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Review

Energy Storage for Water Desalination Systems Based on Renewable Energy Resources

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Abstract: Recently, water desalination (WD) has been required for the supply of drinking water in a number of countries. Various technologies of WD utilize considerable thermal and/or electrical energies for removing undesirable salts. Desalination systems now rely on renewable energy resources (RERs) such as geothermal, solar, tidal, wind power, etc. The intermittent nature and changeable intensity constrain the wide applications of renewable energy, so the combination of energy storage systems (ESSs) with WD in many locations has been introduced. Thermal energy storage (TES) needs a convenient medium for storing and hence reuses energy. The present work provides a good background on the methods and technologies of WD. Furthermore, the concepts of both thermal and electrical energy storage are presented. In addition, a detailed review of employing ESSs in various WD processes driven by RERs is presented. The integration of energy storage with water desalination systems (WDSs) based on renewable energy has a much better capability, economically and environmentally, compared with conventional desalination systems. The ESSs are required to guarantee a constant supply of fresh water over the day.

Keywords: desalination; renewable energy resources; energy storage systems; energy sustainability

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1. Introduction

In the near future, the scarcity of global fresh water is a colossal danger due to serious overpopulation and the pollution of the available fresh water resources of the underground and rivers as a result of industrial waste. One of the most crucial solutions to avoid this danger is a new supply of clean drinking water. Seawater holds almost 97% of accessible water resources, making the use of WD technologies a successful solution to the potable water shortage [1]. In order to confront the rising demand for fresh water for drinking, WD is a technique that effectively removes dissolved salts. The admissible salinity range for potable water, according to the WHO (World Health Organization), is between 500 and 1000 ppm.

Generally, WD is accomplished either mechanically via membrane distillation or thermally by evaporation of seawater. Otherwise, large-scale WD projects involve a number of risks that should be precisely considered for evaluating the system's feasibility [2]. The different methods of water desalination processes (WDPs) that are categorized into thermal and membrane are introduced in Figure 1. The thermal process contains humidification–dehumidification (HDH), solar stills (SS), vapor compression (VC), multi-stage flash (MSF), and multi-effect distillation (MED); the membrane techniques include reverse osmosis (RO) and electrodialysis (ED) [3–5]. Overall, the thermal WDP share is almost 35% of the global systems, while RO technology contributes nearly 61% [6].

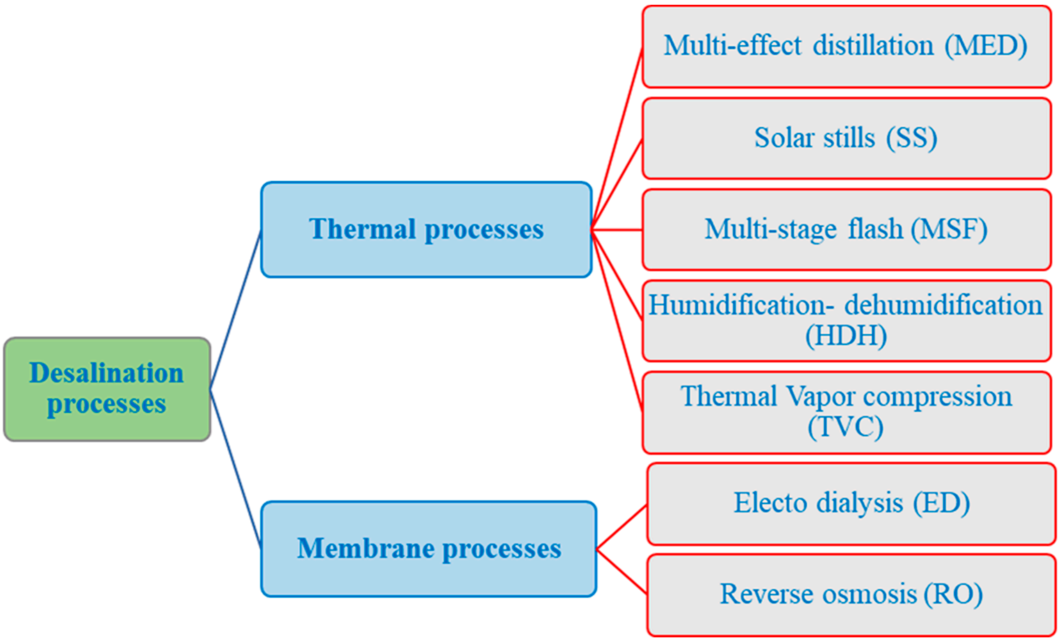


Figure 1. Common water desalination processes.

Generally, the sources of waste heat are fundamentally categorized into low- and high-grade energies. High-grade sources of waste heat are recovered by various plant processes; however, the low-grade sources are not economically viable for recovery, and they are essentially rejected into the environment [7]. Waste heat, either low- or high-grade energy, is the elementary source of thermal energy losses in industrial processes such as the refining of petroleum, petrochemical, beverage and food, pulp and paper, textiles, etc. [8]. Thermal methods of WD systems may be on a large scale coupled with industrial applications based on the utilization of waste heat or small-scale systems integrated with electric heaters based on fossil fuels or renewable energy resources (RERs). Large-scale water desalination plants based on industrial applications, viz., MSF, MED, and RO, with relatively high water productivity were reviewed [9,10].

Joining both energy and fresh water frameworks can distinguish new options for enhancing the efficiency of the overall resource [11]. Detailed knowledge of the current combination of water and energy in water desalination systems (WDSs) is indispensable, along with a good understanding of key factors involved in decision making to recognize and realize the opportunities for required energy [12]. Water is necessary to refine petroleum products and cool the condensers in power plants. Additionally, energy is required for WD, the treatment of wastewater, purification, conveyance, and pumping for end use [13]. Improved knowledge based on the incorporation of water and energy was presented in many locations across the world [14]. Moreover, the developing issue of a multi-plant accompanying the economical implementation of energy and water was presented [15].

The energy that is demanded to drive WDSs could be supplied from RERs such as solar, wind, tidal energies, etc. One of the most popular technologies of WD is the HDH process. Since HDH systems operate at a modest operating pressure, only minimal mechanical energy is required to circulate air and water using fans and pumps [16]. HDH techniques have several benefits, including the capability to function in low-temperature conditions, ease of construction, cheap initial and operational costs, and integration with sustainable RERs, among others.

Initially, non-renewable-energy-based resources were utilized to obtain desalination systems with 1000 m^3 daily of drinking desalinated water by depleting 10,000 tons of oil yearly [17]. These systems increase greenhouse gas emissions, deplete the available limited stores of fossil fuels, and threaten the progress of sustainable development. Therefore, thermal WD technology depends on renewable energy for supplying thermal energy, which has a growing trend to provide abundant advantages compared to traditional energy resources. Solar energy appears to be the appropriate choice to supply the necessary thermal energy, particularly in regions having high solar irradiation and insufficient resources of fresh drinking water [18]. Seawater absorbs solar energy from the sun in thermal WDSs powered by solar energy, and then it evaporates as clean water droplets from the ocean's surface. Finally, accumulating clouds are condensed, and rain is produced, providing fresh water for drinking.

As a result of the high energy consumption of reverse osmosis (RO) WDSs, which require almost 3–10 kWh of electricity to create 1 m^3 of desalinated water, this technology is not sustainable [19]. RO-WDSs function with a nominal load of constant pressure and flow rate of the feed water to the membranes, while a variable operating load of RO-WDSs, i.e., different flow rater and feeding pressures, introduces outstanding results [20]. The benefits of combining wind energy [21] and photovoltaic (PV) panels [22] with RO-WDSs have already been implemented. Both gravitational potential and wind energies were combined in RO-WDSs [23]. Traditional WD processes such as TVC, MVC, and RO are the most commonly employed technologies in industries, whereas hybrid technologies such as MSF-RO [24,25], MED-adsorption systems [26], MED-RO [27], MED-MSF [28], etc., are developed to augment both the production of fresh water and the thermodynamic synergy.

One of the promising recent technologies for water desalination as well as power generation which have been implemented intensively is pressure retarded osmosis (PRO), which could be beneficial for recycling RO brine [29]. Generally, the PRO process has greatly evolved since 1973 due to the fast advances in membrane technologies. PRO consists mainly of a membrane and a hydro turbine to transfer the hydraulic energy into electric energy. It has a unique characteristic in which the waste stream can be reused as a feed supply into the PRO system. Initially, the fundamental challenge faced by the development of PRO techniques was to select a suitable membrane with reasonable mechanical stability, high salt rejection, and high permeability of water [30,31]. This method has a number of advantages according to its commercialization, such as operation throughout the day; not being affected by RESs, viz., wind and solar radiation; requiring a small footprint, etc. The descriptions of thermal and membrane WD technologies are introduced in Table 1.

Table 1. Descriptions of thermal and membrane WD technologies.

Technology	Thermal	Membrane
Mechanism	Evaporation and condensation.	Pressure and concentration gradient driven.
Applications	HDH, SS, TVC, MED, MSF.	ED, RO.
Operating temperature	60–120 °C.	Less than 45 °C.
Driving force	Gradient of concentration and temperature.	Gradient of temperature and pressure.
Form of energy required	Steam, waste heat, renewable energy, and limited mechanical power for the pumping processes.	Prime fossil energy or renewable-energy-driven power.

Given the preceding background and prior research work, the motivation of this review paper is to discuss the current energy storage strategies for various technologies of WD based on RERs. The principles of WD technologies and their sustainability with details on renewable energy supply for different WD applications are discussed. Additionally, various applications of WD plants combined with energy storage systems (ESSs) and powered by RERs, viz., solar, wind, geothermal, and tidal, in addition to the hybridization of energy resources are studied. Finally, barriers, challenges, and encouraging policies for the future work of employing different methods of ESSs integrated into WDSs powered by RERs are presented.

2. Desalination Systems Based on Renewable Energy Resources

Renewable energy is accessible everywhere, which makes it an effective alternative to depleted fossil fuels. Renewable energy is becoming continuously reliable, with decreasing costs year-on-year; therefore, renewable energy is a practicable choice in different regions. With the rising demand for desalinated drinking water, renewable-energy-powered WDSs have a massive worldwide potential market [32]. The dependence on depleted fossil fuels for WDSs continues, since they are the most reliable energy form and cost-effective. However, developing WDSs based on fossil fuels has a number of challenges, i.e., high energy demand and emissions of CO_2. There is considerable potential in integrating WD technologies with RERs, by supporting technically and funding feasible renewable energy systems. Sustainable WD schemes are technically feasible for producing remarkable amounts of desalinated water using the available RERs [33]. When compared to traditional fossil-fuel-powered WDSs, the combination of WDSs and RERs has been discovered as a more sustainable, desirable, and financially feasible choice. A global analysis of utilizing solar energy for WD was conducted [34].

Recent advancements in WD technologies contribute to lowered cost, affordability, and higher efficiency. In recent years, energy consumed by WDSs based on RERs has been significantly reduced. Utilization of RERs such as solar, geothermal, wind, tidal, etc., for WDSs appears to introduce sustainable alternatives. Figure 2 illustrates the various paths through which common RERs may be employed to drive various WDS processes. The WD technology should be integrated with proper RERs, having the ability to use the available RERs effectively.

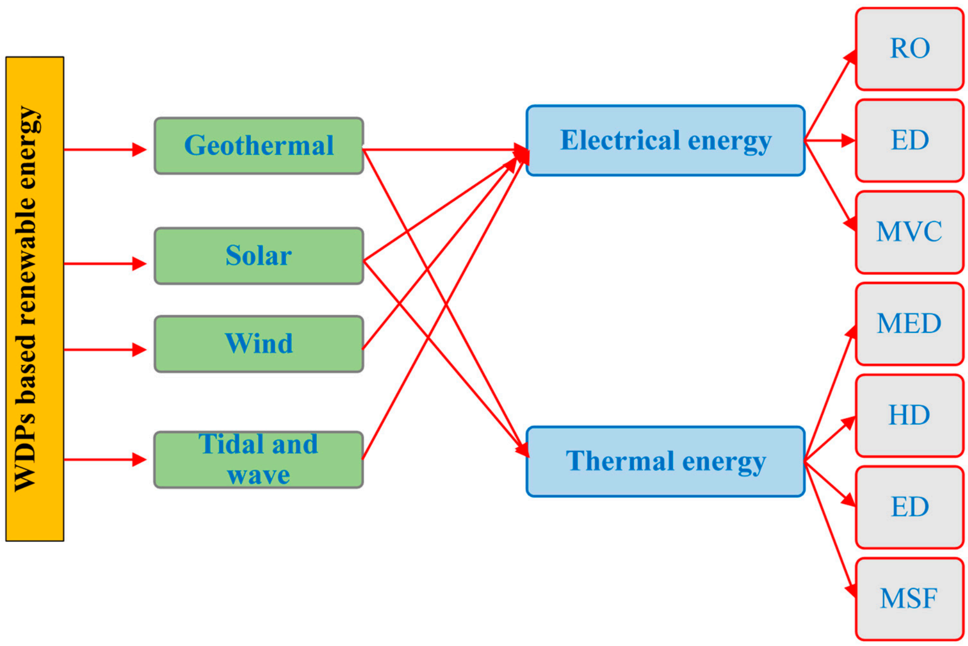


Figure 2. Possible pathways for renewable-energy-driven WD techniques.

3. Energy Storage for Water Desalination

The fundamental issue with RERs for WDSs is their intermittent discontinuous form and intensity, which restrict their widespread applicability in a variety of sites. In addition, the costs associated with the technologies of WD based on RERs are another major barrier to the successful implementations of these available and sustainable RERs. Energy storage technologies that could improve the performance of RERs for WDSs aid in improving the intermittent behavior of RERs and may enhance the long-term sustainability of WDS investment. WD technologies powered by thermal energy may employ the storage units known as TES to capture, store, and then release energy to correspond to the trends of energy demand and supply. TES could be combined with readily available energy supplies, whether waste heat or renewable energy [35]. From thermodynamic aspects, the heat capacity of storage materials is proportional to their specific heat, volume, density, and operating temperature difference [36].

The functions of TES units include charging, storing, and discharging [37]. TES in WDSs can be implemented by diverse principal methods: sensible TES, using either solid or liquid materials; phase-change/latent energy storage; and thermochemical energy storage. Sensible TES is accomplished via the fundamental modes of heat transfer, i.e., convection, conduction, and radiation, whereas phase-change heat storage materials are known as latent-heat-storing materials. Usually, the solid–liquid phase is highlighted, whereas liquid–solid phase change involves solidification/melting for discharging/charging processes. It is a cyclical process that demonstrates the durability and thermal stability of a material as a thermal storage medium [38].

Sensible heat storage (SHS) materials for WDSs are superabundant in nature, making them convenient, economical, and accessible, whereas latent heat storage (LHS) material increases nocturnal production of fresh water [39]. TES can store and transport with the working fluids associated with operating parameters such as pressure and temperature. According to the availability of thermal resources, the working medium's capacity to store thermal energy determines its suitability for use. One of the auspicious materials for TES systems is phase-change material (PCM); however, the commonly employed PCMs have limited thermal conductivity. However, nanotechnology uses a highly efficient thermal system to enhance the functionality of the TES system and is suitable in terms of the efficiency of the recovery process, financial feasibility, and environmental aspects. Thus, raising the thermal conductivity of PCM composites via different nanoparticles is an encouraging option for improving thermal performance. Table 2 lists the benefits and drawbacks of the various TES system types.

In the last decades, the prompt growth in heat capacity of various RERs requires further advancements in ESSs that can store the excessive rise in energy capacity. The quantity of energy stored by SHS material is directly impacted by the temperature differential between the storage medium at the inflow and outflow, the mass flow rate, and the storage medium's heat capacity [40]. Depending on the medium temperature, the stored energy inside the TES system may be utilized for diverse purposes. Low-temperature applications of WD are suitable for energy resources with a temperature range of 60–80 °C, whereas other industrial processes and the production of electrical power require energy resources with a temperature range of 100–400 °C [41]. Sensible heat TES systems using water as a working medium can store energy under the boiling water temperature; as a result, only WD at low temperatures, such as that in solar stills, multi-effect evaporation systems, membranes, HDH-WDSs, etc., may use them. On the other hand, liquid salt materials or solid-state materials can store high-grade thermal energy within a 200–500 °C temperature range, which is ideal for electric power generation integrated with WDPs, such as multi-effect evaporation of MED, MSF, and M/TVC.

The unavoidable fluctuations of various RERs such as solar, wind, and others, make it exceedingly difficult to connect these systems with cooling/heating needs and client electricity demands. Therefore, massive research has investigated different technologies of ESSs, both thermal and electrical, to fulfill more stability of power supply for WDSs [42]. Furthermore, implementing convenient energy technology can create significant challenges for establishing grid stability; thus, energy storage of excess RER output is critical for voltage and power balance. Electricity storage is required for backup generation, frequency control, load balancing, peak shaving, and thermal energy management.

Table 2. Characteristics of TES systems.

Thermal Energy Storage	Advantages	Disadvantages	Desalination Applications
Liquid-state sensible heat materials	▪ High storing capacity. ▪ Relatively low cost. ▪ Effective in different applications. ▪ Appropriate for synthetic oil fluid.	▪ Temperature reduction is necessary for heat transfer. ▪ Molten salts freeze around 120–230 °C.	Large-scale units for MED, MVC, MSF, and RO.
Solid-state sensible heat materials	▪ Proper for synthetic oil fluid. ▪ Effective in various industrial applications. ▪ Convenient for superheating and pre-heating in direct generation of steam.	▪ Not proper for condensation/ evaporation in steam collectors.	Large-scale usage of MED, MVC, MSF, and RO.
Phase-change material (PCM)	▪ Latent heat storing enables heat transfer at constant temperature. ▪ Available material. ▪ Convenient for evaporation and condensation process.	▪ Not suitable for superheating and pre-heating. ▪ Quite early stage of development.	Large-scale usage for MSF, MED, RO, and MVC.
Water/steam	▪ Latent heat storage (LHS) enables heat transfer at constant temperature. ▪ Low material requirements. ▪ Convenient for both evaporation and condensation processes.	▪ Not suitable for superheating and pre-heating.	Large-scale units.
Hot water	▪ Low cost for storing process under 100 °C. ▪ Effective in different industrial usage.	▪ Sensible heat storing needs a temperature drop. ▪ Not proper for power generation.	Solar still, HDH, membrane distillation and low-temperature processes.

In addition, the power demand of WDSs does not permanently and conveniently match the electrical power supply; therefore, suitable ESSs are requisite for a reliable power supply. Recently, the most convenient devices for storing electricity have been batteries that supply electricity periodically as needed. However, the batteries emit toxic harmful substances during malfunction situations and at disposal times [43]. Batteries are promising techniques for storing electrical energy. Recent advances in battery technology promise practical energy storage with low self-discharge rates and high energy densities (gravimetric and volumetric) [44]. Batteries are required in WDSs driven by RERs, to prevent the inevitable dumping of energy and elevate the running period for producing fresh water. However, these batteries are costly and have a limited lifespan.

As a result of extensive progress in RERs, traditional ESSs such as batteries cannot counter the requirements of energy storage, particularly when the grid connection is not accessible. Flow batteries introduce a promising solution for the high density of energy and lifetime [45,46]. In spite of this, their application is accompanied by high cost due to the issues related to the materials and technical circumstances that should be solved prior to the commercialization of the product [47]. Accordingly, innovative methods are required to find methods of effective energy storage, such as electrolyzer/fuel cell cycle systems [48,49].

4. Water and Energy Sustainability

Conventionally, WDPs are powered using fossil fuels, which account for climate change and acid rain by releasing greenhouse gases and a number of harmful emissions. Furthermore, as the currently finite resources of fossil fuels deplete, the need to introduce other energy resources is critical for energy security, as well as for future sustainable development [50]. The recovery of waste heat dissipated from thermal power plants can be employed for supplying potable water by improving the overall system efficiency and mitigating environmental pollution as a result of reducing the burning of fossil fuels [51,52]. Currently, the global capacity of WD, which represents almost 7.5% of the total universal fresh water demand, requires around 1.42×10^6 tons of oil daily, which generates approximately 156 tons of carbon dioxide per day [53]. The minimal energy necessary to remove salts from saline water sources in order to produce fresh water is around 0.706 kWh/m^3 [54]. When all heat is efficiently removed from the oil, approximately 0.05 tons of oil are desired for each ton of new desalinated water produced [55]. As a result, finding options to replace the conventional energy resources used in the WD processes with hybridization technologies based on RERs to minimize energy usage at a reasonable cost is critical.

Almost 84% of the worldwide energy consumption is generated by non-RERs that are being depleted, whereas 16% comes from RERs. Recently, it has become critical to develop new innovative processes for fresh water production that are practically sustainable. The available possibilities are to manage the energy and water crisis in a sustainable manner such as utilizing RERs, implementing hybridization processes, developing energy-efficient and low-cost technologies, and reusing the available water resources. RERs' contribution to the total global prime energy consumption is projected to increase from 24% in 2020 to 48% by the year 2040. It has been demonstrated that fossil fuel resources will be consumed within 50 years, assuming a constant rate of energy consumption. Renewable energy technologies should be properly studied for a sustainable energy future [56].

Energy plays an indispensable role in developing nations, so for WDSs powered by RERs to be sustainable, they must be environmentally friendly, economically feasible, and socially acceptable. To achieve a sustainable energy system for WDSs, two achievements should be accomplished: enhancing system performance and fuel-switching from depleted fossil fuels to RERs.

5. Applications of WD-Based RERs Combined with ESSs

5.1. Solar Energy

The sun radiates a large amount of solar energy to the Earth's upper atmospheric layer. Oceans and land receive around 51% of the incident solar energy in total. Solar energy can be classified as light/photons as well as heat with electromagnetic waves. Basically, the sun produces most of the RERs, as represented in Figure 3. The solar-powered HDH-WDSs are classified as direct or indirect processes; in direct systems, evaporation, and condensation processes are accomplished in one device. A small solar collector area will have a high gained output ratio (GOR) when the available solar energy is employed as heat input, which lowers capital expenses [57].

In regions where reasonably large areas of solar collectors are required, hundreds of thousands of square meters, solar ponds are applicable, and they would be the most feasible among all other options for collectors. This is due to their low construction cost per unit area and delivered thermal energy, as well as the large energy storage provided. Initially, several researchers proposed using thermal energy supplied from solar ponds to power WDSs [58]. Sensible heat technology was effectively employed in numerous applications of WD, including solar stills and solar ponds [59].

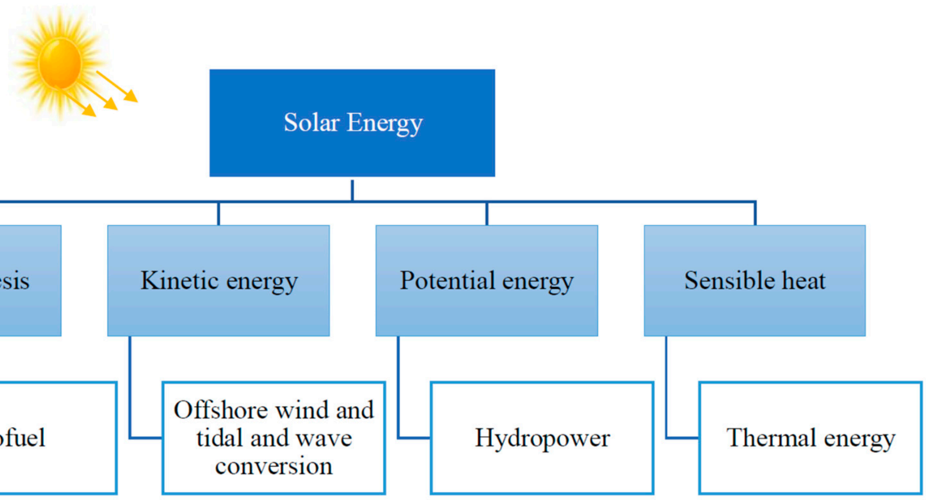


Figure 3. Continuous flow of solar energy on Earth.

Solar energy is a promising renewable energy for WDSs in most countries encountering limited energy resources. The solar energy used in WDSs may be either in membrane units to supply the required electricity or in thermal processes to introduce the required thermal energy [60]. Using solar energy as an alternative to traditional energy resources in WDSs to produce fresh water has many advantages such as avoiding fresh water scarcity, high flexibility, decreasing greenhouse gas emissions, low maintenance, and low operating costs; however, it has a high initial cost [61,62]. A detailed review of various desalination technologies utilizing solar energy was presented [63].

5.1.1. Photovoltaic (PV)

PV panels are commonly used as green energy for producing electric power. The thermal energy dissipated from PV panels should be controlled to avoid a rise in operating temperature that has a negative impact on performance. Solar energy is the primary source for delivering on-site renewable energy to PV panels which represent a clean substitution to fossil fuels, ideal particularly for isolated islands or remote communities [64]. Integrating the PV panels with WDSs in remote areas is cost-competitive, especially with the reduction happening in their prices. The electricity generated by PV panels for WDSs can be utilized for electro-mechanical applications.

A suitable technological overlap between RERs and WDPs suggests that among the different possible configurations, the PV-ED and PV-RO techniques are attractive. For the PV-RO plants, lead–acid batteries with a capacity of 46.5 kWh were initially used in 1982 [65]. Khatib et al. [66] addressed a number of difficulties with the proper size of PV solar arrays and battery storage systems. Mohamed and Papadakis [67] demonstrated a PV-RO combining an energy storage system of a battery with a design daily capacity of 12 cubic meters, producing fresh water with a cost of 7.22 USD/m^3.

Salameh et al. [68] used a multiple-criteria decision approach to optimize a PV panel and battery ESS to supply power to WDPs and deliver continuous electric power. Different battery technologies were employed: nickel–iron (Ni–Fe), lead–acid ($PbSO_4$), and lithium–iron–phosphate ($LiFePO_4$) with different discharge depths for various configurations of the proposed system. The optimization process's inputs and outputs, in addition to the United Nation's (UN) sustainable development goals (SDGs), were utilized as indicators for multiple-criteria decision analysis. PV–Li-ION battery with a 50% discharge depth was the best choice based on different optimization algorithms. Suleimani and Nair [69] studied a PV-RO with a 9.6 kWh battery for WDSs. The proposed system produced fresh water at a daily rate of 5 m^3; however, the amount of daily water production sometimes exceeded 7.5 m^3, with a water cost of 6.5 USD/m^3. Herold and Neskasis [70] implemented PV-RO

WDSs with 60 kWh battery storage and a daily water output of 0.8–3 m^3 under various energy management strategies.

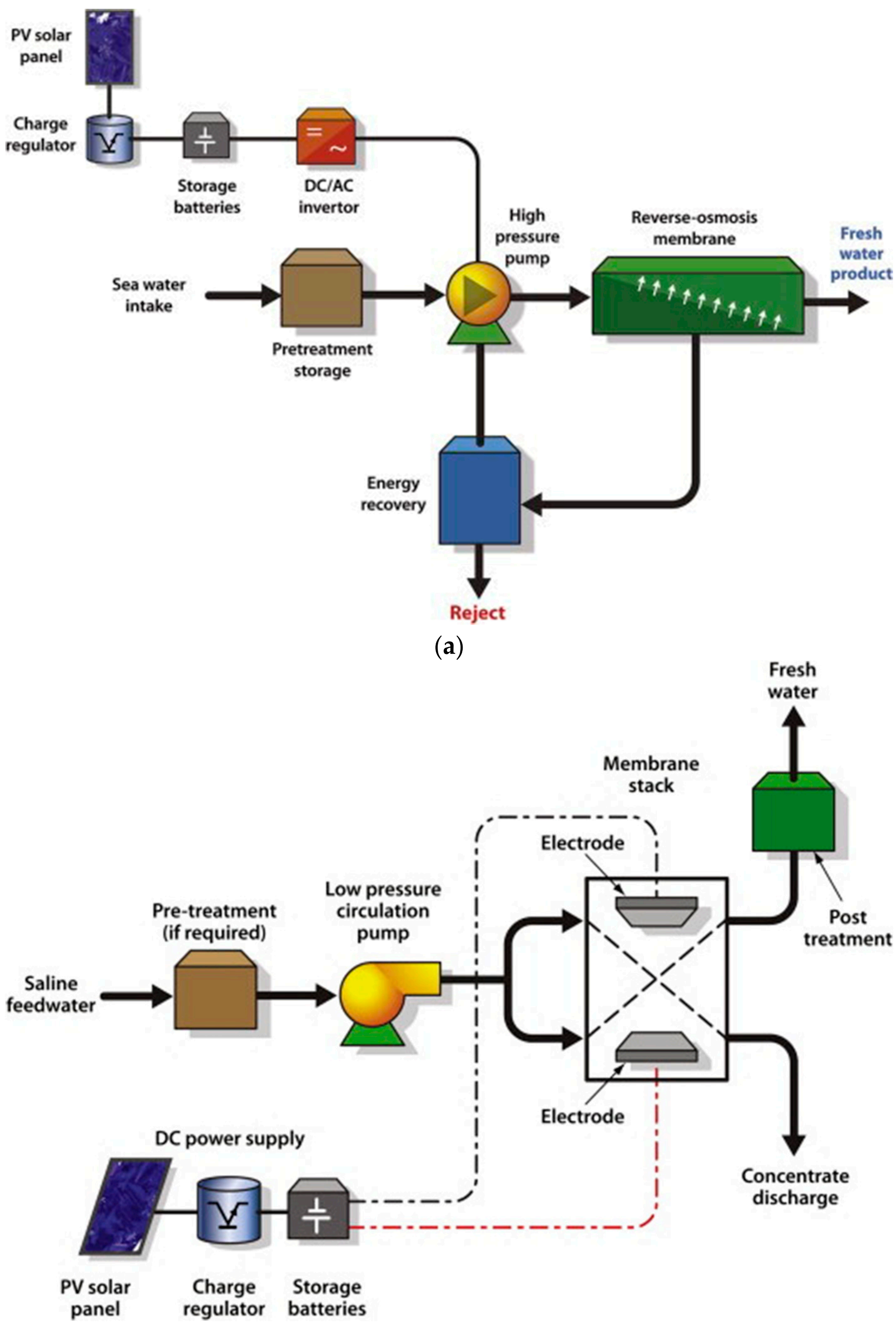
An attempt to assess the water production cost of two WDSs, RO and multiple effects based on solar thermal and PVs, was conducted by Fiorenza et al. [71]. The influences of PV module cost, oil price, depreciation factor, and economic incentives were taken into account. The results revealed that the desalinating water cost of the solar-power WD plant utilizing the two technical alternatives was roughly 2.5 times more than that of the traditional system. The high price was due to the solar plants' expensive initial investment and extensive land utilization.

Solar PVs represent an effective, clean substitute for conventional fossil fuel, principally for remote communities such as isolated grid-unconnected regions and remote areas. These applications of PV panels for WD are cost-competitive to conventional systems due to reductions in the prices of PVs and growing prices of fossil fuels through the last years. The electrical energy of solar PV panels can be utilized for mechanical pumping devices. RO- and ED-WDSs are the most appropriate to be integrated with PV systems, and ESSs are required for sustained system operation. The potential to establish sea WDSs on a large scale using RO powered by PV panels was analyzed using a simulation approach by Ganora et al. [72]. The results demonstrated that providing desalinated potable water to 100–200 million human beings requires the installation of PV panels with a capacity of 14.2–28.4 GW. Additionally, local energy storage-controlled power transfers to the nearest grid, reducing the risk of an electrical system overflow.

As represented in Figure 4, Al-Karaghouli et al. [73] analyzed the electricity demand, capital and operating expenses, and cost of generating fresh water using PV-RO and PV-ED systems. The proposed systems introduced reliable, compact water desalination devices powered by RERs at a reasonable cost. However, a number of non-technical barriers could be defeated by collecting the required data for design, installation, operation, and maintenance training. Tafech et al. [74] proposed four scenarios for operating an RO-WDS plant and supplying fresh water during daylight hours with water storage, as indicated in Figure 5, by sizing a 13 MW solar PV. The transient operation of RERs of solar and wind and the dynamic consumption of water was accounted for by sizing the solar PV, water energy storage, and plant capacity. It was concluded that good integration of PV with wind power showed more profit for regular energy and water that harmonization of the unsteady operation of RERs with dynamic consumption of water.

Calise et al. [75] introduced a methodology for solar energy using PV panels and RO seawater desalination management based on water storage systems. The system was proposed to preclude the electric storage systems, maintain stable production of water, and maximize water consumption. The results showed that the system combination was highly lucrative with a 1.3 year payback period. Additionally, increasing the PV area from 4827 to 12,067 m^2 increased the fresh water from 67 to 94%. Additionally, Karavas et al. [76] examined various configurations of RO-WDS powered by PV panels that were in autonomous mode to evaluate the optimum economic and technical conditions and minimize total installation and operation costs for a system lifetime of 20 years. The system included water storage as well as a small capacity battery. The results showed that the PV/RO-WDS, which used a small capacity ESS of lead–acid batteries, generated fresh water of the requisite intended quality under all operating situations and exploited the potential RER of PV panels to the greatest extent possible.

Ajiwiguna et al. [77] introduced a PV/RO with a battery and a storage tank of water (seasonal). The results indicated that the reduction in water cost for a PV-RO with the battery system and the storage tank for constant and variable demands was in the range of 10.21–2.31 USD/m^3 and 36.96–3.06 USD/m^3, respectively. The PV/RO WDS with a storage tank and no battery was the most effective PV/RO-WDS design since it cost the least to produce water. Rezk et al. [78] designed a hybrid RO-WDS plant of 150 cubic meters per day with PV and fuel cells (FCs) for irrigation purposes in distant places, as shown in Figure 6. The ideal system configuration was determined by the lowest overall cost and the lowest energy cost. The results revealed that the avoided CO_2 emissions from the introduced design compared with that for diesel fuel were 70,974 kg per year. Furthermore, the FCs appeared to be an environmentally and economically viable storage option for PVs. Castro et al. [79] performed a techno-economic study of mechanical vapor compression (MVC), MSF, MED, and RO combined with a solar PV–lithium-ion–diesel hybrid system to assess the interdependence between the energy and main components of WDS. The results indicated that RO was appropriate due to the low cost and energy of distilled water, and the compatibility with RERs. MED and MSF units had benefits due to the system's robustness.



(a) (b)

Figure 4. (**a**) RO- and (**b**) ED-WDSs integrated with PV panels [73], reused with permission from Elsevier (license number 5491411208517).

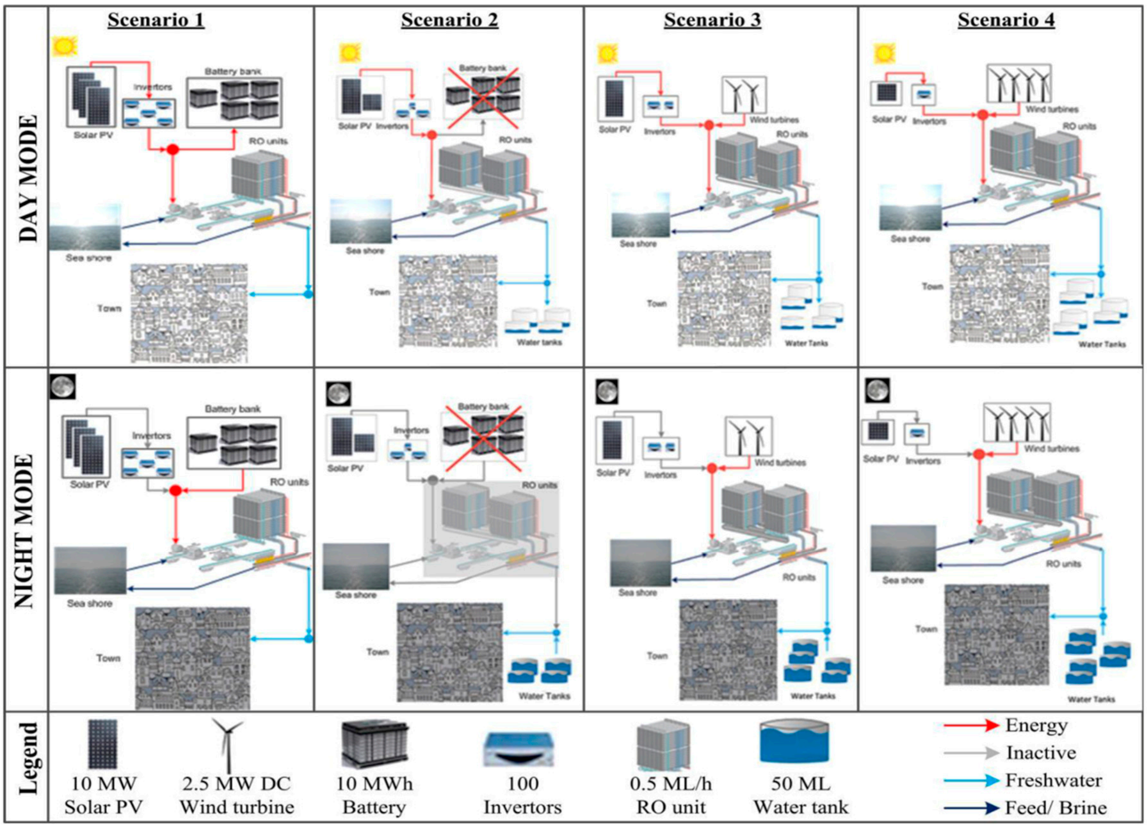


Figure 5. Representation of day and night operations for four scenarios [74], open access.

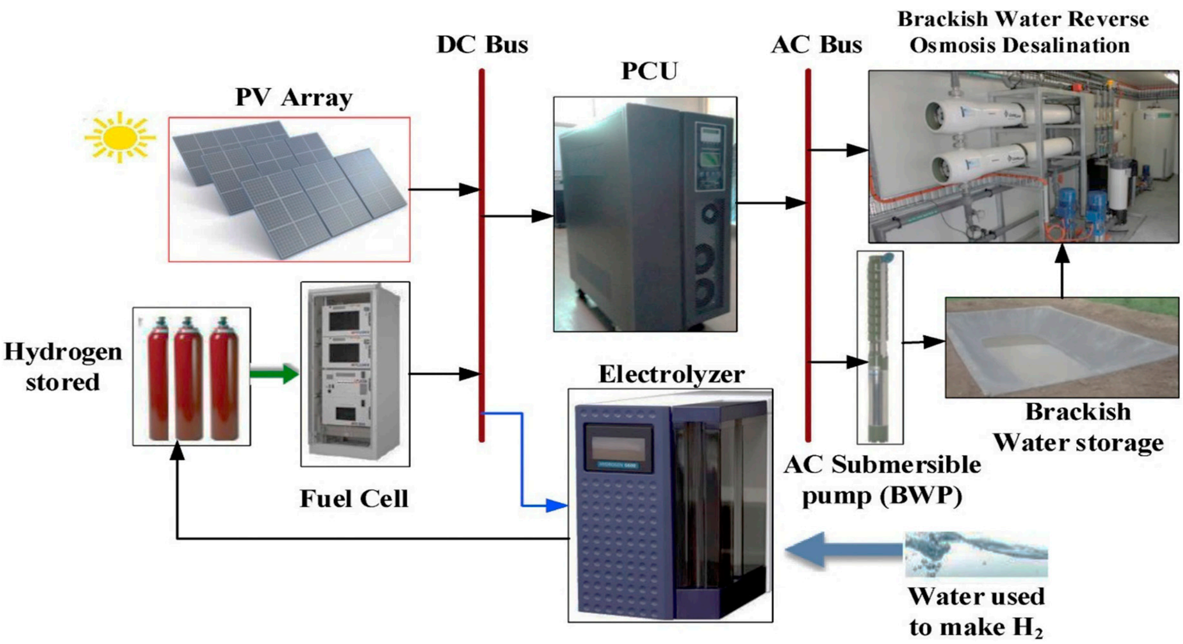


Figure 6. Block diagram of the hybrid desalination system [78], reused with permission from Elsevier (license number 5491420656683).

5.1.2. Solar Collectors

The solar collector gathers solar thermal energy using working fluids for different applications. Solar collectors are classified into concentrated and non-concentrated thermal systems [80]. Concentrated solar collectors are based on a simple general scheme of mirrors, where the sunlight may be redirected to collect the available heat to be used. Concentrated solar collectors (CSC) encompass parabolic dishes, parabolic troughs, linear Fresnel reflectors, heliostat field collectors, etc. The technology of concentrated collectors can not only be utilized for the production of electricity, but also for WDSs, heating, cooling, water disinfection, detoxification, etc. [81]. A technology called concentrated solar thermoelectrics, was introduced by Zhang et al. [82], with the impact of the daily, monthly, and annual levels of direct solar irradiation on the power of the concentrated power plant. In addition, Moharram et al. [83] achieved a techno-economic approach to solar power and WDS. As introduced in Figure 7, the proposed system consists of a solar thermal power plant and a steam Rankine cycle to produce energy for the RO plant, while the surplus electricity is sent to the electrical grid and the thermal MED-WDS. The system generated 22,775 m^3 of fresh water per day and delivered 15.5 MWe to the grid due to using molten salt as the working fluid.

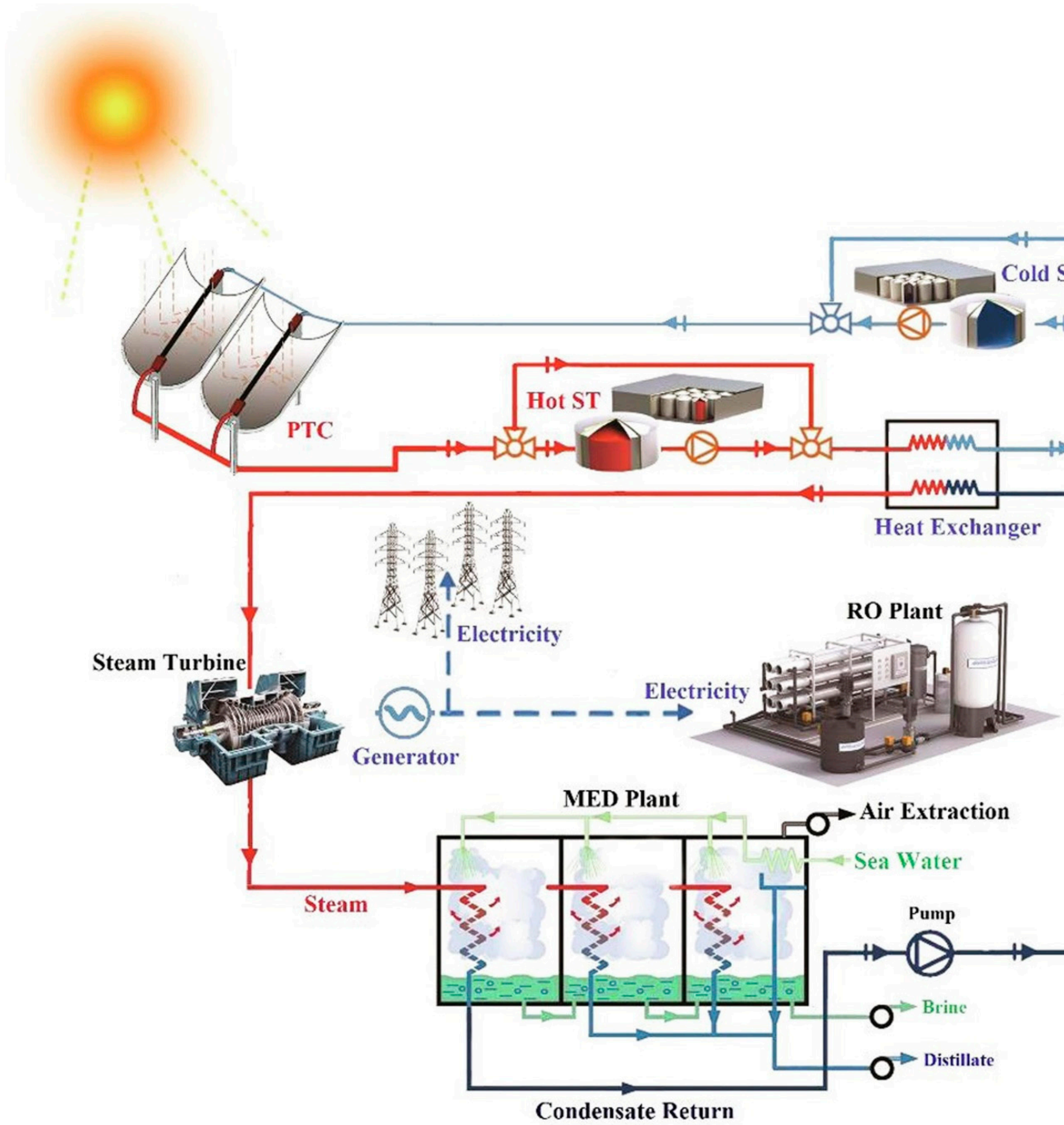


Figure 7. Configuration of the proposed system [83], reused with permission from Elsevier (license number 5491421034545).

Gude et al. [84] created a low-temperature WDS that uses flat plate solar collectors to produce fresh water. Based on the significant fluctuations in sun irradiation, the area of the solar collector combined with TES was calculated. The findings established that TES was a critical component for preserving thermal energy and meeting the demand for energy, particularly when direct solar energy was unavailable. Furthermore, despite the changes in weather circumstances, a collector with an 18 m^2 surface area and TES with 3 m^3 capacity were adequate to deliver fresh water with a daily flow rate of 100 L around the clock. Bacha et al. [85] used the concepts of multiple condensation and evaporation cycles to simulate the characteristics of the essential components of a solar heating system of water for WDS. The results revealed that the tank of heating water with an internal heat exchanger significantly increased fresh water output compared to alternative configurations.

Additionally, Figure 8 depicts a self-sustaining solar system developed by Chen et al. [86] that combines solar collectors, a spray-assisted low-temperature WDS, and heat storage tanks. By improving the effectiveness of solar collectors, the temperature of the storage tank, and the energy efficiency of the WDS, this number was raised. A daily water flow rate of 20 kg/m^2 of the collector was provided by the solar WDS. Additionally, the anticipated cost of desalination was 1.29 USD/m^3, which was less expensive than the expenditures related to other solar thermal WDSs.

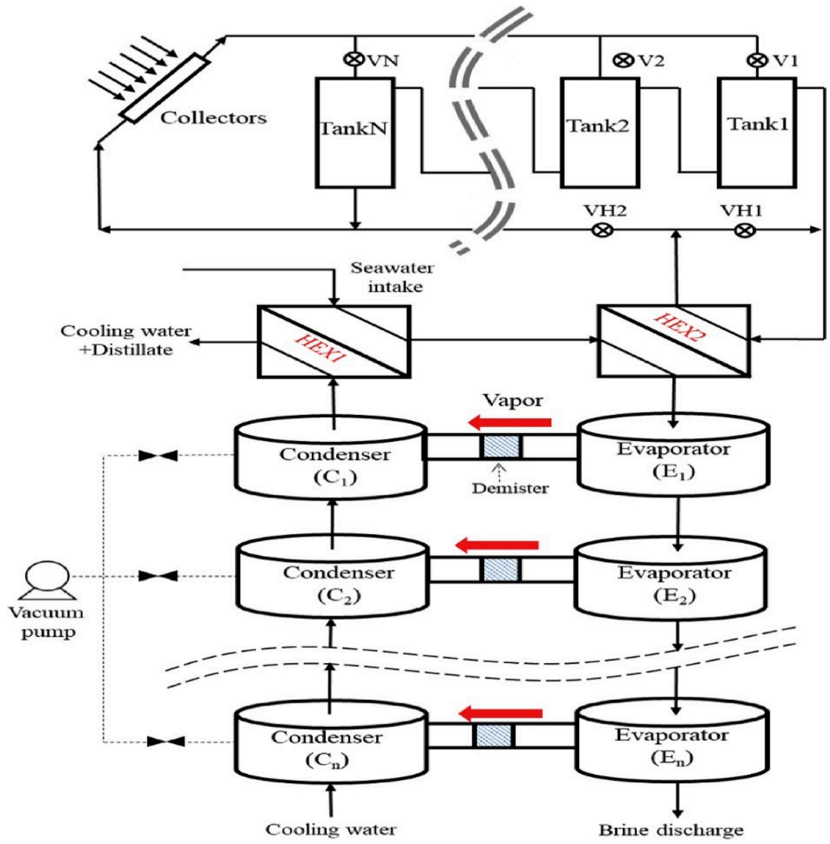


Figure 8. Solar spray-assisted low-temperature WDS integrated with TES [86], reused with permission from Elsevier (license number 5491421395079).

A solar-assisted HDH-WDS featuring a heat recovery system, a TES unit, an auxiliary energy supply, and solar collectors was created by Fouda et al. [87] The mathematical modeling of the equations regulating the conservation of mass and energy was successfully accomplished using iterative approaches and an engineering problem solver. The results showed that the proposed system can reduce operational expenses while increasing water production.

Chandrashekara and Yadav [88] conducted an experiment to evaluate the effectiveness of an exfoliated graphite (EG) solar coating applied to a solar energy receiver using a Scheffler dish and a solar high-speed dish (SHS). The findings demonstrated that by applying a coating of exfoliated graphite to the plate of the absorber, the system was able to improve its performance by as much as forty percent, maintain a thermal stability of 643.9 degrees Celsius over a rough surface, and absorb more than ninety-seven percent of the solar radiation that hit it. As a result, an increased rate of fresh water productivity of 1091 mL was kept, despite the application of EG coating. The processes of WDSs were investigated by Gude and Nirmalakhandan [89] under conditions of near-vacuum pressures that were passively induced by low-grade thermal energy. Using a low-grade waste heat source, a TES system that was maintained at 55 degrees Celsius was used to provide the energy for a low-temperature WDS. The heat that was lost from the condenser of the absorption refrigeration system was employed as a source of thermal energy to drive the system, and the integration of grid power and a solar collector system provided the energy that was needed for the generator. According to the findings, the loss of thermal energy via the refrigeration system, in conjunction with an additional input of 208 kJ/kg for the WDS, was appropriate to supply the required quantity of fresh water at a rate of 4.5 kg per hour. Liu et al. [90] investigated the economic and thermal performance of a WDS using solar collectors with a multi-effect at low temperatures. A mathematical and economic model was introduced, including the evacuated tube solar collector, multi-effect distillation, flash tank, storage tank, and electrical heating and cooling units. The influences of heating steam temperature and the number of multi-effect processes on the system performance were studied. The results revealed that increasing the temperature of heating steam decreased the evaporator area and cost of fresh water, while raising the volume of the storage tank, and the production of fresh water per unit area of the collector changed slightly. Moreover, increasing the number of effects slightly changed the storage tank volume, but it increased the evaporator area and the water productivity, and the cost of fresh water was decreased greatly.

5.1.3. Solar Still

SSs that are developed worldwide have different geometries having a great effect on the system productivity [91,92]. The production of potable distilled water can vary by the location and design of the SS. The main concern of SSs is to augment water production using different absorbing materials [93,94]. Furthermore, the performance of SSs was evaluated using an internal condenser [95]. The aforementioned concepts have also been studied, with consideration for the comprehensive analysis in a combination of passive and active SSs using LHS and SHS techniques and economic aspects [96].

Shoeibi et al. [97] designed a solar WDS for district heating as well as drinking water in domestic applications. Nano-enhanced phase-change material (NePCM) of copper oxide nanoparticles in paraffin wax with 0.2 wt% concentration was employed in an SS-WDS and absorber with a porous surface to conserve the available thermal energy and improve the system performance of the district heating. The results indicated that the hot water employed for district applications in a solar WDS based on NePCM and an absorber with a porous surface was 41.94% greater than that for the traditional WDSs. Moreover, CO_2 gas removal, according to the exergoenvironmental and environmental analysis in SSs employing NePCM and a porous surface of the absorber, was raised by 41.7 and 18.4%.

Voropoulos et al. [98] studied theoretically and experimentally the characteristics of an SS combined with a hot water storage tank via a solar collector. The model used the coefficients characterized for each specific solar WDS, while considering the operating and technical data. The model predicted the long-term output of an SS with 3% accuracy compared to the real data. In addition, the model was employed as a worthy tool for optimizing the system design, as well as for evaluating the existing installation of solar WDSs during the short-term tests.

Yousef and Hassan [99] assessed the performance of SS-WDSs incorporated with a TES unit of PCM according to the energy and exergy methodologies. Experiments were accomplished for an SS with and without PCM in the summer and winter months. The result indicated that the utilization of PCM with the SS augmented the exergy and annual energy savings by 3% and 10%, respectively. Ansari et al. [100] investigated a WDS based on a passive SS integrated with the ESS of PCM using a transient mathematical model. The results demonstrated that the choice of PCM considerably affected the maximum temperature of brackish water. Moreover, the ESS considerably enhanced both the fresh water productivity and the performance of the WDS. Furthermore, Kabeel and Abdelgaied [101] studied the production of potable water of an SS-WDS integrated with an ESS based on a PCM, as shown in Figure 9. The experimental results indicated that the productivity/day of fresh water by the SS with PCM was about 7.54 L/m^2, while the corresponding value was recorded as 4.51 L/m^2 for the traditional SS. Moreover, the estimated cost of one liter of potable water was 0.03 and 0.032 USD for an SS with PCM and traditional SS, respectively.

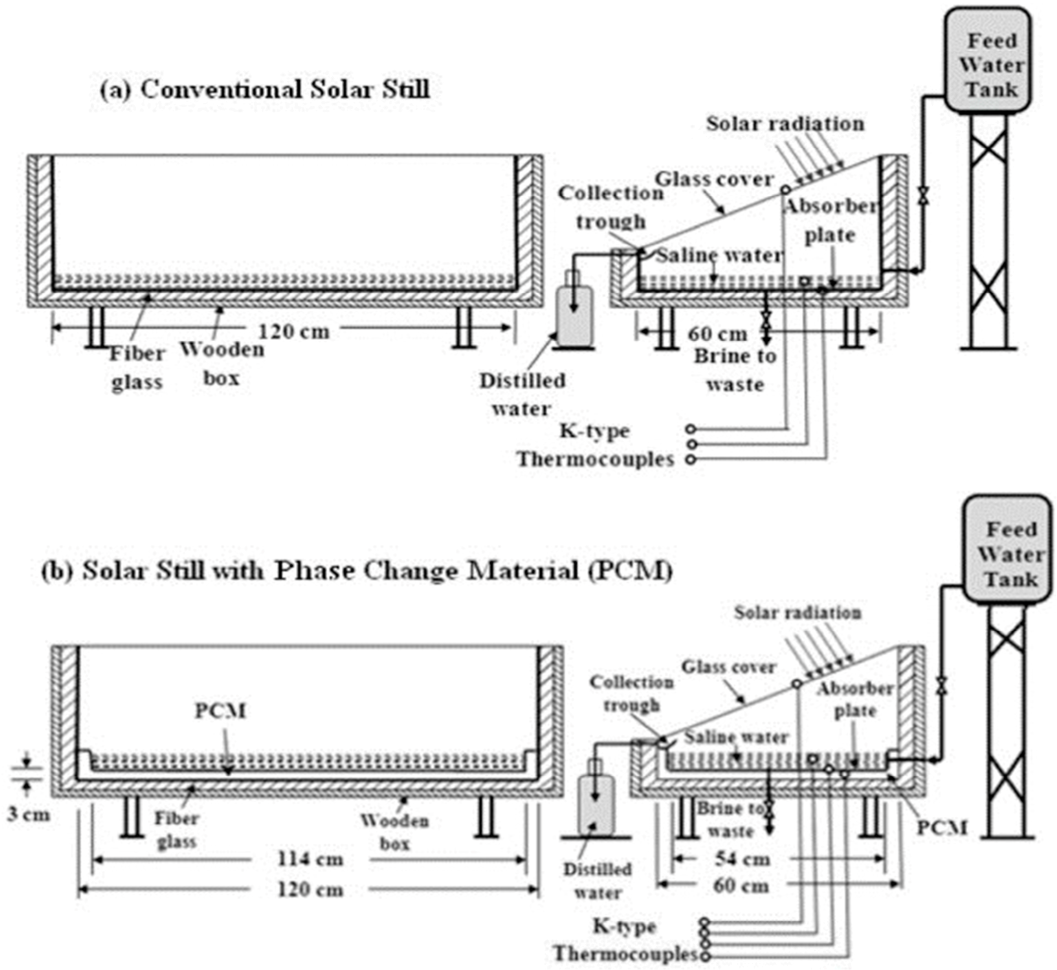


Figure 9. Solar still with and without PCM [101], reused with permission from Elsevier (license number 5491440494608).

5.2. Wind Energy Resources

The wind is created by the pressure differences of the atmosphere, induced by the available solar energy. Almost 1200 TW (0.7%) of the 173,000 TW representing the global solar energy that arrived on the earth is utilized to motivate the system's atmospheric pressure [102]. This energy conversion essentially takes place in the upper atmosphere layers at a 12 km height. By assuming that 1% of the generated kinetic energy is accessible in the lowest layer of the atmosphere, the universal wind potential energy is 10 TW, which is greater than the current demand for the world's electricity. One of the most fundamental times for wind energy synchronization with the work of the US in the research of wind energy and development was around the time of the 1973 oil crisis [103]. Then, between 1973 and 1986, the business market for wind turbines was promoted for domestic and agricultural uses, with a capacity of 1–25 kW, and for utility technologies, with a capacity of 50–600 kW [104]; the wind energy resources powering WDSs were reviewed [23].

The integration of storage technologies and wind power systems is an efficient choice to overcome the stability and reliability challenges of large-scale wind power generation systems [105]. Segurado et al. [106] optimized the size and operation strategy of a wind-powered WDS and hydro ESS via a multi-objective optimization method. The results indicated that the combination of RERs in WDS reached a decrease of 84%, with a 27% reduction in the consumed power and system productivity costs and a 67% mitigation in CO_2 emissions, in 2020.

Duić et al. [107] proposed a RenewIslands methodology for a wind-powered hydro system. The results indicated that using an ESS and water resource systems enhanced the merging of available RERs with WDSs and thus ensure supply security and decrease import dependence. Colmenar-Santos et al. [108] optimized the sizing of wind and solar renewable resources combined with electrochemical storage to feed an RO-WDS using the black box global stochastic techniques.

Lai et al. [109] optimized the size of an ESS based on a realistic power system to ensure a required energy supply for an RO-WDS. The ESS included batteries, hydrogen, supercapacitors, compressed air, pumped water, and flywheel, in different combinations. Additionally, a hybrid system in which wind resources were integrated with PV panels, diesel, and potential energy to avoid the fluctuation of RERs was proposed. Furthermore, Maleki et al. [110] designed and modeled a hybrid wind/PV/hydrogen/RO-WDS for enhancing the availability of fresh water and maintaining the load demand. The system configuration shown in Figure 10 was optimally determined using artificial bee swarm optimization, considering the life cycle cost and the losses of the power supply. The results demonstrated that the maximum power loss was 0–10%, and the PV/hydrogen/RO-WDS was the most effective system.

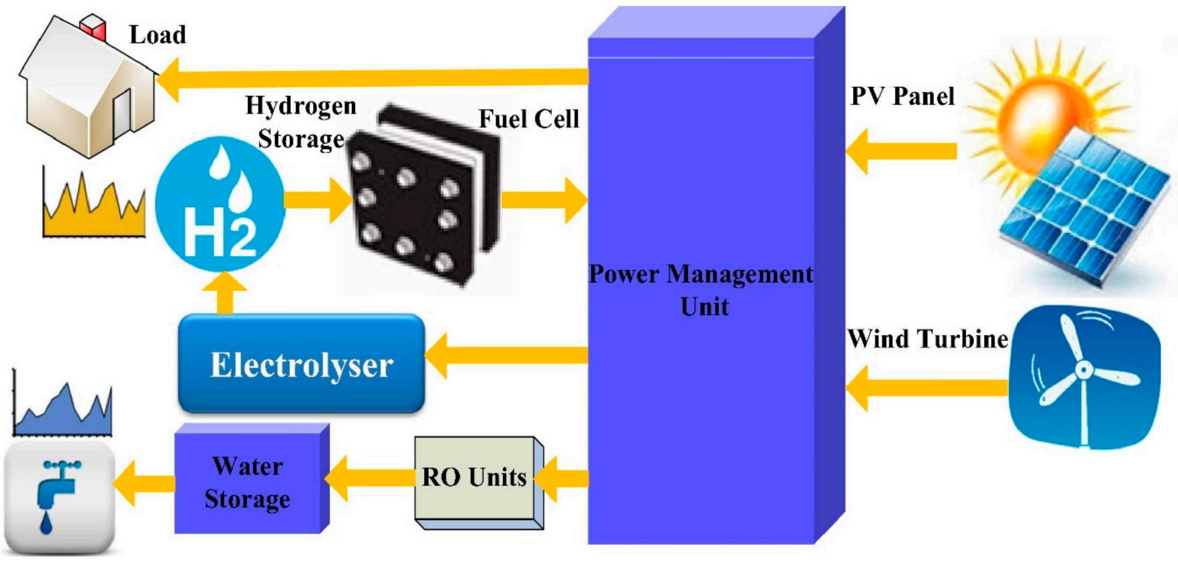


Figure 10. Schematic of examined hybrid renewable energy system [110], reused with permission from Elsevier (license number 5491441217120).

Guo et al. [111] managed the performance of a stand-alone microgrid, including generators of wind turbine and a diesel engine, an ESS, and a SWD. The energy management of a real-time rolling horizon was employed utilizing hourly wind speed. The maximizing employment of energy generator-based wind and minimizing the use of diesel generator according to the stability of the system operation were implemented. The introduced energy management was tested, and the results verified the effectiveness of the suggested hybrid system. Lilas et al. [112] evaluated the integration of compressed air and batteries together with RO-WDS employing offshore wind turbines and PV panel RERs to supply electricity and fresh water. The results indicated that the system of compressed air was more suitable than batteries to cooperate with the peaks of renewable energy production.

Cutajar et al. [113] suggested a hybrid system containing an offshore wind-powered RO-WDS with a hydropneumatic ESS to avoid pressure fluctuation and mitigate the mismatch of supply–demand. The results demonstrated that a 5 MW wind turbine combined with a 6.5 MWh pneumatic ESS ensured about 33,000 m^3 of fresh water per day from a medium-scaled RO unit. Kotb et al. [114] studied the feasibility of different hybrid standalone energy system alternatives and conducted an optimization methodology based on a multicriteria decision-making method. Energy storage technologies of a zinc–bromine battery and turbine-pumped hydro were integrated. The results revealed that the optimal system contained 112 batteries, five wind turbines with 20 kW, a 328 kW PV array, a 100 kW diesel generator, and a 235 kW converter.

5.3. Geothermal Energy Resources

Geothermal energy resources can be employed for diverse uses including cooling, snow melting, bathing, swimming, greenhouse heating, agricultural drying, space heating, heating of aquaculture ponds, geothermal heat pumps, industrial processes, and power generation [115]. The broad applications of geothermal energy resources were acknowledged, and they were approved for WD to produce fresh water [116]. There are a number of benefits accompanying the utilization of geothermal energy resources for desalination applications, as listed below [117–119]:

- Geothermal energy resources which have a high capacity factor, which is known as the source availability in terms of quality and quantity, provide a reliable and stable heat supply, maintaining the stability of thermal WDSs as well as RO-WDSs;
- The technology of geothermal production is mature, and it is uninfluenced by weather fluctuations and seasonal changes;
- Typical temperatures of the geothermal resources in most parts around the world are between 70 and 90 °C, which are typical for MED-WDSs at low temperatures;
- Geothermal WDSs are cost-effective for simultaneously producing power and desalinated water;
- Geothermal WDSs save fossil fuels, which can be utilized for other goals of enhancing environmental sustainability and national energy security;
- Geothermal energy resources have a relatively low land surface area per MW compared with the available RERs.

Sohani et al. [120] optimized the operating conditions of a multi-generation system driven by solar–geothermal resources (see Figure 11) to produce hydrogen, electricity, heat, and fresh water, along with energy storage, via a dynamic approach of a multi-objective optimization method. The yearly production of hydrogen, electricity, heat, and fresh water increased by 13.5, 14.4, 16.1, and 14.3%, respectively, whereas the exergy and energy efficiencies increased by 3 and 5.2%, respectively. Moreover, the system payback period was reduced from 5.56 to 4.43 years, with reducing in the storage pressure of hydrogen by 4.4%.

Li et al. [121] suggested a trigeneration system based on a transcritical CO_2 cycle for producing hydrogen, electric power, and fresh water powered by solar-geothermal RERs. Thermoelectric generators and HDH-WDSs utilized the waste heat from the transcritical CO_2 cycle. Thermoeconomic analysis and an objective optimization approach were implemented, and the system performance was assessed monthly with actual data. The results revealed that the hybrid system maintained the highest hydrogen, power, and desalinated water during May, of 1.989 kg/h, 1286 kW, and 13.38 m^3/day, respectively. For optimized conditions, the system accomplished a 23.35% energy thermal efficiency with a cost of 17.07 USD/GJ and an improvement in efficiency via increasing the share of solar energy.

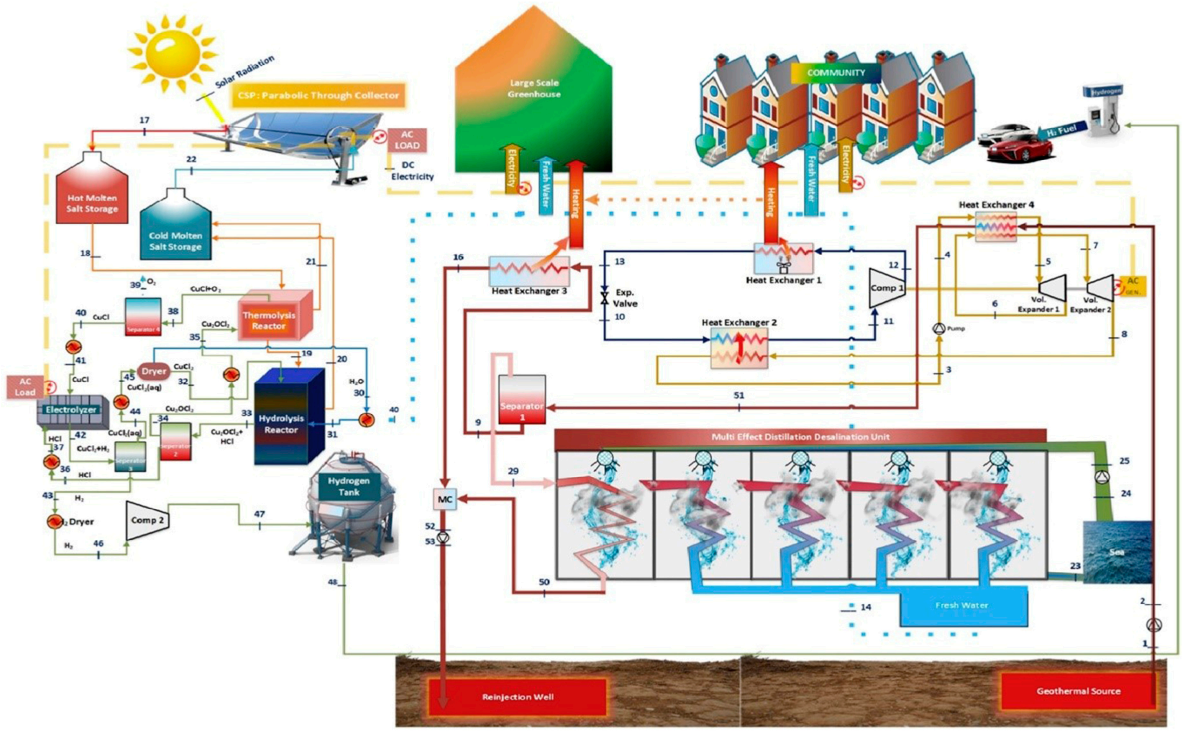


Figure 11. Schematic of hybrid system [120], reused with permission from Elsevier (license number 5491441455072).

Temiz and Dincer [122] implemented thermodynamically the integration of concentrated solar and geothermal to produce electricity, heating, hydrogen, and desalinated water. The system consisted of a copper–chlorine hydrogen unit, a geothermal unit, a trilateral ammonia Rankine plant, a MED-WDS, a parabolic trough collector with TES, and a residential heat pump. The obtained results demonstrated that the system generated 5.5 MWp geothermal, 12.97 MWt solar systems, and 296.9 tons of hydrogen with a cost of 2.84 USD/kg, and 47.6 GWh electricity with a cost of 0.03 USD/kWh. The payback period for the production of hydrogen was 6 years, and the overall investment of the proposed system possessed a 17% internal return rate as well as the levelized cost of electricity of 0.029 USD/kWh. Additionally, Gevez and Dincer [123] analyzed a hybrid system based on geothermal RER and a thermo-chemical cycle for the production of hydrogen and multistage subsystems of a WDS, examining the influences of the working and ambient conditions on the overall performance. The system was designed to produce 8277 kW of net electric energy, 47.887 kg/s of fresh water, and 7.25 kg/h of hydrogen. The results of the thermodynamic analysis concluded that the overall thermal and exergy efficiencies were 42.06% and 49.65%, respectively.

Ghorbani et al. [124] introduced a novel structure to integrate compressed air energy storage (CAES), a mechanical ESS with a multistage-PCM as TES. The power generated by the wind farm was shared among three compression trains with a pressure ratio based on the minimum energy consumption during the off-peak times. Additionally, the dissipated heat from each compression stage process was transmitted to PCMs to work under a low carbon footprint and consequently maintain the sustainability of the system. Mousavi et al. [125] designed and analyzed a compressed air energy storage system combined with organic rankin cycle (ORC) powered by solar and geothermal RERs, as illustrated in Figure 12. For the purpose of evaluating the effectiveness of the system, the energy, exergy, and exergoeconomic (3e) analyses were carried out. According to the findings, the solar collector unit that contributed 47% was the most reliable source for the highest rate of exergy destruction. The proposed system generated a power output of 1314 kWh and

0.3 kg/s of hot water, while maintaining overall efficiencies of 31.17 and 35.41% in terms of exergy and energy, respectively.

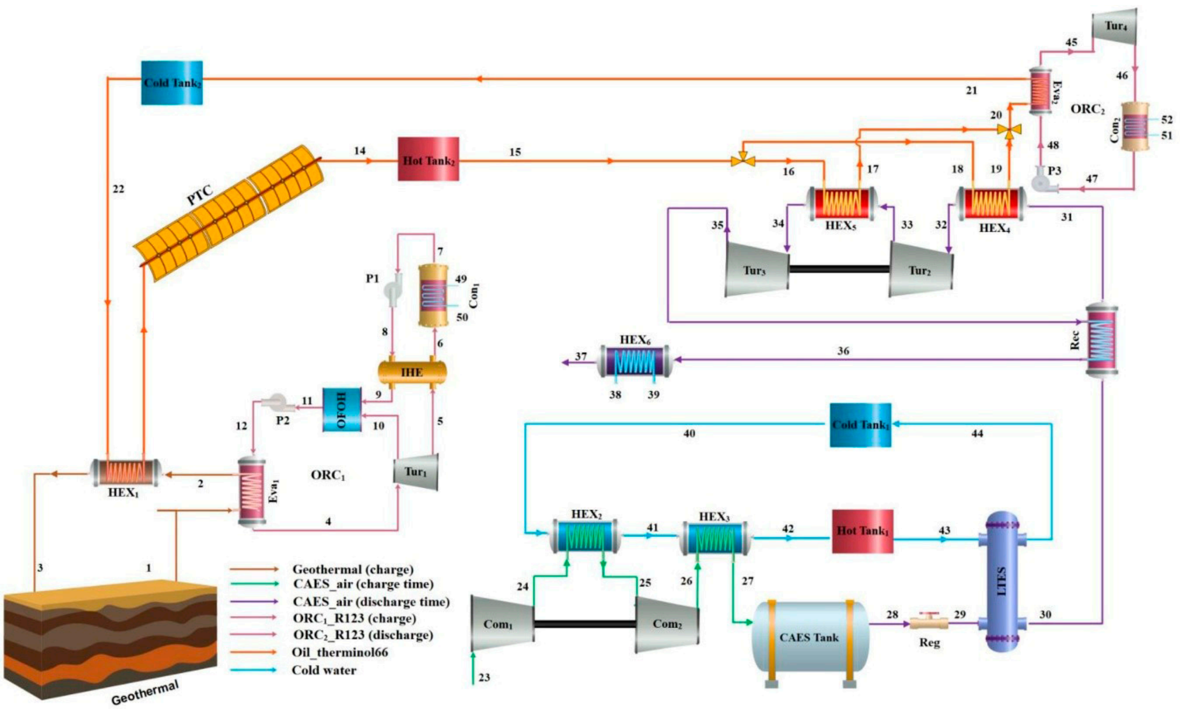


Figure 12. Schematic of the designed compressed air energy storage system [125], reused with permission from Elsevier (license number 5491450180668).

5.4. Tidal Energy Systems

Tidal energy, employing the tidal ocean currents, introduces a responsible RER with the great advantage of being predictable for the long term into the future and having significantly high energy density compared with solar and wind RERs [126]. Tidal-energy-based WDSs have become a new approach to water desalination [127]. Ocean renewable energy has powered WD since the 20th century, as reported by Crerar and Pritchard [128], Crerar et al. [129], and Hicks et al. [130]. However, these systems have been barely studied in comparison to water desalination technologies powered by solar or wind renewable energies, and the review of these pilot systems was proposed by García-Rodríguez [131]. Moreover, Bundschuh et al. [132] conducted a recent excellent review that mainly focused on the wave and tidal current energies used in WDSs. Direct coupling of the wave to the tidal turbine by a horizontal axis and a pump of a seawater RO-WDS was accomplished [133].

Delgado-Torres and García-Rodríguez [134] innovated a seawater RO-WDS driven by combined PV/tidal RERs. A tidal-range plant of a single mode with a 25.0 MW tidal turbine was combined with a WDS with a nominal daily capacity of 100.000 m^3, considering the energy consumed of 3.5 kWh/m^3. The investment cost per cubic meter of supplied fresh water was 0.67 USD/m^3. In addition, Khanjanpour and Javadi [135] employed horizontal axis tidal turbines to power an RO-WDS combined with a water storage system, as shown in Figure 13. The Taguchi method was employed to perform a numerical optimization of the impacts of the blade number, size of blades, shape of the hub, and radius. According to the findings, the parameters that had the greatest impact on the power output of horizontal-axis tidal turbines were, in order of importance, the size and number of blades, the radius of the hub, and the shape of the hub. At a tip speed ratio of five, the power coefficient of the optimized turbine was 0.44, which was 10% greater than that of the baseline model with 0.40, and the weight for the optimized model was 17% lower than the weight of the conventional model.

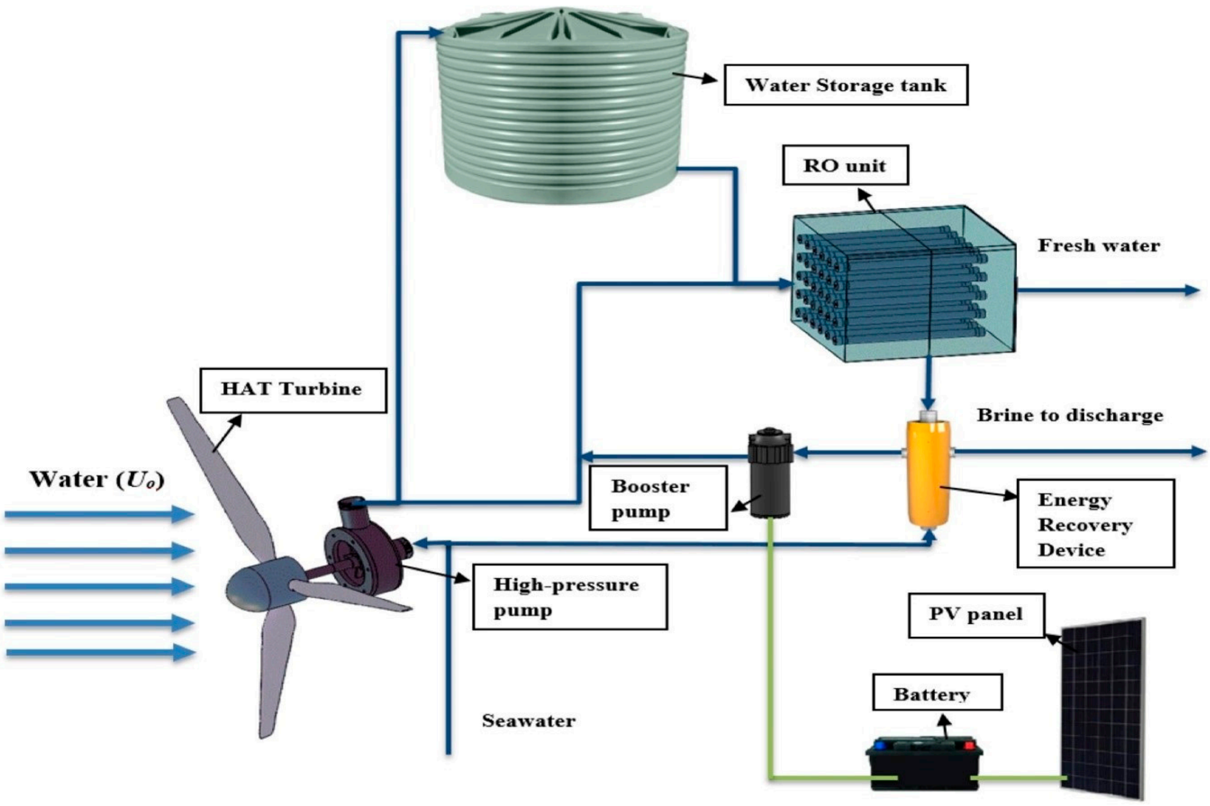


Figure 13. Hybrid tidal/PV-WDS powered by horizontal axis tidal turbines [135], reused with permission from Elsevier (license number 5491450395991).

Delgado-Torres and García-Rodríguez [136] introduced seawater RO plants based on hybrid RERs of tidal/PV systems to promote WDSs with large capacities, as shown in Figure 14. Based on the annual simulations, a sensitivity analysis was conducted on the main parameters that affected the performance of WDS based on hybrid solar/tidal RERs for the WDS. This analysis was carried out using the WDS. The total investment cost per unit of water production, the consumed energy as a percentage of the overall energy production, and the energy that the WDS did not make use of were all evaluated. According to the findings, the off-grid RO-WDSs that were powered by hybrid tidal/PV systems were able to achieve an actual water production that was equal to one-half of the nominal production when the appropriate design parameters were selected. The recommended size of the energy generator to minimize the system's overall capital costs was equivalent to 25–27 MWp of photovoltaic power and 20 MW of tidal power for every 12 MW of total consumption by the system. Additionally, 14.1 $\times$ 10^6 m^3 per year of fresh distilled water was supplied with an energy consumption of 3.5 kWh per cubic meter and was powered by 2.0 MW of tidal energy and 26.9 MWp of photovoltaic power.

Delgado-Torres et al. [137] innovated an RO water desalination system integrating a tidal range and PV RERs with a battery storage system. The result revealed that for the installed PV generator, using a tidal plant increased the operation time with a nominal capacity of 1.8 and 2.8 times compared with the WDS system driven only by PV. In addition, the recommended design for an off-grid WDS, with a minimum capacity of the battery, powered by RERs, produced a capacity of fresh water of 55 $\times$ 10^3 m^3 per day for each 10 MW hydraulic turbine.

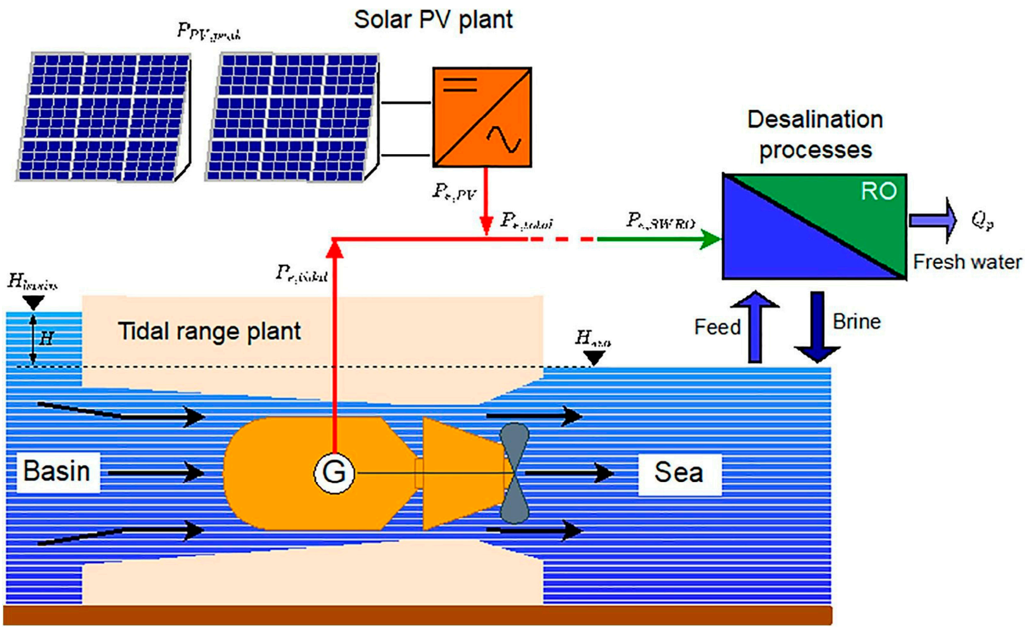


Figure 14. Hybrid tidal/ PV-WDS [136], open access article distributed under the terms of the Creative Commons CC-BY license.

5.5. Hybridization Energy Resources

In particular, the combination of various resources of renewable energy is promising to maintain stable production of energy to produce the required amount of fresh water [138]. In fact, compared with the WDSs powered by RERs, hybrid applications exhibit high flexibility of fresh water capacities, simple system design, and easy management. The inputs of the hybrid systems are any RER, hybrid renewable energy, or hybrid renewable–fossil fuel resource; on the other hand, the outputs are hydrogen, biofuels, electricity, potable fresh water, heating, cooling, etc., [139–141]. The multiple utilities of hybridization WDSs make for low levelized costs of electricity and a low environmental impact.

Focusing on specific hybridization of RERs is a promising solution to mitigate the fluctuations, particularly by employing separate RERs for WDSs. In fact, solar energy is essentially accessible through the diurnal hours; conversely, the wind velocity increases during the night hours. Moreover, integrating solar and wind RERs enhances the stability of power production for WDSs and minimizes the size of the energy storage system. Furthermore, in addition to solar and wind RERs, there are some innovative sophisticated techniques that can be utilized in hybrid systems [142]. WDSs are especially attractive to be integrated into polygeneration systems [143], particularly when combined with RERs [144]. Supplying cooling or heating, potable water, and electrical energy required for a residential building without consuming the national grid power was proposed [145].

Campione et al. [146] analyzed the behavior of a single-pass ED process for WDS-based hybrid wind/PV RERs using dynamic simulations for time scales of both day and year. Quasi-steady-state models were employed to evaluate the annual operation of four ED units that maintain highly flexible, fast, and controlled process dynamics of the ED system; this was provided by coupling with high non-constant power resources. In addition, the ED process was successfully operated in battery-less hybrid systems for WD, also working as an energy buffer device. In addition, the proposed system produced daily fresh water up to several thousand cubic meters for large-scale plants.

Khan and Martin [147] assessed and optimized a polygeneration unit powered via PV panels and a waste-fed digester of animal and agriculture waste integrated with a gas engine. The excess digester gas was utilized for lighting and cooking, while the waste heat operated the membrane WDS. The result revealed that the system payback period was 3–4 years. Moreover, Maleki [148] designed and modeled different grid-independent hybrid RERs for WDSs such as hydrogen/RO, namely solar/battery, wind/battery, and solar/wind/ battery, as illustrated in Figure 15. The results demonstrated that the system with the battery ESS was more cost-efficient than that based on the hydrogen ESS, and in the near future, the system-based hydrogen ESS will be the most reliable and cost-effective for fulfilling energy demands.

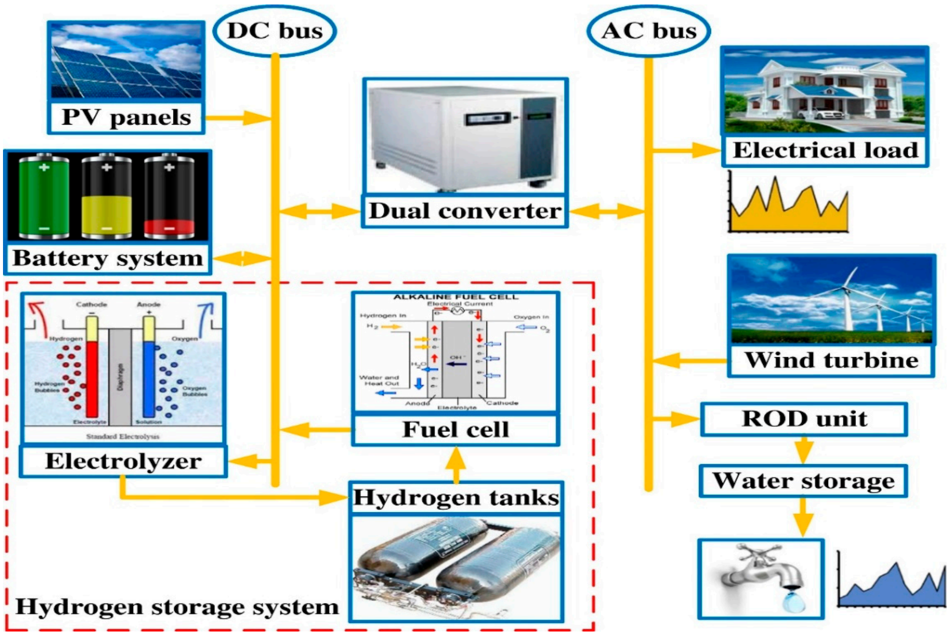


Figure 15. Illustration of six hybrid renewable energy systems [148], reused with permission from Elsevier (license number 5491450782466).

Spyrou and Anagnostopoulos [149] optimized the operation and design of a hybrid WDS to fulfill the fresh water demand in remote coastal areas. The system was integrated from wind, a solar-powered RO-WDS, and a pumped storage unit. The plant's weekly performance during winter and summer is presented in Figure 16. Additionally, Caldera et al. [150] introduced hybrid PV/wind RERs with a battery for optimal capacity of the installed WDS, resulting in producing water at a competitive cost compared with that of RO-WDSs powered by fossil fuel. The reduction in levelized cost of water (LCOW) was 10% on average, obtained by the power-to-gas (PtG) capacities. The required capacities of PV, wind, and battery were decreased by 24%, 14%, and 33%, respectively. The global cost estimation of fresh water production by 2030 using renewable electricity generation for the optimum local system configuration was estimated. The capacity of RO-WDSs desired to produce the global water demand by 2030 was approximately 2374 million m^3 per day.

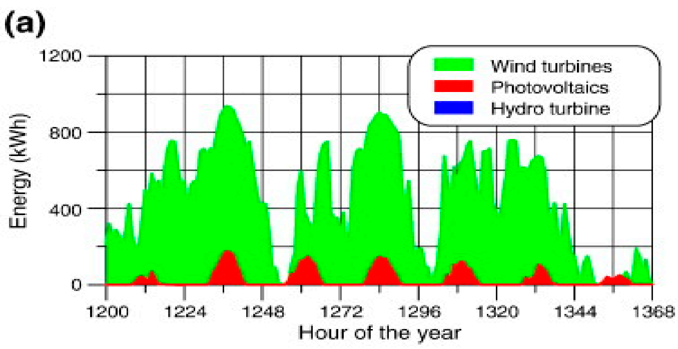


Figure 16. *Cont.*

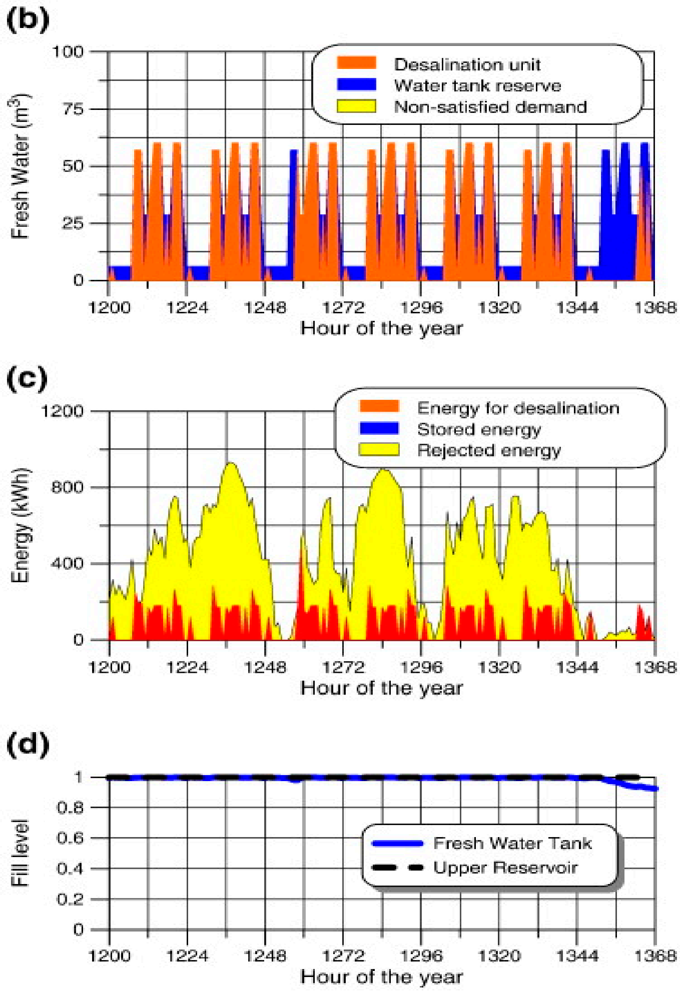


Figure 16. Plant weekly performance during a winter: (**a**) energy production, (**b**) water needs satisfaction, (**c**) energy consumption, (**d**) tank and reservoir contentand summer [149], reused with permission from Elsevier (license number 5491451072350).

Novosel et al. [151] analyzed an integration of a WDS based on RERs with a pump ESS that utilized the brine produced in Jordan utilizing the EnergyPLAN. The suggested system generated an additional annual 95 m^3 of fresh water per capita. In addition, the combination of water and energy systems introduced a benefit regarding the fresh water supply, energy security, and environment. Additionally, Abbasi et al. [152] proposed an innovative solar system to supply power, cooling, and fresh water. Exergoeconomic analysis according to the dynamic modeling of PCM to capture the system performance during a day was performed. The proposed system was composed of Heliostat solar recovers, a gas turbine, Kalina cycle, TES system, liquefied natural gas (LNG), and an RO-WD unit, as shown in Figure 17. Moreover, the cooling capacity was provided by the LNG stream for domestic applications, while the RO-WD unit produced fresh desalinated water. The exergoeconomic model indicated that the electricity levelized cost and total system cost rate were 0.1275 USD/kWh, and 25.20 USD/GJ, respectively.

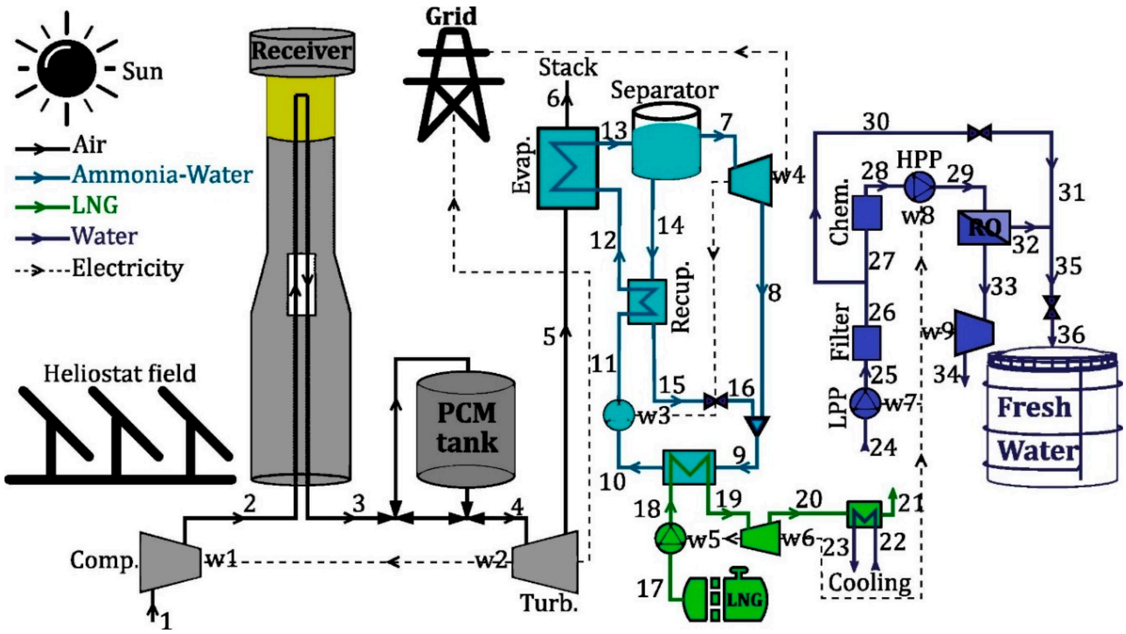


Figure 17. Schematic of the proposed integrated system [152], reused with permission from Elsevier (license number 5491451264329).

6. Barriers and Challenges

Research and development has shown that WDSs powered by RERs integrated with ESSs are the most convenient choice for decentralized WD in rural zones. Today, abundant plants on a small scale are operating sufficiently, while the technical as well as non-technical barriers of commercial WD plants are effectively overcome. Extensive utilization of RER-powered WDSs has been obstructed by cost and intermittency issues [153]. Nevertheless, this challenge may be avoided with the different applications of thermal energy storage. For understanding the reality of existing systems, limitations and strengths are essential parameters for designing new energy WDSs. The primary barrier for these applications is the water production cost that can be lessened via a number of procedures, such as the following:

- Increasing the awareness of design, installation, operation, and maintenance through intensive training via international activities;
- Appropriate investment motivation to widen the market for renewable energy devices by lowering the prices of system components;
- Implementations of RERs for WDSs are still not steady in view of the remarkable yearly and daily variations of the available energy;
- Using WDSs combining ESS based on PCM with low phase-change temperature for weather conditions of low incident solar intensity is not effective;
- Planning, selecting, sizing, and optimizing the energy resources for WDSs in combination with energy storage depend on various parameters, including the site location that is changed from one application to another;
- PVs are still a non-competitive choice for installing hybrid WDSs. However, PV patterns match the needs of daily water consumption well, and these units are predicted to become the fundamental component of hybrid WDSs in the forthcoming period with reductions in their investment costs;
- The development of WD technologies powered by the tidal energy resource is at its beginning, and further investigations are required prior to obtaining fully operational systems. Additionally, designing and optimizing the geometry of tidal turbines hybridized with different energy resources should be implemented;

- Considerable investigations should be dedicated to the system control and potentials of RERs for WDSs; however, it should be beneficial to more profoundly to study the RER-powered WDSs utilizing exergoeconomic analysis;
- Further implementation is required for composite fiber membranes that can be physically deformed at high pressure for PRO with appropriate energy storage systems, considering the feasibility aspects.

7. Encouraging Policies for Future Work

A massive number of research studies have been conducted in depth in this critical domain, so there are still further facts and concerns that have been implemented. The below encouraging points can be considered for future work, with more development and dedicated research to enhance the overall performance of energy storage for WDSs based on RERs.

Conventional WDSs powered by RERs satisfy the requirements of mankind, hence the establishment of innovative TES materials with pronounced thermophysical properties can be a breakthrough in this field. Design alternative fabrication to introduce a large surface area of heat absorption can augment the effectiveness of WDSs based on RERs. Using quantum dot materials such as metal composite materials with PCMs or semiconducting nanoparticles can enhance thermal efficiency. Using of hybrid RERs to drive WD units with ESSs is a promising choice to sustain the production of potable water. Otherwise, the water desalination units based on RERs operate at variable capacities. Moreover, the potential of waste heat in different industries is economical to utilize to cover a portion of the growing water demand at an acceptable cost. However, in each case of combination with ESSs, detailed economically feasible analyses should be conducted.

Composite phase-change materials such as epoxy resin with a paraffin wax are introduced with a great benefit over pure PCM, considering the quantity of energy storage and its release. Additionally, these materials enhance the charging/discharging rates along with the PCM durability. In addition, microencapsulation PCM is presented, with great attention to the various heat storage materials. The essential advantage associated with it is the increase in the surface area for exchange heat. Furthermore, embedding different PCMs with another sophisticated material such as plasmonic material can improve the whole structure to store the available renewable energy.

Renewable energy inputs are essentially intermittent, and integration of convenient storage systems may need further research in the futue. Integrating new methodologies of energy storage to the WDSs powered by RERs with new inventions will continue, in search of faster development of these systems. Future research on hybrid WDSs may be required in innovating prototypes based on the optimum theoretical performance and economic assessment. With variable input/output parameters for the hybrid WDSs, smart monitoring and control are crucial for the effective performance of hybrid systems. Performance assessment criteria of hybrid systems may be diverse, depending on assessment objectives or the weighting of several objectives. Additionally, it is preferred to design and construct an SS-WDS based on a PCM TSS that sustains a prolonged operating lifetime, leading to further savings in energy and mitigation of CO_2.

Integrating utility outputs in various methodologies is the fundamental motivation for developing hybrid systems, and this will sustain the prospective advancement of innovative integration, fulfilling the availability of RERs and utility requirements. In addition, to ensure the sustainability of hybrid systems, which have multiple inputs and outputs, thermodynamic and economic optimization is necessary. The economics of WDSs based on renewable energy integrated with ESSs should be investigated for different geographical locations, economic components, material costs, etc. Furthermore, conducting advanced exergy analyses according to the theoretical work to assess the system's irreversibility for each component should be studied. Moreover, employing advanced energy, environmental, and economic methodologies can introduce conceptual insights into the thermodynamic efficiency of each system component and the overall system cost and environmental aspects of RERs.

The development of contemporary systems of renewable energy integrated with WD and ESSs in terms of operating time may be affected by the gradual upscaling of components, the rationale for higher land utilization, existence of economies of scale, operation and maintenance requirements, and development programs. Among the major trends influencing the global market for RERs over the years, one may note that the thermal efficiency enhancement and the reduction in specific cost per kW for the long term for installed WDSs with ESSs should be investigated. In this context, the importance of utilizing the considerable growth of RERs in WDSs should be reflected in various support mechanisms such as feed-in-tariffs, commercial projects, investment tax credits, competitive tenders, etc.

Also, there are some challenges for WD technology such as elevating the utilization of green and clean technology for the manufacturing cells of solar PV based on nanotechnologies such as gallium arsenide, silicon, gallium phosphide, and quantum dots as the third generation of nanostructures, and graphene and carbon nanotubes as the fourth generation for the manufacturing of PV panels on a large scale. In addition, concentrated photovoltaic (CPV) systems should be analyzed instead of conventional PV panels; however, this solution also requires effective cooling systems. Furthermore, WDSs powered by wind RERs that are not integrated into the national grid are micro-grids and commonly have been installed on small-scale WDSs.

The utilization of geothermal WD systems has been chosen for decentralized regions with small-scale applications. However, commercial WD application has been decelerated by the high investment costs and technical problems. The environmental and economic impacts of the WD applications should be evaluated, considering the site-specific data to avoid failure in the future. Additionally, great challenges for the efficient utilization of wind RERs include the amalgamation of ESSs on a large scale. In addition, it is of critical importance to further study the hybrid of wind energy and HDH units based on ESSs, considering the optimization of design and operating parameters, as well as the cost evaluation. Furthermore, it is recommended to develop simple models to evaluate the performance of RER-powered WD systems based on EESs. Intelligent innovative techniques such as artificial neural networks may be an appropriate solution for studying these systems given their the ability for modeling sophisticated hybrid WD systems.

8. Discussion

The International Atomic Energy Agency (IAEA) claimed that 1.1 billion people cannot acquire safe and pure drinking water, and globally, more five million die annually due to water diseases, and the provision is not adequate for the near future. Moreover, by 2025, more than 2.7 billion people will confront water shortages, and the population growth will achieve the forecasted trend. Depletion of available fossil fuels as well as climate change force people to employ sustainable RERs with high efficiency and optimum energy utilization. Integrating ESSs with WD powered by intermittent RERs is an efficient solution, matching the available energy resource with multiple inputs and outputs. Salinity gradient energy is a promising and valuable technique for the utilization of RERs and ESSs for WDS. However, more research is required to effectively investigate WDSs powered by RERs with large-scale applications.

WDSs powered by geothermal RERs has a number of advantages in the areas having available adequate geothermal resources, which are proven by the different economic feasibility analyses for each case. Moreover, there is essentially no limit to the scale of WDSs powered by geothermal RERs, which have a good efficient capacity, and the low cost and enthalpy of geothermal RERs can be broadly employed for various conventional WD technologies based on thermal energy.

WD has confirmed its potential to find a practical solution to the supply of fresh water in numerous countries around the world. Considering the fact that remote areas have no connection to national grids and are exposed to scarcity of potable water, yet feature high solar irradiation, proper and deep consideration needs to be invested in the opportunities for integrating available solar energy with WDPs.

In addition, WD is a high-power-consuming technology, so its coupling with RERs is a fundamental stage for the sustainable production of fresh water in large-scale applications. Using solar renewable energy instead of traditional energy resources in WDSs to supply fresh water has a number of advantages, i.e., avoiding water scarcity, operation flexibility, dependence on sustainable energy resources, reducing environmental pollution, and decreasing the operating and maintenance costs. Tidal energies based on the ocean tidal currents introduce a reliable RER with the benefit of being available for a number of future years and considerably higher in energy density compared with solar and wind RERs, albeit discontinuous on a daily or a twice-daily scale.

Recent technologies have been introduced to directly/indirectly integrate wind energy into the WD process such as RO, SS, MVC, and ED. However, RO is the major WD process connected to wind power, and MVC is the major WDP integrated with solar energy. However, due to the high operating temperatures, additional thermal energy is always necessary. Moreover, the recovery of energy from waste heat resources for the production of fresh water is one of the critical issues for industries; however, some of these investigations have not been published.

9. Conclusions

This review article presents the global experience of using RERs in conjunction with energy storage systems to operate various WDSs effectively and economically. The cost of WD depends essentially on different parameters, including the configuration of the WDP, energy resources, local capital, and operation and maintenance costs. Thermal methods of WD may be coupled with industrial applications on a large scale, integrate with electric heaters in small-scale systems based on fossil fuel waste heat or RERs. Large-scale water desalination plants based on industrial applications with relatively high water productivity include MSF, MED, and RO. Significant theoretical and experimental experience, as well as rapid advancements in the use of RERs, demonstrate that renewable and hybridization technologies can be effectively integrated with various WD techniques. However, there is still a necessity to optimize the techno-economic aspects of these systems to sustain long-term effective systems. ESSs can enhance the stability of these fresh water production systems. Here is a summary of the potential RER-ESS combination for WDSs.

WDSs that use RERs are still far from reaching their full potential. However, it should be noted that, despite the feasibility and dependability of WDPs, the issue of high energy consumption should be addressed. As a result, advanced technology will continue to augment these systems, which will benefit the expanding market for renewable energy systems. With a large gap in energy demand during peak and off-peak times, the advantage of an energy store is expected to be significant. For various WD applications, large energy quantities for significant periods of time, ranging from several hours to days, are required to fulfill the time-shifting function.

At the moment, small-scale WDSs based on RERs are convenient for remote regions with high solar irradiation but no access to the electric grid. Large-scale applications of WD integrated with ESSs, on the other hand, are still hampered by a number of non-technical barriers, such as economic perspectives of high investment costs. Several research directions on hybrid WDSs powered by RERs integrated with energy storage take the system modeling, performance evaluation, economic feasibility, and optimization into account. Wind-powered RO-WD plants seem to be among the most encouraging alternative RER systems, followed by solar-powered MED, PV-powered ED, solar-powered MSF, and wind-powered MVC. Wind turbines can also be utilized to produce the necessary electrical energy for WD in an efficient and environmentally friendly manner. Furthermore, using hybrid systems integrated with wind turbines improves system reliability and avoids the critical issues associated with wind energy's intermittent nature. The basic procedures involved in utilizing the geothermal source for WD applications are the recognition of the geothermal reservoir, estimation of the reservoir volume, type, temperature, pressure, flow, and chemical characteristics, and assessment of future availability of the geothermal reservoir. Geothermal resources are more convenient for WD applications when the other RERs have high challenges.

WDSs powered by PV panels can now be predicted to be highly competitive with traditional systems as a result of progressively lowered operating and investment costs, with rises in the system lifetime. As a result, this segment of RERs has grown in popularity. In contrast, the energy nature of PV panels is affected by climatic conditions such as soiling, fouling of PV panels, dust accumulation, and rising operating temperatures in regions with high solar intensity.

The current operation and control of WDSs based on RERs in conjunction with energy storage are focused on mitigating daily schemes of fluctuating renewable energy. To assess the best operating strategy for single or hybrid energy resources for WDSs, various factors such as technical constraints, forecast errors, topographical conditions, market rules, and national energy prices are considered.

Environmental factors such as ambient air temperature, humidity, solar insolation, and so on are critical in the design and sizing of RER-powered WDSs integrated with ESSs. Increasing the capacity of WDS technologies requires sophistication in order to introduce appropriate solutions to the supply/demand mismatch of energy and to enhance the feasibility of WDSs powered by RERs. Finally, significant research efforts must be dedicated to investigating innovative energy storage technologies in the area of WDSs in order to maintain low cost, high capacity, and low environment impacts.

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Nomenclature

CAES	compressed air energy storage
CSC	concentrated solar collectors
ED	electrodialysis
ESS	energy storage system
FC	fuel cell
GOR	gained output ratio
HDH	Humidification–dehumidification
LCOW	levelized cost of water
LHS	latent heat storage
LNG	liquefied natural gas
MED	multi-effect distillation
MSF	multi-stage flash
MVC	mechanical vapor compression
NePCM	nano-enhanced phase-change material
ORC	organic Rankin cycle
PCM	phase-change material
PV	photovoltaic
RER	renewable energy resource
RO	reverse osmosis

PRO	pressure retarded osmosis
SDGs	sustainable development goals
SHS	sensible heat storage
SHS	solar high-speed
SS	solar stills
TES	thermal energy storage
TVC	thermal vapor compression
VC	vapor compression
WD	water desalination
WDP	water desalination process
WHO	World Health Organization

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