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Review

Integration of Wind Energy and Desalination Systems: A Review Study

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Abstract: Desalination is a well-established technology used all over the world to mitigate freshwater scarcity. Wind-powered reverse osmosis plants are one of the most promising alternatives for renewable energy desalination, particularly for coastal areas and islands. Wind energy can satisfy the high energy consumption of desalination while reducing costs and CO_2 emissions. However, the mismatch between the intermittent availability of the wind resource and the desalination's power demand makes the integration between the two technologies critical. This paper presents a review of wind-powered desalination systems, focusing on the existing topologies and technological advances. An overview of the advantages and disadvantages are analysed based on the theoretical and experimental cases available in the scientific literature. The goal of this work is to show the current status of wind-powered desalination and to present the technical challenges that need to be overcome in order to ensure a sustainable freshwater source.

Keywords: wind energy; wind-driven desalination; wind energy integration; renewable energy desalination; sustainable technologies

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1. Introduction

1.1. Wind Energy as a Viable Option for Desalination

The lack of sufficient freshwater resources is already affecting one fourth of the global population [1]. The increasing demand, the progressing depletion and the uneven distribution of global freshwater resources have promoted seawater desalination processes as a potential freshwater supply. Seawater is free, abundant and represents 97% of Earth's water resources, and the progress and development of desalination technologies have made it a feasible and promising solution to the freshwater scarcity problem. Currently, more than 95 million m^3 of water are desalinated per day; of these, 60.8% is obtained from seawater as feed, 20.7% from brackish water and the remaining from groundwater and rivers [2].

Even though the installed desalination capacity has doubled in the last 10 years and continues to grow, it covers only 1% of the global freshwater supply [3]. Hindering the spread of desalination processes is their high energy consumption, affecting both their cost and the impact on the environment. With an average consumption of 75.2 TWh per year, conventionally powered desalination through fossil fuels is responsible for yearly emissions of 76 Mton of CO_2 [3]; thus, the shift to renewable-energy-powered desalination could decrease, at the same time, desalination costs and CO_2 emissions.

As a renewable energy source, wind energy has already proven to be a mature and reliable technology. Due to the development of larger and more efficient wind turbines among other factors, wind power production is continuously increasing in both onshore and offshore applications. In 2017, wind power accounted for 18% (1134 TWh) of the world's electricity production from renewable energy sources, and for 30% of European production [4].

Both the installed wind capacity and its energy production are currently enlarging by 9.50% and 18.8%, respectively [5]. It is foreseen that, by 2024, the combined installed capacity of wind and solar photovoltaic (PV) will surpass natural gas and coal [6] However, the fast growing rate of wind power installed capacity comes with important challenges, including integration into the electrical grid. Many conventional grid power networks are not well suited for the high intermittency due to the variable renewable power generation. Therefore, the high penetration of wind power requires an augmentation of grid flexibility.

Directly utilising wind power for desalination would partially alleviate the power grid flexibility, while contributing to solve the water scarcity problems. Furthermore, the use of wind energy could reduce the desalination environmental impact up to 75% in comparison with fossil fuel alternatives [7]. In fact, wind power is already the second-most frequent renewable energy source choice for driving desalination plants, following solar PV [8].

The global distribution of wind resources, especially in coastal areas where seawater is also available, and the wide range of sizes at which it can be harvested, makes wind power a suitable choice for a variety of applications, from small stand alone systems in remote locations, to multi-megawatt wind farms both onshore and offshore. In addition, wind energy consumes the least amount of water during its life cycle when compared to other energy sources and emits the least amount of gCO_2 per kWh of energy generated [9]. In 2012, 387 billion litres of water were saved due to wind energy [10]. Therefore, wind-driven desalination is a promising combination for sustainable and long-term freshwater production.

1.2. Wind Driven Desalination

Several renewable energy technologies, including wind energy, have been applied to water desalination and have been extensively described and compared in the scientific literature, see for example [9,11–17]. From these works, it is clear that wind and solar PV-driven membrane processes are the most mature and disseminated technologies, even though the effectiveness of the integration strongly depends on the site location, on the resource availability and on the energy cost.

A separate review of wind-driven desalination systems for both seawater and brackish water was presented in [8,18–20]. These studies investigated the feasibility of wind-driven desalination considering an economic analysis as well as the technical aspects with the underlying coupling problems. The identified areas of improvement concern the reliability and efficiency of the systems. In particular, they underlined the need for better handling of wind intermittency. This could be achieved by improving the energy utilization through the customized design of desalination equipment to be used in combination with wind energy.

Wind-powered reverse osmosis (RO) is the most popular wind-driven desalination combination. The existing literature focusing on this configuration [21–23] shows that the design and rating aspects, related to the plant capacity and wind resource availability, have a substantial impact on the fresh water cost.

In addition, the large interest in renewable-energy-powered desalination has led to the development of new methods and products aimed at improving the efficiency and decreasing the costs. Integrated commercial solutions have also been developed for onshore wind applications, such as a direct-drive wind turbine powering a variable capacity desalination unit [24,25]. A compilation and description of patents related to desalination by renewable energy can be found in [26].

1.3. Scope and Structure of This Review

Despite the intensive research and development, one of the main issues of the integration between wind energy and desalination remains in the operational matching of the two technologies. In other words, how to adapt the variability and intermittency of wind energy to the power demand required by the desalination systems, from the large temporal scales associated with yearly variations, to the smaller time scales in the order of seconds due to turbulent fluctuations in the wind resource.

In this regard, the coupling between the two technologies and the presence of back up or intermediate buffers acquires great relevance. This review aims to give the reader an overview of the existing developments, interactions and synergies between wind energy technologies and desalination systems.

This paper is structured in the following manner: in Section 2, a brief introduction on the main desalination methods suitable for integration with wind energy is presented. Section 3 presents examples of wind-driven desalination systems connected to the electrical grid. Currently, the connection between the wind turbine and the desalination plant is mediated by an electrical power conversion. Then, stand alone systems with a backup, such as as diesel generators and energy storage, and systems without a backup are discussed in Sections 4 and 5, respectively. Finally, Section 6 presents alternative solutions where the intermediate electrical conversion is eliminated by using, for example, fluid power technology.

2. Desalination Technologies and Selection Criteria for Wind Energy Applications

The selection criteria for desalination technologies to be integrated with wind energy are presented in this section, followed by a brief description of their working principle; a more complete overview is provided in [2,14,15,27,28].

When integrating renewable energy with desalination, several aspects need to be considered for the selection of the most suitable desalination technology [12,13]. The following aspects will have a direct impact on the levelised cost of (fresh) water produced:

- The water demand or desalination plant required capacity.
- The feed water quality available at the location. Some desalination technologies are more suitable for higher concentration feed waters than others. Pre-treatment requirements also vary depending on the desalination process.
- The renewable energy resources at the location.
- The availability and feasibility for connection to the electrical grid.
- The specific technical requirements that are needed to ensure a proper matching of the operational conditions between the desalination plant and the renewable energy technology.

Regarding the last point, the most suitable combination varies depending on the selected renewable energy. In particular, wind energy can power desalination plants directly or indirectly through three types of energy media: electricity, thermal energy and mechanical energy, including potential and/or kinetic energy [19]. However, desalination processes that require electricity or mechanical energy are more suitable for use in combination with wind turbines.

In Figure 1, an overview of the desalination technologies considering the type of input energy required is presented. A summary of the relevant operating parameters for each desalination technique is given in Table 1.

Table 1. Summary of desalination techniques [2,28].

Desal. Tech.	Energy Source	Capacity Range [m^3/Day]	Temp. Range [°C]	Recovery Rate [%]	Feed Concentration [ppm]
MED	Thermal	2000–20,000	90–120	30–50	20,000–100,000
MSF	Thermal	40,000–75,000	90–110	20–30	20,000–100,000
TVC	Thermal	10,000–35,000	40–100	25–40	20,000–100,000
MVC	Mechanical	100–3000	40–100	25–40	20,000–100,000
SWRO	Mechanical	<1000–320,000	ambient	40–50	10,000–46,000
BWRO	Mechanical	<1000–320,000	ambient	85–90	50–10,000
ED	Electricity	up to 14,500	ambient	up to 95	200–3000

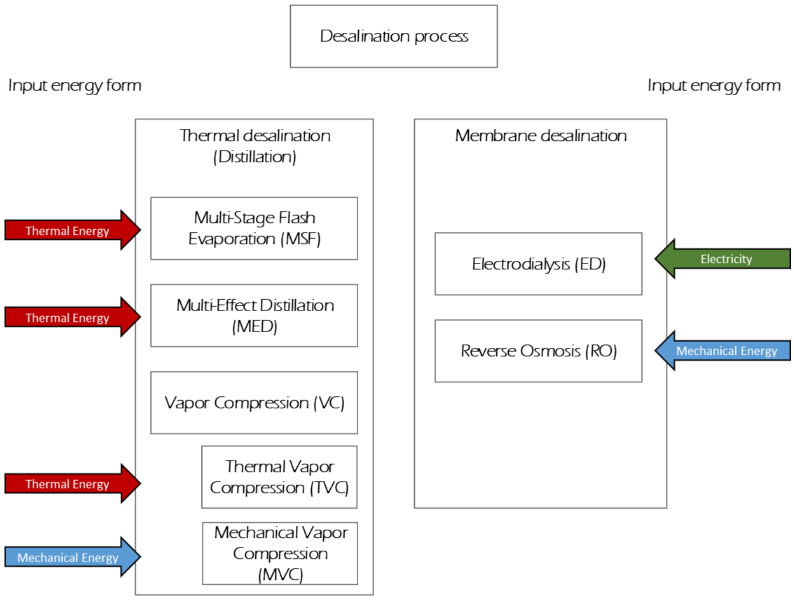

Figure 1. Desalination technologies can be divided in two groups: thermal desalination and membrane desalination. Adapted from [13].

2.1. Thermal Desalination Technologies

Thermal desalination, or distillation, involves a phase change: the separation between freshwater and salts occurs through evapouration. Vapour is produced by heating the feed saline water, and then condensing it again to obtain freshwater. The main distillation technologies are MultiStage Flash Evapouration (MSF), Multi-Effect Distillation (MED) and Vapour Compression (VC). Several new desalination technologies are emerging, including Membrane Distillation (MD), but these are still used for niche or smaller industrial applications. The thermal desalination processes differ by the temperature and pressure at which water evapouration is achieved. The heat necessary for the vapour formation can be provided by thermal or mechanical energy.

In all the distillation processes, heat is exchanged between the vapour and the feed water, so that the vapour condenses as pure water and releases heat to the feed saline water. Only a part of the energy necessary for the vapour formation is supplied by an external source. In MSF and in MED, the external source is steam (e.g., in co-generation). MD operates at lower temperatures, and therefore a low-grade waste heat at low pressure can be used as an external heat source [29].

In VC, the extra heat is provided to the vapour by means of compression. The feed water is evaporated in a chamber, and then the vapour produced is extracted from the chamber and compressed to increase its temperature. After compression, the vapour is sent back into the evapouration chamber inside heat exchange pipes, where it releases heat to the feed water for the generation of steam while condensing. The compression can be done by means of mechanical energy with a compressor, known as Mechanical Vapour Compression (MVC), or by means of thermal energy with a steam jet ejector, known as Thermal Vapour Compression (TVC).

As MVC does not require an external heat source, it is the most-used thermal desalination technology that is applied in combination with wind energy. In the context of wind energy integration, the turbine rotor can be used to mechanically drive the compressor through the low speed shaft (or a high speed shaft if a gearbox is employed) or by supplying electricity from its generator to an electrical motor and compressor assembly.

2.2. Membrane Desalination

The other family of desalination technologies is membrane desalination. In membrane desalination, there is no phase change of the working fluid. The separation process is based on semi-permeable membranes, that selectively allow the passage of specific substances and retain others. The most-used membrane desalination processes in combination with wind energy are electrodyalisis (ED) and RO.

Forward osmosis, pressure retarded osmosis and membrane capacitive deionization are still in their development stages and, together with reverse electrodialysis, they are not commonly used in desalination plants. For this reason, we chose not to include these technologies in this section. Further details on these technologies are provided in [2,16,17].

In ED, an electrochemical desalination process, the power is supplied in the form of electricity. An ED desalination plant is composed of several cells. A cell is formed by an anode and a cathode, separated by a series of semipermeable membranes. Anionic membranes can trap cations, while cathionic membranes retain anions. When the two electrodes are supplied with direct current, an electric field is generated between two electrodes.

Thus, the ions contained in the saline water are attracted by electrodes with the opposite charge. While flowing towards the electrodes, ions are trapped and collected by the semipermeable membranes in between and are, thereby, removed from the feed water, thus, obtaining freshwater. The cells in ED plants can be stacked in series and staged to achieve recovery rates of up to 95% [28], or in parallel configuration.

However, ED is limited to the desalination of water with low salts concentrations below 5000 ppm. This is due to the relatively low number of total dissolved salts (TDS) removal efficiency (15.0% to 90.0%) and to the amount of electricity required with the concentration of the feed, which makes it very expensive for higher concentrations. Instead, for higher TDS concentrations, Brackish Water Reverse Osmosis (BWRO) or Seawater Reverse Osmosis (SWRO) are typically preferred.

RO is a pressure-driven process, which means that the feed water needs to be pressurised above a certain value [30,31]. This value is known as the osmotic pressure and is the pressure at which pure or low concentration water solution is in equilibrium with a high concentration water solution when both solutions are separated by a semipermeable membrane.

If the saline water is pressurised above the osmotic pressure, pure water flows through the membrane from the high concentration side to the low concentration side, obtaining freshwater. Considering that the osmotic pressure is proportional to the feed water concentration, the RO energy consumption increases with the salinity of the feed water. As a rule of thumb, at least 7 kPa (1 psi) are required for every 100 mg/L of salts dissolved in the water [32]. This means that, for typical seawater concentrations (35,000 ppm) a pressure between 50–70 bar has to be supplied.

In many cases, the use of an Energy Recovery Device (ERD) is included to recover part of the energy contained in the rejected high concentration solution, i.e., the brine, since the brine's pressure at the exit of the reverse osmosis module is close to the pressure of the feed at the inlet. The recovered energy is then used to pressurise the feed seawater. Two types of ERD exist, turbines and pressure exchangers [33]. In turbine ERDs, the pressure from the brine is converted into mechanical energy and/or electrical energy to drive the main high pressure pump or an auxiliary pump.

In these applications, a Pelton turbine is commonly used, where the brine flows into the Pelton runner, which is connected to a generator in order to produce electricity. The electrical power is then fed to a motor and high pressure pump, thereby, reducing its energy consumption. When a turbocharger ERD is used, the feed is pressurised in two steps: first, by the main high pressure pump, and then by a pump whose shaft is also driven by the turbocharger turbine. A separate combination of the pump and hydromotor is also possible—where the turbine directly drives the high pressure pump.

In the pressure exchanger type of ERD, also called an isobaric device, the pressure of the brine is directly transferred to part of the feed water. A further energy boost is needed for covering the pressure drops inside the membranes. With the use of an ERD, the power consumption of an RO desalination plant can be reduced up to 2–2.50 kWh/m^3 [34]. A number of ERDs designed for applications in water desalination systems powered by renewable energy have been proposed in [24,25,35,36].

An overview of the energy consumption and water cost ranges of each desalination technology is shown in Table 2; for a more detailed overview of the energy requirements and costs, see [16]. The water costs for the thermal desalination technologies, MED, MSF and TVC, found in the literature [2], appear to be on the low side if heat has to be generated.

Conversely, the low water cost could be explained in the case of free heat being available, for example as the waste heat of an electricity plant. A comparison between several desalination techniques to be combined with wind energy was presented in [37], where different types of desalination modules, RO, ED and VC, were separately connected to the system, tested and compared.

Table 2. The average energy consumption and water cost of each desalination technique [2,15,38].

Desal. Tech.	Electrical kWh/m^3	Thermal kJ/kg	Thermal Equivalent to Electrical kWh/m^3	Total Electricity kWh/m^3	Water Cost \$/m^3
MED	1.5–2.5	230–390	19.1–32.5	20.6–35	0.52–1.5
MSF	4–6	190–390	15.8–32.5	19.8–38.5	0.56–1.75
TVC	1.5–2.5	145–390	12.1–32.5	13.6–35	0.87–0.95
MVC	6–12	-	-	6–12	2.0–2.6
SWRO	3–6	-	-	3–6	0.45–1.72
BWRO	1.5–2.5	-	-	1.5–2.5	0.26–1.33
ED	2.64–5.5	-	-	2.64–5.5	0.6–1.05

Currently, RO is the most applied technology for desalination, producing 68.7% of desalinated water [2] as shown in Figure 2. The RO prevalence [23] is due to its low energy consumption, which can be further reduced when using an ERD, and the wide range of capacities available, which makes it flexible from laboratory-size experimental applications up to full scale desalination plants. In practical situations, large capacities are achieved by connecting several stacks of RO units in series and in parallel configurations.

Furthermore, reverse osmosis is suitable for both brackish water and seawater treatment. For all the above mentioned reasons, RO is considered by many experts as the most suitable desalination technology for wind-driven applications. In the wind integration context, RO desalination requires mechanical energy to pressurise seawater, and this could be provided by a wind turbine directly via a mechanical or hydraulic connection or by means of a pump and an electric motor assembly.

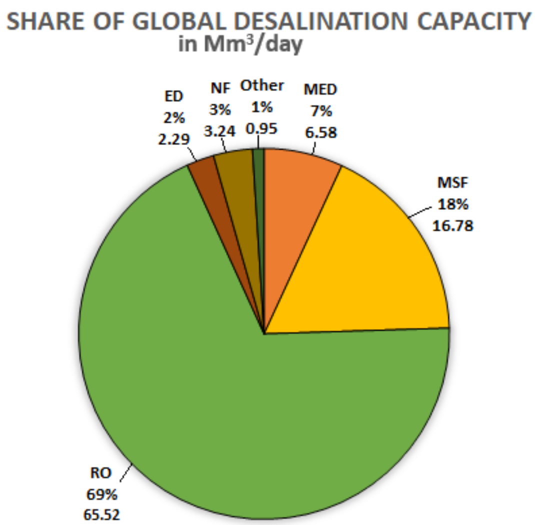

Figure 2. The global desalination capacity per technology in 2020 with data from [2].

3. Wind-Powered Desalination with Grid Connected Systems

A large part of the literature found on wind-driven desalination concerns configurations and topologies that require wind energy conversion into electricity to power the desalination process equipment. Since conventional wind turbines transform the mechanical energy extracted by the rotor into electricity, it is a straightforward approach to directly use that electricity in different ways: it can be directly fed to the desalination plant, injected into the electrical grid, or further transformed and stored in different manners.

The energy storage alternatives include electric-chemical storage forms, such as batteries, mechanical storage (like flywheels) or mechanical-hydraulic storage (like pressurised tanks or hydro-pumped storage systems). Depending on the choice, different advantages and disadvantages arise. In the next subsections, an overview of these options is discussed.

3.1. Interconnection to the Electrical Grid

Whenever an electrical grid connection is available, it facilitates the possibility to balance the power supplied to the desalination system with the power required by the desalination processes. The electricity produced from the fluctuating wind resource is fed to the electrical grid, while the desalination plant imposes a relatively constant power demand. This condition is valid in the case of bulk electricity production from individual wind turbines and to complete wind farms. In this way, the water production is completely independent and decoupled from the local wind power generation and its availability limitations.

The presence of the grid connection therefore ensures that the desalination plant consumption is guaranteed, and the desalination plant is designed to work in the most suitable operating conditions. This is especially convenient for desalination processes, such as RO, which are more sensitive to variations and fluctuations in the operating conditions. Furthermore, the optimization of the wind turbine systems and the desalination plant can be realised almost independently. In Table 3 a summary of wind energy systems that rely on a grid connection to power desalination processes is presented.

Table 3. Summary of grid-connected systems for wind desalination.

Ref.	Energy Source	Size	Desalination Technology	Desalination Capacity	ERD	Energy Storage	Commiss. Year	Notes
[39]	WT + grid	10 MW	SWRO	5000 m^3/d	-	-	-	Economical analysis
[34]	WT + grid	2.64 MW	SWRO	5000 m^3/d	ERI	-	2002	Prototype
[40–42]	WT + grid		SWRO		-	Hydraulic storage	-	Optimization analysis
[43]	WT + solar PV + grid	50 kW + 60 m^2	MVC		-	Yes	-	Optimization analysis
[44,45]	WT + solar PV + grid	275 kW + 50 kW	SWRO	300 m^3/d	-	-		Prototype
[46]	WT + grid	6–30 kW	SWRO	24 m^3/d	-	-	-	On and off-grid comparison

A typical grid-connected wind desalination topology is schematised in Figure 3. A few projects that illustrate this grid-connected topology are worth mentioning, such as the Perth SWRO Plant in Western Australia, which opened in November 2006. The power required by the plant is provided by the 80 MW Emu Downs Wind Farm, which is able to produce 270 GWh per year into the local power grid; in this way, the required yearly consumption of 180 GWh from the desalination plant is easily fulfilled [47].

Another example of a grid-connected seawater desalination system powered by wind energy was built in Gran Canaria, one of the Canary Islands in Spain, and commissioned in 2002 [34]. The RO desalination plant is powered by four 660 kW wind generators and produces water for irrigation purposes. Two ERD pressure exchangers are used to recover the residual energy from the brine obtained with the RO membranes. As a result, the desalination plant supplies water for irrigation purposes with a minimal environmental impact.

Regarding environmental impacts, wind energy can avoid the CO_2 emissions associated with the power injected into the grid that is generated by conventional fossil fuels and is used for the continuous operation of a desalination plant. This idea was evaluated in [39], where the opportunity for integrating wind energy with a grid connection for powering a n RO desalination plant in Ténès, Algeria was analysed.

A hypothetical wind farm consisting of five wind turbines of 2 MW was proposed, resulting in savings of almost 8600 tons of green house gases per year. The authors also concluded that, for this particular location, with a resulting cost of electricity of USD$0.07 per kWh, wind energy not only resulted in a promising source for electricity production when integrated with the electrical grid but also demonstrated great potential in combination with RO desalination.

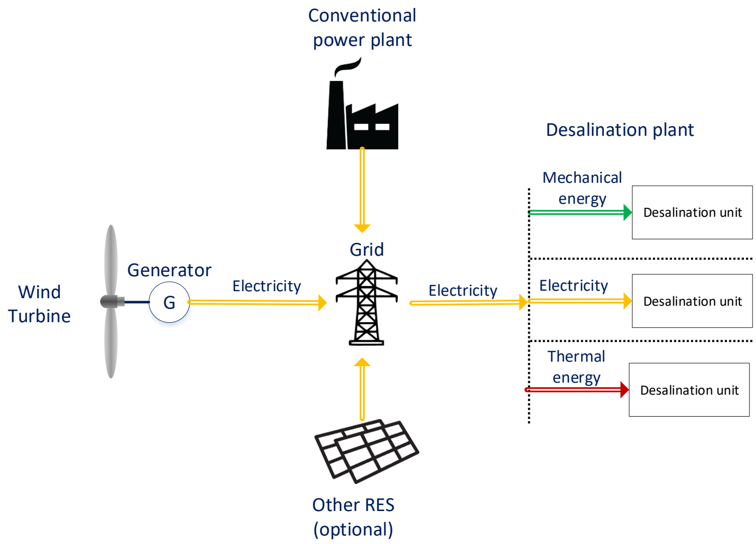

Figure 3. Schematics of grid-connected desalination systems. Depending on the desalination technology, the electricity provided by the grid is first converted to mechanical or thermal energy or directly supplied to the desalination unit.

3.2. Desalination for Increasing Wind Energy Penetration

In addition to reducing the cost of electricity by making use of the excess in wind energy produced, the desalination of seawater could also help increase the wind energy penetration in the case of isolated power supply systems. For these systems, the instantaneous power from renewable energy sources (RES) that can be fed into the grid is limited depending on grid stability aspects. To address this issue, the work in [40–42] suggested the use of seawater desalination in combination with a pumped hydro storage to minimize curtailments in the island of S. Vicente, Capo Verde in the Atlantic Ocean.

In the proposed system, the excess energy produced by wind turbines is partially used for producing freshwater, which is stored in a lower reservoir of a pumped hydro storage; the remaining exceeding energy is used to pump the freshwater from the lower to the higher reservoir, respectively. Then, the pumped hydro storage can be used to generate electricity to power the grid when the wind energy production is low. The optimization analysis showed a reduction in the total annualised production costs between 22% and 27% with a four-times increase of power production from from the RES share of wind and hydro-pumped storage. Furthermore, CO_2 emissions were reduced between 67% and 77% [42].

Similarly, in [48] a wind-hydro electricity production system was proposed for the Aegean Archipelago, where the desalinated water was used to store the excess of energy production. The idea of the project was to satisfy the increasing electricity demand of the islands of the Archipelago by building several wind farms. Thereby, it would be possible to increase the capacity of the electrical grid and reduce electricity costs by limiting the dependence on fossil fuels necessary for the existing thermal power plants. The combination of the wind farms with hydraulic power plants and desalination plants would compensate for the variations of the energy supply and the imbalances with the power demand.

In addition, the surplus in energy could be first used for pumping water to the upper reservoir and then to produce freshwater in the seawater desalination plant. Conversely, the lack of wind energy could be compensated for by the reversible pump-turbines of the hydraulic plant, both for freshwater production and for covering the electricity demand of the villages.

The presence of the electrical grid has an important effect on the costs and performance of desalination systems. This is illustrated in [46] where a comparison between grid-connected and off-grid systems was presented. The authors compared the water production costs for a wind-powered SWRO desalination system for the on-grid and off-grid situation for Gökçeada Island, the largest island of Turkey. In both cases, the desalination system was designed for supplying 1 m^3 of water per hour, while wind turbines with different rated power sizes varying from 6 to 30 kW are used.

The estimation of the levelised cost of water varies between USD$2.962 and USD$6.457 for the off-grid option and for all wind turbines, between USD$1.489 to USD$1.750/m^3 in the case of only grid powered desalination, and between USD$0.866 and USD$2.846/m^3 for a wind-driven grid-connected desalination system. In addition, the authors evaluated the reduction in tonnes of CO_2 when using the wind turbines for powering the SWRO desalination.

The reduction increased with the increase in the size of the wind turbine, from 16 to 80 tons for the 6 kW and the 30 kW wind turbines, respectively, proving that a high penetration of wind energy for desalination in site can greatly reduce the ecological footprint in terms of CO_2 emissions.

3.3. Desalination including Combinations of Wind with Other RES

In some cases, wind energy constitutes only one of the many components of the renewable energy mix used in combination with the grid. The use of a combination of RES can improve the reliability of the system, as well as its economic efficiency and environmental impact [17]. In particular, wind and solar PV energy has been a preferred combination with many examples in the literature. With the goal of finding the best energy combination for powering seawater reverse osmosis desalination, an experimental research facility powered by a hybrid PV-wind and grid-connected system has been implemented at Ras Ejder in Lybia [44,45].

The RO desalination system, requiring 70 kW of electrical power, is powered by the grid and by a 50 kW solar PV field, a 200 kW wind turbine (WT) or by both. From the simulations of yearly production, it was shown that, on one hand, using the grid in combination with the PV panels and the WT reduces the overall energy required from the grid and the corresponding CO_2 emissions, up to 31% of the demanded annual energy. On the other hand, from an economical point of view, the grid and WT combination was the most favourable solution, since it offers the lowest levelised cost of energy, 0.112 €/kWh (0.37 €/kWh for grid only), the lowest levelised water costs, 1.769 €/m^3 (1.346 for grid only) and the lowest cost of CO_2 avoidance at 91 €/ton.

In the work of [43], the simulation of a hybrid PV-wind energy system powering a MVC desalination plant was presented. The system is provided with energy storage, and it is connected to the electrical grid. The 60 m^2 of PV modules and the 50 kW wind turbine feed the MVC plant. Any excess in the energy produced can be equally given to the energy storage system or to the grid, and viceversa, the energy can be provided to the desalination plant from the storage or from the grid if needed. To control the energy flows between all the components to satisfy the water demand, an optimization model was presented and applied to three different locations in Morocco.

Two different temporal windows were considered, hourly and monthly variations in the water demand, in order to take into account both the real time management and the longer term planning. The simulation results prove the ability of the system to satisfy the water demand for domestic use of the three locations and showing that, for MVC plant with a capacity greater than 120 m^3 per day, the cost of the water produced was comparable to traditionally produced water costs.

From the reviewed literature, we found that wind power desalination plants that are connected to the electrical grid represent the most feasible and viable solution for reducing the water production costs and the environmental impact of the desalination processes. Through an adequate design of a desalination plant, considering the wind resource availability and seasonality at the specific locations, the use of wind power for desalination purposes can help to increase the penetration level of renewable energies into the grid.

However, the presented solutions are restricted by the availability and access to such an electrical grid. The number of potential sites is reduced, excluding isolated and/or poor rural areas where the construction of a grid infrastructure is not possible for technical or economical reasons.

4. Autonomous Wind-Powered Desalination: Stand Alone Systems with Backup

In many cases, a connection to the grid is not always available, especially in remote coastal areas and island communities. Due to their geographical isolation or to their economical conditions, building the grid and its infrastructure may not be a viable option. On the contrary, wind energy is often an available and abundant resource at these locations, which can be utilised for stand-alone electricity generation.

In stand-alone or autonomous systems, the challenge comes from the intermittent nature of the wind resource with a variability in the output power that can fluctuate in ratios of 1:10 or more, depending on the specific site conditions [49]. Oscillations or interruptions in the power input are a concern for the operation of desalination plants, which are designed to operate under steady and relatively constant conditions. Power variations have a negative impact in the component life and the performance of the desalination plant, which, in turn, can send disturbing feedback to the wind power plant as stated in [39,49].

In addition, interruptions in the water electricity supply could create serious inconveniences to those areas that completely rely on stand-alone systems. Hence, robustness and reliability become critical aspects of the system design. Important attention is needed in the sizing of each component in order to meet the water and electricity production needs, to minimize disruptions and to reduce the investment and operational costs [50].

With the aim to avoid disruptions and to smooth out the fluctuations in the power supply, back-up systems, such as diesel generators and energy storage solutions, have been commonly used in combination with wind power systems. A summary of stand alone wind energy and desalination systems with power backup is shown in Table 4, while a schematic of the possible configurations is sketched in Figure 4.

Table 4. Stand-alone systems with intermediate electrical conversion.

Ref.	Energy Source	Size	Desalination Technology	Desalination Capacity	ERD	Energy Storage	Size	Commiss. Year	Notes
[24,25]	WT (+grid/diesel gen.)	600–2000 kW	SWRO	180–1400 m^3/d	Enercon 3-pistons ERD	Flywheel + several options	-	2007	Commercial system
[51]	WT	100 kW	SWRO	100 m^3/d			-	-	Pilot plant
[52]	WT + diesel gen.	15–22.5 kW	SWRO/MVC	30 $m^3/d/$	-	-		-	Feasibility study
[53]	WT + solar PV	10–400 kW	SWRO	8.4 m^3/d		Batteries + micro hydraulic plant	100 Ah + reservoir	-	simulation tool
[54]	WT	5 kW	SWRO	6.2 m^3/d	-	Batteries	125–1000 Ah		Pilot plant
[55]	WT	100–300 kW	SWRO	1000 m^3/d		Flywheel/batteries	1200 Ah		Pilot plant
[56]	WT	460 kW	SWRO	72–192 m^3/d		Flywheel + batteries	125–1000 Ah		Pilot plant
[37]	WT	460 kW	SWRO/MVC/EDR	200/50/72–192 m^3/d		Flywheel		1999	Pilot plant
[57]	WT	15 kW	SWRO	18 m^3/d		Batteries + supercapacitor			Experimental test
[58]	WT + solar PV	2 kW + 2 kWp	BWRO	7.2 m^3/d		Hydraulic storage	2.18–4.36 m^3		Experimental test
[59]	WT	5.4 MW	BWRO	62,208 m^3/d		Batteries			Optimization analysis
[60]	WT + solar PV	0.9 kW + 3.96 kWp	SWRO	3.12 m^3/d		Batteries	1800 Ah	2001	Pilot plant
[50]	WT	15–50 kW	SWRO	18–96 m^3/d		Batteries		-	Simulation and sizing
[61]	WT + solar PV	800 kW + 200 kWp	SWRO	4320 m^3/d		Hydraulic storage	40,000 m^3 (480 kW)		
[49]	WT	300 kW	MVC	360 m^3/d	-	-	-	1993	
[62]	WT	26.43 kW	SWRO	<96 m^3/d	-	-	-	2001	Experimental test
[63]	WT	2.2 kW	SWRO		Clark pump	-	-	2002	Simulation
[64]	WT	30 kW	SWRO	5–20 m^3/d		-	-		
[65]	WT	14–20 kW	BWRO	22–33 m^3/d		-	-		Conceptual design and economic analysis
[66,67]	WT/solar PV	6 kW/2.5 kW	BWRO	9 m^3/d 1.5 m^3/d		-	-		Pilot plant
[68,69]	WT	4–19 kW	EDR	92.4 m^3/d		-	-		Pilot plant

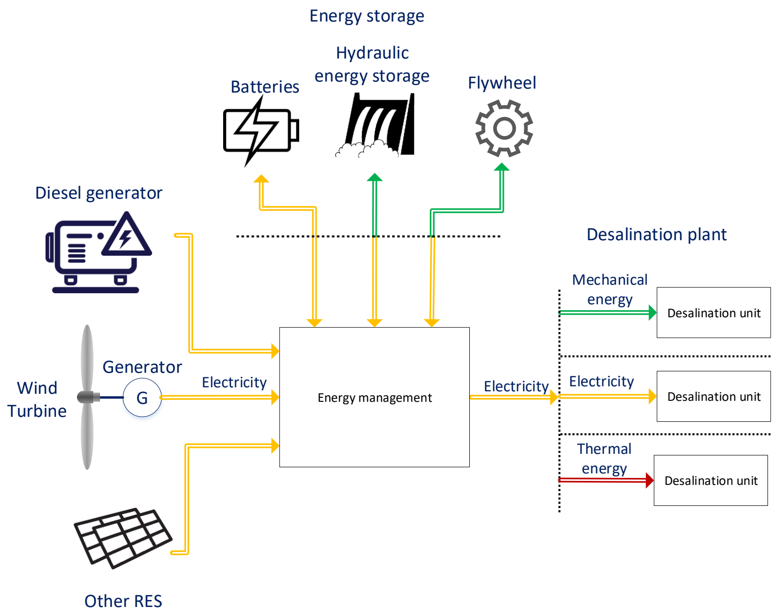

Figure 4. Schematics of no-grid-connected wind-driven desalination systems, with backup. The back up can be provided by a diesel generator and/or by energy storage.

4.1. Diesel Generators

The same considerations for grid-connected systems hold true for systems connected to diesel generators. Similarly to the grid, diesel generators can provide a steady power supply to desalination plants by backing-up when instantaneous wind power generation is not sufficient. Alternatively, supporting the power consumption with wind energy can reduce the fuel consumption of diesel-based grid connection and water desalination plants. As a consequence, benefits are evident in the reduction of both CO_2 emissions and water production costs as shown in Habali and Saleh [65].

In their work, a stand alone BWRO desalination plant entirely powered by a diesel engine is compared with a wind assisted option where the diesel engine is only used as the base load. Their results suggest that the integration of the wind turbine with the power system guarantees a smaller cost per cubic meter of water produced compared with the diesel engine only case, with costs decreasing for increasing wind turbine capacity and average annual wind speed.

A similar study was presented in Henderson et al. [52], where the possibility of desalinating seawater for using the surplus of energy produced by a hybrid wind-diesel generator system is evaluated. The authors proposed to install two or three 7.5 kW wind turbines to reduce the fuel consumption of the diesel generator supplying electricity to Star island in New Hampshire.

Although the feasibility study of this particular application concluded that neither MVC nor RO desalination were economically convenient, the authors indicated that the results would be different in the case of larger islands with a more stable population. Furthermore, they indicated seawater desalination and fresh water storage as an interesting solution for energy storage or long-term load management for wind-diesel hybrid systems.

However, the use of diesel generators brings several drawbacks: first, it increases the environmental costs of the desalination process in terms of emissions; second, it binds the cost of the water produced to diesel prices, which increase when the supplies are limited by the isolation of the site location; and last, fuel shortages, diesel generator maintenance and interruptions in the power supply can limit the water production since the wind turbines are not sized for fully covering the power demand of the desalination plant [63].

4.2. Energy Storage for Achieving Steady Operating Conditions for the Desalination Plants

Energy storage can be used to reduce the dependency on diesel. Elaborate reviews of suitable energy storage systems to be integrated with wind power systems are presented in [70,71], with specific consideration of energy storage options for renewable-energy-powered desalination presented in [38]. In [72], the main features of the storage energy solutions for wind energy are summarised, in terms of the energy capacity, discharge time and cost.

Among the benefits that energy storage provides for wind energy, time (load) shifting, regulations and control and a decrease in wind power uncertainty are the most valuable. One of the first wind-powered desalination plants was installed by the GKSS-Research Centre in Süderoog island, in Germany [66,67].

Due to the wind fluctuations and intermittency, the desalination plant could not be operated, since it was subject to varying operating conditions. The changing volumetric flow rate caused the plant to switch on and off too often. In order to compensate for the energy supply discontinuities in an hourly range, a battery was adopted, which allowed the desalination system to work for the execution of the remaining tests.

Small islands are typical sites where stand alone systems are necessary to provide electricity and water. Energy storage can alleviate the discomforts of uncertainties and inconsistency from local wind power. This is the case of the Merssinin village in Donuoussa Island, presented in Manolakos et al. [53]. The village is non-electrified and suffers from fresh water scarcity. In the paper, a hybrid PV-wind-powered desalination system is proposed to provide electricity and freshwater to the village. A Pelton turbine generator is used as energy recovery device for the brine. To reduce the amount of batteries needed, the energy storage includes a micro-hydraulic station, in which freshwater is pumped from a lower reservoir to a high reservoir when there is any surplus of electricity production.

Another wind-driven reverse osmosis desalination is proposed for supplying water to the islands of the County of split and Dalmatia in Vujčić and Krneta [51] since the construction of large regional pipelines from the mainland is hindered by the limited economic strength of the area. Therefore, the authors proposed the installation in more than 100 different locations of desalination plants with a capacity of 100 m^3 per day powered by a 100 kW wind energy plant to satisfy the water demand for agricultural and tourism purposes of the islands.

As a consequence of the absence of a grid or diesel generator connection, it is not possible to decouple the wind generated power from the desalination operation. Therefore, different strategies have to be implemented to ensure the system can operate safely and effectively as described in Miranda and Infield [63]. From the desalination plant perspective, these strategies can be grouped according to their required operating conditions: near constant operating conditions and variable operating conditions.

As mentioned before, when properly sized, integration of energy storage systems can ensure nearly constant operating conditions, by dampening fluctuations, absorbing excess energy production, and providing stored power when the wind power is not sufficient. The desalination unit is activated and deactivated only when the power supply, either from wind or from the energy storage, can provide the minimum power demand of the desalination plant.

Ben Ali et al. [58] proposed a modular energy storage system to absorb the varying input power and to handle fluctuations and discontinuity of wind and renewable power. In their BWRO desalination prototype powered by a hybrid solar PV and wind turbine system, they integrated a modular capacity hydraulic storage. In this case, for increasing the availability of the renewable power, the system can pump brackish water from a well to an elevated storage system, desalinate seawater through the RO desalination system, or do both pumping and desalination.

As a result, brackish and freshwater tanks act as energy storage. Furthermore, the brackish water pumping system is constituted by different pumps, which can be used individually or in parallel to make better use of the energy available. The simplicity and modularity of this configuration makes it particularly interesting for rural regions. Nevertheless, the authors underline the complexity and the importance of a proper sizing and design of the system as well as of the system's water-power flow management due to the different natures and functionalities of the components included and interacting with each other.

One of the drawbacks of aiming to operate the desalination plant at constant conditions is the required capacity of the energy storage system and, therefore, the capital costs of the plant. Infield [54] presented a study on the sensitivity of operation of a stand alone wind-powered RO plant to key parameters, such as wind speed, battery storage capacity and RO operating pressure.

In the study, the desalination plant is operated only when the power provided by both a 5 kW wind turbine and a system of batteries was sufficient to satisfy its electricity needs, and thus operation with variable conditions was not allowed. The water produced by the desalination plant was proportional to the time in which the desalination plant was operating. The operating time depended on the average wind speed, the operating pressure and the capacity of the batteries, which was selected to minimize the on and off cycling of the RO unit.

From the analysis, the author concluded that, for stand alone systems, detailed design calculations are necessary, aiming at a proper match between the components of the system, e.g., the wind turbine, the desalination unit and the energy storage capacity. In particular, the local wind conditions and the battery storage capacity influence the ideal operating pressure of the desalination unit. In turn, the optimal desalination capacity depends on the average wind speed at the site.

Furthermore, the minimum energy storage capacity is required to reduce capital costs and losses, since it is more convenient to store water than energy for matching the water supply and demand. Thus, sometimes it is preferable to minimise the size of the energy storage, limiting its function to the regulation of the system.

To reduce the size storage system capacity but provide constant power supply to the desalination unit, a mix of renewable energies can be used in combination with wind energy. For example, an autonomous hybrid solar PV-wind energy driven desalination prototype was installed and tested in Lavrio, Athens [60].

The small prototype consisted of photovoltaic generators, a wind generator, a SWRO desalination unit and batteries. There, the batteries are used as energy buffer and to provide stable power to the RO unit. The combination of wind and solar PV power, and energy storage, enabled the desalination plant to operate in average five hours during winter and more than eight hours during summer, producing sufficient amount and quality of fresh water.

However, the use of a mix of renewable energies increases the complexity of the energy management system and impose the need of a proper regulation system to control and optimize the switching between the energy sources. Unfortunately, these options did not reduce the initial capital costs. On the contrary these costs may be even higher, and thus a suitable compromise should be found.

4.3. Variable Desalination Capacity

A different option for achieving nearly steady operating conditions with a minimal size of the energy storage is by adopting a modular desalination capacity. A modular desalination capacity can increase the flexibility of the system, allowing the power load to discretely adjust to the power supply. However, this requires the frequent switching on and off of the desalination unit, which can have detrimental effects on the components. For an RO desalination plant, for example, intermittency could lead to a faster decrease in the performances of the membrane due to membrane compaction, increased fouling and concentration polarization [73,74].

Penate et al. [55] presented the simulation of a modular desalination plant powered by wind and compare it with a fixed capacity desalination plant. In the modular SWRO system, the capacity is adjusted by connecting or disconnecting part of the RO units to match the wind availability. According to the simulations, the gradual capacity SWRO plant is more versatile because it enables the match with the amount of energy available, allowing the operation of the system for more hours during the year. However, the amount of water produced is less. An important conclusion of the paper is that the power control of the wind energy system has a key role for maximising water production and that it is important to adjust the power produced with the power demand.

Similarly, Carta et al. [56] proposed a small-scale prototype with modular capacity, in which a flywheel is used for power fluctuations smoothing. The quality and flow of the average daily water produced was not significantly affected by the variations in the frequency of the electrical grid, and no deterioration of the membranes was detected due to the variations in pressure, since pressure spikes were avoided. However, the testing time was not sufficient to prove the long-term effects on the membrane life.

The paper also underlines the importance of defining an appropriate threshold for the wind speed to start up the desalination unit, depending on the wind availability in the location and the design of the system to optimize the operation time of the system. An optimization of the modular capacity system was then presented in [75], and the results from the application of the optimal system to a case study were compared with the configuration with batteries. The analysis showed that the specific product costs were higher for the configurations with batteries.

The feasibility of adopting a variable capacity RO plant in a wind-powered desalination prototype was also discussed in Carta et al. [57]. Through preliminary testing of the desalination plant under varying electrical input simulating the wind turbine, the operational limits of the system while operating with one or two pressure vessels in parallel were identified, and an operational strategy was proposed.

Feed pressure and volumetric flow rates are allowed to change in order to keep the recovery rate constant. The tests show the feasibility of using a variable capacity desalination system achieved by connecting and disconnecting the pressure vessels according to the wind availability. However, for most tested intervals, a good fit was not found between the theoretically generated power from the wind turbine and the electrical load of the desalination system, and the need of a dynamic regulation system is underlined. The authors concluded that the strategy adopted in the paper could be replicated on a larger scale, with the advantage of further reducing the frequencies of connection and disconnection of each desalination system module.

The effect of a continuous switch on and off is one of the parameters taken into account in the analysis on component selection and sizing presented in Koklas and Papathanassiou [50]. Considering an autonomous wind-driven reverse osmosis desalination plant, the study simulated the annual operation of the system when key parameters are changed. The key parameters are the size of the wind turbines, of the desalination plant, of the battery storage, and the operational strategy. As for the output, the annual water production, the number of starting and stopping of the desalination plant, and the relative capital and per cubic meter of water costs are compared.

Increasing the desalination plant capacity to increase the water production and reducing the starting and stopping of the system results to be more efficient than increasing the capacity of the wind farm; the size of the batteries, instead, has to be minimized to guarantee a short operation and the rinsing of the system in wind absence. The authors suggest that 2:1–3:1 is a good ratio between the wind turbine and desalination capacity, depending on the average wind speed and the wind turbine power curve.

Between the two operational strategies proposed, one aimed at maximizing the water produced and the other aimed at minimizing the start and stop of the system guaranteeing the washing of the desalination plant at every stop, the latter appeared more favourable, even if it implies a reduction in the water. Nevertheless, a capacity factor up to 60% for desalination plants in highly windy sites is possible.

A similar study was presented in Spyrou and Anagnostopoulos [61], where the optimum design and operational strategy of a stand alone wind-solar PV energy powered desalination plant was investigated. Differently from the system presented in Koklas and Papathanassiou, in this case, batteries were replaced by a hydraulic storage system, and the addition of solar PV generated power was evaluated. From the optimization analysis, it is interesting to notice that, for low water demand, the hydro-pump storage is not convenient.

Conversely, it is included in any optimization result for water demand above 5000 residents. When considering wind energy only, the resulting cost per cubic meter of water produced is always lower than the typical water costs from conventional sources in the same area (1.5–3.0 €/m^3 instead of 5–8 €/m^3), and this reduces with desalination plant size, wind farm size and per decreasing percentage of water demand to be satisfied at any time, which corresponds to reducing the size of the storage system.

The effects of using of a variable capacity desalination plant, i.e., variable load, on the wind turbine were investigated in Neris et al. [64]. There, two units, of 5 and 20 m^3 per day, respectively, are connected together or separately depending on the power generated by the wind turbine. The wind turbines are fixed pitch and stall regulated, intentionally selected due to their lower costs and maintenance.

The frequency of the wind turbine generator system is kept constant by balancing the supplied and consumed power by means of a fast regulating resistive dump load. Furthermore, a fluid coupling connects the gear box to the synchronous generator with automatic voltage regulation. The simulations' results show that the disturbances and oscillations due to wind fluctuation in combination with the (dis)connection of the load are well damped. The regulation allows the system to work within the design goals, thus, showing satisfying performances.

The different operational strategies were analysed and compared in [59]. In the paper, the optimization of design and operations of a wind-powered BWRO system was presented, aiming at satisfying the water demand of Arar province in Saudi Arabia. For the optimization, several options were considered: variable or fixed operation of the RO system, that means variable or fixed operating pressure; fixed or variable capacity of the RO system, that corresponds to a constant or variable number of active pressure vessels at any time; type of energy storage, batteries and hydraulic storage tanks.

The optimization is done to satisfy an hourly or yearly demand of freshwater, leading to different results. In particular, the use ofa storage tank that is less expensive, less complicated and easier to operate is preferable in general, but an hourly demand optimization needs to include batteries. Even though variable pressure operations of the RO system better attenuates wind intermittency and disturbances, constant operating conditions (fixed pressure), a variable capacity guarantees a smoother operation and water production rate.

In [72], instead, the modular capacity desalination configuration was found to be uneconomical, due to the higher investments cost, even if recommended for minimizing the number of starts and stops and maximising the operation time. Despite the higher water cost, this configuration is still considered more favourable if compared with the reference case of fixed capacity and constant operating conditions, or with the case of variable operation obtained by using the high pressure pump at 2/3 of its nominal capacity.

A combined approach was suggested in [75], where the performances of the modular capacity plant are observed to be better, in terms of specific product water cost, relative frequency of start-up/shut down and exploitation of the available wind energy, when operated under variable operating conditions instead of under constant pressure and flow conditions.

Finally, a comparison between in [76], a WT-battery, a WT-PV, and a WT-diesel powered desalination configurations were simulated and compared. The simulation was obtained for a fixed capacity SWRO plant operated in variable conditions and for a variable capacity SWRO. As a result, it was shown that the modular capacity SWRO increases the operation time of the system but still resulting in less or the same water produced than the variable operation configuration and in a higher water cost.

5. Autonomous Wind-Powered Desalination: Stand Alone System without a Back-Up and Variable Operation

To reduce capital and operating costs, sometimes the energy storage system is not sized to fully compensate for variations in power availability, provide a steady power input to the desalination unit, or is not present at all. As a consequence, the desalination plant is operated in variable conditions that can be far from being optimal.

For example, for a reverse osmosis desalination plant, this means a variable pressure and/or flow rate feed. In these cases, the system must be designed and controlled to restrict the operation of each component within its operational limits, while being able to handle peaks and abrupt fluctuations in frequency, voltage and power which which could cause equipment damage and compromise the system. Therefore, several aspects becomes fundamental:

- the sizing and design of each component;
- the identification of the allowed operational limits and ranges for each component, in order to define a region where the system can safely operate;
- a control and operational strategy, to ensure the system can operate in the defined operational area; and
- a careful analysis of the system performance in dynamic conditions, to ensure it can handle fluctuations.

The determination of the operational area for a small scale wind turbine supplying electricity to the reverse osmosis desalination unit is described by Miranda and Infield [63]. There, two pumps at different pressure levels, driven by two variable speed drives, are independently controlled to maximise both wind power capture and water produced. Each component in the system is tested in the laboratory over a wide operational range and modelled individually before the integration in a complete system model, to define operational strategies and trajectories.

In the tests presented in de la Nuez Pestana et al. [62], the desalination plant range of operation and limits were tested. The reverse osmosis desalination plant was operated under variable conditions, simulating the fluctuations of a wind energy input. The membranes are tested in the entire range of operation allowed by the manufacturer, and subject to sudden changes in flow and/or pressure. The behaviour of the membranes therefore analysed, showing that variable operation is possible without damage, for at least the duration of the tests (more than 7000 h). The authors concluded that, to reduce the energy consumption and improve the efficiency of the plant, the system had to be controlled to guarantee the adequate (maximum allowed) recovery rate for each available power.

Different strategies to cope with the variations and fluctuations in the (power or flow) input have been investigated and adopted in several studies. A small experimental prototype of SWRO desalination plant, driven by a wind generator simulator, was developed and described by Moreno and Pinilla [32]. With the goal of having a direct interface and without electronic control, the high-voltage wind generator is directly connected to the motor driving the high pressure pump, eliminating additional intermediate devices, as rectifiers, transformers and batteries. A comparison between an AC and DC power supply to the electrical motor is provided, showing that the latter provides better flexibility in the operations and better control, but at a higher price and with the need of a rectifier.

The changes in power supply due to wind speed variation were handled by the compressor and an electrical heater in the wind-powered MVC desalination pilot plants described in [49]. A surplus of energy produced by the wind turbines corresponds to an increase in the compressor speed of the MVC plant. If the compressor is already rotating at full speed, then the extra energy is provided to an electrical heater. This increases the temperature of the seawater in the evapourator condenser, that produces an increase in the evapouration temperature and pressure.

As a consequence, the power demand of the compressor increases, balancing out the power supply and dropping the power to the electrical heater, in a sort of auto-regulation process. Two pilot plants of this type were installed in the Baltic sea, proving the operational efficiency and reliability of the process. The first, in Borkum Island, was run by a 45 kW wind turbine, and had a desalination capacity of 48 m^3/d. Based on the experience gained with the first demonstration plant, a bigger and optimised desalination plant was installed in Rügen Island. This time, the plant was driven by 300 kW wind power, and produced 15 m^3/h of potable water.

Veza et al. [68,69] presented the variable operation of an EDR wind-powered desalination plant. The EDR plant was modified to be able to work when a variable power is supplied, as wind power. Preliminary tests are executed on grid to determine correlations between the main input/output parameter, as the applied input voltage and the product quality for a given flow rate, or between the energy provided and the quality and quantity of the product water. In the defined operational envelope, optimum operating points are defined. All these correlations and data points were then used to define a control and operational strategy in the off grid operations. Depending on the available power, the control system defines the operating points and set the parameters of the system.

A flywheel was also integrated into the system to compensate for sudden wind speed variations and to allow for rinsing of the system in the case of a shut down. From the off-grid tests, good results were obtained in terms of smooth and flexible operation of the system. However, the introduction into the system of variable frequency drivers for the pumps and of rectifiers introduce harmonics in the system that produce disturbances, whose effect on the system must be further investigated.

From the cases presented, it is clear that different solutions and configurations are available for the design of stand alone wind-powered desalination system when no back up is available. On one hand, desalination technologies can be modified and adapted for variable power supply. On the other hand, the sizing and design requires a particular attention, to carefully size the wind turbine and the desalination plant so to match the power supply and demand. Last, proper control strategy and control systems need to be implemented in order to make sure not to damage the system.

Finally, the different operational strategies discussed in the previous sections are analysed and compared in [59]. In the paper, the optimization of design and operations of a wind-powered BWRO system was presented, aiming at satisfying the water demand of Arar province in Saudi Arabia. For the optimization, several options are considered: variable or fixed operation of the RO system, i.e., variable or fixed operating pressure; fixed or variable capacity of the RO system, that corresponds to a constant or variable number of active pressure vessels at any time; type of energy storage, batteries or hydraulic storage tanks.

The optimization was done for satisfying an hourly or yearly demand of freshwater, leading to different results. In particular, the use of storage tank, which is less expensive, simple and easier to operate, is preferable, but an hourly demand optimization needs to include batteries. Even though variable pressure operations of the RO system better attenuates wind intermittency and disturbances, constant pressure but variable capacity guarantees a smoother operation and water production rate.

6. Direct-Driven Wind Powered Desalination: Mechanical-Hydraulic Systems

All the systems presented before consider electricity as the intermediate energy medium: the mechanical energy of a turbine is converted into electrical energy, which is then used to power the equipment needed for the desalination process. To reduce the intermediate energy losses, the electrical conversion step can be avoided. This is the case of stand-alone systems where the wind turbine is mechanically and hydraulically connected to the RO system.

This means that the generator and the electronic components are eliminated. In their place, the rotor is mechanically connected to the shaft of the pump or compressor that drive the desalination process. The pump and compressor can be placed at the bottom of the tower or at the ground level, so that a system of gearboxes, pistons and belt transmission system is used for transmitting the motion [77–80]. Another possibility is to locate the compressor and the pump directly in the nacelle [81–83]. In these cases, the fluid is pressurised directly there, and act as a energy transfer medium. A description of several type of rotor-pump connections in wind turbines with hydraulic transmission system was presented in Chen et al. [84].

The use of a mechanic/hydraulic transmission system bring several advantages. In particular, good performances, robustness and reliability, that are particularly attractive for remote area applications [77,85,86]. In addition, the elimination on the generator leads to a noticeable reduction of weight in the nacelle. An overview of the prototype and conceptual design of wind-driven desalination systems with mechanic and hydraulic connection is presented in the following subsection, and summarised in Table 5.

Table 5. Stand alone with direct mechanic–hydraulic connection.

Ref.	Energy Source	Size	Desalination Technology	Desalination Capacity	ERD	Energy Storage	Size	Commiss. Year	Notes
[77]	WT		BWRO	0.151–0.291 m^3/d	-	2 Accumulators	36 l @ 1100 kPa	1990	Pilot
[81]	Floating WT	5 MW	SWRO	33,000 m^3/d	PX	Hydro-pneumatic	6.5 MWh		Conceptual
[78,79]	WT	1.2 kW	BWRO	4 m^3/d		Hydro-pneumatic	0.3 m^3	2005	Pilot
[82]	WT	600 kW	SWRO/MVC	2730/1400 m^3/d	-	Accumulator	-	2004	Pilot
[80]	WT	60 kW	SWRO	5–10 m^3/d	PX	-	-	2008	Pilot
[87,88]	FLoating WT	400 MW	SWRO/MSF	864,000 m^3/d	-	-	-		Conceptual
[83]	WT	500 kW	SWRO	600 m^3/d	iSave	-	-	-	Pilot

6.1. With Intermediate Energy Storage

One of the first prototypes of directly connected wind-driven desalination systems was developed and tested for groundwater desalination in 1988 [77]. There, an Aermotor fan-blade windmill extracted water from a well. In such a wind pump, the rotational motion of the rotor is converted by a geared mechanism to an up and down motion, that drives a pump rod inside the well.

In this way, water was pumped up the pipe at each upstroke and was delivered to pressure tanks at a pressure of 600–1100 kPa. The pressure vessels had the role of hydraulic accumulator, as energy storage. A solenoid valve allowed the flow of pressurised water from the pressure vessels to the membranes for the desalination process when a pre-set pressure level was reached. A simple schematic of the system is presented in Figure 5.

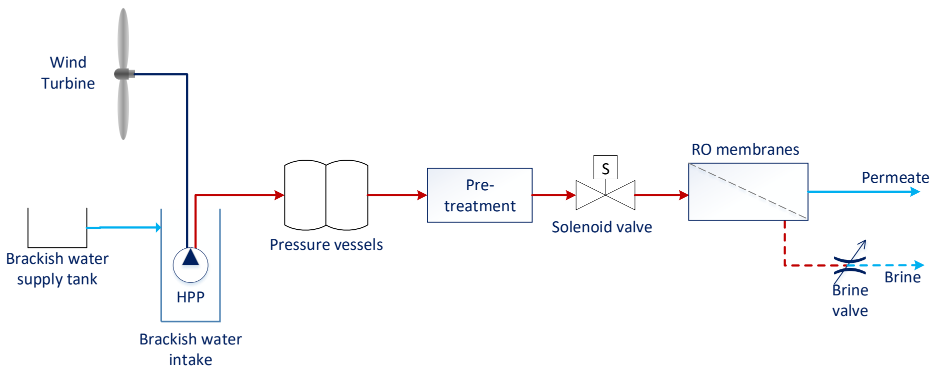

Figure 5. Schematics of the pilot project described in [77].

The prototype was operational for 13 months, and the data collected during operations proved the effectiveness of such a system, even though the pressure losses of the system amounted up to 52%, and the recovery rate achieved values of 9–9.7%: that was very close to the target value of 10%, but still lower than conventional desalination systems.

The plant resulted to be economically feasible if compared with conventional water production technologies when the capacity is 500 L/d or more, but not convenient when water carting is possible at a distance below 30–40 km. To increase the efficiency and reduce the energy losses associated with the brine stream (over 90% at 10% recovery rate), the use of an energy recovery device was suggested. Furthermore, a self regulation and system control is absolutely needed, and a diesel generator or gasoline pump is necessary to cover for always guaranteeing potable water.

A similar prototype was built and tested in Coconut Island, Hawaii [78], see Figure 6. Again, a multivane wind pump was used to pressurised brackish water, that was stored in a hydro pneumatic flow-pressure stabiliser. However, in this case not one but a series of solenoid valves are used to regulate the flow to the desalination unit, opening and closing sequentially in correspondence of different pressure levels reached in the hydro-pneumatic storage. In this way, the operating water pressure is kept approximately constant, regardless of the wind speeds.

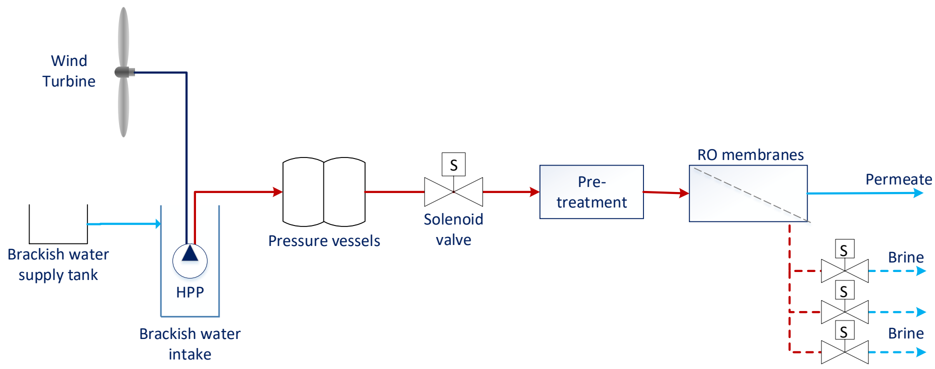

Figure 6. Schematics of the pilot project described in [78].

In the execution of the project [79], the ability to create different pressure levels was used for including water pre-treatment in the system. In the first stage of operation, the water pressure was pretreated. In the second stage, the pretreated water was pressurised further for RO desalination. Furthermore, a modification of the prototype was implemented to let the system work also at different feed water salinities: several RO unit as put in parallel, each one able to work for a specific range of feed water salinity.

The control system measured the concentration of the feed water and then sends the pretreated water to the corresponding reverse osmosis pressure vessel. The prototype was then successfully managing varying wind speed and feed water concentrations. However, both cases discussed above are only suitable for brackish water desalination, since the wind pump system is not able to rise the pressure to the level required for seawater desalination.

A pressure accumulator was presented in WindDeSalter technology [82]. In WindDeSalter technology, the desalination plant is directly connected to the wind turbine, and completely integrated within the wind turbine tower. Two different configurations are possible, either integration with RO desalination or with MVC, as shown in Figure 7. In both cases, seawater is pre-filtrated and stored in a built-in tank on the bottom of the tower. From there, the prefiltrated seawater is pumped up for being desalinated.

In the case of RO desalination, water is pumped up to the nacelle, where pumps connected to the rotor via a gearbox pressurise it and send it to the pressure accumulator and to the RO units, located on the tower just below the nacelle. The pressure accumulator smoothen the pressure fluctuations and the peak loads, while a control device regulate the pressurised volume flow of sea water via a flow control valve, and the power produced by the wind turbine via the blade pitch mechanism. Furthermore, several pumps and RO desalination unit can be activated or deactivated depending on the available wind power.

In the case of MVC desalination, the pre-filtrated seawater is first pre-heated, and then it is pumped to the evapourator/condenser located in the top of the tower. In this case, the compressor of the MVC system is directly connected to the rotor of the wind turbine. Then, the freshwater and the brine produced are handled as in the RO desalination configuration. The authors concluded that such a system is feasible and cost competitive compared with conventional technologies.

An innovative hydro-pneumatic energy storage system was integrated in a floating offshore wind-driven seawater desalination system in Cutajar et al. [81], in Figure 8. In this case study, a floating offshore wind turbine supported by a tension leg platform is directly used for pressurising seawater. The rotational motion of the rotor is converted in linear motion by a swash plate piston pump, replacing the generator in the nacelle.

The pressurised seawater is then accumulated into the submersed chamber, located into the gravity foundation of the tension leg platforms and anchored to the seabed, of a two chamber hydro-pneumatic storage. The air with which both chambers are pre-filled is then pushed trough the umbilical into the other, floating chamber and compressed. This way the system is charging and the energy is stored. When there is not enough wind, instead, the air in the floating chamber is allowed to expand, pushing seawater out at high pressure.

The pressurised seawater is then directed to the reverse osmosis module, located on the platform, and is desalinated. The freshwater obtained can be pumped to the shore by a booster pump, while the brine is recirculated in a PX ERD exchanger. The residual energy in the brine is transmitted to part of the pre-treated water that is stored in the liquid piston chamber, while the exhausted brine is discharged into the open sea.

The paper provides a mathematical and computational model to simulate the system and analyse two flow control schemes. The first one acts to maintain a constant pressure to the feed flow to the RO membranes, while the second one aims at maintaining a constant flow rate. Both schemes prevent the emptying or the overfilling of the lower chamber. Results from the simulation show that the proposed configuration and control schemes provide a good smoothing of the fluctuations, being able to produce 33,000 m^3/d with a 5 MW wind turbine and 6.5 MWh hydro-penumatic storage.

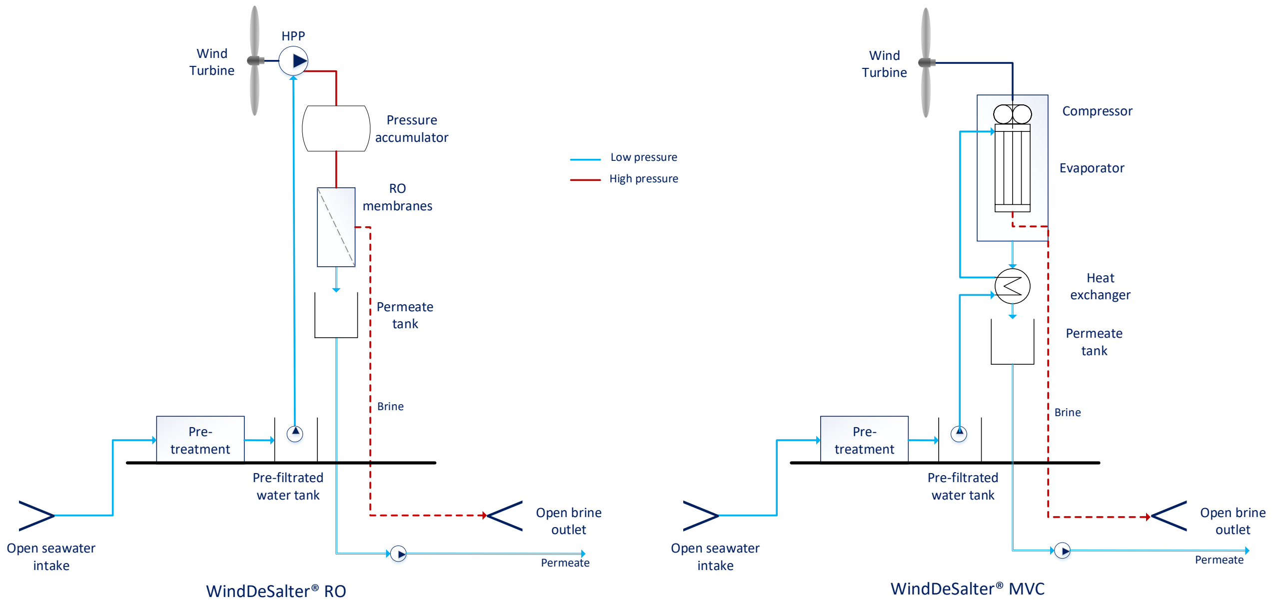

Figure 7. Schematics of the pilot project described in [82]: on the **left**, the version with reverse osmosis as desalination technology; on the **right**, the one with mechanical vapour compression.

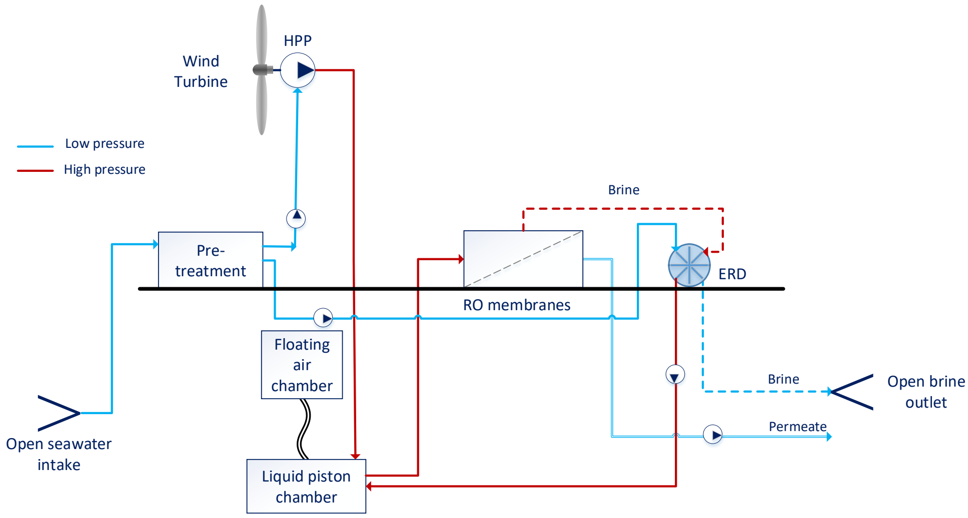

Figure 8. Schematics of the pilot project described in [81].

6.2. Without Energy Storage but Direct Connection

However, energy storage systems increase the initial cost and the weight and volume of the wind-driven desalination plant. There is no energy storage in the small prototype described by Heijman et al. [80], in Figure 9. The rotor of the multivane wind turbine is directly connected to the shaft of the high pressure pump of the SWRO desalination unit at ground level, by means of a bevel gear, a vertical shaft and a belt drive.

The motor of the energy recovery device is mounted on the same shaft of the high pressure pump, therefore they always have the same rotational speed. Due to the direct mechanical connection of the wind turbine and the pump and the absence of any intermediate storage device, the pump speed, and so the permeate production, varies with wind. In this way, the recovery rate can be maintained fixed without the need of any extra regulators ad controls. Dealing with variable process conditions, the prototype was able to achieve a maximum recovery of 25% (compared with 40–50% of typical value for seawater desalination in commercial systems) and a variable permeate flow. The system includes a tank for storing freshwater to cover for the period of wind unavailability.

The high pressure pump replacing the generator is located in the nacelle and directly connected to the wind turbine rotor in the prototype described in Greco et al. [83], see Figure 10. Pre-filtrated seawater is pressurised in the nacelle and delivered partly to a SWRO desalination module for freshwater production and partly to a Pelton turbine generator for electricity production.

An isobaric energy recovery device (iSave) is used to recover energy from the brine, pressurising part of the seawater. This portion of seawater is then deducted from the water that is processed by the high pressure pump. The prototype, that is mainly composed of on-shelf components, is designed for a rated desalination capacity of 600 m^3/d of produced water. Given the direct connection between the wind turbine rotor and of the high pressure pump, the flow rate and the pressure of the stream provided by the latter vary depending on the wind speed.

Therefore, an operational strategy is proposed to let the system operate within the limits imposed by each component, maximising freshwater and electricity production. The operational strategy is based on the active control of the collective blade-pitch mechanism, on the opening position of the spear valve of the Pelton turbine, and on the flow rates handled by the ERD.

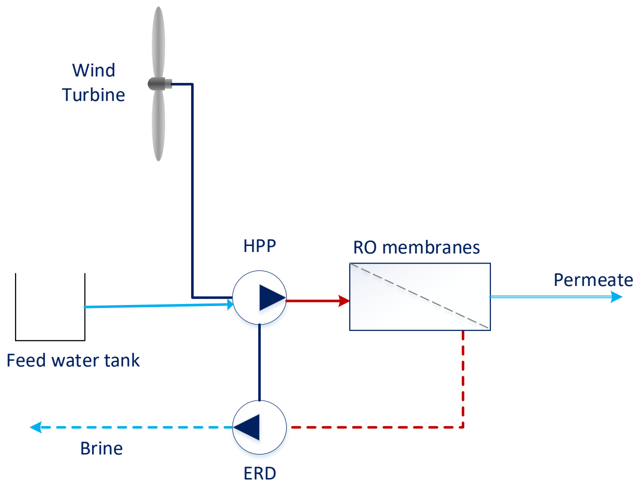

Figure 9. Schematics of the pilot project described in [80].

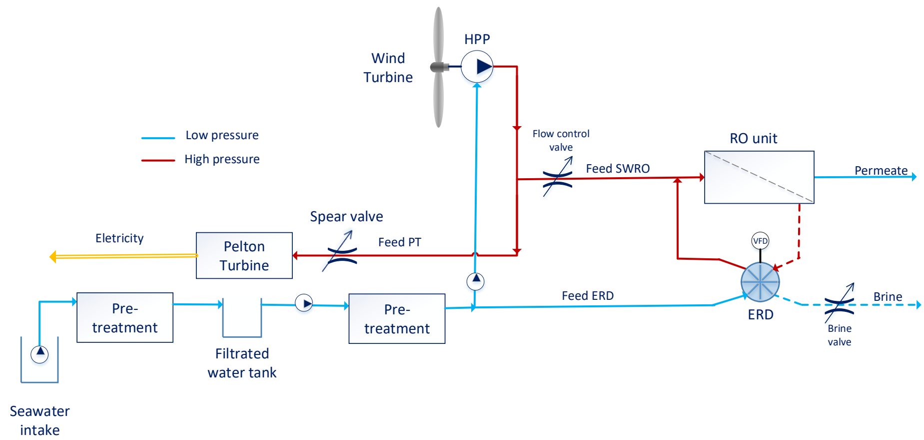

Figure 10. Schematics of the pilot project described in [83].

Finally, a new concept of floating wind turbine, the Wind Energy Marine Unit WEMU, is employed for desalinating seawater in [87,88]. A WEMU is a wind turbine with vertical axis, around which rotates a semi-subermgible rotating pontoon, as a sort of vertical blades structure. A WEMU is provided of a a hydraulic transmission system, consisting of hydrostatic water pumps directly connected to the rotor, and high head water turbines for the production of electricity.

For its application for seawater desalination, two different configurations are proposed, as represented in Figure 11. In [87], the WEMU is used for Multi Stage Flash distillation (MSF) desalination. The water pumped by the hydraulic transmission system of the WEMU is partly used for electricity production via a hydraulic head turbine generator. The electricity generated is used for heating the remaining pressurised seawater, which is than distilled in the MSF plant.

Heat can be recycled from the brine and the permeate by pre-heating the feed seawater through heat exchangers. In [88], instead, the water pressurised by the hydraulic transmission system is directed to an RO module and desalinated. The permeate is then set to the shore. Even in this case energy is recovered, by processing the high pressure brine through a high-head hydraulic turbine generator, producing electricity. According to the authors such a system is the most promising for partially solving the water lack problem in Northern Crimea, with the additional advantage of providing also electrical energy.

While the conventional electrical drive transmission system is well diffused and predominant for wind turbines, the use of hydraulic or mechanical drive transmission systems in wind energy is still in the development phase and covers a niche market. The lower diffusion is therefore reflected in the limited number of prototypes and studies on directly connected wind drive desalination systems. The few pilot tested or proposed have a wide range of wind power capacity (from below 1 kW to 8 MW) and water production capacity (from below 1 m^3/d up to 864,000 m^3/d), have different layout configurations and wind turbine shapes.

However, there is a clear predominance of the reverse osmosis as desalination technology. It is also interesting to notice that the majorities of the most recent prototypes or case studies are intended for offshore applications, rather than onshore. From the tests and simulations presented it is seen that there are several operational strategy that can be adopted to successfully cope with the fluctuations of wind energy and, once the technologies will develop further, the results may be promising and competitive with respect to conventional systems.

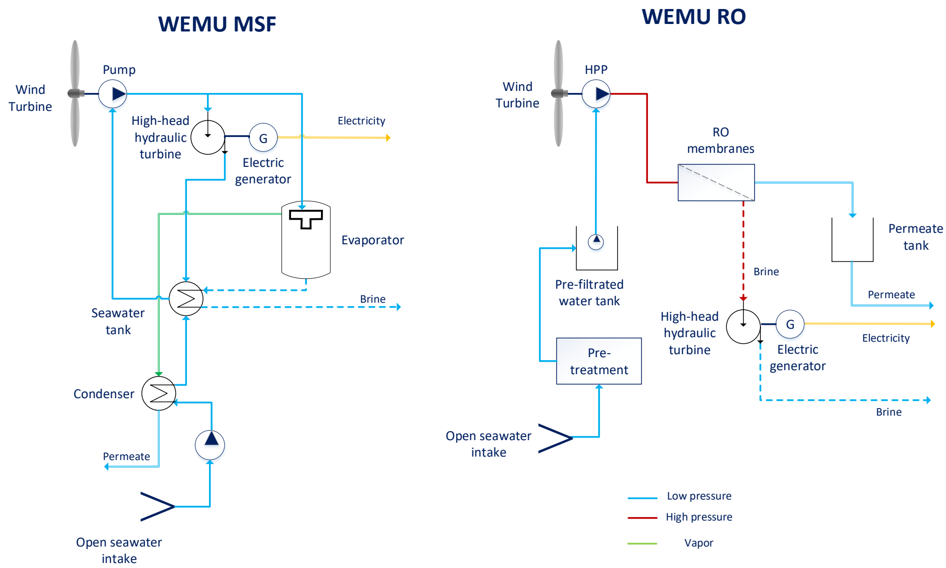

Figure 11. Schematics of the pilot project described in [87] (on the **left**) and on [88], on the **right**.

7. Conclusions

The growing interest in wind-driven desalination in the last years led to an intensive research production, thrust by the need of fighting water stress. The recent developments and dissemination of wind energy together with the increased efficiency of desalination technologies have led to a decrease in the cost of wind turbines and desalination plants. However, the actual penetration of wind-powered desalination is still low, compared to the global freshwater supply.

This paper reviewed the studies on wind-powered desalination and the status of the technology employed in such studies. Direct or indirect connection, the use of electricity or other energy transport media, and the availability of a grid with or without energy storage solutions were considered.

One of the main factors hindering the penetration of wind-driven desalination is the intermittency of wind availability with the associated power fluctuations. Therefore, the effective integration of wind energy with desalination systems depends on the ability of the selected configuration to mediate between the variability of the wind resource and the approximately steady operations required by the desalination system. The most common desalination methods used in combination with wind energy were identified to be RO and MVC.

RO is the most common technology for standalone applications due to its high versatility, being suitable for a wide ranges of feed water salinity and plant capacity. In addition, the studies so far has shown that RO membranes have sufficient abilities to handle variable operating conditions, within the safe operation range provided by suppliers. The challenges are in the possible deterioration and wearing effects in the long term, which need to be investigated further.

Systems directly connected to the grid allow an independent operation of both wind and desalination technologies, making it easier for the desalination plant to operate at the design point and steady conditions. They remain the most favourable and cost effective configuration where a grid connection is available. In the absence of grid connection, a storage system can capture the exceeding energy during peak production and/or smooth power fluctuations, but at the expense of higher capital and maintenance costs. The preferred energy storage options for compensating fluctuations and short term storage in wind-driven desalination applications are flywheels and hydraulic energy storage. Batteries are preferred instead for longer duration of required energy storage.

The direct connection between wind energy and the desalination plant uses electricity as energy transfer medium or mechanical-hydraulic energy, which also allow for standalone configurations. Direct-driven solutions, although still in the research and development phase, can be applied in locations where sufficient wind and seawater or brackish water resources are present, and therefore they have great potential for remote coastal areas as well as for small islands.

In the case that an energy storage system is present, or the desalination plant has a variable desalination capacity or is operated under variable conditions, the optimization of the energy management and of the process control assumes fundamental importance; the management of pre-treatment and auxiliaries constitutes an additional challenge, especially in case of direct mechanic–hydraulic connection. Furthermore, it is necessary to assess the effect of fluctuations on equipment behaviour and ageing. Nevertheless, in recent years, research on standalone systems with direct connection is being developed for offshore applications.

In conclusion, wind-powered desalination has the clear potential to produce cost effective and low CO_2 emission freshwater, especially for small islands and remote locations. The main techno-economical challenges remain in the optimization and integration of the whole system.

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Abbreviations

The following abbreviations are used in this manuscript:

BWRO	Bracksih water Reverse Osmosis
ERD	Energy Recovery Device
HPP	High Pressure Pump
MED	Multi Effect Distillation
MSF	MultiStage Flash Evapouration
MVC	Mechanical Vapour Compression
PV	Photovoltaic
RES	Renewable Energy Sources
RO	Reverse Osmsosis
SWRO	Seawater Reverse Osmosis Desalination
TDS	Total Dissolved Salts
TVC	Termal Vapour Compression
USD	US Dollar
VC	Vapour Compression
WT	Wind Turbine

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