Design Optimization of RES-Based Desalination Systems Cooperating With Smart Grids

Athanasios Malisovas and Eftichios Koutroulis, *Senior Member, IEEE*

***Abstract*—Water desalination combined with renewable energy sources (RES) constitutes an environmentally friendly technology for alleviating the scarcity of potable water. In this article, a new methodology is presented for calculating the optimal structures of desalination plants that are power-supplied by RES and cooperate with smart grids. The proposed technique takes into account the tradeoff between the three alternative degrees of freedom in the operation of the overall desalination plant, i.e., battery storage, water storage, and dynamic exchange of energy with the smart grid. The design results verify that the economically optimized configurations derived by applying the proposed design tool are capable to cover the water requirements of the consumers and support the operation of the electric grid by injecting the RES-generated energy surplus. Numerical results are also presented, demonstrating that the application of the proposed methodology enables to reduce the lifetime cost of the desalination plant by 60% compared with the exclusive use of electric grid energy. Also, by employing the total lifetime cost of the grid-connected RES-based desalination plant as objective function of the optimal design problem, the economical viability of the desalination system is improved.**

***Index Terms*—Desalination, optimization, renewable energy sources, smart grid, water supply.**

I. Introduction

MORE than 25% of the world population does not have access to potable water [1]. Also, significant amounts of freshwater resources are consumed for the cooling process of thermal electricity production plants [2]. The total demand for both water and electricity is expected to be further increased significantly during the following years due to the population growth and the continuous economic development. Simultaneously, the environmental degradation imposes additional threats on the security of water supply. This necessitates the application of appropriate water processing and management technologies [3], [4]. Among them, water desalination is now considered as a major technology for alleviating the scarcity of potable water [5], [6]. The application of desalination technology is assisted by the significant reduction of the associated costs during the last years.

Therefore, the global desalination capacity has been increased by more than ten times during the last four decades, across more than 120 countries [7].

Extensive research has been conducted on the deployment of renewable energy sources (RES) for covering the energy requirements of desalination plants. The use of RES in desalination systems enables to reduce the environmental and economic impacts of conventional fossil-fuel-based electric energy generators [5], [8]. The role of such an energy–water nexus becomes especially important in areas exhibiting both high RES potential and low resources of potable water (e.g., the Mediterranean region, middle-east, etc.). Till present, photovoltaics (PV) and wind–generators (W/Gs) are the most frequently used types of RES in water desalination applications due to the wide availability of the corresponding environmental resources across the world.

Desalination plants constitute a system of systems formed by merging critical infrastructure, such as the electric energy production and water supply systems. These two systems operate interdependently, being simultaneously affected by their environment [2], [9]. The existing methods developed for designing RES systems that serve purely electrical loads (for e.g., in buildings, telecommunication repeaters, etc.) are not suitable for RES-based desalination applications. The reason is that the water storage tank that is typically included in desalination systems offers an additional degree of freedom in terms of satisfaction of the consumer's water demand. Many design techniques for seawater and brackish water desalination systems power-supplied by autonomous RES systems (i.e., not interconnected with an electric grid) have been developed in the past. They target to maximize the production of freshwater, or minimize the loss of power supply probability, or minimize the lifecycle system cost and simultaneously ensure the satisfaction of the consumer water demand (e.g., [10]–[14]). However, smart grids, where RES are also integrated, have been developed during the last years. In smart grids, both electric energy and data/information are interchanged between distributed energy producers, consumers, and energy storage units [15], [16]. Smart grids serve as a means of enhancing the efficiency, reliability, and quality of electricity supply and reduce the negative environmental impacts of electricity generation by thermal power plants [17]–[22]. In RES-based desalination applications, the smart grid may absorb any RES energy surplus during the time periods of low water demand or cover the electric energy deficits for setting the

Manuscript received July 4, 2019; revised September 25, 2019 and January 18, 2020; accepted January 20, 2020. This work was supported in part by the Operational Program "Competitiveness, Entrepreneurship and Innovation 2014–2020" and in part by the European Regional Development Fund, and in part by the Greek General Secretariat of Research and Technology, Ministry of Education, Research, and Religious Affairs of Greece under the Project DES^{2}iRES T3EPA-00017 of the ERAnet, ERANETMED_NEXUS-14-049. *(Corresponding author: Eftichios Koutroulis.)*

The authors are with the School of Electrical and Computer Engineering, Technical University of Crete, Chania 73100, Greece (e-mail: tmalisovas@isc.tuc.gr; efkout@electronics.tuc.gr).

This article has supplementary downloadable material available at https://ieeexplore.ieee.org, provided by the authors.

Digital Object Identifier 10.1109/JSYST.2020.2968842

desalination units into an operation. Such a dynamic energy exchange can be implemented through appropriate control/coordination schemes. Thus, a third degree of freedom is offered during the design of grid-connected RES-based desalination systems, in addition to the battery storage and water storage options [23]. The adoption of a design technique enabling to optimally exploit such a capability is required.

In this article, a new methodology is presented for the optimal design of desalination plants that are power-supplied by PVs, W/Gs, and battery-based energy storage and able to dynamically exchange electric energy with a smart grid. The novelty of the proposed technique is that, in contrast to the existing methods of designing grid-connected RES-based desalination systems [24]–[30], it encompasses all of the following features in an integrated design process.

1) It calculates the optimal sizes and optimal structures of both the energy- (generation and storage) and water-related subsystems, respectively, of the overall desalination plant, which are required for satisfying a given water demand with the minimum lifetime cost. The desalination system is considered to be installed in a location specified by the designer, but the installation-site-dependent fluctuation of the RES energy production during the year is also taken into account in the proposed technique.
2) It derives the optimal tradeoff between the three alternative degrees of freedom in the operation of the overall desalination plant (i.e., battery storage, water storage, and energy exchange with the electric grid).
3) It derives the optimal configuration of the overall RES-based desalination system. This is implemented by investigating the concurrent impacts of its location (with respect to both the electric grid and the water distribution network) and structures of the electric energy and water production components that it comprises on the lifetime cost of the desalination system.

The proposed optimization technique comprises an integrated design tool that enables the designer to derive the optimal configuration of grid-connected RES-based desalination plants prior to their installation. An additional scientific contribution of this article is that for the first time in the existing literature, alternative types of objective functions are incorporated in the design optimization process, and the impact of each of them on the design results is investigated. Numerical results are also presented, which 1) verify the capability of the optimized desalination plants to support the operation of the electric grid by injecting significant amounts of RES-generated energy surplus and 2) demonstrate the impact of the installation location of the desalination plant on the resulting optimal structure, energy exchanged with the electric grid, and lifetime cost.

The rest of this article is organized as follows. The proposed modeling and simulation procedure of a desalination system that is power-supplied by a grid-connected hybrid PV-W/G RES system is presented in Section II. The proposed design optimization process is described in Section III, whereas alternative optimization criteria of the overall desalination plant are described in Section IV. The design optimization results are analyzed in Section V. Finally, Section VI concludes this article.

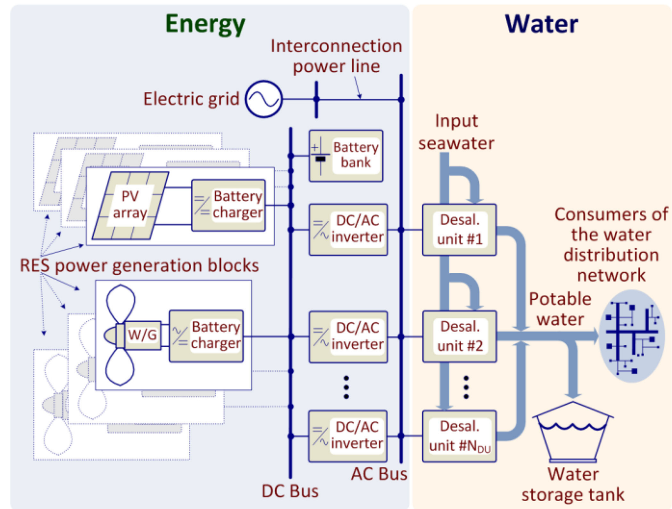

Fig. 1. General diagram of the grid-connected RES-based desalination system under study.

II. Modeling and Simulation of a Grid-Connected RES-Based Desalination System for Optimization

The desalination plant under study is power-supplied by a grid-connected hybrid RES system. Its target is to produce enough potable water in order to satisfy a predefined demand of the consumers in a water distribution network. A diagram of the overall RES-based desalination system is illustrated in Fig. 1. The RES-based power supply system comprises multiple PV arrays and W/Gs in order to produce the electric energy required by the desalination units to operate. A battery bank is also used in order to store any energy surplus. Multiple dc/ac inverters are employed for providing the ac power required to the desalination units. Moreover, the ac bus of the RES-based power supply system is interconnected with the electric grid for selling/buying any energy surplus/deficit. The RES/battery devices and the desalination units can be considered to be installed either at the same location or at different locations, as described next. The desalination system also comprises a water tank in order to store the excess water produced by the desalination units when it is not needed by the consumer. The mathematical modeling and simulation of the RES-based desalination system under design are presented in the following sections.

A. Modeling of the RES-Based Desalination System

Each PV array consists of N_S PV modules connected in series and N_P such PV strings that are connected in parallel. A PV battery charger is connected to the output of each PV array in order to 1) interface the power produced by the PV array to the battery bank and 2) maximize the power produced by the PV array by applying a maximum power point tracking (MPPT) control technique, thus maximizing the exploitation of the installed PV capacity [31]. The value of N_P is calculated as follows:

$$N_P = \text{floor}[P_{\text{CH}}/(N_S \cdot V_{M,\text{STC}} \cdot I_{M,\text{STC}})] \quad (1)$$

where P_{CH} (W) is the nominal power rating of the PV battery charger and $V_{M,\mathrm{STC}}$ (V) and $I_{M,\mathrm{STC}}$ (A) are the maximum power point (MPP) voltage and current, respectively, of each PV module under standard test conditions (STC). The values of P_{CH}, $V_{M,\mathrm{STC}}$, and $I_{M,\mathrm{STC}}$ are available in the datasheets of the battery charger and PV module, respectively, which are provided by their manufacturers.

The battery bank is comprised of multiple parallel-connected battery strings, $N_{s,p}$, each comprising $N_{s,b}$ batteries connected in series. The value of $N_{s,b}$ is given by

$$N_{s,b} = \mathrm{ceil}\left(V_{\mathrm{BUS}}/V_B\right) \tag{2}$$

where V_{BUS} (V) is the nominal dc output voltage level of the PV battery chargers, and V_B (V) is the nominal voltage level of each battery, both provided in their manufacturer's datasheets.

The total number of battery strings connected in parallel is calculated as follows:

$$N_{s,p} = \mathrm{floor}\left(N_{\mathrm{BAT}}/N_{s,b}\right) \tag{3}$$

where N_{BAT} is the total number of batteries comprising the battery bank.

The total number of dc/ac inverters required to operate the subsystems of the desalination process is given as

$$N_{\mathrm{INV}} = \mathrm{ceil}[(N_{\mathrm{DU}} \cdot P_U + P_T)/P_{\mathrm{INV}}] \tag{4}$$

where N_{DU} is the total number of desalination units, P_U (W) is the ac power required for operation of each desalination unit, P_T (W) is the total power required for pumping seawater from the sea to the installation point of the desalination system and brine disposal back to the sea, respectively, and P_{INV} (W) is the nominal ac power rating of each dc/ac inverter.

When the desalination system is installed along the coastline, the value of P_T in (4) is equal to zero. In this case, the power required for pumping seawater to the desalination system and brine disposal back to the sea, respectively, is included in the value of P_U. For locations of the desalination plant away from the coastline, the value of P_T is calculated as follows [32]:

$$P_T = H \cdot P_H \cdot W_{d,n} \cdot N_{\mathrm{DU}} + E \cdot P_E \cdot W_{d,n} \cdot N_{\mathrm{DU}} \tag{5}$$

where H (m) is the shortest horizontal distance of the desalination system installation point from the coastline, E (m) is the elevation of the desalination system installation point above the sea level, $W_{d,n}$ (L/day) is the daily nominal water production of each desalination unit, and P_H and P_E $[\mathrm{W}/(\mathrm{m} \cdot \mathrm{L})]$ are the powers of the water pumping system per meter of horizontal distance and elevation, respectively, and per liter of daily nominal water production of each desalination unit.

In the proposed design methodology, it is verified that the water requirements of the consumer are completely covered during the entire lifetime period of the desalination system (Y in years). For that purpose, the operation of the grid-connected RES-based desalination system is simulated for each hour t of each year of operation (i.e., with a 1-h time-step resulting in $1 \leq t \leq 8760 \cdot Y$). During this simulation procedure, the following processes are considered: 1) the electric energy flow from the RES units and the electric grid, respectively, to the desalination units, and 2) the flow of potable water from the desalination units and water storage tank to the consumer. For that purpose, the MPP power [31], $P_{\mathrm{PV}}(t)$ (W), produced by each PV array at hour t ($1 \leq t \leq 8760 \cdot Y$) is calculated as follows:

$$\begin{aligned} P_{\mathrm{PV}}(t) &= N_S \cdot N_P \cdot V_{\mathrm{OC}}(t) \cdot I_{\mathrm{SC}}(t) \\ &\quad \cdot \mathrm{FF}(t) \cdot [1 - r_d \cdot (y-1)] \end{aligned} \tag{6}$$

where $V_{\mathrm{OC}}(t)$ (V), $I_{\mathrm{SC}}(t)$ (A), and FF(t) are the open-circuit voltage, short-circuit current, and fill factor, respectively, of each PV array at hour t, r_d (%) is the yearly degradation rate of the PV modules power-production capability due to aging, and y is the year number ($1 \leq y \leq Y$). The values of FF(t), $V_{\mathrm{OC}}(t)$, and $I_{\mathrm{SC}}(t)$ are calculated according to [33] as a function of

1) the PV modules operational characteristics under STC;
2) the ambient temperature $T_A(t)$ (°C);
3) the solar irradiance, $G(t)$ (W/m^2), that is incident on the PV modules during hour t.

The value of $G(t)$ depends on the installation tilt angle, β (°), of the PV modules. Its value is calculated by using the models described in [33] and the time series of solar irradiance on the horizontal plane for each hour t during a year which is input by the designer, as described next. Additionally, the MPP voltage of each PV array during hour t, $V_{\mathrm{PV}}(t)$ (V), is calculated. If $V_{\mathrm{PV}}(t) < V_{\mathrm{MPP,min}}$, where $V_{\mathrm{MPP,min}}$ (V) is the minimum operating MPP voltage of the PV battery charger, then the power produced by each PV array is set equal to zero during the corresponding hour. Also, if $P_{\mathrm{PV}}(t) > P_{\mathrm{CH}}$ then the output power of the PV arrays is set equal to the maximum operating power level, P_{CH} (W), of the PV battery charger.

The power injected into the dc bus of the power supply system at hour t by the power converter connected to each W/G, $P_{\mathrm{WG}}(t)$ (W), is calculated for every hour of the desalination system lifetime period. The value of $P_{\mathrm{WG}}(t)$ is calculated as a function of the length of its installation tower, $l_{\mathrm{W/G}}$ (m), and the corresponding wind speed, $v(t)$ (m/s), at the target installation site. For that purpose, the output power versus wind speed, look-up table of the W/G, provided by its manufacturer, is used according to Koutroulis *et al.* [34].

The total power produced by all RES generators of the desalination system during hour t ($1 \leq t \leq 8760 \cdot Y$) is calculated as follows:

$$P_{\mathrm{RE}}(t) = N_{\mathrm{PVA}} \cdot n_1 \cdot n_2 \cdot P_{\mathrm{PV}}(t) + N_{\mathrm{WG}} \cdot P_{\mathrm{WG}}(t) \tag{7}$$

where N_{PVA} is the total number of PV arrays (which is also equal to the total number of battery chargers N_{CH}), n_1 is the power conversion efficiency of the PV battery chargers connected at the output of each PV array, n_2 is the MPPT efficiency of each PV battery charger and N_{WG} is the total number of W/Gs with integrated battery chargers, respectively, which are included in the RES-based power supply system of the desalination plant. The MPPT efficiency n_2 determines the deviation of the actual power produced by the PV arrays from the maximum possible power that can be extracted, which is calculated by (6) [35].

The power that must be provided to the dc inputs of the dc/ac inverters when the desalination units operate is calculated as follows:

$$P_L(t) = (N_{\mathrm{DU}} \cdot P_U + P_T)/n_i \tag{8}$$

where $n_i\,(\%)$ is the power conversion efficiency of the dc/ac inverters.

The charging/discharging current of the battery bank, $I_{B,C/D}$ (A), depends on the power flow at the dc bus, and its value is given as follows:

$$I_{B,C/D} = [P_{\mathrm{RE}}(t) - P_L(t)]/V_{\mathrm{BUS}} \tag{9}$$

where $I_{B,C/D} > 0$ during charging and $I_{B,C/D} < 0$ during discharging.

In order to protect the batteries from overcharging and overdischarging, respectively, the actual current of the battery bank is calculated as follows:

$$I_B(t) = \begin{cases} I_{c,\max} & \text{if } I_{B,C/D} > I_{c,\max} \\ I_{B,C/D} & \text{if } I_{d,\max} < I_{B,C/D} < I_{c,\max} \\ I_{d,\max} & \text{if } I_{B,C/D} < I_{d,\max} \end{cases} \tag{10}$$

where $I_{c,\max}$ and $I_{d.\max}$ (A) are the maximum permissible values of charging and discharging current, respectively, which have been set equal to $I_{c,\max} = -I_{d.\max} = C_n/5$h, with C_n (Ah) being the total nominal capacity of the battery bank.

At each time step, the electric charge stored in the battery bank, *C*(*t*) (Ah), is calculated as follows:

$$C(t) = \begin{cases} C(t-1) + n_B \cdot I_B(t) \cdot 1\mathrm{h} \;\; \text{if } C(t-1) \\ \qquad + n_B \cdot I_B(t) \cdot 1\mathrm{h} < N_{s,p} \cdot C_B \\ N_{s,p} \cdot C_B \qquad \text{else} \end{cases} \tag{11}$$

where C_B (Ah) is the nominal capacity of each battery, and n_B is the battery round-trip efficiency (i.e., $n_B = 0.8$ during charging and $n_B = 1$ during discharging).

The initial state of charge of the battery bank is set equal to

$$C(0) = (1 - \mathrm{DOD}/2) \cdot C_n \tag{12}$$

where DOD (%) is the maximum permissible depth of discharge of the batteries comprising the battery bank.

If the desalination units operate during hour *t* (depending on the energy availability as described next), then the total volume of water that they produce, $W_{\mathrm{RO}}(t)$ (L), is calculated as follows:

$$W_{\mathrm{RO}}(t) = N_{\mathrm{DU}} \cdot W_U \tag{13}$$

where W_U (L) is the hourly water production of each desalination unit, specified by its manufacturer.

The amount of water contained in the water storage tank during hour *t*, $W_T(t)$ (L), is calculated taking also into account that if its value exceeds the volume of the water tank, then any further addition of water in the tank is stopped and the surplus water is not used. The value of $W_T(t)$ is calculated according to the following equation:

$$W_T(t) = \begin{cases} W_T(t-1) + \Delta W(t) \;\; \text{if } \; W_T(t-1) \\ \qquad +\Delta W(t) < W_{T,n} \\ W_{T,n} \qquad \text{else} \end{cases} \tag{14}$$

where $W_{T,n}$ (L) is the total volume of the water tank and $\Delta W(t) = W_{\mathrm{RO}}(t) - W_D(t)$ (L) is the amount of water supplied to [if $\Delta W(t)>0$] or withdrawn from [if $\Delta W(t)<0$] the water storage tank. The value of $\Delta W(t)$ is affected by the water demand of the consumer, $W_D(t)$ (L), during hour *t* as analyzed next. The initial value of the volume of water contained in the water tank is set equal to 50% of the water tank volume, i.e., $W_T(0) = 0.5{\cdot}W_{T,n}$.

B. Simulation of the RES-Based Desalination Plant Operation

In the proposed methodology, the energy/water flows in the RES-based desalination plant are calculated for every hour t ($1 \le t \le 8760 \cdot Y$) of its lifetime period, as follows.

Case 1: The energy production of the RES generators is enough to cover the power requirements of the desalination units [i.e., $P_{\mathrm{RE}}(t) \ge P_L(t)$]. Then, if a battery bank is available (depending on the system configuration examined by the optimization algorithm, which will be described in the following section), it is charged according to (10), and any energy surplus is sold to the electric grid. The amount of energy sold to the electric grid, $E_G(t)$ (Wh), is calculated as follows:

$$E_G(t) = \begin{cases} [P_{\mathrm{RE}}(t) - P_L(t) - V_{\mathrm{BUS}} \cdot I_{\mathrm{CH}}] \cdot \frac{n_i}{100} \cdot 1\mathrm{h} \\ \text{if } [P_{\mathrm{RE}}(t) - V_{\mathrm{BUS}} \cdot I_{\mathrm{CH}}] \cdot \frac{n_i}{100} \le N_{\mathrm{INV}} \cdot P_{\mathrm{INV}} \\ [N_{\mathrm{INV}} \cdot P_{\mathrm{INV}} - P_L(t) \cdot \frac{n_i}{100}] \cdot 1\mathrm{h} \quad \text{else.} \end{cases} \tag{15}$$

The state of charge of the battery bank is modified according to (11). If the battery bank becomes fully charged before the end of hour *t*, then any energy surplus is also sold to the electric grid. If batteries are not contained in the RES-based power supply system, then the surplus energy sold to the electric grid is calculated by setting $I_{\mathrm{CH}} = 0$ in (15). Also, the amount of the water stored in the water tank is modified by an amount of $\Delta W(t)$ according to (14). However, if the resulting volume of water stored in the tank $W_T(t)$ is lower than the minimum permissible limit, $W_{T,\min} = 0.1{\cdot}W_{T,n}$ (L), then the system operation is considered to be unsuccessful.

Case 2: The energy production of the RES generators is not adequate to cover the power requirements of the desalination units [i.e., $P_{\mathrm{RE}}(t) < P_L(t)$]. Then, in order to optimally exploit the available storage capacities of the battery bank and water tank by importing the minimum possible amount of energy from the electric grid, the following energy/water management procedure is applied.

Case 2.1: If a battery bank is available, then the discharging current of the battery bank is initially calculated according to (10). The energy available in the battery bank is adequate if its state of charge does not drop below the minimum permissible limit, $C_{B,\min} = (1 - \mathrm{DOD}){\cdot}C_B{\cdot}N_{s,p}$ (Ah), before the end of hour *t*. This condition is considered in order to examine the constraints of the battery bank operation, as described next. If $|I_B(t)| < |I_{d,\max}|$ and adequate energy is available in the battery bank, then the battery bank is discharged according to (10) in order to operate the desalination units (*priority #1*). If adequate energy is not available in the battery bank for the implementation of the previous process, or if the value of the discharging current is higher than $|I_{d,\max}|$, then

1) the battery bank is not discharged;
2) the desalination units do not operate;
3) the water demand of the consumer is covered exclusively by the water tank (*priority #2*).

All of the RES-generated energy is used to charge the battery bank with a limit of the battery charging current equal to $I_{c,\max}$.

Simultaneously, any excess RES-generated current above $I_{c,\max}$ is also sold to the electric grid. The state of charge of the battery bank is modified according to (11). If the battery bank is fully charged before the end of hour *t*, then any surplus energy is also sold to the electric grid. If the water of the tank is not enough for the implementation of this process, then the desalination units are set into operation. Additionally, the battery bank is discharged by an amount of current equal to I_B in (11), till the battery bank reaches its minimum permitted level of state of charge, $C_{B,\min} = (1 - \mathrm{DOD}) \cdot C_B' N_{s,p}$. In such a case, the additional energy required to operate the desalination units is purchased from the electric grid (*priority #3*). In the cases of priorities #1 and #3 described above, the amount of water stored in the water tank is modified by an amount of $\Delta W(t)$ according to (14). If the resulting volume of water stored in the tank is lower than the minimum permissible limit [i.e., if $W_T(t) < W_{T,n}$], then the system operation is considered to be unsuccessful.

Case 2.2: If a battery bank is not available, then

1) the water stored in the tank is enough to autonomously cover the consumer demand without operation of the desalination units, and a) the amount of the water stored in the water tank is decreased by $W_D(t)$ [i.e., by setting $W_{\mathrm{RO}}(t) = 0$ in (14)] and b) all of the RES-generated energy is sold to the electric grid;
2) the water stored in the tank is not enough to autonomously cover the consumer demand without operation of the desalination units, and a) the extra energy required for setting the desalination units into operation (in combination with the RES-generated energy) is purchased from the electric grid and b) the amount of water stored in the water tank is modified by $\Delta W(t)$ according to (14). However, if the resulting volume of water stored in the tank is lower than the minimum permissible limit (i.e., if $W_T(t) > W_{T,n}$), then the system operation is considered to be unsuccessful.

In all cases mentioned above, where the overall system operation is unsuccessful, the corresponding structure of the RES-based desalination plant is not considered as a potential solution of the design optimization problem.

A flushing process of the desalination units (if required by the desalination technology employed) with a duration of 1 h is considered to be performed at the end of each week. If this is not feasible due to unavailability of the required amount of electric energy or water, it is performed at the first available time after the end of a week, where all of the following conditions are satisfied: 1) The required amount of water is available in the water storage tank for covering both the flushing process and the consumer demand; and 2) the required amount of power from the RES generators and/or from the battery bank (with discharging current less than $C_n/5\mathrm{h}$) is available. If these conditions cannot be satisfied within 72 h after the end of a week, then the corresponding structure of the RES-based desalination plant is not considered as a potential solution of the design optimization problem. The production of water by the desalination units is suspended during the operating hours in which a flushing process is executed. If batteries are available and the flushing process is performed by also using battery energy, then the battery bank is discharged. If the RES-generated energy is higher than that required for flushing, then the remaining energy is used to charge the battery bank with a limit on the battery charging current equal to $C_n/5\mathrm{h}$. Furthermore, any excess RES-generated current above $C_n/5\mathrm{h}$ is sold to the electric grid. The state of charge of the battery bank is modified according to (11). If the battery bank is fully charged before the end of hour *t*, then any surplus energy is also sold to the electric grid. If batteries are not available in the desalination plant, then any excess RES-generated energy above the amount required for performing the flushing process is sold to the electric grid. In all of the aforementioned cases, the water tank supplies both the water required for flushing and the water required by the consumer. When the flushing process has been finished, the normal operation of the desalination system is continued, as described above.

The battery bank state of charge and the volume of water stored in the water tank at the end of the simulation process must be higher than their initial values, i.e.

$$W_T(8760 \cdot Y) \geq W_T(0) = 0.5 \cdot W_{T,n} \tag{16}$$

$$C(8760 \cdot Y) \geq C(0) = (1 - \mathrm{DOD}/2) \cdot C_n. \tag{17}$$

If (16) and (17) are not met, then the configuration of the grid-connected RES-based system is considered to be operationally unsuccessful.

In the proposed design methodology, the values of the parameters N_S, N_{PVA}, N_{BAT}, β, $W_{T,n}$, N_{DU}, N_{WG}, and $l_{\mathrm{W/G}}$ are calculated by the optimization process as analyzed in the following section.

III. Design Optimization of the RES-Based Desalination System

The design optimization of the RES-based desalination plant requires the calculation of its total lifetime cost and the application of the design optimization procedure, as described in the following section.

A. Calculation of the Total Lifetime Cost

The decision (design) variables of the proposed optimization process are the parameters N_S, N_{PVA}, N_{BAT}, β, $W_{T,n}$, N_{DU}, N_{WG}, and $l_{\mathrm{W/G}}$, which have been defined in Section II. These parameters correspond to energy- and water-related subsystems of the overall desalination plant and synthesize the vector of design variables $\mathbf{X} = [N_S \,|\, N_{\mathrm{PVA}} \,|\, N_{\mathrm{BAT}} \,|\, \beta \,|\, W_{T,n} \,|\, N_{\mathrm{DU}} \,|\, N_{\mathrm{WG}} \,|\, l_{\mathrm{W/G}}]$.

The target of the proposed optimization process is to derive the optimal value of $\mathbf{X}$ that minimizes the present value of the total lifetime cost of the RES-based desalination system under design, $C_{\mathrm{total}}(\mathbf{X})$ (€), i.e.

$$\underset{X}{\text{minimize}} \left\{ C_{\mathrm{total}}(X) \right\}. \tag{18}$$

The constraints of the design variables values are the following:

$0 \leq N_S \leq \mathrm{floor}(V_{\mathrm{MPP},\max}/\max[V_{\mathrm{MPP}}(t)]|_{t=1}^{t=8760 \cdot Y})$, $N_{\mathrm{PVA}} \geq 0$, $N_{\mathrm{BAT}} \geq 0$, $0^o \leq \beta \leq 90^o$, $W_{T,n} \geq 0$, $N_{\mathrm{DU}} \geq 1$, $N_{\mathrm{WG}} \geq 0$, and $9 < l_{\mathrm{W/G}} \leq 15$, where $V_{\mathrm{MPP,max}}$ (V) is the maximum operating MPP voltage level of the PV battery charger.

In order to take into account all factors affecting the cost of grid-connected RES-based desalination systems that cooperate with smart grids, the value of $C_{\text{total}}(\mathbf{X})$ is calculated as the sum of the following components.

1) The costs of connecting the desalination plant to the distribution network of potable water and the electric grid, respectively.
2) The total cost of the pipelines transferring seawater to the desalination plant and dispose brine back to the sea, respectively.
3) The total installation and lifetime maintenance costs of the devices synthesizing the overall desalination plant.
4) The present value of the total cost of buying electric energy from the electric grid.
5) The replacement costs of the batteries and power electronic converters due to malfunctions over the entire lifetime period of the desalination plant.

Therefore, in the proposed methodology, the value of C_{total} in (18) is calculated as follows:

$$\begin{aligned} C_{\text{total}}(\boldsymbol{X}) &= c_w + c_e + c_T + N_{\text{PV}} \cdot C_{\text{PV}} + N_{\text{BAT}} \cdot C_{\text{BAT}} \\ &+ N_{\text{CH}} \cdot C_{\text{CH}} + W_{T,n} \cdot C_T + N_{\text{WG}} \cdot (C_{\text{WG}} + (h \cdot C_h)) \\ &+ N_{\text{DU}} \cdot C_{\text{DU}} + N_{\text{INV}} \cdot C_{\text{INV}} \\ &+ \sum_{j=1}^{Y} \begin{bmatrix} E_p(j) \cdot c_p + N_{\text{PV}} \cdot M_{\text{PV}} + W_{T,n} \cdot M_T \\ +N_{\text{DU}} \cdot M_{\text{DU}} + N_{\text{WG}} \cdot (M_{\text{WG}} + (M_h \cdot h)) + \\ +N_{\text{BAT}} \cdot M_{\text{BAT}} + N_{\text{CH}} \cdot M_{\text{CH}} + N_{\text{INV}} \cdot M_{\text{INV}} \end{bmatrix} \\ &\cdot \frac{(1+g)^j}{(1+i)^j} + R_{\text{BAT}} + R_{\text{CH}} + R_{\text{INV}} \end{aligned} \tag{19}$$

where c_w (€) is the total cost of connecting the desalination plant water production to the water distribution network; c_e (€) is the total cost of the connection with the electric grid; c_T (€) is the total cost of the pipelines (running in parallel) transporting seawater to the desalination system installation point and dispose brine back to the sea, respectively; $N_{\text{PV}} = N_S \cdot N_P \cdot N_{\text{PVA}}$ is the total number of PV modules of the RES system; C_{PV}, C_{BAT}, C_{CH}, C_{DU}, C_{INV}, and C_{WG} (€) are the purchase and installation costs of each PV module, battery, PV battery charger, desalination unit, dc/ac inverter, and W/G, respectively; C_T (€/L) is the construction cost of the water tank per liter of volume; C_h (€/m) is the purchase and installation cost of the W/Gs installation tower per meter of height; Y (years) is the lifetime period of the RES-based desalination system; $E_p(j)$ (kWh) is the total energy purchased from the electric grid during year j ($1 \leq j \leq Y$); c_p (€/kWh) is the present value of the price of the electric energy purchased from the electric grid; M_{PV}, M_{BAT}, M_{CH}, M_{DU}, M_{INV}, and M_{WG} (€) are the present values of the annual maintenance costs of each PV module, battery, PV battery charger, desalination unit, dc/ac inverter, and W/G, respectively; M_T (€/L) is the present value of the annual maintenance cost of the water tank per liter of volume; M_h (€/m) is the present value of the annual maintenance cost of the W/Gs installation tower per meter of height; R_{BAT} (€) is the present value of the total cost of replacing the batteries; R_{CH} (€) is the present value of the total replacement cost of the PV battery chargers; R_{INV} (€) is the present value of the total replacement cost of the dc/ac inverters; g (%) is the annual inflation rate, and i (%) is the interest rate.

The value of c_w in (19) is calculated considering the maximum value of hourly water demand of the consumer during the year, as follows:

$$c_w = c_{w\text{net}} \cdot \max \left\{ W_D(t)|_{t=1}^{t=8760} \right\} \tag{20}$$

where $c_{w\text{net}}$ (€/L) is the cost of connecting the desalination plant water production to the water distribution network per liter of water transferred hourly.

The RES-based desalination plant is designed such that it is able to inject the maximum possible power to the electric grid (if such a surplus is available during system operation). For that purpose, the value of c_e in (19) is calculated according to the total nominal ac power of the dc/ac inverters included in the RES-based power supply system, as follows:

$$c_e = c_{\text{enet}} \cdot N_{\text{INV}} \cdot P_{\text{INV}} \tag{21}$$

where c_{enet} (€/W) is the cost per watt of connecting with the electric grid, including the costs of any infrastructure required, such as the power line and substations.

The value of C_{DU} in (19) also includes the following.

1) The costs of internal constructions related to the desalination units, such as the seawater filters, the holding tanks for water pre- and posttreatment, and instrumentation equipment.
2) The total cost of the pipelines (running in parallel) transporting seawater to the desalination system installation point and dispose brine back to the sea, respectively, when the desalination system is installed next to the sea (i.e., along the coastline).

If the desalination plant is not installed next to the sea, then the total cost of the additional pipelines transporting seawater to the desalination system installation point and dispose brine back to the sea (brine outfall pipeline), c_T (€), is calculated as follows:

$$c_T = H \cdot c_H \cdot W_{d,n} \cdot N_{\text{DU}} + E \cdot c_E \cdot W_{d,n} \cdot N_{\text{DU}} \tag{22}$$

where c_H and c_E [€/(m·L)] are the installation costs of the water transportation system per meter of horizontal distance and elevation, respectively, and per liter of daily nominal water production of the desalination units.

During the desalination plant lifetime period, the batteries should be replaced due to their limited lifetime because of aging, which affects the total system cost in (18) and (19). The lifetime of the battery bank depends on its charge/discharge profile versus time. In order to calculate the associated cost [i.e., parameter R_{BAT} in (19)], the total ampere-hour capacity that the battery bank is capable to provide during its entire lifetime period ($Q_{\text{bat,total}}$) is calculated initially as follows:

$$Q_{\text{bat,total}} = \text{DOD} \cdot C_B \cdot N_{B,p} \cdot N_C \tag{23}$$

where N_C is the number of lifetime charging/discharging cycles with the permitted DOD specified by the battery manufacturer.

The ampere-hour throughput of the battery bank during the system operation, $Q_{\mathrm{Ah},t}$ (Ah), is also calculated during the simulation of the RES system operation described in Section II. This is performed by using the computed values of the battery bank discharging current as follows:

$$Q_{\mathrm{Ah},t} = \sum_{t=1}^{1\leq t\leq 8760\cdot Y} I_B(t)\cdot S\left(I_B(t)\right)\cdot 1\mathrm{h} \tag{24}$$

where the function $S(x)$ is defined as

$$S(x) = 0 \quad \text{if } x \geq 0, \text{ else} \quad S(x) = +1. \tag{25}$$

The batteries are replaced at hour t ($1 \leq t \leq 8760 \cdot Y$), where the value of $Q_{\mathrm{Ah},t}$ at that hour has become equal to the value of $Q_{\mathrm{bat,total}}$, which has been calculated by (23). The present value of the batteries replacement cost during the desalination system lifetime period, R_{BAT} (€), is calculated as follows:

$$R_{\mathrm{BAT}} = N_{\mathrm{BAT}}\cdot C_{\mathrm{BAT}}\cdot\left[\sum_{\forall j=Y_1^*}\frac{(1+g)^j}{(1+i)^j}\right]. \tag{26}$$

The sum in (26) is calculated only for the specific values of year numbers, Y_1^*, that the battery bank replacement is required [36]. During the simulation of the RES-based desalination system operation, after the replacement of the batteries, their state of charge is considered to be equal to its last value before the replacement. Through this process, the distortion of the power supply system energy balance and the deterioration of the energy flow calculations are avoided. Therefore, the replacement of the batteries affects only the total lifetime cost of the desalination system [i.e., the value of $C_{\mathrm{total}}(\mathbf{X})$ in (19)].

The present values of the PV battery chargers and dc/ac inverters replacement costs, R_{CH} and R_{INV} (€), respectively, in (19), are calculated according to the following equations:

$$R_{\mathrm{CH}} = N_{\mathrm{CH}}\cdot C_{\mathrm{CH}}\cdot\left[\sum_{\forall j=Y_2^*}\frac{(1+g)^j}{(1+i)^j}\right] \tag{27}$$

$$R_{\mathrm{INV}} = N_{\mathrm{INV}}\cdot C_{\mathrm{INV}}\cdot\left[\sum_{\forall j=Y_3^*}\frac{(1+g)^j}{(1+i)^j}\right]. \tag{28}$$

The values of Y_2^* and Y_3^* depend on the total number of operating hours of the PV battery chargers and dc/ac inverters during the desalination system lifetime period and their mean time between failures, $\mathrm{MTBF_{CH}}$ and $\mathrm{MTBF_{INV}}$ (in hours), which are specified by their manufacturers

$$Y_2^* = Y\cdot 365\cdot 24/MTBF_{\mathrm{CH}} \tag{29}$$

$$Y_3^* = Y\cdot 365\cdot 24/MTBF_{\mathrm{INV}}. \tag{30}$$

B. Optimization Procedure

A flowchart of the optimization procedure for calculating the optimal configuration of the grid-connected RES-based desalination system is shown in Fig. 2. Initially, the designer provides the input data required for the execution of the optimal design process given as follows.

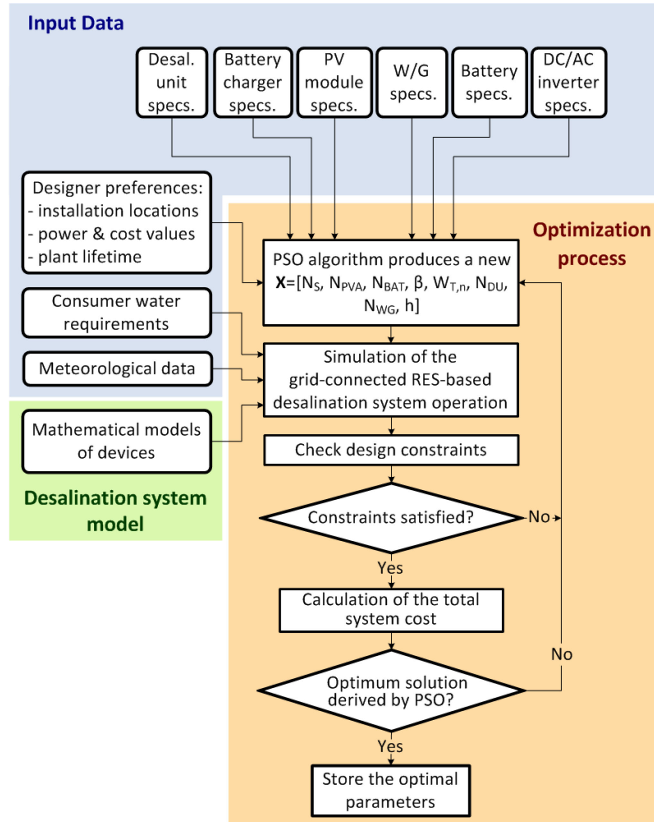

Fig. 2. Flowchart of the proposed design optimization algorithm of the grid-connected RES-based desalination system.

1) the operational specifications of the energy- and water-related devices that will be used for synthesizing the RES-based desalination system under study;
2) the installation location of the desalination plant;
3) the values of power- and cost-related parameters required for simulating the desalination plant operation (as analyzed in Section II) and for calculating the total system cost;
4) the desired operational characteristics of the desalination plant, i.e., lifetime period and hourly values of water demand of the consumer during the year;
5) the hourly values of solar irradiance on horizontal plane, ambient temperature, and wind speed at a reference height (l_{ref} in meters), which prevail at the desired installation location during the year.

The optimal value of $C_{\mathrm{total}}(\mathbf{X})$ in (18) is derived by using the particle swarm optimization (PSO) algorithm. Compared with other evolutionary optimization techniques (e.g., genetic algorithms, firefly algorithm, etc.), the PSO algorithm exhibits relative implementation simplicity and is effective in solving complex nonlinear optimization problems [37]. During the execution of the optimization process (see Fig. 2), multiple alternative values of $\mathbf{X}$ are generated by the PSO algorithm. For each one of them, the desalination plant operation is simulated for each hour of its entire lifetime period, as analyzed in Section II. Additionally, the corresponding lifetime system cost, $C_{\mathrm{total}}(\mathbf{X})$, is calculated according to (19). Among the alternative values of $\mathbf{X}$ evaluated through this process, the vector $\mathbf{X}$ that 1) does not lead to unsuccessful operation during any hour of the desalination system lifetime period according to Sections II and 2) results in the minimum value of $C_{\text{total}}(\mathbf{X})$ is considered as the optimal design solution.

IV. Alternative Optimization Criteria

In order to investigate the impact of the objective function type on the design optimization results, modifications of (19), which express different optimization objectives, have alternatively been employed in the optimization process for comparison purposes.

1) The minimization of the net lifetime cost of the grid-connected RES-based desalination plant, $C_{\text{net}}(\mathbf{X})$ (€). The value of $C_{\text{net}}(\mathbf{X})$ is calculated by subtracting from $C_{\text{total}}(\mathbf{X})$ the lifetime revenues obtained by selling energy to the electric grid, and can be written as follows:

$$C_{\text{net}}(\boldsymbol{X}) = C_{\text{total}}(\boldsymbol{X}) - \sum_{j=1}^{Y} E_s(j) \cdot c_s \cdot \frac{(1+g)^j}{(1+i)^j} \tag{31}$$

where $E_s(j)$ (kWh) is the total energy sold to the electric grid during year j ($1 \leq j \leq Y$) and c_s (€/kWh) is the present value of the price of the electric energy sold to the electric grid that has been specified by the designer.

2) The maximization of the total revenues obtained by selling the excess energy to the electric grid during the desalination plant lifetime period, $C_{\text{rev}}(\mathbf{X})$ (€), which is calculated as follows:

$$C_{\text{rev}}(\boldsymbol{X}) = \sum_{j=1}^{Y} E_s(j) \cdot c_s \cdot \frac{(1+g)^j}{(1+i)^j}. \tag{32}$$

In this case, the total nominal power rating of the RES units has been constrained to be less than three times that of the optimized configuration derived by employing the optimization objective described by (18) and (19).

3) The minimization of the lifetime cost of a desalination plant without RES and energy storage devices, which operates by buying energy from the electric grid. In this case, the vector of design variables is $\mathbf{X_1} = [W_{T,n}|N_{\text{DU}}]$. Also, the optimization process is performed by minimizing the corresponding total lifetime cost objective function $C_{\text{eg}}(\mathbf{X_1})$ (€), which is given as

$$\begin{aligned} C_{\text{eg}}(X_1) &= c_w + c_e + c_T + W_{T,n} \cdot C_T + N_{\text{DU}} \cdot C_{\text{DU}} \\ &+ \sum_{j=1}^{Y} [E_p(j) \cdot c_p + W_{T,n} \cdot M_T + N_{\text{DU}} \\ &\cdot M_{\text{DU}} +] \cdot \frac{(1+g)^j}{(1+i)^j}. \end{aligned} \tag{33}$$

By setting the values of c_p and/or c_s equal to zero enables to investigate configurations of the RES-based desalination system where energy can only be sold to or purchased from the electric grid. Also, it is observed that the objective functions given by (19), (32), and (33) are parts of the objective function (31).

In order to denote the installation of the desalination units next to the sea, the designer should input the values $c_H = c_E = P_E = P_H = 0$ to the optimization algorithm. This affects the values calculated by (5) and (22), (31), or (33). If the RES devices should be installed at a different location from the desalination units (e.g., at a point that exhibits significant RES potential), then the installation point specified initially by the designer corresponds to the location of the RES devices. In such a case, the ac output power of the dc/ac inverters can be transferred to the desalination units through the electric grid (e.g., by applying a net-metering scheme). By appropriately setting the values of c_p and/or c_s in the proposed optimization process facilitates the investigation of such configurations too.

The values of c_{wnet} and c_{enet} in (20) and (21) are specified by the designer taking into account the distances of the desalination plant from the water distribution network and the electric grid, respectively. Therefore, the value of c_w in (20) depends on the water demand and the location of the desalination units with respect to the water distribution network. Also, the values of c_e and c_T in (21) and (22), respectively, are determined by the location of the desalination system and its configuration. The latter is incorporated in (21) and (22) through the values of the decision variables N_{INV} and N_{DU}, which are derived by the optimization algorithm. Finally, the value of P_T in (5), which is also determined by the location of the desalination plant, affects the power flow during the operation of the desalination system. In turn, this affects the design results for optimizing the corresponding objective function given by (19), (31), (32), or (33), respectively. Through the aforementioned approach of selecting the design parameters values, the impact of alternative installation locations on the structure and lifetime cost of the RES-based desalination plant under design can be explored.

In case that the alternative objective functions (31)–(33) are employed in the design optimization process, the desalination plant operational constraints remain the same as described in Sections II and III. The design optimization results for alternative optimization criteria of the overall desalination plant are presented in the following section.

V. Design Optimization Results

A software program has been developed in the MATLAB platform according to the proposed methodology that has been described in Sections II–IV. Due to the computational complexity of the optimization problem, the PSO algorithm has been set to operate with a swarm size of 500 particles, and it is executed for a maximum of 600 generations. However, the optimization process is ended when the relative change of the objective function is less than 10^{-6} for 40 generations.

In order to evaluate its performance, the proposed methodology has been applied for the optimal design of a grid-connected hybrid RES-based desalination system installed in a location of the island of Crete (Greece) with latitude = 35.517° and longitude = 23.856°. The desalination plant is designed to cover the water requirements of a small community for a lifetime

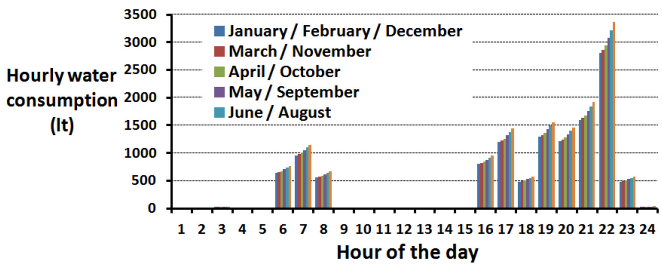

Fig. 3. Hourly variation of the consumers water demand during the year in the water distribution network under study.

TABLE I
OPERATIONAL CHARACTERISTICS AND COSTS OF THE DEVICES USED TO SYNTHESIZE THE DESALINATION PLANT UNDER DESIGN

Device type	Parameter	Value
PV modules	C_{PV}	67 €
	V_{max}	21.6 V
	I_{max}	3.24 A
PV battery chargers	C_{CH}	308.9 €
	V_{BUS}	24 V
	P_{CH}	1440 W
W/Gs	C_{WG}	3460 €
	C_h	70 €
	l_{ref}	10 m
Batteries	C_{BAT}	Type 1: 794.00 €
		Type 2: 712.48 €
		Type 3: 942.97 €
	N_C	Type 1: 1400 for 80 % DOD
		Type 2: 1200 for 60 % DOD
		Type 3: 2400 for 70 % DOD
	C_B	Type 1: 185 Ah
		Type 2: 185 Ah
		Type 3: 610 Ah
	V_B	12 V
DC/AC inverters	C_{INV}	1478 €
	P_{INV}	1200 W
Desalination units	C_{DU}	51608 €
	$W_{d,n}$	18925 lt/day

period of $Y = 20$ years. The corresponding water demand during the year is illustrated in Fig. 3.

The hybrid RES-based power supply system of the desalination plant is synthesized by commercially available devices, which feature the operational characteristics and costs presented in Table I. The proposed methodology has been applied considering three alternative types of commercially available lead–acid batteries, with different values of C_{BAT}, N_C, and C_B (see Table I), as analyzed next. The yearly maintenance costs of the dc/ac inverters and desalination units have been set equal to 10% of the corresponding purchase and installation costs. For the rest devices, the corresponding percentage has been set to 1%.

TABLE II
CONFIGURATION PARAMETERS OF THE DESALINATION PLANT UNDER DESIGN

Parameter	Value
P_H	0.0075 $W/(m \cdot m^3)$
P_E	0.15 $W/(m \cdot m^3)$
c_H	3.04 x 10^{-6} €$/(m \cdot m^3)$
c_E	2.567 x 10^{-3} €$/(m \cdot m^3)$
$C_{w/l}$	8.5 x 10^{-4} € / $(W \cdot m)$
C_T	0.35 € / lt
g	1.2 %
i	3.0 %

The values of the configuration parameters of the desalination plant, which are used in the energy-/water-flow and lifetime-cost calculation models described in Sections II–IV, are shown in Table II.

Initially, the proposed methodology was applied considering battery type 1 (see Table I), as well as (19) and (31)–(33), respectively, as alternative objective functions. The resulting optimized configurations of both the energy- (generation and storage) and water-related subsystems of desalination plants are presented in Table III. In these configurations, the costs of connecting to the water and electric energy distribution networks have been set equal to $c_w = 1.2835$ €$/\mathrm{m}^3$ and $c_e = 425$ €$/\mathrm{kW}$. These values correspond to a 500-m distance of the water and electric energy distribution networks from the desalination plant. The electric energy buying and selling prices have been set equal to $c_p = c_s = 0.10$ €$/\mathrm{kWh}$. The corresponding values of C_{total}, C_{net}, $C_{\mathrm{rev},}$ and C_{eg}, respectively, for each of the optimized configurations #1–4 presented in Table III, are depicted in Table IV. The resulting optimal capacities of the RES devices, battery bank, and desalination units for configurations #1–4 are also displayed in Table IV. The optimal values of $\mathbf{X}$ for configurations #1 and #2, as well as the corresponding values of C_{total}, $C_{\mathrm{net},}$ and C_{rev}, are equal. This is due to the fact that the desalination plant power management process (see Section II-B) directs the RES-generated energy primarily for covering its operational requirements and only any energy surplus is sold to the electric grid. Hence, the revenues obtained by selling energy to the electric grid (i.e., C_{rev}) are only 1.61% of C_{total} for configurations #1 and #2 in Table IV. Therefore, the incorporation of C_{rev} in the objective function (31) does not affect the optimal design results compared with (19). Also, it is observed in Table IV that the desalination plant that has been optimized for maximum revenues by selling the excess energy to the electric grid (i.e., configuration #3) consists only of W/Gs. The value of C_{rev} for configuration #3 is approximately 34 times higher than in configurations #1 and #2. However, the corresponding lifetime cost of that desalination plant [i.e C_{total} in (19)] is disproportionally higher by approximately 30 times since the optimization objective described by (32) does not consider the resulting system cost. The application of the proposed methodology for deriving the optimal configurations #1 and #2 enabled to reduce the lifetime cost of the desalination

TABLE III
DESIGN OPTIMIZATION RESULTS FOR ALTERNATIVE CONFIGURATIONS AND OPTIMIZATION OBJECTIVES OF THE DESALINATION PLANT

Configuration	Optimization objective	Configuration number	Optimal design parameters								
			N_S	N_P	N_{PVA}	N_{BAT}	β (°)	$W_{T,n}$ (lt)	N_{DU}	N_{WG}	$l_{W/G}$
Grid-connected desalination plant with RES	Minimum $C_{total}(\boldsymbol{X})$	1	4	7	9	10	31	98975	1	9	14
	Minimum $C_{net}(\boldsymbol{X})$	2	4	7	9	10	31	98975	1	9	14
	Maximum $C_{rev}(\boldsymbol{X})$	3	0	0	0	102	-	85864	49	69	14
Grid-connected desalination plant without RES	Minimum $C_{eg}(\boldsymbol{X}_1)$	4	-	-	-	-	-	2084	5	-	-

TABLE IV
OPTIMAL CAPACITIES OF DEVICES AND THE ECONOMIC PERFORMANCE INDICES FOR EACH OF THE OPTIMIZED CONFIGURATIONS #1–4 IN TABLE III

Configuration No.		1	2	3	4
Optimal capacities	Total PV power (kW)	12.6	12.6	-	-
	Total W/G power (kW)	5.85	5.85	44.85	-
	Nominal battery capacity (Ah)	925	925	9435	-
	Nominal water production of the desalination units (lt/h)	788.54	788.54	38638.54	3942.71
Performance index	C_{total} (k€)	286.82	286.82	8689.07	-
	C_{net} (k€)	282.21	282.21	8533.12	-
	C_{rev} (k€)	4.61	4.61	155.95	-
	C_{eg} (k€)	-	-	-	717.72

plant by 60.04% compared with that of a desalination plant operating only with electric grid energy without using any RES units (i.e., configuration #4 in Tables III and IV). This is due to the capability of the proposed technique to explore the optimal tradeoff between the RES types/capacities and the amounts of battery storage, water storage, and energy exchanged with the electric grid, respectively.

The total electric energy purchased from the electric grid and sold to the electric grid, respectively, during the operational lifetime period of each of the optimized configurations #1–#4 presented in Table III, is displayed in Fig. 4. In configurations #1 and #2, the amount of energy purchased from the electric grid is 0.017% of the corresponding energy sold to the electric grid. This percentage increases to 28.85% in configuration #3, since the cost of energy purchased from the electric grid for covering the operational requirements of the desalination units is not considered in the objective function given by (32). The energy purchased from the electric grid in configurations #1 and #2 is equal to $1.42 \cdot 10^{-3}$% of the corresponding amount in configuration #4. Therefore, the use of RES for power supplying

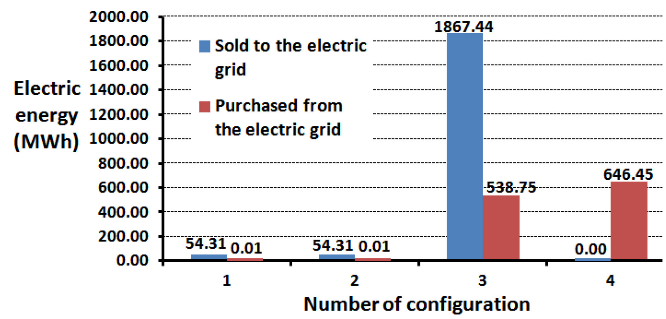

Fig. 4. Lifetime electric energy exchanged with the electric grid for each of the optimized configurations #1–#4 in Table III.

the desalination plant in both configurations #1 and #2 aimed to reduce the energy purchased from the electric grid. However, the resulting optimized configurations #1 and #2 are not fully autonomous. The application of the proposed optimization method enabled to derive the optimal capacities of the energy- and water-related subsystems such that a significant amount of electric energy (8.4% of the electric grid energy purchased by configuration #4) is sold to the electric grid. Thus, the economic viability of the desalination plant is improved and, simultaneously, the electric grid operation is supported.

As an example, the performance of the RES devices, battery bank, and water tank during the first year of operation of configuration #1 in Tables III and IV is illustrated in Fig. 5. It is observed that the daily energy sold to the electric grid is less than 18.29% of the corresponding RES-generated energy. Simultaneously, the battery bank state of charge and the amount of water in the tank vary over a wide range. These features enabled the optimal exploitation of the RES-generated energy for covering the consumer water demand with the minimum possible value of the C_{total} objective function.

The proposed design optimization process for minimizing $C_{\text{total}}(\mathbf{X})$ in (19) was also performed for multiple alternative values of c_w and c_e, in case type 1 batteries (see Table I) are used. The resulting variation of the optimal values of C_{total} for different sets of values of c_w and c_e (corresponding to 0–1000 m distances of the water and electric energy distribution networks from the desalination plant) when $c_p = 0.1$ €/kWh is depicted in Fig. 6. For each value of c_w, the optimized lifetime cost of the desalination plant increases with c_e by 1.08–2.16% compared with

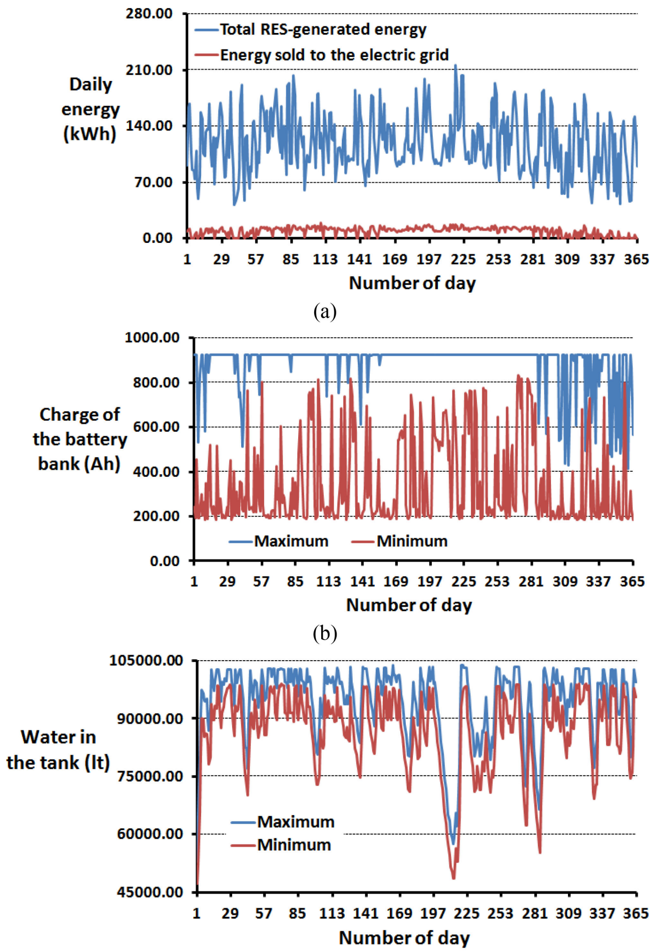

Fig. 5. Performance of the RES devices, battery bank, and water tank during the first year of operation of an optimized desalination system (configuration #1 in Tables III and IV). (a) Total daily RES-generated energy and daily energy sold to the electric grid. (b) Minimum and maximum values of charge stored in the battery bank. (c) Minimum and maximum values of water stored in the tank.

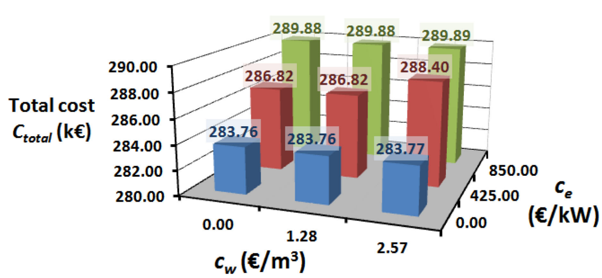

Fig. 6. Design optimization results for various values of c_w and c_e when $c_p = 0.10€/kWh$ and $C_{\text{total}}(X)$ is minimized.

the corresponding optimal values of C_{total} when $c_e = 0\,€/\text{kW}$. Also, for each value of c_e, the value of C_{total} increases with c_w by $1.49 \cdot 10^{-3} - 0.55\%$ compared with the corresponding case with $c_w = 0\;€/\text{m}^3$. Thus, the optimized lifetime system cost of the RES-based desalination plant is affected by the distances of the desalination plant from the electric grid and the water distribution network, respectively.

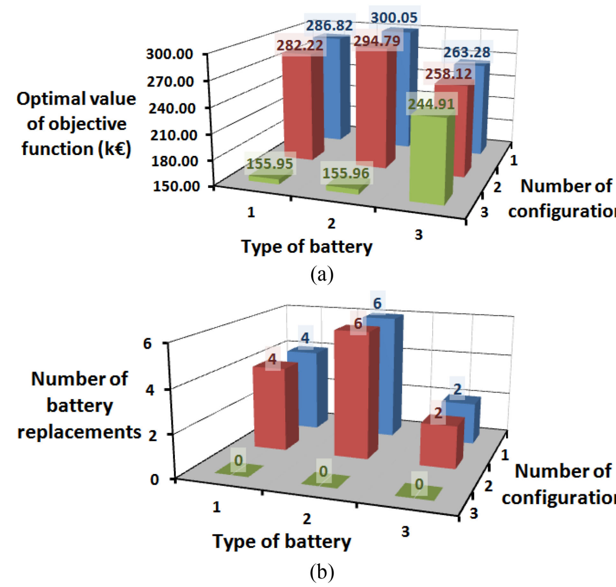

Fig. 7. Design optimization results for various battery types. (a) Optimal values of the objective functions (19), (31), and (32). (b) Number of battery replacements during the lifetime period of the desalination plant.

In order to investigate the impact of the batteries operational characteristics, the proposed methodology was also applied for the three alternative types of batteries included in Table I. The resulting optimal values of objective functions (19), (31), and (32), corresponding to configurations 1, 2, and 3, respectively, are illustrated in Fig. 7(a). The corresponding numbers of battery replacements during the 20 years lifetime period of the desalination plant are presented in Fig. 7(b). For all objective functions, using battery type 2 results in the highest values of C_{total} and C_{net} (i.e., configurations # 1 and #2 in Fig. 7) and number of replacements, due to the lower value of $Q_{\text{bat,total}}$ in (23) that it provides. Using battery type 3 resulted in zero replacements due to the high value of N_C that it features (see Table I). Also, the battery type 3 exhibits the lowest value of the ratio $C_{\text{BAT}}/Q_{\text{bat,total}}$, which enabled to reduce the values of C_{total} and C_{net} by 8.21–12.44%. Also, in case of configuration #3, the value of C_{rev} is increased by 57.04% when this type of battery is employed. Therefore, by reducing the cost and increasing the service lifetime period of the batteries improve the economic viability of the grid-connected RES-based desalination plant.

VI. Conclusion

In this article, a new design methodology has been presented, which takes into account the tradeoff between the three alternative degrees of freedom in the operation of the overall desalination plant, i.e., battery storage, water storage, and exchange of energy with the electric grid. The design optimization results indicated that the application of the proposed methodology enabled to reduce the lifetime cost of the desalination plant by 60% compared with that of a desalination plant operating only with electric grid energy without using any RES units. Also, it was demonstrated that by 1) employing the total lifetime cost of the grid-connected RES-based desalination plant as objective function of the optimal design problem and 2) reducing the cost and increasing the service lifetime period of the batteries improves the economical viability of the resulting configurations.

The proposed methodology has been focused on PVs and W/Gs due to their higher level of industrial maturity. Current and future work include the extension of the design technique presented in this article to include wave energy conversion RES technologies [6], [7], as well as the optimization of the desalination plant location.

Acknowledgment

The authors would like to thank Mrs. V. Agou, Prof. D. Hristopoulos (Technical University of Crete, Greece), Dr. V. Monbet (Université de Rennes 1, France), and Dr. P. Ailliot (Université de Brest, France) for providing the meteorological data used in this article.

References

[1] WWAP (United Nations World Water Assessment Programme)/UN-Water, *The United Nations World Water Development Report 2018: Nature-Based Solutions for Water*. Paris, France: UNESCO, 2018.

[2] W. N. Lubega and A. M. Farid, "A reference system architecture for the energy–water nexus," *IEEE Syst. J.*, vol. 10, no. 1, pp. 106–116, Mar. 2016.

[3] M. Faezipour and S. Ferreira, "A system dynamics approach for sustainable water management in hospitals," *IEEE Syst. J.*, vol. 12, no. 2, pp. 1278–1285, Jun. 2018.

[4] S. Imen, N.-B. Chang, Y. J. Yang, and A. Golchubian, "Developing a model-based drinking water decision support system featuring remote sensing and fast learning techniques," *IEEE Syst. J.*, vol. 12, no. 2, pp. 1358–1368, Jun. 2018.

[5] S. Bhojwani, K. Topolski, R. Mukherjee, D. Sengupta, and M. M. El-Halwagi, "Technology review and data analysis for cost assessment of water treatment systems," *Sci. Total Environ.*, vol. 651, no. 2, pp. 2749–2761, 2019.

[6] J. Leijon and C. Boström, "Freshwater production from the motion of ocean waves—A review," *Desalination*, vol. 435, pp. 161–171, 2018.

[7] Z. Li, A. Siddiqi, L. D. Anadon, and V. Narayanamurti, "Towards sustainability in water-energy nexus: Ocean energy for seawater desalination," *Renewable Sustain. Energy Rev.*, vol. 82, no. 3, pp. 3833–3847, 2018.

[8] Z. M. Amin, A. I. Maswood, M. N. A. Hawlader, E. A. Al-Ammar, J. Orfi, and H. A. Al-Ansary, "Desalination with a solar-assisted heat pump: An economic optimization," *IEEE Syst. J.*, vol. 7, no. 4, pp. 732–741, Dec. 2013.

[9] E. L. Mooney, Y. Almoghathawi, and K. Barker, "Facility location for recovering systems of interdependent networks," *IEEE Syst. J.*, vol. 13, no. 1, pp. 489–499, Mar. 2019.

[10] I. B. Ali, M. Turki, J. Belhadj, and X. Roboam, "Optimized fuzzy rule-based energy management for a battery-less PV/wind-BWRO desalination system," *Energy*, vol. 159, pp. 216–228, 2018.

[11] G. Zhang, B. Wu, A. Maleki, and W. Zhang, "Simulated annealing-chaotic search algorithm based optimization of reverse osmosis hybrid desalination system driven by wind and solar energies," *Sol. Energy*, vol. 173, pp. 964–975, 2018.

[12] C.-S. Karavas, K. G. Arvanitis, G. Kyriakarakos, D. D. Piromalis, and G. Papadakis, "A novel autonomous PV powered desalination system based on a DC microgrid concept incorporating short-term energy storage," *Sol. Energy*, vol. 159, pp. 947–961, 2018.

[13] W. Peng, A. Maleki, M. A. Rosen, and P. Azarikhah, "Optimization of a hybrid system for solar-wind-based water desalination by reverse osmosis: Comparison of approaches," *Desalination*, vol. 442, pp. 16–31, 2018.

[14] B. Wu, A. Maleki, F. Pourfayaz, and M. A. Rosen, "Optimal design of stand-alone reverse osmosis desalination driven by a photovoltaic and diesel generator hybrid system," *Sol. Energy*, vol. 163, pp. 91–103, 2018.

[15] S. Bahrami and M. H. Amini, "A decentralized trading algorithm for an electricity market with generation uncertainty," *Appl. Energy*, vol. 218, pp. 520–532, 2018.

[16] K. G. Boroojeni, M. H. Amini, A. Nejadpak, S. S. Iyengar, B. Hoseinzadeh, and C. L. Bak, "A theoretical bilevel control scheme for power networks with large-scale penetration of distributed renewable resources," in *Proc. 2016 IEEE Int. Conf. Electro Inf. Technol.*, Grand Forks, ND, USA, 2016, pp. 510–515.

[17] N. Saxena and B. J. Choi, "Integrated distributed authentication protocol for smart grid communications," *IEEE Syst. J.*, vol. 12, no. 3, pp. 2545–2556, Sep. 2018.

[18] P. Kou, D. Liang, and L. Gao, "Stochastic energy scheduling in microgrids considering the uncertainties in both supply and demand," *IEEE Syst. J.*, vol. 12, no. 3, pp. 2589–2600, Sep. 2018.

[19] M. Diekerhof, S. Schwarz, F. Martin, and A. Monti, "Distributed optimization for scheduling electrical demand in complex city districts," *IEEE Syst. J.*, vol. 12, no. 4, pp. 3226–3237, Dec. 2018.

[20] F. Ahmad, M. S. Alam, and M. Shahidehpour, "Profit maximization of microgrid aggregator under power market environment," *IEEE Syst. J.*, vol. 13, no. 3, pp. 3388–3399, Sep. 2019.

[21] T. Remani, E. A. Jasmin, and T. P. I. Ahamed, "Residential load scheduling with renewable generation in the smart grid: A reinforcement learning approach," *IEEE Syst. J.*, vol. 13, no. 3, pp. 3283–3294, Sep. 2019.

[22] S. R. Ghatak, S. Sannigrahi, and P. Acharjee, "Multi-objective approach for strategic incorporation of solar energy source, battery storage system, and DSTATCOM in a smart grid environment," *IEEE Syst. J.*, vol. 13, no. 3, pp. 3038–3049, Sep. 2019.

[23] F. M. Gatta *et al.*, "Replacing diesel generators with hybrid renewable power plants: Giglio Smart Island project," *IEEE Trans. Industry Appl.*, vol. 55, no. 2, pp. 1083–1092, Mar./Apr. 2019.

[24] W. Hickman, A. Muzhikyan, and A. M. Farid, "The synergistic role of renewable energy integration into the unit commitment of the energy water nexus," *Renewable Energy*, vol. 108, pp. 220–229, 2017.

[25] N. Vakilifard, P.A. Bahri, M. Anda, and G. Ho, "A two-level decision making approach for optimal integrated urban water and energy management," *Energy*, vol. 155, pp. 408–425, 2018.

[26] A. M. Abdelshafy, H. Hassan, and J. Jurasz, "Optimal design of a grid-connected desalination plant powered by renewable energy resources using a hybrid PSO–GWO approach," *Energy Convers. Manage.*, vol. 173, pp. 331–347, 2018.

[27] R. Fornarelli, F. Shahnia, M. Anda, P. A. Bahri, and G. Ho, "Selecting an economically suitable and sustainable solution for a renewable energy-powered water desalination system: A rural Australian case study," *Desalination*, vol. 435, pp. 128–139, 2018.

[28] L. Perković *et al.*, "Modeling of optimal energy flows for systems with close integration of sea water desalination and renewable energy sources: case study for Jordan," *Energy Convers. Manage.*, vol. 110, pp. 249–259, 2016.

[29] S. Aminfard, F. T. Davidson, and M. E. Webber, "Multi-layered spatial methodology for assessing the technical and economic viability of using renewable energy to power brackish groundwater desalination," *Desalination*, vol. 450, pp. 12–20, 2019.

[30] T. Ishimatsu, A. Doufene, A. Alawad, and O. de Weck, "Desalination network model driven decision support system: A case study of Saudi Arabia," *Desalination*, vol. 423, pp. 65–78, 2017.

[31] N. Priyadarshi, S. Padmanaban, P. K. Maroti, and A. Sharma, "An extensive practical investigation of FPSO-based MPPT for grid integrated PV system under variable operating conditions with anti-islanding protection," *IEEE Syst. J.*, vol. 13, no. 2, pp. 1861–1871, Jun. 2019.

[32] Y. Zhou and R. S. J. Tol, "Evaluating the costs of desalination and water transport," *Water Resour. Res.*, vol. 41, no. 3, pp. 1–10, Mar. 2005.

[33] E. Lorenzo, *Solar Electricity—Engineering of Photovoltaic Systems*, 1st ed. Sevilla, Spain, Progensa, 1994.

[34] E. Koutroulis, D. Kolokotsa, A. Potirakis, and K. Kalaitzakis, "Methodology for optimal sizing of stand-alone photovoltaic/wind-generator systems using genetic algorithms," *Sol. Energy*, vol. 80, no. 9, pp. 1072–1088, 2006.

[35] F. Blaabjerg and D. M. Ionel, *Renewable Energy Devices and Systems with Simulations in MATLAB and ANSYS*. Boca Raton, FL, USA: CRC Press, 2017.

[36] E. Koutroulis, D. Kolokotsa, and G. Stavrakakis, "Optimal design and economic evaluation of a battery energy storage system for the maximization of the energy generated by wind farms in isolated electric grids," *Wind Eng.*, vol. 33, no. 1, pp. 55–81, 2009.

[37] S. R. Ghatak, S. Sannigrahi, and P. Acharjee, "Comparative performance analysis of DG and DSTATCOM using improved PSO based on success rate for deregulated environment," *IEEE Syst. J.*, vol. 12, no. 3, pp. 2791–2802, Sep. 2018.