

Article

Is Small Scale Desalination Coupled with Renewable Energy a Cost-Effective Solution?

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Abstract: Water and energy are two of the most important inputs for a community to thrive. While water is dominant on earth, only 2.5% of the water is fresh water and over 98% of that water is either ground water or locked up in glaciers and ice caps. Therefore, only about 1.2% of all the freshwater is surface water which is able to meet human needs. About 2 billion people currently do not have sufficient access to fresh water. One of the solutions deployed in the last decades for island and coastal areas has been desalination. Desalination of seawater and brackish groundwater is commercially available and still a fast-advancing technology. The decreasing cost of renewable energy coupled with strategies based on renewables for powering populations without access to electricity and policies for complete decarbonization of the economy such as the European Green Deal make the combination of renewables and desalination a really interesting approach. This paper investigates combinations of small-scale RO desalination systems which are able to produce up to a few thousand m³ of desalinated water per day coupled with photovoltaic (PV) and wind energy systems, both in grid-connected, as well as in autonomous scenarios. The results show that RO desalination coupled with renewables can address cost-effectively the current issues in terms of water scarcity, while minimizing the environmental footprint of the process. In this paper, it has been showcased that desalination powered by renewables can be deployed in practically any location on earth having access to sea or a brackish water source. The results show that even for grid-connected systems it is more cost-effective and profitable to include a renewable energy system to power the plant, apart from the corresponding environmental benefits.

Keywords: desalination; renewables; reverse osmosis; photovoltaics; wind turbines; particle swarm optimization



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1. Introduction

Water and energy are two of the most important inputs for a community to thrive. This is highlighted in the United Nations Sustainable Development Goals (SDGs), with SDG 6 targeted at ensuring access to water and sanitation for all and SDG 7 targeted at ensuring affordable, reliable, sustainable, and modern energy for all [1]. While water is dominant on earth, only 2.5% of the water is fresh water and over 98% of that water is either ground water or locked up in glaciers and ice caps. Therefore, only about 1.2% of all freshwater is surface water that is able to meet human needs [2]. There are many areas in the world such as islands and coastal areas (e.g., Mediterranean, Middle East, South Asia, North China, Australia, Western US, Mexico, Southern Africa, Northeastern Brazil, and the west coast of Southern America) that face shortages in access to fresh water. This translates to about 2 billion people not having sufficient access to fresh water [3].

In order to overcome the water shortage problems, one of the prominent solutions especially in the past, that has been implemented in numerous areas around the world, is the transportation of fresh water by land or sea [4]. This can take place using vehicles or by deploying the extended water network infrastructure. Nonetheless, water transfers can

create adverse economic and environmental impacts such as the minimization of water resources and the increase of greenhouse gas (GHG) emissions. One of the solutions deployed in the last decades for island and coastal areas overcoming the disadvantages of water transfers has been desalination.

Desalination is commonly defined as the process of removing dissolved salts from saline or brackish water to make it suitable for human use and consumption, i.e., domestic, agricultural, and industrial purposes. It is considered as an important alternative for the supply of fresh water, especially in water scarce regions. Desalination processes take a saline water source and put in energy to produce two separate streams, a stream of fresh water and a stream of brine (concentrated salt water) (Figure 1). It is desirable that a desalination technology be highly efficient, which means to use a minimal amount of energy and produce a large volume of fresh water and a small volume of highly concentrated brine.

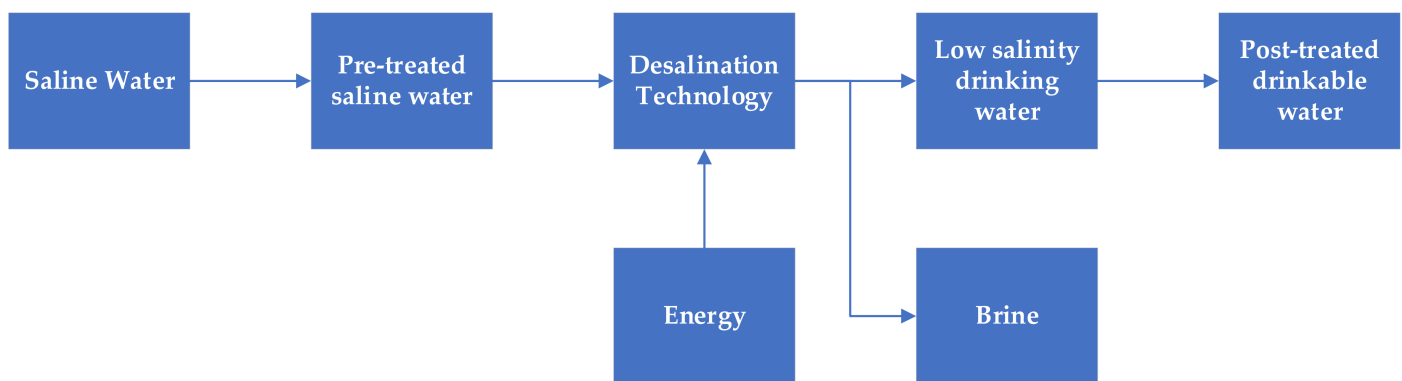


Figure 1. The desalination process.

The desalination of seawater and brackish groundwater is commercially available and still a fast advancing technology, which already provides fresh water to many towns and cities worldwide through large-scale applications as well as from well-established very small-scale applications for ships, yachts, etc. Despite its high cost, desalinated water is also used for land irrigation (agriculture) today [5,6].

The desalination technologies may be categorized as thermal desalination (distillation) processes, membrane processes, and charge based desalination technologies (ion exchange processes). Thermal methods are based on the water phase change. Heat is used to evaporate the salty water (leaving salt behind) and then the water vapour is condensed to obtain fresh water. Membrane desalination processes use differences in osmotic potentials (pressures) across a semi-permeable polymer membrane to physically separate salt from water. Charge-based separation techniques are based on the fact that salt consists of charged ions, which can be withdrawn from water by applying an electric potential. Thermal technologies are highly effective at large capacities (several thousands of m^3/d) while charge-based separation technologies are best suited for smaller operations (few hundreds of m^3/d) and brackish water. Membrane desalination methods are the most popular, have been optimized and commercialized for a broad range of capacities, from very large-scale industrial use (hundreds of thousands of m^3/d) to very small-scale (less than $1 \text{ m}^3/\text{d}$) in-home applications [7].

Reverse osmosis (RO) is a commonly used water purification technology that employs a semipermeable membrane to remove ions, molecules, and larger particles from drinking water. In RO, a pressure is applied, higher than the osmotic one that is driven by chemical potential differences of the solvent. For the seawater of salinity of about $35,000 \text{ mg/L}$ on one side of the membrane (Ocean water) and drinking water of salinity of 500 mg/L on the other side of the membrane, the osmotic pressure created on the membrane is 24 bars [8]. RO can remove many types of dissolved and suspended substances as well as biological ones (principally bacteria) from the water and is used in both industrial processes and the production of potable water. The result is that the solute is retained on the pressurized side

of the membrane and the pure solvent (H_2O) can pass to the other side. To be “selective”, this membrane should not allow large molecules or ions through the pores (holes) but should allow smaller components of the solution (such as solvent molecules, i.e., H_2O) to pass freely. Since RO membranes can be clogged very easily by suspended solids and mineral scaling compounds, RO systems require a special treatment which is not used in thermal desalination systems to process the source seawater [9,10]. Desalinated water then goes through the post-treatment, such as pH regulation and disinfection, to make it potable.

About 80% of the electrical energy requirement in RO systems refers to the high-pressure pumps [11,12]. In RO systems (especially seawater RO) energy from the pressurized concentrate can be recovered by energy exchanger systems, reducing the required pumping energy by about 30 to 50% [13].

A major advantage of RO is its modularity, allowing the design of any plant capacity starting from less than $1\text{ m}^3/\text{d}$ to giant plants such as Taweelah, UAE— $909,200\text{ m}^3/\text{d}$ [14]. The special attraction of RO for small size systems is indicated by a global market share exceeding 90%, considering systems with capacities of the order of $1000\text{ m}^3/\text{d}$ [15].

RO systems are attributed to a high potential for directly applying renewable energy (RE) supply such as wind energy or photovoltaics (PV). RO membrane suppliers recommend continuous operation and smooth shutdown and start-up procedures regarding pressure and flow [16]. Furthermore, flushing of the RO module with desalinated water is recommended when the system is shutdown. Thus, RO systems require energy storages (e.g., electrical or mechanical) to account for changes in energy supply when combined with fluctuating RE sources. Research in intermittent operation as well as variable operation has taken place for over 20 years. Intermittent operation essentially refers to the desalination plant not operating constantly throughout the year. This can happen, for example, when a desalination plant is powered by a PV system and the design choice is made not to operate constantly. This has been investigated both for brackish water [17], as well as sea water desalination plants [18]. Further to that, investigation has taken place in order to operate the desalination plant at variable pressures to better couple the desalination plant with an intermittent RE system [19] and to harvest the decreased specific power consumption albeit with decreased water production [20]. This research is coupled with research in understanding the coupling of PVs [21] and wind turbines [22,23] with desalination systems. As the artificial intelligence applications in the renewable energy sector were expanding in management and control [24] and RE production and load forecast [25–27], such applications were deployed also for desalination systems [28]. While intermittent operation is currently employed even in real world systems [29], the variable pressure operation is still under investigation regarding the effect on the membranes, but results show that there is potential for use in commercial applications as well [30,31], allowing the implementation of more advanced operation schemes for RE based RO desalination systems [32]. A special mention ought to be made to shallow depth low enthalpy geothermal resources ($<150\text{ }^\circ\text{C}$), since they can be used for electricity generation depths [33]. Many such wells are in existence worldwide either drilled as testing boreholes or utilized in thermal applications [34]. Organic rankine cycle (ORC) engines are currently the most mature commercially available technology for small to medium rated power systems from a few kW_e to a few MW_e [35].

The decreasing cost of RE coupled with strategies based on renewables for powering populations without access to electricity [36] and policies for complete decarbonization of the economy such as the European Green Deal [37] make the combination of renewables and desalination a really interesting approach. This paper aims to investigate combinations of small-scale RO desalination systems (for the purposes of this paper small-scale desalination systems are defined as being able to produce a few thousands m^3 of fresh water per day) with PV and wind energy systems, both in grid-connected scenarios, as well as in autonomous/off-grid scenarios. The main questions set to respond are:

- What is currently the cost of water from desalination systems employing RE technologies?

- How does grid-connected and autonomous systems compare?
- Does it make sense to invest in renewables when grid connection is possible?
- How do PV based, wind turbine based, and hybrid systems compare?
- What is the importance of potable water tank size?
- How does the capacity of the desalination plant affect the final price?
- Does it make sense to install a higher production capacity desalination plant in an autonomous system operating for less hours a day than installing a plant operating practically all day long?
- How does the cost of renewables affect different water production capacity desalination plants?

In order to respond to these questions, multiple case studies set in a Greek Island in the Aegean Sea are considered and investigated in this paper and the net present cost of water for over a 20-year period is going to be utilized as the main comparison indicator.

2. Materials and Methods

2.1. Renewable Energy and RO Desalination

RO desalination needs electrical power to operate. Figure 2 presents the various options for powering an RO desalination plant. Generally speaking, the option to connect to an electricity grid can decrease the cost of powering the desalination unit in comparison to an autonomous system. Given the decreasing cost of renewables, scenarios using distributed renewables are going to be investigated under schemes such as net-metering in terms of cost, apart from the environmental benefits this approach presents. Distributed energy storage in grid-connected systems is not investigated in this paper, since no regulatory framework for distributed energy storage exists in Greece yet. In any case, the investigation in a storage system for a grid connected plant has to take place on a per-country basis based on the regulatory framework and the motives given for it.

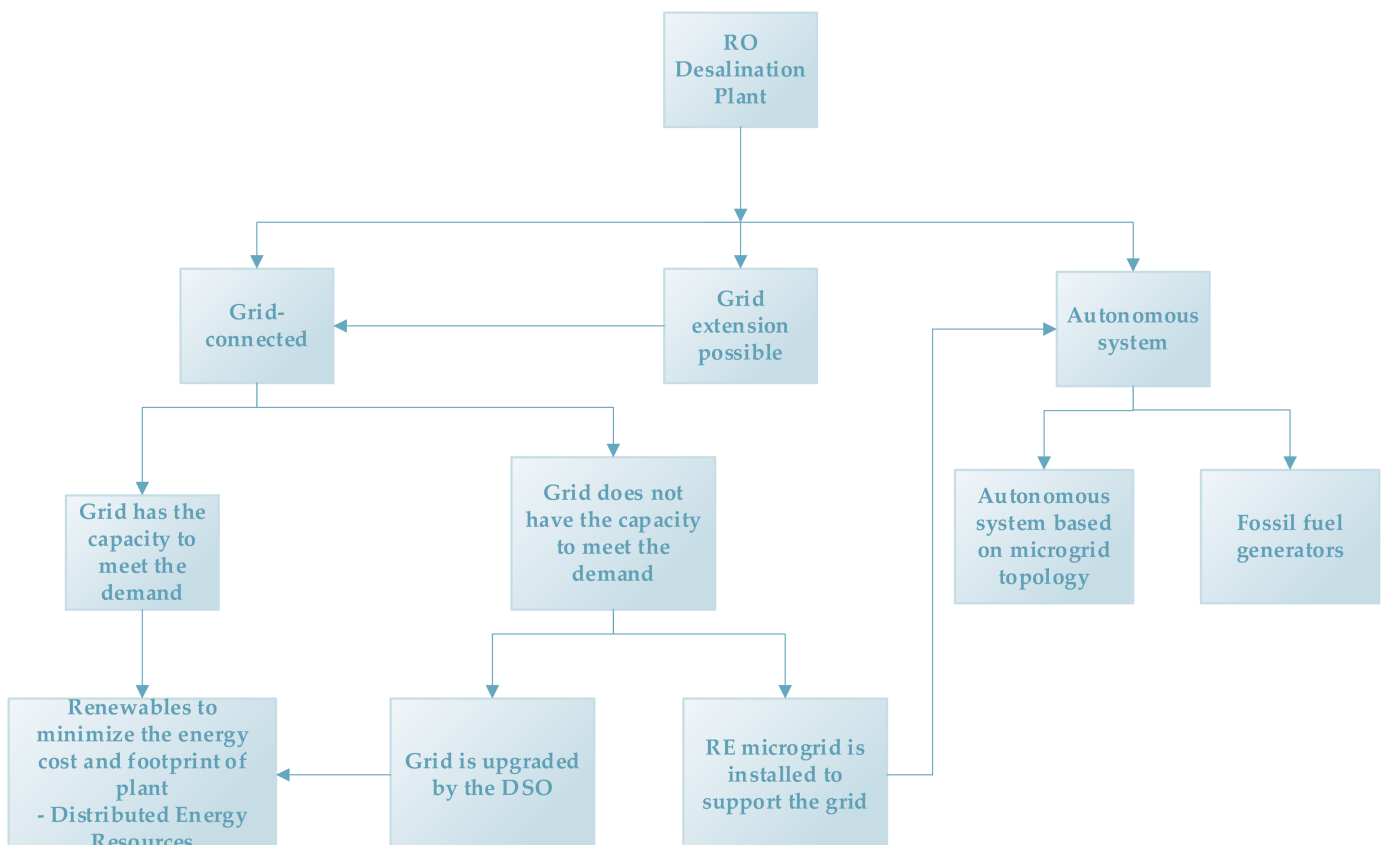


Figure 2. Powering RO desalination.

In many cases, islands are powered by isolated grids. There is a possibility that this grid is not able to meet the electricity demand of the planned desalination plant. In those cases, usually in collaboration with the distribution system operator (DSO) various scenarios are investigated in terms of upgrading the grid to be able to meet the needs of the desalination system. This is the only scenario this paper does not investigate given the complexity and multitude of decision parameters that go beyond a techno-economic study.

In cases where either the grid cannot meet the power demand of the desalination plant or the grid extension infrastructure investment is not cost-effective due to distance and/or topography, autonomous systems can be considered. The main topology used by autonomous/off-grid systems as the power demand is increasing is based on microgrids. According to the CIGRE Working Group C6.22, microgrids are defined as electricity distribution systems containing loads and distributed energy resources (such as distributed generators, storage devices or controllable loads) that can be operated in a controlled, coordinated way either while connected to the main power network or while islanded. This ensures that this infrastructure could be interconnected to the main grid seamlessly in the future, if this makes economic sense.

2.2. Costs

2.2.1. Desalination Plant Costs

The desalination plant costs have been decreasing in the past years. Figure 3 presents real commercial costs of sea water RO desalination plants for 2021 excluding installation costs. It has to be highlighted that the cost presented does not include the supporting infrastructure (e.g., transport of water from sea to the desalination plant, connection to a water grid, etc.) since that is heavily dependent on the topography and actual installation places of the various subsystems, nor the brine treatment and disposal, the costs do include pre- and post- treatment subsystems. All systems in the figure include energy recovery.

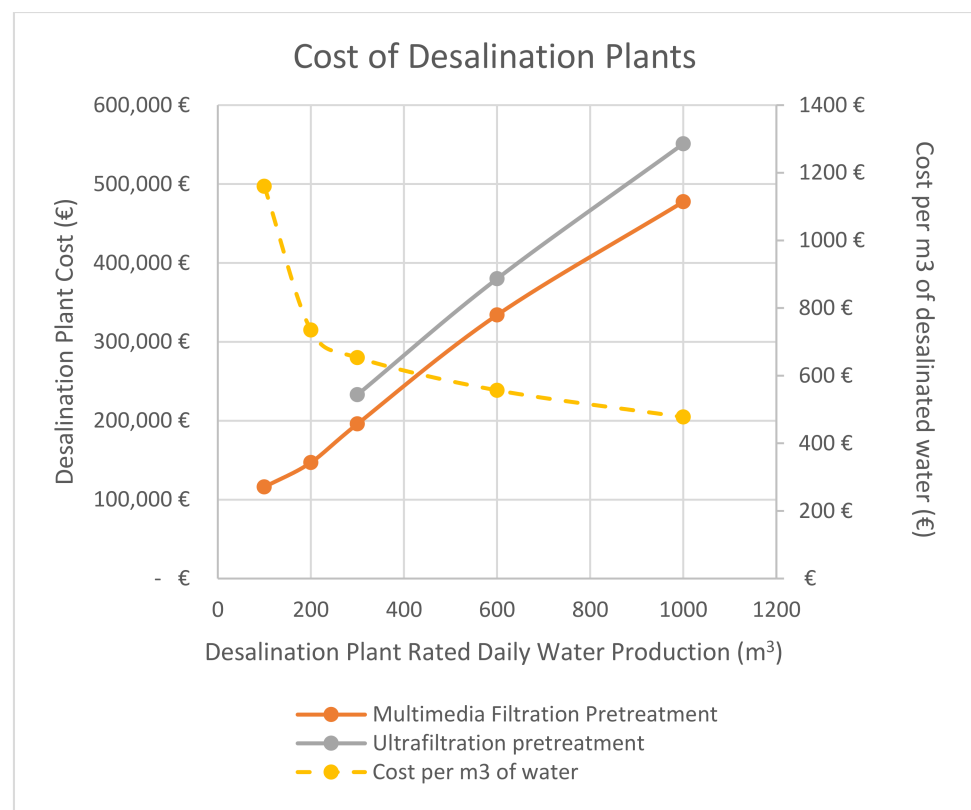


Figure 3. Desalination plant cost (Source: Personal communication with Orfeas Mavrikios—CEO of Watera Hellas, Athens, Greece).

As visible in Figure 3, there is a very steep decrease in the cost from 100 m³/day to 200 m³/day with diminishing scale economies as the plants are increasing in capacity. Two different types of pre-treatment technologies (multimedia filtration and ultrafiltration) are presented to highlight that this choice can play an important role in the final cost. In all cases investigated in this paper, multimedia filtration prefiltering is considered.

2.2.2. PV Cost

The pricing of PVs has been in constant decline, currently at USD 0.2/Wp [38]. For the purposes of this study, a price of USD 1000/kWp has been utilized, in line with current commercial pricing in Greece. This is a turn-key price, including the PV panels, cabling, mounting, inverters, and other needed consumables for connection to the main grid or a microgrid.

2.2.3. Wind Turbines

The wind turbine cost has been decreasing as the power for each wind turbine has been increasing. Figure 4 presents full project costs from a 100 kW wind turbine up to a 3.5 MW one [39,40]. Experience has shown that the actual wind turbine cost is about 69% of the total project costs [39].

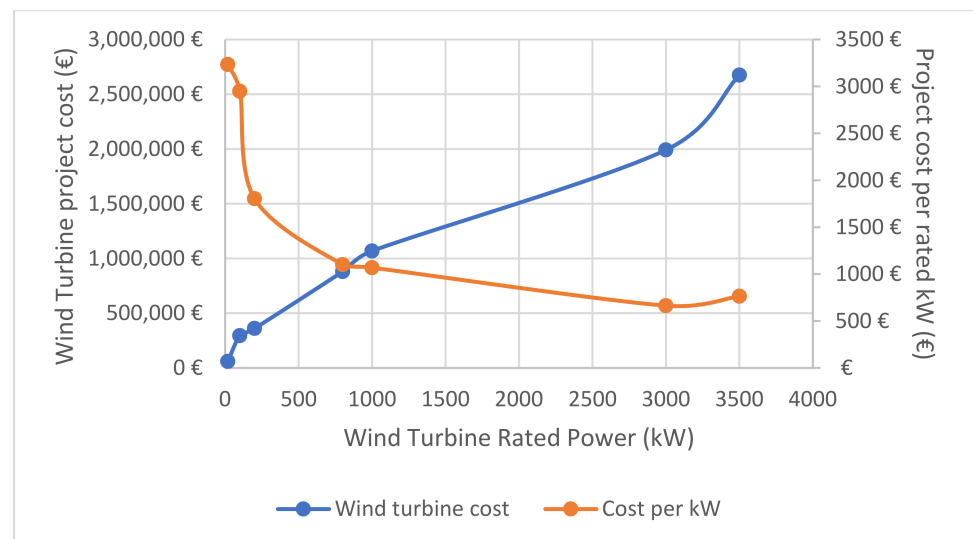


Figure 4. Wind turbine project cost.

As visible in Figure 4, there are major scale economies and until the wind turbine power reaches about 1 MW there is a very steep price decrease.

2.2.4. Batteries

Mainly due to electromobility applications, the lithium-ion batteries cost has been decreasing considerably in the past years. In 2020, for the first-time battery pack prices have been cited below USD 100/kWh with the average being at USD 137/kWh [41].

Stationary application lithium-ion batteries are now featuring 10-year manufacturer warranties as well as round-trip efficiencies beyond 95%.

2.2.5. Grid Electricity Cost

The tariff in Greece is composed of the Transmission System Operator tariff, Distribution System Operator Tariff, Energy generation cost, CO₂ emissions cost, social contribution cost all adding up to USD 0.17/kWh plus VAT for professional users' tariff which is used as a reference. It has to be noted that large consumers can get in contact directly with energy producers in the free market achieving a lower cost.

2.3. Case Studies Design

2.3.1. Overview

In order to compare various combinations of RE and RO desalination plants a big number of case studies were deployed. The main points to highlight are as follows:

- Three main water consumption profiles were considered, 100, 600, and 2000 m³/day. These profiles were chosen since they cover the range of the small-scale desalination systems. The most commonly used technology for energy recovery is applicable from systems rated beyond 80 m³/day [42] and this is the lower of the three profiles chosen. The 600 m³/day water profile is roughly in the middle of the small scale systems and is where the prices have shown a decrease, as depicted in Figure 3. Finally, the 2000 m³/day is the highest water profile considered and in line with the real systems present in the Aegean Sea, Greece [43].
- Net-metering was considered for utilizing RE technologies when grid-connected. Under the current regulatory framework of Greece, PV net-metering installations up to 3 MW and wind turbines up to 60 kW are allowed and as such the wind turbine option was investigated only for the 100 m³/day case. It has to be highlighted that under the net-metering scheme a cost of USD 0.04/kWh still has to be paid by the end-user as a tariff. It is considered that the grid is able to accommodate any given renewables installation up to the maximum allowed by the regulatory framework.
- In order to calculate the net present cost of water, optimizations based on simulations take place (see Section 2.3.3 for more details).
- In all case studies, the size of the PV array, number of wind turbines, and capacity of the battery bank was determined through optimization. For case studies 11, 15, and 24 (see Table 1), the size of the desalination plant and the size of the water tank were also optimized.
- To see the impact of the water tank size, for the 100 m³/day group of case studies, a tank equal to 1, 3, and 10 days was considered. To make the comparison realistic, the cost of the water tank was included. Typical water tanks suitable for potable water were considered.
- One case study utilizing low-enthalpy geothermal power generation through an ORC engine has been included. Geothermal energy is not available anywhere, but where it is, it might be a very interesting choice to investigate. The ORC engine and conclusions of [44] have been utilized in order to implement this case study.

Table 1. Case studies.

Case Study No.	Water Consumption (m ³ /Day)	Nominal Water Production of Desalination Plant (m ³ /Day)	Renewable Energy Technologies	Type of Interconnection	Water Tank (Days)
1	100	100	No renewables	Grid-connected	1
2	100	100 No Energy Recovery	No renewables	Grid-connected	1
3	100	100	PV	Grid-connected/Net-metering	1
4	100	100	Wind	Grid-connected/Net-metering	1
5	100	100	PV	Autonomous	1
6	100	100	Wind	Autonomous	1
7	100	100	Hybrid (PV and Wind)	Autonomous	1

Table 1. Cont.

Case Study No.	Water Consumption (m ³ /Day)	Nominal Water Production of Desalination Plant (m ³ /Day)	Renewable Energy Technologies	Type of Interconnection	Water Tank (Days)
8	100	100	PV	Autonomous	3
9	100	100	Wind	Autonomous	3
10	100	100	Hybrid (PV and Wind)	Autonomous	3
11	100	100	PV	Autonomous	10
12	100	100	Wind	Autonomous	10
13	100	100	Hybrid (PV and Wind)	Autonomous	10
14	100	Optimal	Optimal	Autonomous	Optimal
15	100	100	Geothermal	Autonomous	1
16	600	600	No renewables	Grid-connected	1
17	600	600	PV	Grid-connected/Net-metering	1
18	600	600	PV	Autonomous	1
19	600	600	Wind	Autonomous	1
20	600	600	Hybrid (PV and Wind)	Autonomous	1
21	600	600	PV	Autonomous	3
22	600	600	Wind	Autonomous	3
23	600	600	Hybrid (PV and Wind)	Autonomous	3
24	600	Optimal	Optimal Autonomous System	Autonomous	Optimal
25	2000	2000	No renewables	Grid-connected	1
	2000	2000	PV	Grid-connected/Net-metering	1

2.3.2. Case Studies Parameters and Assumptions

The main parameters and assumptions for the case studies are presented below:

- The system is considered to be installed on Naxos island in the Aegean Sea, Greece.
- Typical Meteorological year data are utilized for the Cyclades complex islands in the Aegean Sea, Greece.
- The prices of all system components are on par with commercial pricing in Greece.
- The interest rate is assumed at 5% and the investment period is equal to 20 years.
- The lifetime of all components is considered to be 20 years and 1 battery exchange is considered in this 20-year period, on par with the current 10-year warranties of high-quality lithium batteries.
- High efficiency (~20% efficiency) PV modules are considered.
- Ener E200 18.5 kW wind turbines are considered in order to be able to do optimizations for the 100 m³/day system and Hummer 200 kW wind turbines for the 600 m³/day

- one. In reality, a single higher rated power wind turbine would be chosen in any project in order to minimize costs rather than deploying a small wind farm.
- Supporting works for the desalination system are not considered, since their cost is dependent on the specific site realities.
 - Brine treatment and disposal costs are not considered.
 - High quality lithium-ion batteries with 10 years of manufacturers guarantee are considered. There is an increasing trend of commercial lithium-ion batteries to come in modular racks which can be expanded based on the needs of the consumer with an ease facilitating system integration. This also facilitates the optimization process. Such a battery is considered with a base size of each module equal to 2560 Wh.
 - The water consumption profile is considered constant on an hourly basis throughout the day.
 - Operation and maintenance costs (OPEX) as a percentage of produced water or installed power used are based on bibliography [45,46].
 - The minimum battery size considered in optimizations is able to meet at least 1 h of the load for the largest system considered.
 - The intermittent operation (ON/OFF) of a desalination unit is considered throughout the day rather than the continuous operation for autonomous systems. This was allowed after the communication with desalination plant manufacturers who verified that the commercial units face no problems operating under that scheme. For the purposes of this study, the desalination units cannot be deactivated and activated again in a time period of less than 1 h.
 - A simple controller was implemented essentially deactivating the plant either when the water tank was full or the battery bank had a state of charge below 5% (in line with the technical specifications of the batteries considered).
 - Land cost has not been taken into consideration since the prices vary extensively even in nearby islands, as is the case of islands in the Aegean Sea. Since most of the desalination plants operated either by the public sector or under a Public-Private Partnership agreement and in most of the cases of public land is used.
 - For the purposes of case study 15, it was assumed that the ORC unit is connected to an existing 95 °C geothermal well. This is in line with the geothermal potential found in the Cyclades islands complex (i.e., Milos) [44]. The cost of the well drilling is not included, since in many parts of the world, there are existing low-enthalpy geothermal wells being used for multiple applications such as for buildings' heating and agriculture-related applications [34] and it is assumed that such a well is utilized.
 - The ORC engine tested extensively in [47] was considered, along with the economic considerations presented in [44]. This unit produces 3.35 kW_e when fed with a temperature of 95 °C. Since that unit cannot form a grid, a microgrid topology is considered for this system as well and a battery bank being able to meet the load for 1 h has been assumed.

2.3.3. Software

For each case study of an autonomous system, an optimization took place based on hourly simulations of the system. For the rest, hourly simulations were performed. The software platform used, consisting of TRNSYS, GenOPT, and TRNOPT allows for the simultaneous optimization of up to 100 parameters and a combination of discrete and continuous variables. This platform has been used successfully in the past for microgrids and desalination systems [28,44]. Particle swarm optimization (PSO) is used for the optimization. The parameters of the PSO utilized are presented in Table 2 and is a set that has been utilized extensively with success for microgrids and desalination systems powered by renewables [48–51]. The included sub-routines in TRNSYS for the weather processor, the PVs, the wind turbine, and the batteries were used. The model presented in [18] for the desalination plant was updated with the data presented in Figure 3. As far as the geothermal system is concerned the models developed and used in [44] were utilized.

Table 2. PSO parameters.

Topology	lbest
Neighborhood size	3
Particles	20
Generations	100
Seed	0
Constriction gain	0.729
Cognitive acceleration constant	2.05
Social acceleration constant	2.05

The optimizations are techno-economic ones. The designed systems needed to meet the needs in water at 100% throughout the year. As such, the optimization process aims to design the system with the lowest net present cost (NPC) which at the same time fulfils this technical constraint. As such, the optimization process aims to design the system with the lowest net present cost (NPC) while fulfilling at the same time all the technical constraints. The technical constraint is monetized using a simple process. Moreover, a penalty was included to make certain that the water in the tank in the beginning of the year is equal or less than the water in the tank at the end of the year. For each timestep if a single technical constraint is not met, a very large monetary penalty of USD 1,000,000 is added to the net present cost, while the tank penalty is only added at the end of the simulation. When the technical constraints are met for all the time-steps of the yearly simulation, then the penalty related to them is zero. The optimization cost function (CF) is thus formed as follows:

$$CF = NPC + \sum_{t=1}^{8760} P_W(t) + P_S \quad (1)$$

where NPC is the net present cost for a 20-year period (€); P_w is the water penalty equal to USD 1,000,000; and P_S is the tank penalty equal to USD 1,000,000.

The above equation has been modelled in TRNSYS with new subroutines written in order to realize the specific penalties (water and tank). GenOPT has been used for implementing the particle swarm optimization process. GenOPT is written in Java and the code is available. The GenOPT software is provided under a modified BSD license [52].

In order to calculate the net present cost of water per m^3 , the net present cost of the system was divided by the amount of water considered to be utilized by the consumers for the 20-year period.

3. Results

The results of the 25 case studies are presented in detail in Table 3. Figure 5 presents the cost of water for the best system in each interconnection type (grid-connected, grid connected with a net-metering renewables installation, autonomous), and water consumption profile, excluding the results of case study 25 of the geothermal ORC engine system. This was decided due to the assumptions made on the existence of a geothermal well. Furthermore, Appendix A presents the optimization search space for each of the autonomous system case studies, along with the optimal values.

Table 3. Optimization results.

Case Study No.	Water Consumption (m ³ /Day)	Nominal Water Production of Desalination Plant (m ³ /Day)	Type of Interconnection	Water Tank (Days)	PV Power (kWp)	Wind Power (kW)	Battery Bank (kWh)	Net Present Cost (€/m ³ of Water)
1	100	100	Grid-connected	1	-	-	-	0.69
2	100	100 No Energy Recovery	Grid-connected	1	-	-	-	0.95
3	100	100	Grid-connected/Net-metering	1	28.5	-	-	0.51
4	100	100	Grid-connected/Net-metering	1	-	18.5	-	0.62
5	100	100	Autonomous	1	290.6	-	384.0	1.35
6	100	100	Autonomous	1	-	55.5	281.6	1.17
7	100	100	Autonomous	1	103.1	37	128	0.95
8	100	100	Autonomous	3	290.6	-	332.8	0.96
9	100	100	Autonomous	3	-	55.5	281.6	1.12
10	100	100	Autonomous	3	112.5	37	76.8	0.91
11	100	100	Autonomous	10	271.9	-	230.4	1.20
12	100	100	Autonomous	10	-	55.5	281.6	1.18
13	100	100	Autonomous	10	103.1	18.5	128	0.91
14	100	200	Autonomous	4	37.5	37	25.6	0.78
15	100	100	Autonomous	1	Geothermal: 13.4 kW	-	12.8	0.52
16	600	600	Grid-connected	1	-	-	-	0.59
17	600	600	Grid-connected/Net-metering	1	450.8	-	-	0.48
18	600	600	Autonomous	1	1743.80	-	2355.2	1.26
19	600	600	Autonomous	1	-	600	3020.8	1.14
20	600	600	Autonomous	1	740.63	400	499.20	0.78
21	600	600	Autonomous	3	1781.3	-	2099.2	1.23
22	600	600	Autonomous	3	-	600	1945.6	1.00
23	600	600	Autonomous	3	740.63	400	499.20	0.79
24	600	900	Autonomous	3	159.38	400	102.4	0.60
25	2000	2000	Grid-connected	1	-	-	-	0.58
26	2000	2000	Grid-connected/Net-metering	1	1495	-	-	0.47

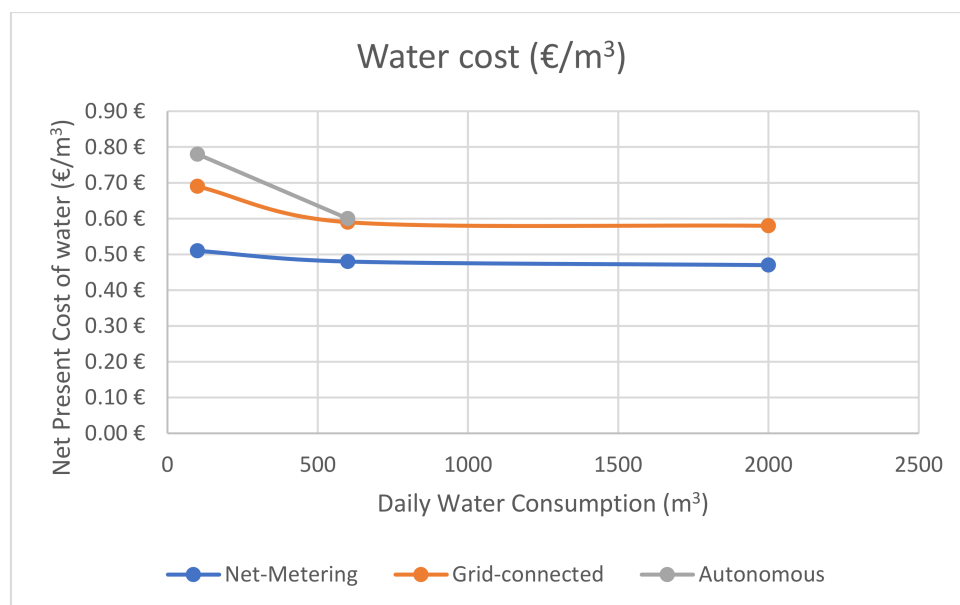


Figure 5. Water cost (excl. geothermal).

It has to be stated again that the net present costs per m³ of desalinated water presented do not include supporting works and brine treatment and disposal costs, while installation costs are considered as a lump sum. At the same time, these costs would be comparable for all investigated systems in any given location and as such they do not affect the outcomes drawn from this analysis. The key insights these results highlight can be summarized as:

- For small seawater RO desalination systems, it does not make any sense not to use energy recovery.
- The most cost-effective solution overall is the combination of a grid-connected system with a net-metering PV plant. The current cost of electricity is USD 0.17/kWh in Greece, but it is expected to increase in the future, so this combination will only become more attractive.
- Autonomous systems can be of comparable cost to systems consuming grid electricity, as shown in Figure 5.
- Hybrid systems (PV and wind) are the most cost-effective solutions for autonomous systems.
- Even considering double sized desalination plants as is the case for the 100 m³/day system, it makes sense to utilize the intermittent (ON/OFF) operation rather than getting a unit that runs constantly for autonomous systems. This is due to the fact that the energy storage in an autonomous system costs overall much more to ensure a continuous operation throughout the year than getting a larger plant and operating it for less hours. As the systems become larger, increased size desalination plants are still more economically favorable for autonomous systems.
- Water tanks make sense, but up to a specific capacity for any given configuration. This is clearly observed in case studies 19 and 22 where the extra water tank is in reality not needed for the given configurations and as such the system with the 3-day tank presents a slightly increased water cost. If the tank already exists, of course the bigger it is, the better.
- Even though batteries' cost is decreasing considerably in the last years due to electromobility, optimizations still favor minimizing their size.
- Low enthalpy geothermal sources can decrease the cost of the autonomous RE system considerably. If such a source is available, investigation of the use possibility is strongly recommended and this expands also to the location of the geothermal well in relation to the desalination plant location, since most wells are not on the seashore and the cost for deploying the grid for connecting the desalination plant to the geothermal unit might be prohibitive.

4. Discussion

There are many communities in the world still suffering from lack of fresh water. Many of these communities also face problems regarding access to electricity. Desalination has proved to be a mature cost-effective technology to locally produce the needed fresh water using sea or brackish water. The two most important factors affecting the environmental outlook of desalination are brine treatment and disposal and the energy consumed. As far as brine treatment and disposal is concerned, many efforts are taking place worldwide to minimize the desalination's environmental footprint [53–55]. This paper is focused on the energy aspect of desalination. RE costs have been declining heavily during the past decades providing the world with a clean alternative to fossil fuel based energy [56]. Global policies around the world related to sustainable development, climate, and energy as the UN Sustainable Development Goals [1], Paris Agreement [57], the European Green Deal [37], and the African Union Energy Transition strategy [58] are driving defossilization efforts.

RO desalination coupled with renewables can address cost-effectively the current issues in terms of water scarcity, while minimizing the environmental footprint of the process. In this paper, it has been showcased that desalination powered by renewables can be deployed in practically any location on earth having access to sea or a brackish water source. Moreover, the use of renewables mostly in the form of PVs provides a simple and mature solution to employ green energy. It is highlighted that even in the cases that connection to the grid is possible, it is preferable to also deploy a PV system under a net-metering or comparable scheme depending on the country (e.g., net-billing). Keep in mind that for Greece, the current net-metering benefit is around USD 0.13/kWh, while the last auctions for PV parks ended with an average price around USD 0.05/kWh, highlighting the profitability of the net-metering scheme, taking into consideration that the

installations can be up to 3 MWp. While the wind turbines can be more cost-effective than PVs in cases of high wind potential, especially for wind turbines not under the “small wind turbines” scheme (in Greece up to 60 kW which is also the limit for wind energy under the net-metering framework) the needed licenses and environmental permits can become a burden to the desalination plant developer, hence the priority given to PV installations.

Based on the outcomes of this study (Table 3 and Figure 5), the following recommendations can be made:

- Project developers should employ energy recovery for sea-water desalination plants and a techno-economic study to be made for brackish water plants, since the salinity of feed water greatly affects the impact of energy recovery.
- Project developers should employ a RE system in addition to the desalination system. For grid connected plants the easiest approach is to use a PV plant connected under a net-metering or comparable (e.g., net-billing) scheme.
- For cases where there is either no space for the optimal size of PV installation to meet the load under a net-metering or comparable scheme or the needed PVs are beyond the maximum allowed by the regulatory framework, it is advised that the maximum feasible installation is realized.
- Distributed energy storage in a grid connected system ought to be investigated only in cases that the regulatory framework provides relevant incentives.
- Autonomous systems are technically feasible, but more expensive than grid-connected including renewables under net-metering schemes and ought to be deployed only in cases where grid connection is either more expensive due to distance and topography or simply not existing.
- Larger desalination plants operating for less hours during the day are more cost-effective in autonomous scenarios.
- When a low-enthalpy geothermal power source is available near the installation site it is strongly advised to investigate its possible use for autonomous systems. The final real cost of the investment is related to many factors including the existence or not of an appropriate geothermal well, the cost related to the studies and licensing process needed to be followed, the cost for complying with air quality regulations [59], etc. and can be lower in comparison to other RE sources.

On-going research is still strong for advanced energy management schemes of desalination plants [28] and variable load operations of the membranes [30], which can further decrease desalination costs in the future as these new technological advances are incorporated in commercial systems.

5. Conclusions

This paper investigated the current state of the art in terms of commercially available desalination systems and the possibilities of coupling these with RE systems. The results show that even for grid-connected systems it is more cost-effective and profitable to include a RE system under a net-metering or comparable scheme, apart from the environmental benefits. The cost of RE and storage is expected to continue dropping following the decreasing trends observed in the past decades, making their use even more attractive.

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Appendix A. Detailed Results of the Optimizations

This Appendix presents in detail the search space and optimal value of the case studies for which a PSO optimization took place. The limits of the optimization space and the steps for each variable were decided upon performing a number of simulations to understand the investigated systems better.

Table A1. Case study 5.

Variable	Lowest Value	Highest Value	Step	Optimal Value
System Components				
Typical Si modules rated at 375 Wp each	300	900	25	775
2.56 kWh 48 V LiFePO ₄ batteries	50	300	10	150

Table A2. Case study 6.

Variable	Lowest Value	Highest Value	Step	Optimal Value
System Components				
Number of Ener 200 18.5 kW wind turbines	2	6	1	3
2.56 kWh 48 V LiFePO ₄ batteries	100	250	10	130

Table A3. Case study 7.

Variable	Lowest Value	Highest Value	Step	Optimal Value
System Components				
Typical Si modules rated at 375 Wp each	100	500	25	275
Number of Ener 200 18.5 kW wind turbines	1	3	1	2
2.56 kWh 48 V LiFePO ₄ batteries	20	120	10	50

Table A4. Case study 8.

Variable	Lowest Value	Highest Value	Step	Optimal Value
System Components				
Typical Si modules rated at 375 Wp each	300	900	25	775
2.56 kWh 48 V LiFePO ₄ batteries	50	300	10	130

Table A5. Case study 9.

Variable	Lowest Value	Highest Value	Step	Optimal Value
System Components				
Number of Ener 200 18.5 kW wind turbines	2	6	1	3
2.56 kWh 48 V LiFePO ₄ batteries	100	250	10	110

Table A6. Case study 10.

Variable	Lowest Value	Highest Value	Step	Optimal Value
System Components				
Typical Si modules rated at 375 Wp each	100	500	25	300
Number of Ener 200 18.5 kW wind turbines	1	3	1	2
2.56 kWh 48 V LiFePO ₄ batteries	20	120	10	30

Table A7. Case study 11.

Variable	Lowest Value	Highest Value	Step	Optimal Value
System Components				
Typical Si modules rated at 375 Wp each	300	900	25	725
2.56 kWh 48 V LiFePO ₄ batteries	50	300	10	90

Table A8. Case study 12.

Variable	Lowest Value	Highest Value	Step	Optimal Value
System Components				
Number of Ener 200 18.5 kW wind turbines	2	6	1	3
2.56 kWh 48 V LiFePO ₄ batteries	100	250	10	110

Table A9. Case study 13.

Variable	Lowest Value	Highest Value	Step	Optimal Value
System Components				
Typical Si modules rated at 375 Wp each	100	500	25	275
Number of Ener 200 18.5 kW wind turbines	1	3	1	1
2.56 kWh 48 V LiFePO ₄ batteries	20	120	10	50

Table A10. Case study 14.

Variable	Lowest Value	Highest Value	Step	Optimal Value
System Components				
Typical Si modules rated at 375 Wp each	25	300	25	100
Number of Ener 200 18.5 kW wind turbines	1	2	1	2
2.56 kWh 48 V LiFePO ₄ batteries	10	100	10	10
Desalination unit rated output	100	200	100	200
Potable water tank	100	1000	100	400

Table A11. Case study 18.

Variable	Lowest Value	Highest Value	Step	Optimal Value
System Components				
Typical Si modules rated at 375 Wp each	4500	5000	25	4650
2.56 kWh 48 V LiFePO ₄ batteries	700	1000	20	920

Table A12. Case study 19.

Variable	Lowest Value	Highest Value	Step	Optimal Value
System Components				
Number of Hummer 200 kW wind turbines	1	2	1	2
2.56 kWh 48 V LiFePO ₄ batteries	1100	1200	20	1180

Table A13. Case study 20.

Variable	Lowest Value	Highest Value	Step	Optimal Value
System Components				
Typical Si modules rated at 375 Wp each	900	2000	25	1975
Number of Ener 200 18.5 kW wind turbines	1	3	1	2
2.56 kWh 48 V LiFePO ₄ batteries	50	200	5	195

Table A14. Case study 21.

Variable	Lowest Value	Highest Value	Step	Optimal Value
System Components				
Typical Si modules rated at 375 Wp each	4500	5000	25	4750
2.56 kWh 48 V LiFePO ₄ batteries	700	1000	20	820

Table A15. Case study 22.

Variable	Lowest Value	Highest Value	Step	Optimal Value
System Components				
Number of Hummer 200 kW wind turbines	1	3	1	2
2.56 kWh 48 V LiFePO ₄ batteries	600	1000	20	760

Table A16. Case study 23.

Variable	Lowest Value	Highest Value	Step	Optimal Value
System Components				
Typical Si modules rated at 375 Wp each	900	2000	25	1975
Number of Ener 200 18.5 kW wind turbines	1	2	1	2
2.56 kWh 48 V LiFePO ₄ batteries	50	200	5	195

Table A17. Case study 24.

Variable	Lowest Value	Highest Value	Step	Optimal Value
System Components				
Typical Si modules rated at 375 Wp each	400	600	25	425
Number of Ener 200 18.5 kW wind turbines	1	2	1	2
2.56 kWh 48 V LiFePO ₄ batteries	30	70	5	40
Desalination unit rated output (m ³ /day)	600	1000	50	950
Potable water tank	2000	2400	100	2400

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