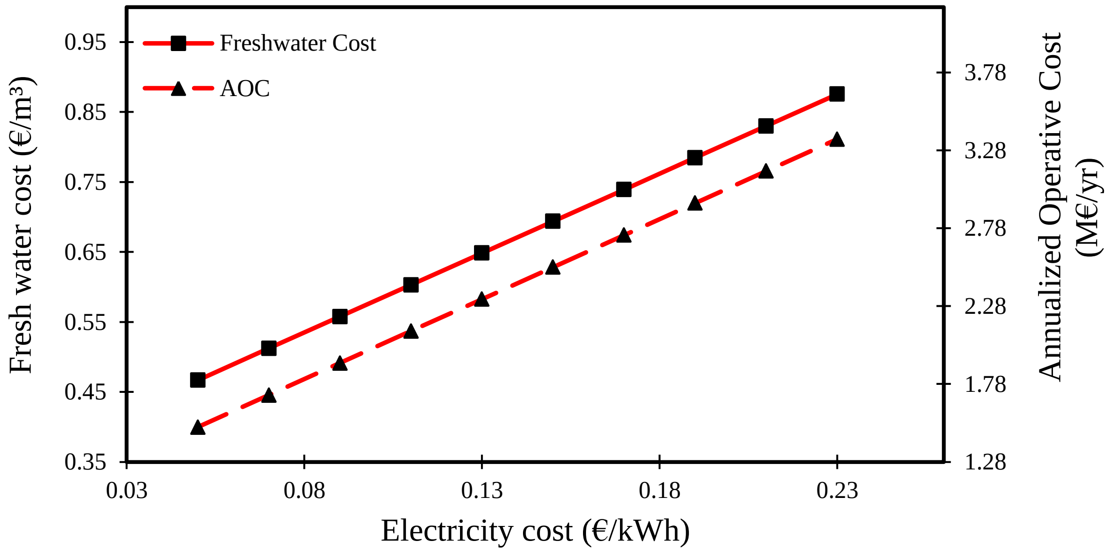


**Fig. 2**. Fresh water cost against electricity cost. Seawater salinity and temperature fixed at 39000 ppm and 25 °C. (Adapted from Al-Obaidi at. al, 2019)

### 3. Description of proposed photovoltaic system

In a photovoltaic (PV) system, solar radiation is converted into electrical power using a semiconductor material. Solar radiation causes electrons to be released and to move accordingly to internal electric potential. If a load is connected, an external path is created outside the cell and electrons start flowing in the circuit, generating a current. The generated voltage depends mainly on the material and design of the cell, while the current intensity is primarily a function of solar radiation and cell area. However, only a small part of the incident solar power can be converted into electrical power by a PV system. This is due to the efficiency of conventional solar cells, which is in the order of 10% to 20 %. Many materials have been implemented in order to improve efficiency and reduce manufacturing costs.

Nowadays, solar cell production is dominated by crystalline silicon modules, which represent around 90% of the market (Waldau, 2004). Other materials, for example amorphous-silicon, cadmium-telluride, and gallium arsenide have been proposed in more recent years and significant investments are being made in their development. Many solar cells are packed together in a PV module or panel; modules are usually connected in large arrays to satisfy the power requirement and mounted on fixed or sun-tracking supports. Additionally, other components like batteries, cabling, controllers and converters are necessary to interface the PV with the electrical grid. Given the intermittent nature of solar radiation, coupling the solar modules with a battery stack is mandatory to store electrical power and to provide it in a continuous way. The most common types of battery coupled with a solar system are lead-acid, cheaper and mostly used for small installations, and lithium-ion, which are more expensive but guarantee better efficiency and durability. The cost of the energy storage system is usually relevant and must be assessed when performing an economical evaluation of the system.

The maximum power production of a module is expressed in Watt-Peak (Wp). A PV module exposed to a standard solar radiation of 1000 W/m$^2$ at a cell temperature of 25 °C will produce a quantity of electrical energy equal to its peak capacity. However, the real power output of a PV module is usually around 20-30 % of its maximum output (Solanki, 2015). This is attributed to the average solar radiation received by the panel, which is smaller than the standard solar radiation and mainly dependent on geographical location.

The power output of a solar panel in (W) depends on its overall efficiency ($\eta_{tot}$), its area ($A_{mod}$) in (m$^2$), and solar radiation ($G$) in (W/m$^2$) as depicted in Eq. (1)

$$P = \eta_{tot} \, A_{mod} \, G \qquad (1)$$

An accurate evaluation of the overall efficiency must account for the module efficiency ($\eta_{MOD}$), losses due to dirt on panel's surface ($\eta_{DIRT}$), losses due to inverters ($\eta_{INV}$), and losses due to connections ($\eta_{CON}$). The value of $\eta_{DIRT}$ greatly depends on the location and frequency of cleanings. In this respect, a number equal to 0.95 should be reasonable assuming a frequent cleaning (Maghami et al., 2016). Inverters and connections efficiency are assumed equal to 0.98.

$$\eta_{tot} = \eta_{MOD}\,\eta_{DIRT}\,\eta_{INV}\,\eta_{CON} \quad (2)$$

The module efficiency can be evaluated as a function of cell temperature $T_C$ (°C), implementing a correction with respect to its value at standard operating condition (SOC). The module efficiency at $T_{SOC}$ = 25 °C is $\eta_{MP,SOC}$. The temperature coefficient $\mu$ (°C$^{-1}$) has a negative value. Therefore, the module efficiency decreases for higher cell temperatures (Koroneos et al., 2007).

$$\eta_{MOD} = \eta_{MOD,SOC} + \mu(T_C - T_{SOC})$$

(3)

The module efficiency at standard temperature depends on several parameters including the current at maximum power point $I_{MP,SOC}$ (A) , the voltage at maximum power point $V_{MP,SOC}$ (V), standard solar radiation $G_{SOC}$ = 1000 W/m$^2$ and the module area $A_{MOD}$ (m$^2$) (Koroneos et al., 2007). For this study, a solar panel by *TopSun Energy Ltd* has been considered and its specifications are reported in Table 1.

$$\eta_{MOD,SOC} = \frac{V_{MP,SOC}\,I_{MP,SOC}}{A_{MOD}\,G_{SOC}}$$

(4)

Eq. (4) identifies that the calculated efficiency for standard module is 17.17%. This is in accordance with the value of 17.2% provided by the supplier. The temperature coefficient $\mu$ can be calculated using Eq. (5), where $\mu_{VOC}$ is the voltage temperature coefficient (%/°C) that is already provided by the manufacturer. The factor 38/100 is used to convert the value of $\mu_{VOC}$ from (%/°C) to (V/°C).

$$\mu = 0.38\,\eta_{MOD,SOC}\,\frac{\mu_{VOC}}{V_{MP,SOC}} \quad (5)$$

The cell temperature $Tc$ can be obtained by increasing the ambient temperature by a quantity that accounts for the solar radiation $G$ (w/m$^2$), transmittance of panel cover $\tau$, fraction of incident radiation absorbed by cells $\alpha$ and heat losses to the surroundings $H_{loss}$. The product $\tau\alpha$ is assumed constant and equal to 0.9 (Koroneos et al., 2007). Heat losses can be approximated as a linear function of the nominal operating temperature of the panel $T_{C,NOM}$, which is the temperature reached on the panel surface with a solar radiation $G_{NOM}$ = 800 W/m$^2$ and ambient temperature $T_{amb,NOM}$ = 20 °C. $T_{C,NOM}$ is assumed equal to 45 °C (Koroneos et al., 2007).

$$T_C = T_{amb} + H_{loss} \frac{1-\eta_{MOD,SOC}}{\tau\, \alpha} \tag{6}$$

$$H_{loss} = \frac{T_{C,NOM} - T_{amb,NOM}}{G_{NOM}} \tag{7}$$

At this point, it is possible to evaluate the module overall efficiency $\eta_{tot}$, which results to be in the range of 15% to 16%, depending on the assumed ambient temperature and solar radiation. Using Eq. (1), is it possible to evaluate the power output of a single module, P (W), as a function of solar radiation. The power output of the module and the required energy production, both in (kWh/day), are evaluated by Eqs. (8) and (9), respectively

$$P_{mod} = 0.001\, P\, hours \tag{8}$$

$$P_{tot} = \frac{P_{DES}}{\frac{hours}{24} + \left(1 - \frac{hours}{24}\right) \eta_{CH}\, \eta_{DIS}} \tag{9}$$

$hours$ (hr/day) means the average duration of daylight, $P_{DES}$ (kWh/day) is the required power by desalination system, $\eta_{CH}$ and $\eta_{DIS}$ are the charge and discharge efficiency of the batteries.

The electrical power required by the hybrid desalination system of MED+RO takes into account the energy requirement of RO feed pump ($P_{el,RO}$) and MED pumps ($P_{el,MED}$). The latter is assumed equal to 2 kWh/m$^3$ of fresh water produced (Gude et al, 2010), while the energy requirement for RO is evaluated in kWh/m$^3$ using the model of the desalination process (Filippini et al., 2018). The productivities of the two process, $M_{MED}$ and $M_{RO,}$ are evaluated in ($m^3$/day).

$$P_{DES} = P_{el,MED}\, M_{MED} + P_{el,RO}\, M_{RO} \tag{10}$$

The value of $P_{DES}$ depends on seawater conditions of salinity and temperature, being less energetic intensive to desalt a warm and less saline water. For fixed values of salinity (39000 ppm) and temperature (25 °C), the power required by hybrid desalination is about 37000 kWh/day, which corresponds to a productivity of about 143 kg/s of fresh water (Filippini et al., 2018).

The number of modules required to satisfy this energy requirement will be the ratio between the total energy production $P_{tot}$ and the production of a single panel $P_{mod}$. However, the total area $A_{tot}$ will be the number of panels multiplied by the area of a single module $A_{mod}$, increased by 15% to account for additional space for cabling, workers' mobility, etc.

$$N_{modules} = \frac{P_{tot}}{P_{mod}} \tag{11}$$

$$A_{tot} = 1.15\, N_{modules} A_{mod} \tag{12}$$

Electricity generated with a PV system is almost free. This is because of very low operating costs due to the absence of moving parts where the solar energy is obviously free of charge. However, the capital expenses required to install such systems are often high and it is important to develop an economical model to predict such costs. There are two identified major contributions to the total capital cost of the PV system, namely the cost of modules $TCC_{mod}$ and the cost of energy storage system $TCC_{batt}$, which includes also a minor cost for the ACDC conversion (Notton et al, 1998).

$$TCC_{PV} = TCC_{mod} + TCC_{batt} = C_{mod} P_{peak} + C_{batt} S_{batt} + C_{ACDC} P_{load} \tag{13}$$

Cost of modules ($C_{mod}$), which includes also the cost of supports, inverters and cabling, is assumed equal to 0.8 €/Wp for a solar farm greater than 1MW (email with TopSun Energy

Ltd). Cost of Li-Ion batteries ($C_{batt}$) is assumed equal to 150 €/kWh. Cost of ACDC conversion ($C_{ACDC}$) in €/kW is calculated by Eq. (14) (Notton et al, 1998).

$$C_{ACDC} = 1099\, P_{load}^{-0.69} \tag{14}$$

$P_{load}$ is the electrical power consumption of desalination system in kW

$$P_{load} = \frac{P_{des}}{24} \tag{15}$$

The peak power $P_{peak}$ (Wp) that can be produced by the PV system is calculated assuming no losses due to dirt, inverters and connection and a solar radiation of 1000 W/m$^2$.

$$P_{peak} = \eta_{mod} A_{tot} G_{SOC} \tag{16}$$

The storage capacity of the storage system $S_{batt}$ (kWh) depends on the power output from PV and on charging efficiency of the batteries, considering the fraction of day when batteries are charging.

$$S_{batt} = \frac{P_{tot}\frac{hours}{24}}{\eta_{CH}} \tag{17}$$

Maintenance costs of a PV system are remarkably low. Indeed, according to the cost benchmark performed by the US National Renewable Energy Laboratory (NREL) for PV systems installed in Q1 of 2017, the O&M costs for large scale plants are in the order of 15 USD/kW per year, while the installation cost are less than 2 USD/W (U.S. NREL, 2017). This translates to O&M costs of about 1% of the total capital cost per year. In this respect, the total annualized cost of PV (€/yr) is calculated by Eq. (18). This is already based on assuming 5000 as the number of cycles before batteries deterioration (lifespan of Li-Ion batteries) and one charge-discharge cycle per day.

$$TAC_{PV} = TCC_{PV} CRF + 0.01\, TCC_{PV} + \frac{365\, C_{batt} S_{batt}}{5000} \tag{18}$$

By dividing the total annualized cost by the annual electric energy production of the PV system, it is possible to evaluate the cost of electrical energy $C_{el}$ in (€/kWh). This value is useful to make a direct comparison whit the cost of electrical energy provided by the grid.

$$C_{el} = \frac{TAC_{PV}}{365\ P_{tot}} \quad (19)$$

**Table 1**. Technical specifications of PV module (*TopSun Energy Ltd*).

| **TS-S440** | | | |
|---|---|---|---|
| Data | Symbol | Unit | Value |
| Current at maximum power point | $I_{MP,SOC}$ | (A) | 8.86 |
| Voltage at maximum power point | $V_{MP,SOC}$ | (V) | 49.67 |
| Voltage temperature coefficient | $\mu_{VOC}$ | (%/°C) | -0.33 |
| Module length | L | (mm) | 1960 |
| Module height | H | (mm) | 1308 |
| Module depth | d | (mm) | 40 |
| Module efficiency | $\eta_{MOD}$ | (-) | 0.172 |
| Maximum power output | $P_{MAX}$ | (Wp) | 440 |

**Table 2**. Technical specifications of a generic Li-Ion battery.

| Data | Symbol | Unit | Value |
|---|---|---|---|
| Charge efficiency | $\eta_{CH}$ | (-) | 0.95 |
| Discharge efficiency | $\eta_{DIS}$ | (-) | 0.95 |
| Life of the battery | $N_{cycles}$ | (-) | 5000 |

## 4. Results and discussion

Fig. 3 shows the number of panels and solar farm area in hectares (1 ha = 10000 $m^2$) required to satisfy the energetic demand of the proposed MED+RO desalination system, assuming 9.5 hours of useful daylight per day (average hours of sunny or moderately cloudy weather per day in a given region), as a function of solar radiation (1 $kWh/m^2$ day = ${}^{1}/_{0.024}$ $W/m^2$). Fixing a value for the daylight duration is required to have a simple by-dimensional plot. The dependence is strong for both parameters, suggesting that a value at least moderate of solar radiation is required to design a cost-effective PV system.

Fig. 4 represents the cost of electricity produced with the analysed PV system, as a function of geographical location. It is possible to observe that the final cost of electricity strongly depends both on the average solar radiation and on the hours of useful daylight duration. The proposed solar farm should preferable be installed in a sunny and well irradiated location to achieve a cost of electricity of 0.1 €/kWh or lower and to be competitive with the cost of electricity from other sources. The cost calculated by the proposed model is in line with the recent estimations of the *International Renewable Energy Agency (IRENA)* for solar electricity cost, which is from 0.05 to > 0.20 USD/kWh, depending on the region.

IRENA report allows for a comparison with the recent and cost-competitive solar park of Mohammed bin Rashid Al Maktoum in UAE, which has a planned capacity of 1 GW for 2020 and will be able to provide electricity at 5.85 USD/kWh (IRENA, 2016). As we can see from Fig. 4, the model presented in this work can achieve slightly worse results in terms of electricity costs when the PV plant is operated in a region with high solar radiation and daylight duration, like the Dubai region.

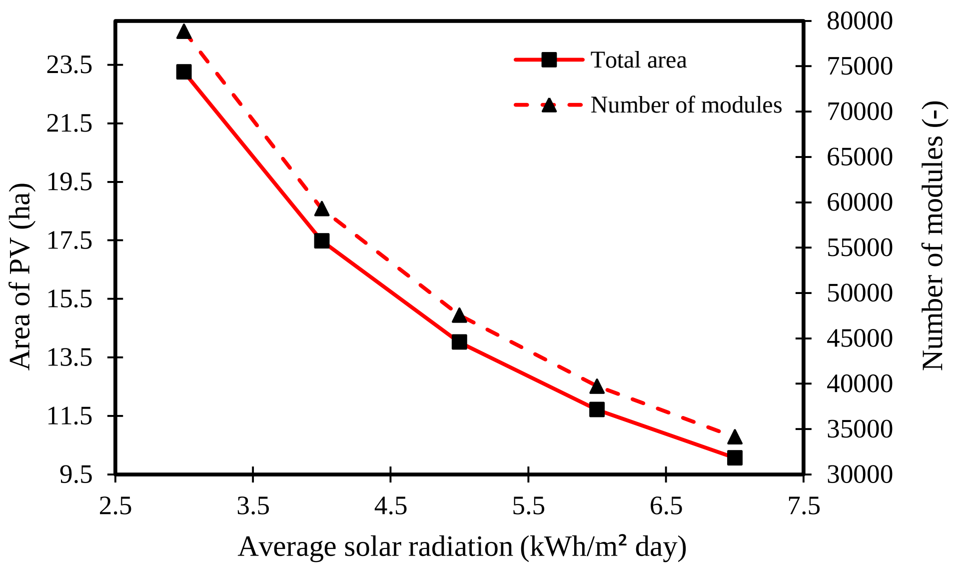


**Fig. 3**. Required area of PV system and number of panels for different values of solar radiation (9.5 hours of average daylight duration).

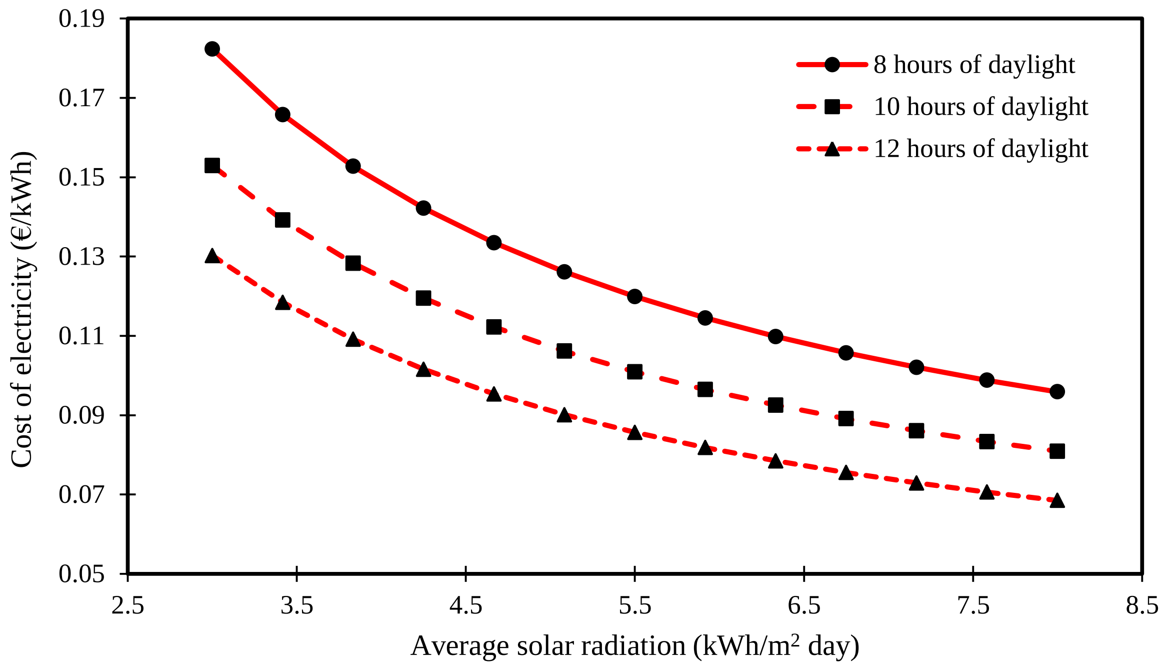


**Fig. 4.** Cost of electricity produced by the proposed PV for different values of solar radiation and daylight duration.

The next section illustrates the testing of the PV solar farm developed in this study with the actual input data related to real locations, namely the hourly solar irradiation, the duration of daylight, the seawater properties in the area and the cost of electricity. Therefore, the feasibility of constructing this hypothetical hybrid MED+RO desalination plant will be investigated for four real locations, namely Isola di Pantelleria (IT), Las Palmas (ES), Abu Dhabi (UAE) and Perth (AUS). More importantly, the convenience of installing the solar PV as an electricity source for the hybrid system will be assessed for the selected locations considering the characteristic of each region. This in turn will include the seawater properties, solar radiation, hours of light, cost of electricity from fossil fuels or other sources. Total capital costs are assessed for both plants (with or without PV) and a comparison with the actual cost of fresh water in the region if often highlighted. Data about average solar radiation are gathered from the *Global Solar Atlas*, information on seawater properties from the *Global Sea Temperature* website. Average hours of daylight are evaluated dividing the number of sunny hours per year in the region by 365 and increasing the result by 20% to account also for cloudy weather, since a non-negligible quantity of radiation still reaches the module's surface (Liou, 1976).

### 4.1 Isola di Pantelleria (IT)

Pantelleria is a small Italian volcanic island located 100 km South from coasts of Sicily. High population density especially in summer because of tourism, scarcity of natural fresh water sources and few precipitations make desalination as a mandatory technology to tackle the problem of water suppling. In Pantelleria, two MED desalination plants coupled with fossil-fueled power generation were installed in 1988 and 1994. Nowadays, those plants are not productive enough due to aging of unit operations and increase in fresh water demand, so a large quantity of water is supplied by carriers with tankers at a very high cost of about 3.5 €/$m^3$ (Manenti et al., 2013). More recently, RO desalination plants have been proposed for installation on Pantelleria and the neighboring islands of Lampedusa and Linosa. Electrical energy cost is very high on those islands, like in most isolated locations. The feasibility of installing the proposed MED+RO hybrid desalination system is analyzed here, as well as the economic advantage of producing electricity with PV.

Input of the model are reported in Table 7. The Mediterranean Sea has intermediate values of salinity and temperature. Pantelleria receives a good amount of solar radiation (over 5 kWh/$m^2$ day) and the average sunshine duration is slightly above 10 hours.

Table 3 summarises the results of the simulation. PV costs 11.3 M€ and exceeds the cost of desalination plant. About 1/5 of the total PV cost is due to the storage system. However, given the very high price of electricity in Pantelleria of 0.24 €/kWh (Manenti et al., 2013), the annual operating cost (AOC) of the desalination plant running with grid electricity is extremely high, at 3.6 M€/yr. Generating electricity with PV will cut down the AOC to 1.16

M€/yr. This means that the proposed PV system will pay itself back after about 4.5 years, which is a reasonable amount of time, considering that the operation of the plant is expected to last 25 years. The cost of fresh water produced with MED+RO is estimated to be 0.93 €/$m^3$ and the cost of fresh water with MED+RO+PV is 0.61 €/$m^3$. Both values are much lower than the actual cost of fresh water in Pantelleria. However, the implementation of PV will cut down the cost of another 34% with respect of the option using electrical energy from grid. Having said this, the installation of PV system could be an issue due to acknowledging the small surface of the island of only 83 $km^2$, while the estimated required area of PV system is about 10 ha (0.1 $km^2$).

**Table 3**. Result of the simulation for Isola di Pantelleria.

| Result | Unit | Value |
|---|---|---|
| Number of panels | - | 32941 |
| Area of solar farm | ha | 9.71 |
| TCC of desalination plant | M€ | 6.48 |
| TCC of PV plant | M€ | 11.31 |
| TCC of modules | M€ | 8.89 |
| TCC of storage | M€ | 2.42 |
| AOC with grid electricity | M€/yr | 3.60 |
| AOC with PV | M€/yr | 1.16 |
| Fresh water cost with grid electricity | €/$m^3$ | **0.93** |
| Fresh water cost with PV | €/$m^3$ | **0.61** |

### 4.2 Las Palmas (ES)

Las Palmas is a Spanish city in the Island of Gran Canaria, one of the seven Canary Islands, an archipelago of volcanic islands located in the Atlantic Ocean, about 100 km from African coast. The Canary Islands always suffered from fresh water shortage, due to low rainfall and over-exploitation of aquifers. Before the '70s, the Canary Island relied on tankers to receive water supply from Spain, at high cost. The first MSF desalination plant was installed in Lanzarote Island in 1964 and operated until 1977. In 1974, another small plant was built in Fuerteventura. Gran Canaria Island installed the first MSF plant in 1970, followed by several RO plants in the following years, mainly around the city of Las Palmas (Gòmez et al., 2018). In 2002, the first RO plant of Spain connected with wind turbines to generate electricity was installed in Las Palmas. This plant has very low energy requirement (3 kWh/$m^3$) and final cost of fresh water is about 0.6 €/$m^3$ (Rybar, 2005).

Input for the proposed MED+RO+PV model are reported in Table 7. Average salinity of the Atlantic Ocean is lower than that of Mediterranean Sea. The region of Las Palmas has a good solar irradiation and a moderate daylight duration, which is not very high due to frequent cloudy weather. The cost of electricity, assuming a diesel plant as generating option, is very high at 0.19 €/kWh. On the other hand, the cost of electricity generated with wind turbines can be very competitive, at about 0.07 €/kWh (Marrero et al, 2010).

To understand how the proposed MED+RO+PV plant would perform in this region, a simulation has been taken and results are summarised in Table 4. Capital cost for PV installation is high and exceeds the cost of desalination plant, at almost 12 M€. About 1/5 of the PV cost is due to the storage system. When electricity is generated with a non-renewable source (i.e. diesel), its cost is very high and therefore the annual operative cost (AOC) of the desalination plant running with grid electricity is high, at 2.82 M€/yr. Generating electricity with PV will cut down the AOC to 1.17 M€/yr. This means that the proposed PV system will pay itself back after about 7.3 years. The cost of fresh water produced with MED+RO is estimated to be 0.75 €/$m^3$. This value is already quite low because of the low salinity of inlet oceanic water, which improves the performances of desalination plant. However, the cost of fresh water can be reduced to 0.59 €/$m^3$, which is a 22% reduction, by implementing the PV system. If wind is used as a source of electricity, it will be possible to generate it at about 0.07 €/kWh. Using this value in the MED+RO model, the calculated cost of fresh water is only 0.55 €/m$^3$, which is an 8% reduction with respect to the PV option. Results suggest that in Las Palmas the proposed MED+RO plant could run with both solar and wind sources to produce fresh water at low cost. However, the wind energy will be the useful option, considering also the possibly of building an off-shore plant.

**Table 4.** Result of the simulation for Las Palmas.

| **Result** | **Unit** | **Value** |
|---|---|---|
| Number of panels | - | 35963 |
| Area of solar farm | ha | 10.6 |
| TCC of desalination plant | M€ | 6.48 |
| TCC of PV plant | M€ | 11.98 |
| TCC of modules | M€ | 9.71 |
| TCC of storage | M€ | 2.27 |
| AOC with grid electricity | M€/yr | 2.82 |
| AOC with PV | M€/yr | 1.17 |
| Fresh water cost with grid electricity | €/m$^3$ | **0.75** |
| Fresh water cost with PV | €/m$^3$ | **0.59** |
| Fresh water cost with wind | €/m$^3$ | **0.55** |

### 4.3 Abu Dhabi (UAE)

Abu Dhabi is the capital of the United Arab Emirates. Underground water supplies of the region are good. However, the very rapid increase of population and water demand, together with an arid climate, made desalination as a mandatory technology to satisfy the need of fresh water. Today, several seawater desalination plants are running in the region. They mostly operate with fossil fuel as a source of energy. In 2018, the project for the world's biggest RO plant, to be built just outside the city, was presented at the World Water Summit. This plant will produce 200 MIGD (millions imperial gallons per day), or about 8.700 kg/s of fresh water. The expected fresh water production cost will be 0.01 AED (Arab Emirates Dirham)/gallon, or about 0.61 €/m$^3$ (Binsal, 2018).

Input for the proposed MED+RO+PV model are reported in Table 7. The Gulf region is characterized by a very high salinity and water temperature. Solar radiation in this hot region is very high as well, at about 6.5 kWh/m$^2$ day, and daylight duration is over 11 hours. Electricity cost for industries is 0.27 AED/kWh, or 0.07 €/kWh (Abu Dhabi's water and electricity tariffs, 2017).

To assess the performances and economic feasibility of the proposed MED+RO+PV plant in the Abu Dhabi region, a simulation has been taken and the results are summarised in Table 5, where the costs are reported in Euro to have a direct comparison with other locations. Capital cost for PV installation, at almost 10 M€, of which 1/3 is the cost of storage system, is now lower than the cost of desalination plant. Indeed, a smaller number of modules is required in this region to satisfy the energy requirement of the desalination. This is because of the very intense solar radiation at this region. However, when electricity is generated with a non-renewable source, its cost is remarkably low, because of the great availability of cheap fossil fuel in the region. The annual operative cost (AOC) of the desalination plant running with grid electricity is 1.9 M€/yr, while generating electricity with PV will reduce the AOC to 1.25 M€/yr. The cost of fresh water produced with MED+RO is estimated to be 0.54 €/m$^3$, which is a very low value that highlights the cost-effectiveness of the proposed MED+RO plant. Implementing the PV system, the cost of fresh water becomes 0.61 €/m$^3$, which is a 12% increment. This highlights the fact that PV is not an extremely competitive technology in this region from a solely economical point of view, because of the very low price of grid electricity nowadays. This does not account for the environmental aspect and for possible taxes on $CO_2$ production.  However, if the cost of electricity from fossil fuels will raise and PV modules will be manufactured at lower price as expected, the gap will be closed very fast.

Table 5. Result of the simulation for Abu Dhabi.

| Result | Unit | Value |
|---|---|---|
| Number of panels | - | 25713 |
| Area of solar farm | ha | 7.58 |
| TCC of desalination plant | M€ | 10.8 |
| TCC of PV plant | M€ | 9.91 |
| TCC of modules | M€ | 6.92 |
| TCC of storage | M€ | 2.99 |
| AOC with grid electricity | M€/yr | 1.90 |
| AOC with PV | M€/yr | 1.25 |
| Fresh water cost with grid electricity | €/$m^3$ | **0.54** |
| Fresh water cost with PV | €/$m^3$ | **0.61** |

## 4.4 Perth (AUS)

As the last case study, the city of Perth in Western Australia has been selected. More than 2 million people live in Perth and population is increasing rapidly. Rainfalls are frequent in the cold season from May to September, but in the remaining months the climate is quite arid. To satisfy the need for fresh water in this region, a big seawater RO plant has been installed in 2006, with a productivity of about 1500 kg/s, which provides 18% of Perth's water supply. This plant is the world's biggest desalination system powered by renewable energy. Specifically, it consumes electrical energy at 0.052 €/kWh from an 80 MW wind station. Other sources of energy are not required, being the plant very energy-efficient with an energy demand of 2.5 kWh/$m^3$. The cost of produced fresh water is about 0.64 \$/$m^3$ ( 0.55 €/$m^3$) (Sanz et al., 2007). Table 7 summarises the input of the proposed MED+RO+PV system for the Perth region. Seawater salinity is low (oceanic water), solar irradiation is very good as well as daylight duration. The value of 0.052 €/kWh has been assumed as the electricity cost by considering wind as a generating option. From the proposed PV model, the predicted cost of electricity is 0,089 €/kWh.

Table 6 shows the results of the simulation, where the costs are reported in Euro to have a direct comparison with other locations described above. Capital cost for PV installation is over 10 M€, of which 1/4 is the cost of storage system, and it is higher than the cost of desalination plant. The number of modules and required solar farm area is quite small. This is due to the very intensive solar radiation in this region. The annual operating cost (AOC) of the desalination plant running with electricity produced by wind is 1.61 M€/yr. However, generating electricity with PV will reduce the AOC to 1.20 M€/yr. It should be noted that the electricity generated with wind turbines is basically "free", like the one generated with PV. However, the estimated cost of wind electricity has been used to evaluate the AOC, despite the calculation of TCC of wind turbines not being included in this study. The cost of fresh water produced with MED+RO+wind is estimated to be 0.47 €/m$^3$, which is a very low value that highlights the cost-effectiveness of the proposed hybrid desalination plant. However, the cost of fresh water becomes 0.54 €/m$^3$, which is a 14% increment, in case of implementing the PV system. This highlight the fact that PV is not an extremely competitive technology in this region from a solely economical point of view, if compared with wind turbines.

**Table 6**. Result of the simulation for Perth.

| **Result** | **Unit** | **Value** |
|---|---|---|
| Number of panels | - | 28270 |
| Area of solar farm | ha | 8.33 |
| TCC of desalination plant | M€ | 7.74 |
| TCC of PV plant | M€ | 10.24 |
| TCC of modules | M€ | 7.61 |
| TCC of storage | M€ | 2.63 |
| AOC with grid electricity | M€/yr | 1.61 |
| AOC with PV | M€/yr | 1.20 |
| Fresh water cost with wind | €/m$^3$ | **0.47** |
| Fresh water cost with proposed PV | €/m$^3$ | **0.54** |

**Table 7**. Summary of MED+RO+PV model input, for the four locations.

| | **Pantelleria** | **Las Palmas** | **Abu Dhabi** | **Perth** |
|---|---|---|---|---|
| Av. seawater salinity (ppm) | 38000 | 35000 | 40000 | 35000 |

| | | | | |
|---|---|---|---|---|
| Av. seawater temperature (°C) | 22 | 22 | 27 | 24 |
| Av. solar radiation (kWh/m$^2$ day) | 5.3 | 5.1 | 6.5 | 6.2 |
| Av. hours of daylight (hr) | 10.2 | 9.6 | 11.5 | 10.5 |
| Electricity cost (€/kWh) | 0.24 | 0.19 (diesel)<br>0.07 (wind) | 0.07 | 0.052 |

## 5. Conclusions

In the present study, the possibility of generating the electrical power required by the hybrid desalination plant of MED+RO with a photovoltaic solar farm has been investigated. A mathematical and cost model for the PV system has been implemented. The predicted cost of electrical energy produced by the proposed PV system is in the order of 0.1 €/kWh (0.06 – 0.15 €/kWh, depending on solar radiation and duration of daylight), in accordance with the most recent data about solar energy cost. The PV model has been combined with the previous model for the desalination plant, developed by the authors in two previous works.

To test the whole MED+RO+PV plant, data of four real locations have been selected as input to the model.

In Isola di Pantelleria (IT), the predicted fresh water cost when using PV is 0.61 €/m$^3$, which is a 34% reduction with respect to the non-renewable option. Therefore, it can be said that the proposed MED+RO+PV plant would be an economic and environmentally convenient option.

In Las Palmas de Gran Canaria (ES), the predicted fresh water cost when using PV is 0.59 €/m$^3$, which is a 22% reduction with respect to the non-renewable option. However, it is affirmed that the coupling of wind farm with the desalination plant would be the feasible option to generate fresh water at 0.55 €/m$^3$.

In Abu Dhabi (UAE), the predicted cost of fresh water using grid electricity from fossil fuels is only 0.54 €/m$^3$, because of the very low price of industrial electrical energy. Installing the proposed PV causes a fresh water cost of 0.61 €/m$^3$. Therefore, the renewable option appears to be not convenient if only the economical aspect is considered.

In Perth (AUS), electrical energy can be produced by wind turbines at a very low price. Hence, the cost of fresh water when the proposed desalination plant is coupled with a wind farm is only 0.47 €/m$^3$. The cost when using PV is calculated to be 0.54 €/m$^3$.

The present study highlights how the use of renewable energy in desalination nowadays is very competitive from the economical point of view, especially in isolated locations, where the cost of electricity from other conventional sources is prohibitive. In addition to that, the possibility of producing fresh water at a very low cost with the proposed MED+RO plant has been confirmed for every case study. This in turn highlighted how the use of a hybrid system is a cost-competitive option with respect to stand-alone processes.

## Appendix

**Table A.1**. Equations of MED mathematical model (Filippini et al., 2018).

| Description | Equation | Unit |
|---|---|---|
| Feed flow rate | $Mf = \frac{Ms\,\lambda(Ts)}{Q_{sensible} + Q_{latent}}$ | kg/s |
| Sensible heat in first effect | $Q_{sensible} = Mf \int_{t1}^{T1} cp(T1, x1)dT$ | kJ/s |
| Latent heat in first effect | $Q_{latent} = D1\,\lambda(Tv1)$ | kJ/s |
| Temperature drop among effects (first attempt) | $\Delta T = \frac{Ts - Tb}{n}$ | °C |
| Temperature drop among pre-heaters (first attempt) | $\Delta T = \Delta t$ | °C |
| Feed temperature in first effect | $t1 = tn + (n-1)\,\Delta t$ | °C |
| Temperature of vapor phase | $Tv = T - BPE(T, x)$ | °C |
| Flowrate of flashed distillate | $D_{flash,i} = \alpha B_{i-1}$ | kg/s |
| Fraction of distillate by flashing | $\alpha = \frac{cp(T_{mean}, x_{mean})\Delta T}{\lambda(T_{mean})}$ | - |
| Mean temperature | $T_{mean} = \frac{T1 + Tb}{2}$ | °C |
| Mean salinity | $x_{mean} = \frac{xf + xb}{2}$ | ppm |

| | | |
|---|---|---|
| Fraction of distillate by evaporation | $\beta = \frac{\alpha[xb(1-\alpha)^n - xf]}{(xb - xf)[1-(1-\alpha)^n]}$ | - |
| Flowrate of evaporated distil. | $D_{i,boiled} = \beta M_D$ | kg/s |
| Total distillate | $D_i = D_{i,boiled} + D_{i,flashed}$ | kg/s |
| Rejected brine flowrate | $B_i = B_{i-1} - D_i$ | kg/s |
| Salinity profile in the effects | $x_i = \frac{x_{i-1}B_{i-1}}{B_i}$ | ppm |
| Area of i-th effect | $\frac{Q_i}{U_{ev,i}\Delta T_{ev,i}} = A_{ev,i}$ | $m^2$ |
| Heat load in i-th effect | $Q_i = D_{boiled,i-1}\, \lambda(T_{v,i-1})$ | kJ/s |
| Temperature drop in heat exchangers | $\Delta T_{ev,i} = \Delta T - BPE_{i-1}$ | °C |
| Area of i-th pre-heater | $Mf \cdot \int_{t_{i+1}}^{t_i} cp(t, xf)dt = U_{ph,i} A_{ph,i} \Delta t_{\log,i}$ | $m^2$ |
| Logarithmic temperature difference in pre-heaters | $\Delta t_{\log,i} = \frac{\Delta t}{\log(\frac{Tv_i - t_{i+1}}{Tv_i - t_i})}$ | °C |
| Area of final condenser | $Q_{COND} = U_{COND} A_{COND} \Delta T_{log,COND}$ | $m^2$ |
| Heat load in final condenser | $Q_{COND} = D_n \lambda(Tv_n)$ | kJ/s |
| Logarithmic temperature difference in final condenser | $\Delta T_{\log,COND} = \frac{tn - Tw}{\log(\frac{Tv_n - Tw}{Tv_n - tn})}$ | °C |

**Table A.2**. Equations of RO mathematical model (Filippini et al., 2018)

| **Description** | **Equation** | **Unit** |
|---|---|---|
| Water flux through the membrane | $Q_p = A_{w(T)} \left(P_f - \frac{\Delta P_{drop,E}}{2} - P_p - \pi_w - \pi_p\right) A_m$ | $m^3/s$ |
| Solute flux through the membrane | $Q_s = B_{s(T)}(C_w - C_p)$ | $m^3/s$ |
| Osmotic pressure in feed and permeate channels | $\pi_w = 0.76881\, C_w \qquad \pi_p = 0.7994\, C_p$ | atm |
| Impact of temperature on water transport parameter | $A_{w(T)} = A_{w(25\,C)} \exp[0.0343\,(T-25)] \quad < 25\,°C$<br>$A_{w(T)} = A_{w(25\,C)} \exp[0.0307\,(T-25)] \quad > 25\,°C$ | - |
| Impact of temperature on solute transport parameter | $B_{s(T)} = B_{s(25\,C)}\,(1 + 0.08\,(T-25)) \quad < 25\,°C$<br>$B_{s(T)} = B_{s(25\,C)}\,(1 + 0.05\,(T-25)) \quad > 25\,°C$ | - |
| Pressure drop per element and Reynolds number | $\Delta P_{drop,E} = \frac{9.8692x10^{-6}\, A^* \rho_b\, {Q_b}^2\, L}{2 d_h\, Re_b^n\, (W\, t_f\, \epsilon)^2} \qquad Re_b = \frac{\rho_b\, d_h\, Q_b}{t_f\, W\, \mu_b}$ | atm<br>- |
| Bulk flow rate and concentration | $Q_b = \frac{Q_f + Q_r}{2} \qquad C_b = \frac{C_f + C_r}{2}$ | $m^3/s$<br>ppm |
| Membrane surface concentration | $\frac{(C_w - C_p)}{(C_b - C_p)} = exp\left(\frac{Q_p/A_m}{k}\right)$ | ppm |
| Mass transfer coefficient, Schmidt number | $k = 0.664\, k_{dc}\, Re_b^{0.5}\, Sc^{0.33} \left(\frac{D_b}{d_h}\right)\left(\frac{2d_h}{L_f}\right)^{0.5}$<br>$Sc = \frac{\mu_b}{\rho_b\, D_b}$ | m/s- |

| | | |
|---|---|---|
| Density parameter | $\rho_b = 498.4\, m_f + \sqrt{[248400\, m_f^2 + 752.4\, m_f\, C_b\,]}$<br>$m_f = 1.0069 - 2.757x10^{-4}\, T$ | kg/m$^3$ |
| Diffusivity parameter | $D_b = 6.72510^{-6}\, exp\left\{0.154610^{-3}\, C_b - \frac{2513}{T+273.15}\right\}$ | m$^2$/s |
| Viscosity parameter | $\mu_b = 1.234x10^{-6}\, exp\left\{0.0212\, C_b + \frac{1965}{T+273.15}\right\}$ | Pa*s |
| Total mass and solute balance | $Q_f = Q_r + Q_p \qquad Q_f\, C_f - Q_r\, C_r = Q_p\, C_p$ | - |
| Permeate concentration | $C_p = \frac{B_s\, C_f \quad e^{\frac{J_w}{k}}}{J_w + B_s \quad e^{\frac{J_w}{k}}}$ | ppm |
| Rejection and recovery rate | $Rej = \frac{C_f - C_p}{C_f} \qquad Rec = \frac{Q_p}{Q_f}$ | - |

**Table A.3**. Economic model of MED+RO hybrid system (Al-Obaidi et al., 2019)

| **MED process** | | |
|---|---|---|
| **Description** | **Equation** | **Unit** |
| Fresh water cost | $sTAC = \frac{TAC}{M_{fresh,MED}\, THY\, 3600}$ | €/m$^3$ |
| Total Annual Cost | $TAC = AOC + CRF * TCC$ | €/yr |
| Total Capital Cost | $TCC = CAPEX_{dir} + CAPEX_{indir}$ | € |
| Direct CAPEX | $CAPEX_{dir} = CAPEX_{equipment} + CAPEX_{civil\_work}$ | € |
| Indirect CAPEX | $CAPEX_{indir} = 0.25\, CAPEX_{dir}$ | € |
| Equipment Cost | $CAPEX_{equipment} = C_{intake} + C_{MED} + C_{cond} + C_{TVC}$ | € |
| Civil Work Cost | $CAPEX_{civil\_work} = 0.15\, CAPEX_{equipment}$ | € |
| Seawater intake and pre-treatment cost | $C_{intake} = \frac{K_{intake}\, 24\, 3600\, M_{seawater,MED}}{\rho}$ | € |
| MED plant cost | $C_{MED} = K_{MED}\, C_{mat\_MED}\, A_{MED}{}^{0.64}$ | € |
| Final condenser cost | $C_{cond} = K_{cond}\, C_{mat\_cond}\, A_{cond}{}^{0.8}$ | € |
| Annual Operative Cost | $AOC = AOC_{chem} + AOC_{lab} + AOC_{pow} + AOC_{man} + AOC_{steam}$ | €/yr |
| Cost of chemical treatment | $AOC_{chem} = \frac{C_{chem}\, THY\, 3600\, M_{seawater,MED}}{\rho}$ | €/yr |
| Cost of human labor | $AOC_{lab} = \frac{C_{lab} THY\, 3600\, M_{fresh,MED}}{\rho}$ | €/yr |
| Cost of power for pumps | $AOC_{pow} = \frac{C_{pow} THY\, 100\, M_{fresh,MED}}{\rho\, \eta} * f(\Delta P)$ | €/yr |
| Cost of manutention | $AOC_{man} = 0.002\, TCC$ | €/yr |

| Cost of steam utility | $AOC_{steam} = \frac{C_{steam} THY\ (T_s - 40)\ M_{steam}}{80} + 0.005 * TCC$ | €/yr |
|---|---|---|
| **RO process** | | |
| **Description** | **Equation** | **Unit** |
| Total Annual Cost | $TAC = TCC * CRF + AOC$ | €/yr |
| Total Capital Cost | $TCC = \left[\left(C_{wwip} + C_{Pump} + C_{me}\right)\right]$ | € |
| Annual Operating Cost | $AOC = AOC_{Pu} + AOC_{sc} + AOC_{ch} + AOC_{me} + AOC_{lab} + AOC_{maint} + AOC_{bd}$ | €/yr |
| Wastewater intake and pre-treatment cost | $C_{wwip} = 996\ (24x3600\ Q_{f(plant)})^{0.8}$ | € |
| Capital cost of high-pressure pump | $C_{Pump} = \left[52\ (3600\ Q_{f(plant)}\ (P_{f(plant)} 0.101325))^{0.96}\right]$ | € |
| Membrane module and pressure vessel capital cost | $C_{me} = N_s\ N_{PV} (C_{ele}\ N_{ele} + C_{PV})$ | € |
| Pumping operating cost | $AOC_{pu} = 365x24\ \left[\left(\frac{(3600\ (P_{f(plant)}\ 0.101325)\ )\ Q_{f(plant)}\ )}{3.6\ \varepsilon_{pump}\ \varepsilon_{motor}}\right)\right] E_c\ L_f$ | €/yr |
| Annual operating spares cost | $AOC_{sc} = 3600\ THY\ C_{cf}\ Q_{p(plant)}\ L_f$ | €/yr |
| Effluents disposal cost | $AOC_{bd} = 3600\ THY\ C_{bd}\ Q_{p(plant)}\ L_f$ | €/yr |
| Annual chemical treatment cost | $AOC_{ch} = 3600\ THY\ C_{ct}\ Q_{f(plant)}\ L_f$ | €/yr |
| Annual membrane replacement cost | $AOC_{me} = 0.2\ C_{me}$ | €/yr |
| Annual labor cost | $AOC_{lab} = C_{lab}\ 3600\ THY\ Q_{p(plant)}$ | €/yr |
| Fresh water cost | $sTAC = \frac{TAC}{3600x\ THYx\ Q_{p(plant)}}$ | €/m³ |
| Annual maintenance costs | $AOC_{main} = 0.02\ TCC$ | €/yr |
| Capital Recovery Factor | $CRF = \frac{Ir(1+Ir)^{life}}{(1+Ir)^{life} - 1}$ | 1/yr |

**Table A.4**. Input parameters for MED+RO hybrid system simulation.

| **Optimised parameters** | **Optimised value** | **Unit** |
|---|---|---|
| Steam to MED temperature | 68.1 | °C |
| Steam to MED flow rate | 9.71 | kg/s |
| Seawater feed to RO | 0.107 | $m^3/s$ |
| Feed pressure to RO | 77.9 | atm |
| **MED parameters** | **Value** | **Unit** |
| Number of effects | 10 | - |
| Rejected brine temperature | 40 | °C |
| Rejected brine salinity | 60000 | ppm |
| **RO parameters** | **Value** | **Unit** |
| Effective membrane area | 37.2 | m² |
| Module width | 37.2 | m |
| Module length | 1 | m |
| $A_{w\ (T_o)}$ at 25 °C | $3.1591x10^{-7}$ | (m/s atm) |
| $B_{s(T_o)}$ NaCl at 25 °C | $1.74934x10^{-8}$ | m/s |
| Feed spacer thickness | $8.6x10^{-4}$ | m |
| Hydraulic diameter of the feed spacer channel | $8.126x10^{-4}$ | m |

| | | |
|---|---|---|
| Length of filament in the spacer mesh | $2.77x10^{-3}$ | m |
| Spacer characteristic: $(A^{'})$ and $(n)$ | 7.38 and 0.34 | - |
| Voidage $(\varepsilon)$ | 0.9058 | - |

**Table A.5**. Input parameters for the economic model.

| Parameter | Value | Unit | Parameter | Value | Unit | Parameter | Value | Unit |
|---|---|---|---|---|---|---|---|---|
| THY | 8760 | hr/yr | $C_{ele}$ | 850 | € | Cbd | 0.0013 | €/$m^3$ |
| $K_{intake}$ | 43 | € day/m3 | $C_{PV}$ | 85 | € | Clab | 0.02 | €/$m^3$ |
| $K_{MED}$ | 1.4 | - | Ns | 3 | - | life | 25 | yr |
| $K_{COND}$ | 2.8 | - | $N_{PV}$ | 43 | - | $\eta_{pump}$ | 0.85 | - |
| $C_{steam}$ | 0.0036 | €/kg | $N_{ele}3$ | 344 | - | $\eta_{motor}$ | 0.98 | - |
| $C_{mat\_MED}$ | 3300 | €/$m^2$ | $L_f$ | 0.85 | - | | | |
| $C_{mat\_cond}$ | 425 | €/$m^2$ | Ccf | 0.028 | €/$m^3$ | | | |
| Ir | 0.07 | - | Cct | 0.015 | €/$m^3$ | | | |

## Correlations for MED process

**Collected from :** El-Dessouky HT, Ettouney H.M., 2002. *Fundamentals of salt water desalination*. Elsevier.

### Boiling Point Elevation

Correlation valid in the range: 1% < w < 16%, 10°C < T < 180°C

$$w = x \cdot 10^{-5} \quad [w/w\%]$$
$$BPEa = 8.325 \cdot 10^{-2} + 1.883 \cdot 10^{-4} \cdot T + 4.02 \cdot 10^{-6} \cdot T^2$$
$$BPEb = -7.625 \cdot 10^{-4} + 9.02 \cdot 10^{-5} \cdot T - 5.2 \cdot 10^{-7} \cdot T^2$$
$$BPEc = 1.522 \cdot 10^{-4} - 3 \cdot 10^{-6} \cdot T - 3 \cdot 10^{-8} \cdot T^2$$
$$BPE = BPEa \cdot w + BPEb \cdot w^2 + BPEc \cdot w^3 \qquad [°C]$$

### Specific heat at constant pressure

Correlation valid in the range: 20000 ppm < x < 160000 ppm, 20°C < T < 180°C

$$s = x \cdot 10^{-3} \quad [gm/kg]$$
$$cpa = 4206.8 - 6.6197 \cdot s + 1.2288 \cdot 10^{-2} \cdot s^2$$
$$cpb = -1.1262 + 5.4178 \cdot 10^{-2} \cdot s - 2.2719 \cdot 10^{-4} \cdot s^2$$
$$cpc = 1.2026 \cdot 10^{-2} - 5.3566 \cdot 10^{-4} \cdot s + 1.8906 \cdot 10^{-6} \cdot s^2$$
$$cpd = 6.8777 \cdot 10^{-7} + 1.517 \cdot 10^{-6} \cdot s - 4.4268 \cdot 10^{-9} \cdot s^2$$
$$cp = \frac{cpa + cpb \cdot T + cpc \cdot T^2 + cpd \cdot T^3}{1000} \quad [\frac{kJ}{kg \cdot °C}]$$

**Latent heat of evaporation**

$$\lambda = 2501.89715 - 2.40706 \cdot T + 1.19221 \cdot 10^{-3} \cdot T^2 - 1.5863 \cdot 10^{-5} \cdot T^3 \quad [\frac{kJ}{kg}]$$

**Global heat exchange coefficients**

$$U_{ev} = 1.9695 + 1.2057 \cdot 10^{-2} \cdot T - 8.5989 \cdot 10^{-5} \cdot T^2 + 2.5651 \cdot 10^{-7} \cdot T^3 \quad [\frac{kW}{m^2 \cdot °C}]$$

$$U_{cond} = U_{ph} = 1.7194 + 3.2063 \cdot 10^{-3} \cdot T + 1.597 \cdot 10^{-5} \cdot T^2 - 1.9918 \cdot 10^{-7} \cdot T^3 \quad [\frac{kW}{m^2 \cdot °C}]$$

## Nomenclature

$A_{mod}$: area of a single module ($m^2$)

$A_{tot}$: total area of the solar farm ($m^2$)

$C_{ACDC}$: cost of AC/DC conversion (€/kWh)

$C_{batt}$: cost of batteries (€/kWh)

$C_{el}$: final cost of electricity produced by the PV system (€/kWh)

$C_{mod}$: cost of solar modules (€/Wp)

$CRF$: capital recovery factor (-)

$G$: average solar radiation ($W/m^2$)

$G_{NOM}$: nominal average solar radiation ($W/m^2$)

$G_{SOC}$: standard average solar radiation ($W/m^2$)

$H_{loss}$: heat loss to the surrounding ($W/m^2$)

$I_{MP,SOC}$: standard current at maximum power point (A)

$M_{MED}$: productivity of MED process ($m^3$/day)

$M_{RO}$: productivity of RO process ($m^3$/day)

$N_{modules}$: number of modules (-)

$P$: power output of a single module (W)

$P_{DES}$: electrical power requirement from desalination plant (kWh/day)

$P_{el,MED}$: electrical power requirement of MED process (kWh/day)

$P_{el,RO}$: electrical power requirement of RO process (kWh/day)

$P_{load}$: electrical power requirement from desalination plant (kW)

$P_{mod}$: power output of a single module (kWh/day)

$P_{peak}$: peak power generated by PV system (Wp)

$P_{tot}$: total power output of the PV system (kWh/day)

$S_{batt}$: storage capacity of batteries (kWh)

$T_{amb}$: ambient temperature (°C)

$T_{amb,NOM}$: nominal ambient temperature (°C)

$T_C$: cell temperature (°C)

$T_{C,NOM}$ : nominal cell temperature (°C)

$TCC_{batt}$: total capital cost of storage system (M€)

$TCC_{mod}$: total capital cost of solar modules (M€)

$TCC_{PV}$: total capital cost of the entire PV system (M€)

$T_{SOC}$: standard temperature (°C)

$V_{MP,SOC}$: standard voltage at maximum power point (V)

**Greek**

$\alpha$: fraction of incident radiation absorbed by the cell (-)

$\eta_{CON}$: efficiency loss due to connections (-)

$\eta_{CH}$ : charge efficiency of Li-Ion batteries (-)

$\eta_{DIS}$: discharge efficiency of Li-Ion batteries (-)

$\eta_{DIRT}$: efficiency loss due to dirt (-)

$\eta_{INV}$: efficiency loss due to inverters (-)

$\eta_{MOD}$: ideal efficiency of the module (-)

$\eta_{MOD,SOC}$: ideal efficiency of the module in standard conditions (-)

$\eta_{tot}$: overall efficiency of the module (-)

$\mu$: temperature coefficient (°C$^{-1}$)

$\mu_{VOC}$: voltage temperature coefficient (V/°C)

$\tau$: transmittance of the panel cover (W/m$^2$ °C)

## References

Ang W., Nordin D., Mohammad A., Benamor A., Hilal, N., 2017. Effect of membrane performance including fouling on cost optimization in brackish water desalination process. *Chemical Engineering Research and Design,* 117, 401–413.

Al-Obaidi M.A., Li J-P., Kara-Zaïtri C., Mujtaba I.M., 2017. Optimization of reverse osmosis based wastewater treatment system for the removal of chlorophenol using genetic algorithms. *Chemical Engineering Journal*, 316, pp. 91-100.

Al-Obaidi M.A., Filippini G., Manenti F., Mujtaba I.M., 2019. Cost evaluation and optimisation of hybrid multi effect distillation and reverse osmosis system for seawater desalination. *Desalination*, 456, 136–149.

Al-Sahali M, Ettouney H., 2007. Developments in thermal desalination processes: design, energy, and costing aspects. *Desalination*, 214, 227–240.

Azevedo Santos Moniz FDA. Renewable energy powered desalination systems: technologies and market analysis; 2014.

Calise F, D'Accadia MD, Piacentino A, 2014. A novel solar trigeneration system integrating PVT (photovoltaic/thermal collectors) and SW (seawater) desalination: dynamic simulation and economic assessment. *Energy*, 67, 129–148.

Espino T, Penate B, Piernavieja G, Herold D, Neskakis A. 2003. Optimised desalination of seawater by a PV powered reverse osmosis plant for a decentralised coastal water supply. *Desalination*, 156, 349–50.

Filippini G., Al-Obaidi M.A., Manenti F., Mujtaba I.M., 2018. Performance analysis of hybrid system of multi effect distillation and reverse osmosis for seawater desalination via modelling and simulation. *Desalination,* 448, 21–35.Gómez-Gotor A, Del Río-Gamero B, Prado IP, Casañas A, 2018. The history of desalination in the Canary Islands. *Desalination*, 428, pp. 86-107.

Gude V.G., Nirmalakhandan N., Deng S., 2010. Renewable and sustainable approaches for desalination. *Renewable and Sustainable Energy Reviews* 14, pp. 2641-2654.

Hilal N., Wright C.J., 2018. Exploring the current state of play for cost-effective water treatment by membranes. npj Clean Water 1(1). https://cronfa.swan.ac.uk/Record/cronfa40094 doi:10.1038/s41545-018-0008-8.

Irena, 2016. Renewable Energy Market Analysis: the GCC region. IRENA, Abu Dabhi.

Khan M.A.M., Rehman S., Al-Sulaiman F.A., 2018. A hybrid renewable energy system as a potential energy source for water desalination using reverse osmosis: A review. *Renewable and Sustainable Energy Reviews,* 97, 456–477.

Koroneos C, Dompros A, Roumbas G, 2007. Renewable energy driven desalination systems modelling. *Journal of Cleaner Production*, 15, pp. 449-464.

Koutroulis E. Kolokotsa D., 2010. Design optimization of desalination systems power-supplied by PV and W/G energy sources. *Desalination*, 258, 171-181.

Liou K, 1976. On the absorption, reflection and transmission of solar radiation in cloudy atmospheres. *Journal of Atmospheric Science*, 33, pp. 798-805.

Maghami MR, Hizam H, Gomes C, Radzi MA, Rezadad MI, Hajighorbani S, 2016. Power loss due to soiling on solar panel: A review. *Renewable and Sustainable Energy Reviews*, 59, pp. 1307-1316.

Manenti F, Masi M, Santucci G, Manenti G, 2013. Parametric simulation and economic assessment of a heat integrated geothermal desalination plant. *Desalination*, 317, pp. 193-205.

Marrero GA, Ramos-Real FJ, 2010. Electricity generation cost in isolated system: the complementarities of natural gas and renewables in the Canary Islands. *Renewable and Sustainable Energy Reviews*, 14, pp. 2808-2818.

Mohamed E.S., Papadakis G., 2004. Design, simulation and economic analysis of a standalone reverse osmosis desalination unit powered by wind turbines and photovoltaics, *Desalination,* 164, 87–97.

Mohamed E.S., Papadakis G., Mathioulakis E., Belessiotis V., 2006. An experimental comparative study of the technical and economic performance of a small reverse osmosis desalination system equipped with a hydraulic energy system. *Desalination,* 194, 239–250.

Notton G, Muselli M, Poggi P, 1998. Costing of a stand-alone photovoltaic system. *Energy*, 23, pp. 289-308.

Novosel T, Ćosić B, Krajačić G, Duić N, Pukšec T, Mohsen MS, 2014. The influence of reverse osmosis desalination in a combination with pump storage on the penetration of wind and PV energy: a case study for Jordan. *Energy*, 76, pp. 73-81.

Ophir A, Lokiec F., 2005. Advanced MED process for most economical sea water desalination.
*Desalination*, 182, pp. 187-198.

Palenzuela P, Zaragoza G, Alarcón D, Blanco J, 2011. Simulation and evaluation of the coupling of desalination units to parabolic-trough solar power plants in the Mediterranean region. *Desalination*, 281, pp. 379-387.

Rybar S, 2005. Experience with Renewable Energy Source and SWRO Desalination in Gran Canaria. SP05-100 International Desalination Association World Congress.

Sanz M.A., Stover R, 2007. Low energy consumption in the Perth seawater desalination plant. IDA World Congress–Maspalomas, Gran Canaria, Spain.

Smaoui M, Abdelkafi A, Krichen L, 2015. Optimal sizing of stand-alone photovoltaic/wind/hydrogen hybrid system supplying a desalination unit. *Solar Energy*, 120, pp. 263-276.

Solanki CS, 2015. Solar photovoltaics: fundamentals, technologies and applications. PHI Learning Pvt. Ltd.

Jager-Waldau A, 2004. PV status report 2004. Research, Solar cell production and market implementation of photovoltaic.

Weiner A.M., Blum D.H., Lienhard V J.H., Ghoniem A.F., 2015. Design of a hybrid RO-MED solar desalination system for training agricultural draining water in California. The International Desalination Association World Congress on Desalination and Water Reuse, San Diego, CA, USA. Desalination, 182, pp. 187-198.

**Websites (accessed on 11/02/2019)**

Abu-Dhabi water and electricity tariffs: https://www.addc.ae/en-US/residential/Documents/02-English.pdf

Binsal A.K, 2018. Abu Dhabi to build world's largest desalination facility: https://gulfnews.com/news/uae/environment/abu-dhabi-to-build-world-s-largest-desalination-facility-1.2158039

TopSun Energy Ltd: http://topsunenergy.com/

IRENA: http://www.irena.org/costs/Charts/Solar-photovoltaic

Global Solar Atlas: http://globalsolaratlas.info/

Global Sea Temperature: https://www.seatemperature.org/

U.S. NRELSolar Photovoltaic System Benchmark: Q1 2017: https://www.nrel.gov/docs/fy17osti/68925.pdf