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ENERGY-WATER NEXUS (AS STILLWELL, SECTION EDITOR)

# Integration of Renewable Energy Technologies With Desalination

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**Abstract** Remote communities in many countries are in need of dependable and affordable fresh water that must be derived from local brackish water or seawater. Thermal and membrane desalination technologies are available, with significant electrical or thermal energy requirements. Renewable energy from wind, solar, geothermal, or other sources may be necessary when access to grid electricity is limited. This literature review summarizes the research reported in the last three years (mid-2010 to mid-2013) by teams of experts in water treatment, renewable energy generation, variable-power system controls, system optimization, and economic analyses.

**Keywords** Desalination · Renewable energy · Wind energy · Solar energy · Photovoltaic · Reverse osmosis · Electrodialysis · Membrane · Hybrid energy · Distillation · Multi-effect distillation · Economic analysis · Seawater · Brackish water · Off-grid · Optimization · Control · Intermittency · Geothermal energy

**Abbreviations**

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| AD | Adsorption desalination |
| BWRO | Brackish water reverse osmosis |
| CDP | Combined desalination and power |
| CSP | Concentrating solar power |
| DPG | Diesel power generation or diesel power generator |
| ED | Electrodialysis |
| EDR | Electrodialysis reversal |
| ESS | Energy storage system |
| ETC | Evacuated tube thermal collector |
| FC | Fixed capacity |
| FPSC | Flat-plate solar collector |
| GC | Gradual capacity |
| HOMER | Hybrid Optimization Model for Electric Renewables |
| MD | Membrane distillation |
| MDC | Microbial desalination cell |
| MED | Multi-effect distillation |
| MEE-FF | Multi-effect evaporation forward-feed |
| MSF | Multi-stage flash |
| NF | Nanofiltration |
| PRO | Pressure-retarded osmosis |
| PTC | Parabolic trough collector |
| RE | Renewable energy |
| RO | Reverse osmosis |
| SEC | Specific energy consumption |
| SGP | Salinity gradient power |
| SWRO | Seawater reverse osmosis |
| TDS | Total dissolved solids |
| UF | Ultrafiltration |
| WEC | Wave energy converter |
| WT | Wind turbine |

## Introduction

Many communities around the world have limited or no local access to fresh drinking water sources, leading to dependence on BW or SW for potable water supplies. Thermal, such as MSF and MED, and membrane, such as RO and ED, desalination processes can effectively lower the TDS concentrations

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to acceptable levels, but with significant energy requirements. Remote locations in developing countries or small islands may lack access to dependable electrical grid power. Local RE from WTs, PV, CSP, and other sources provides potential alternatives that can either reduce electrical demand from the grid or allow standalone operation. Most RE sources can be intermittent, so the application of RE to produce a target volume of reliable drinking water must address variations in both the water demands and RE supply. During 2010–2013, many researchers published their findings related to conceptual descriptions and designs of potential technology combinations, observations of laboratory, pilot, and full-scale applications, as well as simulations of projected operational and economic conditions. This review provides brief summaries of the major reported findings as well as citations for the interested reader to gather additional details.

Three significant concepts emerge from the recent literature on combinations of RE and desalination, as noted in multiple references.

- Power experts can use “smart grid” concepts to improve RE and desalination combinations through control systems that adjust for variable RE supply or by considering desalination systems as controllable loads.
- Energy storage systems (ESSs), such as batteries or thermal storage, and planned treated water storage volumes can mitigate the intermittency of wind and solar power sources for continuous water production in standalone applications.
- Hybrid energy combinations of solar, wind, geothermal, and fossil fuel generators can be evaluated for both cost efficiency and freshwater demand satisfaction.

Al-Qaraghuli and Kazmerski [1••] assembled an excellent and succinct overview of the capabilities of conventional thermal and membrane desalination processes and their integration with renewable energy. Their article included comparison of technical aspects, such as process description and energy consumption, and economic aspects, such as estimated cost of water, for various combinations of desalination with RE. In the brief summaries that follow, we have attempted to group the articles based on certain common themes, although there were often multiple overlapping topics shared across their objectives and findings.

## Reverse Osmosis Desalination Systems With Various Renewable Energy Sources

### RO Powered by Wind

Peñate et al. [2•] compared the energy requirements and water production from two hypothetical off-grid SWRO systems. The first, a FC system, was sized at 1000 m$^3$/d, while the second, a GC system, included one 200 m$^3$/d and two 400 m$^3$/d racks that could be turned on as needed. The GC system is able to adapt energy consumption to available WT power. Operational parameters relative to water quality and RO details were simulated with electrical demands of 15–124 kW for different water production rates. Simulations of RE generation were based on 100, 225, and 300 kW WTs assisted by a battery ESS and flywheel energy recovery devices. Wind data from the Gran Canaria island in the Spanish archipelago provided the input for the energy generation simulations. Overall, the GC system produced less water than the FC system, with almost 7 % higher SEC in kWh/m$^3$ of water produced. The GC system had less excess energy production, requiring less energy storage capacity. The authors also recommended consideration of treated water storage capacity as another buffer for system security.

Direct impact of variable electrical supply from WTs on off-grid RO systems has received some attention. Park et al. [3••, 4, 5••] investigated the impact of wind speed fluctuations on the performance of a BWRO system. In the first two studies, a portable small-scale trailer-mounted 300 L/hr BWRO system and 1 kW (at 12.5 m/s) WT were placed in a wind tunnel for controllable wind speed ranges and turbulence fluctuations. Park et al. [3••] observed permeate flux and NaCl concentration with changing wind speed for 10 min experiments with 30 sec oscillations. The BWRO system performance was unaffected by the wind speed variations from 3.7–10 m/s. Next, Park et al. [4] investigated the impact of intermittency on the performance of the BWRO system or no-power intervals of 0.5–3 min in the wind tunnel. Observed permeate TDS concentrations increased most for the shorter 0.5 min and 1.0 min no-power intervals, indicating the potential need for ESS or water storage for dilution. Finally, Park et al. [5••] used simulations of their small-scale system to investigate the potential use of supercapacitors to absorb the impacts of both wind speed fluctuations (oscillations of 15 sec to 20 min) and intermittency (no-power intervals of 0.5–5 min). Dahioui and Loudiyi [6] simulated a hypothetical wind RO system typical of Morocco and found that reducing maximum capacity of the WT could reduce power fluctuations, as would the use of solenoid valves to manage pressure in the RO system.

Xenarios et al. [7] presented design considerations for selection of a WT for an existing 4500 m$^3$/d SWRO plant on the island of Mykonos, Greece. The SWRO plant electrical demand was estimated at 614 kW. Several commercially available WTs were considered, using one year of local wind data, and a 1.5 MW or 1.65 MW WT was sufficient.

Rainwater et al. [8] described a pilot-scale BWRO installation powered by grid-assisted wind energy at Seminole, Texas. An on-site 50 kW WT provides intermittent electricity for a deep well that taps a brackish aquifer, as well as the

BWRO system designed to produce 220 $m^3$/d (40 gpm) of permeate. The system will be monitored for one year to demonstrate the value of the WT's electrical generation and the production capacity of the deep well.

## RO Powered by PV

Bilton et al. [9] performed theoretical simulations for technical and economic feasibility of PV for remote small-scale off-grid SWRO and BWRO applications. The BWRO sites included New Mexico, Jordan, Australia, and Tunisia. The SWRO locations were Boston, Los Angeles, Cyprus, Jordan, Haiti, and Saudi Arabia. The cost ranges of treated water were 2.17–2.41 \$/$m^3$ and 4.96–7.01 \$/$m^3$ for BWRO and SWRO, respectively. The remote PV/BWRO costs were more than 50 % lower than those with DPG, while the PV/SWRO costs were similar or higher than the DPG equivalent.

Qiblawey et al. [10] described the performance of a small 500 L/d BWRO system in northern Jordan powered by PV with battery storage. The system's actual production averaged 267 L/d for raw water with 1700 mg/L TDS, and SEC ranged from 26–31 kWh/$m^3$. Poovanaesvaran et al. [11] presented a conceptual discussion of BWRO with PV supplemented with battery ESS, with a brief review of several installations around the world, as well as comparison of PV and DPG.

Clarke et al. [12, 13••] observed the performance of a small lab-scale BWRO system with a capacity of 15 L/hr of permeate, and then used those data in simulation of PV power utilization. SEC increased and permeate flux decreased as the raw water salinity increased from 1 % to 4 %. Less permeate water was produced under dynamic conditions with battery ESS, as the battery lost power faster in a dynamic system.

Peterson and Gray [14] reported a small stand-alone PV/BWRO system at the Brisbane Botanic Gardens in Queensland, Australia. The system had a 30,000 L/d capacity designed for raw groundwater at 1900 mg/L TDS. Detailed operational data were reported for November 2008 to February 2010. Touati et al. [15] presented a procedure for feasibility design and operational simulation of a standalone RO system powered by PV, a hydrogen-producing electrolyzer powered by excess solar energy, and a fuel cell ESS. They recognized the water problem as an energy problem, leading to this unique proposal that could reduce the required PV area.

## RO Powered by RE Combinations

Spyrou and Anagnostopoulos [16] simulated the energy and economics of a SWRO system for a hypothetical Greek island population of 5,000, with PV (200 kW) and WTs (800–1500 kW) assisted by pumped storage for hydropower generation. Various combinations were evaluated in optimization studies, such as minimizing the cost of produced water, maximizing satisfaction of the variable water demands, impact of population served, and optimal capacity of the pumped-storage reservoir. Typical projected water costs were 2–4 \$/$m^3$.

Khalifa [17] applied the theoretical HybridRO model to simulate a 50 $m^3$/d BWRO system using data for Karbala, Iraq. Electrical supply was provided with a 4 kW DPG alone, the DPG with WT (6, 30, and 55 kW), or the DPG with PV (1.9–20 kW). The resulting cost of produced water was \$1.8/$m^3$ for diesel only or DPG with WT and PV, \$2.2/$m^3$ with WT and PV, \$2.3/$m^3$ with PV only, and \$2.4/$m^3$ with WT only.

Karellas et al. [18] analyzed a potential off-grid SWRO system powered by an organic (R134a) Rankine cycle (ORC) turbine driven by solar PTCs. The system was aided by PV and battery ESS to provide electricity to other system components. The system was projected to produce 230 $m^3$/d for simulated conditions on the Greek island of Chalki (Halki) at \$13/$m^3$. Peñate and García-Rodríguez [19] considered simple (hexamethyldisiloxane) and two-cycle cascade (hexamethyldisiloxane and isopentane) ORC turbines with a solar PTC heat source for SWRO application in Spain. Their hypothetical system produced 2500 $m^3$/d at combined SEC 2.99 kWh/$m^3$. Two different PTC types were also evaluated in detail.

Ben Ali et al. [20] examined a BWRO system in Tunisia powered by both PV and WT, with the advantage that one RE source could be available when the other was not. The control system turned on the BWRO when the available RE was sufficient. Excess energy was dumped, and water storage was used to buffer low-RE periods. Lab-scale experiments provided data for the BWRO, and computer simulations predicted water production under projected RE supply schedules for PV and WTs.

Hossam-Eldin et al. [21] simulated 150 and 300 $m^3$/d SWRO systems powered by a hybrid WT/DPG system and a WT/PV/DPG system, respectively, at a site on the coast of Egypt. Both energy systems included battery ESS. The smaller system's optimal cost of energy was \$0.10/kWh, with associated cost of produced water at \$1.79/$m^3$ and excess energy at 33 %. The larger system's optimal cost of energy was \$0.11/kWh, and the cost of water was \$1.40 /$m^3$, with 30 % excess energy. Under existing conditions, RE from wind was more economical than PV.

Attia [22] proposed a parabolic dish solar collector to convert water to steam and drive a piston device to provide the required pressure to force the raw feed water through a single-stage BWRO or SWRO system. Theoretical analysis indicated potential production rates of 0.055 $m^3/m^2$/d and 1.833 $m^3/m^2$/d for seawater and brackish water, respectively.

Olwig et al. [23] performed technical and economic analyses of a CSP system to run a 24,000 $m^3$/d SWRO facility at Ashdod, Israel, and Aqaba, Jordan. At both sites, the CSP/RO system could produce water for \$2/$m^3$, at best (2.2 and 1.86 times the cost of conventional UF-RO plants at Ashdod and Aqaba, respectively). Similar analyses compared the cost of

CSP/MED at these two sites. At the Aqaba site, the CSP/MED water would cost \$3.4/m$^3$ (3.6 times the UF-RO price), while the water cost at the Ashdod site would be \$2.6/m$^3$ (2.14 times the UF-RO price). At both sites, RO systems seemed to be superior for the same water production.

Kim et al. [24] provided a theoretical and conceptual review of the application of SGP to drive a PRO system to generate energy for a SWRO process. The brine from a conventional SWRO process can be placed opposite the seawater side of the PRO membrane to produce pressure increases and thus electricity. Unfortunately, appropriate membranes for PRO were not currently commercially available.

In their theoretical investigation of RE and desalination for the Cape Verdean island of Brava, Bognar et al. [25••] simulated conditions for three energy supply scenarios for an existing remote SWRO plant producing 200–600 m$^3$/d of permeate. The scenarios considered energy supply from two 600 kW DPGs and three 275 kW WTs: (1) for energy only, (2) for constant-production SWRO, and (3) for variable-production SWRO. The variable-production plant performed best, reducing the overall cost of electricity and the unit cost of water.

Moser et al. [26] compared costs of alternative power supplies for a hypothetical 100,000 m$^3$/d desalination system in the Middle East and North Africa (MENA) region. They considered WT, PV, CSP, and a mix of WT/PV/CSP for SWRO, as well as CSP for MED. Battery storage and backup DPGs were combined with WTs and PV, while thermal ESS and backup boilers were associated with CSP. In general, the RE/RO systems had lower unit costs of water than the CSP/MED alternative, and the individual RE sources were less costly than mixed RE.

## Other Membrane Desalination Systems With Various RE

Lopez-Ramirez et al. [27] demonstrated NF desalination in a pilot plant at the Metropolitan Drinking Water Treatment Plant, El Montañés, Puerto Real, Cadiz, Spain. The 50 m$^3$/d treatment system was powered by two 3 kW WTs, one 4.2 kW PV field, and a battery ESS, while producing 1.1 L/hr of permeate at average SEC of 0.60 kWh/m$^3$ during a 64-day demonstration.

Porrazzo et al. [28] observed the behavior of a standalone 150 L/d MD system in Italy powered by solar heat collectors. A neural-network multi-input/single-output (MISO) model was developed to project the system's behavior under various solar irradiation conditions. No water cost data were included.

Peñate et al. [29] tested an off-grid EDR system for brackish water desalination powered by PV in Pozo Izquierdo, Spain. The system was powered by two modular PV fields and designed to produce 96 m$^3$/d. While the feed-water conductivity ranged from 3500 to 5300 μS/cm, the product water varied from 114 to 2413 μS/cm for solar irradiation from 600 to 800 W/m$^2$.

Kim and Logan [30] reviewed the state of the art for MDCs that combine exoelectrogenic bacteria with ED to facilitate seawater desalination. The bacteria congregate at the anode, oxidizing organics and transferring electrons to the anode, thus creating an electrical potential gradient for transport through the ion-exchange membranes. The process is not currently feasible for drinking-water plants.

## Thermal Desalination Systems With Various Renewable Energy Sources

Zhao and Wang [31] observed the performance of convergent/divergent, orifice, and spray nozzle designs in a lab demonstration of CDP production with a solar pond as the heat source. The convergent/divergent and spray nozzles performed adequately in simultaneous production of energy and potable water. The fresh product water fraction relative to the saline raw water ranged from 4–12 % for input temperatures of 40–90 °C. Ge et al. [32] theoretically modeled a CDP system with a convergent/divergent two-phase nozzle disc integrated into a simple-reaction turbine attached to a generator with a solar pond heat source.

Baharudin et al. [33, 34] considered a PV assembly with battery ESS to power a small lab-scale system for seawater distillation for remote areas such as Kuala Perlis, Malaysia. The experimental results indicated that fresh water was produced, but the water quality analytical method was unclear. The authors performed an economic analysis of the PV distillation system using the HOMER program, but the water production capacity was not specified.

Liu et al. [35] analyzed the thermal and economic performance of a low-temperature parallel-flow MED system for seawater at a hypothetical site in Dalian, China, powered by solar ETCs. The hypothetical system also included a thermal storage tank. The simulations indicated fresh water production at 33 L/d/m$^2$ of ETC area, with amortized fresh water cost of approximately \$4.80/m$^3$.

Koroneos and Roumbas [36] contended that geothermal heat sources could be best coupled with MED systems for seawater desalination. They considered the conditions at the Greek island of Nisyros, and performed mathematical simulation and economic analysis for a hypothetical 500 m$^3$/day plant. Projected treated water costs were less than \$1.4/m$^3$, and environmental impacts were evaluated over the system's life cycle.

Ayhan and Al-Madani [37] proposed combining hybrid wind and solar RE to power natural vacuum desalination of seawater in Bahrain. Solar thermal collectors would provide heat to evaporate seawater under low-pressure conditions, and a WT could power pumps and fans for system operation. The estimated cost of fresh water from a 0.13 m$^3$/d system was \$0.70/m$^3$. Gude et al. [38] reported a preliminary field test of a two-stage low-temperature/low-pressure distillation process for seawater desalination powered by a FPSC. Experimental and economic results projected that a 500 L/d system could generate fresh water at $7/m$^3$. Gude et al. [39, 40] also provided theoretical and economic analyses of a smaller low-temperature desalination that employed FPSCs coupled with thermal energy storage or geothermal energy to allow continuous operation. Their hypothetical system was projected to produce up to 100 L/d for solar collector areas up to 18 m$^2$, with 6 m$^3$ of thermal energy storage volume at a $14/m$^3$ cost of fresh water.

AD achieves low-temperature thermal distillation using silica gel reactor pairs to facilitate water vapor separation for eventual condensation. Ng et al. [41•] reported theoretical simulation and lab experiments for AD of seawater in Singapore. AD had higher capital cost coupled with potentially lower electricity cost if RE-provided heat through solar or geothermal sources was more expensive than RO without RE. As was observed in their lab experiments, these costs could be interpreted more positively if the cooling capacity of the AD cycle was also valued. Missimer et al. [42] proposed combining AD with STCs and geothermal energy in alternating 12-hr cycles to maximize desalination capacity in Saudi Arabia.

## Evaluation of RE and Desalination Alternatives

Kavvadias and Khamis [43] reviewed the International Atomic Energy Agency's Desalination Economic Evaluation Program, released as DEEP 3.2, in 2009. This economic model can be used to compare the economics of different membrane or thermal desalination plants powered by nuclear, fossil fuel, and RE. The authors used default model parameters to perform generic comparisons of hypothetical plants and energy sources, and they found that the DEEP code was robust and provided reasonable results. The current DEEP version is DEEP 4.0 (2011, http://www.iaea.org/NuclearPower/Desalination/).

It is challenging to rank the best couplings of RE and desalination systems, and most authors argue for case-by-case assessments. Baharudin et al. [33] devised a multi-criteria analysis that considered (1) technical and operational aspects, (2) environmental and land-use impacts, (3) economic cost evaluation, (4) site location characteristics, and (5) energy consumption to compare various RE/desalination system combinations. Kondili et al. [44•] used the same five criteria to evaluate combinations of RE and desalination for the Greek islands of Agios Efstratios, Anafi, and Kimolos. They evaluated PV-powered RO, WT-powered RO, and geothermal desalination. WT/RO was favored for Agios Efstratios, PV/RO for Anafi, and geothermal for Kimolos.

Kaldellis et al. [45] used the HOMER software system (Lilienthal et al. [46]) to design and simulate an SWRO system powered by a combination of WTs, PV, and biogas-fueled internal combustion generator for cogeneration of electricity, heat, and water for the Greek island of Agathonísi. The average water demand was 35 m$^3$/d, and other energy and heat demands were estimated from observed data. The selected system included three 100 kW WTs, 200 kW of PV panels, a 60 kW biogas generator, and 32 batteries for ESS, all of which easily supplied the SWRO plant.

## Energy Load Management With RE and Desalination

Yoshihara et al. [47] analyzed the interaction between a hypothetical SWRO system and the existing power system at Hateruma-jima, Okinawa Prefecture, Japan. The power system included two 150 kW DPGs and one 300 kW DPG, eight 190 kW flywheel ESSs, and a 275 kW WT. The challenges were to integrate intermittent wind energy and its attendant power into this electrical grid, and also to consider storage of treated water as part of the temporal simulations. The 20 kW-maximum SWRO plant served as a buffering device for wind energy fluctuations, electricity demand fluctuation, and DPG starting time.

Yılmaz and Söylemez [48] designed and simulated a MEE-FF seawater desalination system in Turkey. RE was provided by a FPSC and a small WT. The simulated plant could produce 1000 L reliably over an average 9 hr/d, which was comparable in performance to a previous pilot-study MED plant in Muscat, Oman.

Malek et al. [49] compared the performance of an ED membrane under both constant and variable voltage to determine the capacity of pulsed voltage to disrupt concentration polarization at the membrane boundary and improve ED performance for brackish (5 g/L NaCl) water treatment. The pulsed regime had a wider safe voltage operating window, and reduced the required desalination time and decreased pH required at the higher-voltage regime.

Abad et al. [50] performed small-scale experiments to compare the performance of a solar still with pulsating heat pipes and solar thermal collector to that of a basic passive solar still system. Results indicated 75 % improvement in maximum treated water yield over the basic solar still configuration (875 mL/m$^2$/hr vs. 500 mL/m$^2$/hr), at an 8 % increase in water cost ($0.00745/L/m$^2$ vs. $0.00690/L/m$^2$).

## Optimization Modeling for Design and Operation of RE and Desalination Systems

Koutroulis and Kolokotsa [51] assembled an optimization methodology to size SWRO systems powered by PV and/or WTs, both in combination with a battery ESS. Genetic algorithms were used to minimize the total system costs, including treated water storage volume, for a 20-year period for both a 15-resident community and a single residential household at a site in Crete. In both cases, the combination of wind and PV provided the lowest overall costs.

In Cyprus, Poullikkas [52] also used genetic algorithms to optimize cost of RO-treated water, with 25–100 % of the electricity provided by PV and the balance by the grid, for treatment capacities of 20,000–80,000 $m^3$/d. Based on the assumed existing conditions, grid-powered RO had the lowest water cost per unit volume.

Barrufet and Mareth [53] used the HOMER software to simulate standalone BWRO powered by combinations of PV, WTs, DPG, and battery storage for freshwater production in the oil fields of West Texas. They considered a hypothetical 23 $m^3$/d system treating feed water at 10,000 mg/L TDS for interest rates of 4–6 % and project lifetimes of 5–20 years. The ranges of optimal power provided by the PV panels, WTs, and DPG were 0–2, 2–4, 6.4–12.8, and 6–7 kW, respectively. If single power sources were used, the optimal power source was 8 kW by DPG, followed by 15 kW by WTs, and 25 kW by PV panels.

Cherif and Belhadj [54] simulated a hypothetical hybrid BWRO system powered by a 10 kW WT and 400 $m^2$ of PV panels in the southern Djerba Tunisian island. The raw water TDS was 5400 mg/L, and the BWRO system performance was simulated with the ROSA software package. Estimated permeate production ranged from 57 to 111 $m^3$/d, but no cost of water was provided.

Chaaben et al. [55] simulated a small BWRO system powered by PV with battery storage as a multi-input/multi-output (MIMO) process. Their model was intended for process control to optimize operating conditions and reduce water cost for small standalone systems in Tunisia.

Bourouni et al. [56] and M'Barek et al. [57] developed an optimal design model based on genetic algorithms to compare alternative combinations of small RO systems with WT, PV, and battery power for sites in Tunisia. The optimization minimized the total net present cost of the system, including capital, operation, maintenance, and replacement costs. The model was demonstrated for the conditions of the village of Ksar Ghilène, with 300 residents and water demand of 15 $m^3$/d. The optimal solution of 11 kW PV/RO with 200 Ah battery storage at \$2.62/$m^3$ of produced water differed from the existing 10 kW PV/RO with 600 Ah battery storage at \$3.56/$m^3$. The optimal solution result also compared well with the numerical result of the HOMER software.

Mousa et al. [58] developed a numerical optimization model for design of hybrid WT and PV RE to drive BWRO in Abu Dhabi. Capital and operating costs were considered for a hypothetical community of 100 people for a 20-year project life. For estimated SEC of 2.5, 5, and 7.5 kWh/$m^3$, the respective costs for produced water were 0.50, 0.85, and 1.21 \$/$m^3$.

Palacin et al. [59] employed a hybrid predictive control algorithm to optimize the operation of a standalone RO plant powered by wind and solar RE, supplemented by a diesel generator. Their hypothetical simulations included sizing of treated water storage tanks and membrane maintenance to prevent fouling, while trying to meet variable water demand.

## Conclusions

Researchers around the world continue to look for ways to provide fresh drinking water in remote locations that must rely on brackish water or seawater supplies. The reviewed articles demonstrate concern for a wide spectrum of treatment capacities, from individual residences to communities of several thousand people, most often in standalone off-grid locations. Experiments and simulations demonstrated that the variability and intermittency of wind and solar RE as power sources for desalination can be addressed through ESSs, proper sizing of treatment capacity and water storage, and hybrid combinations with fossil fuel generators or grid access. Optimal combinations of energy supply and treatment systems are likely to vary from region to region with variations in local raw water qualities, RE sources, and access and cost of grid energy. In light of the variety and novelty of these RE and desalination combinations, more effort should be devoted to clarifying their cost structure so that decision-makers (either individuals or municipalities) can confidently select the best technologies for implementation. We hope that this summary of the state of the art for RE-powered desalination will provide incentives for the advanced water treatment and RE equipment manufacturers to recognize the market potential for appropriately sized systems for these remote applications.

### Compliance with Ethics Guidelines

**Conflict of Interest** Ange Abena Mbarga, Lianfa Song, W. Ross Williams, and Ken Rainwater declare no conflicts of interest.

**Human and Animal Rights and Informed Consent** This article does not contain any studies with human or animal subjects performed by any of the authors.

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- •• Of major importance

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