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Lessons learned in wind-driven desalination systems in the Canary Islands: Useful knowledge for other world islands

Pedro Cabrera [a,*], José A. Carta [a], Carlos Matos [a], Henrik Lund [b]

[a] Department of Mechanical Engineering, University of Las Palmas de Gran Canaria, Campus de Tafira s/n, 35017 Las Palmas, Spain
[b] Department of Sustainability and Planning, Aalborg University, Rendsburggade 14, Denmark

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ABSTRACT

This study addresses the imperative transition towards renewable energy for the powering of desalination technologies, focusing particularly on island contexts. The Canary Archipelago serves as a unique wind energy-desalination laboratory, with numerous experimental projects conducted since the late 1980s. The lessons learnt that are identified in this paper highlight the critical factors influencing project success or failure, including the modernization of desalination plants, the optimal selection of wind farm sites and turbine technology, adequate resources for operating and maintenance tasks, and optimal battery sizing to minimize system shutdowns. In this context, reverse osmosis emerges as the most advantageous technology for variable operating conditions. System interfaces between wind turbines and desalination units are also discussed and it is identified that further research is needed for mechanical or hydrostatic interface systems, while electrical interface systems suit low-medium water demand areas. Recommendations are given for system design and maintenance with the aim of providing valuable information for other island communities grappling with the water-energy nexus and climate change mitigation.

1. Introduction

Increased water use in agriculture and industry, a continuously rising world population, the effects of economic development and climate change, and the resulting changes to consumer patterns are all factors contributing to the growing interest in desalination in many regions of the world [1–3]. While many desalination technologies have been employed, the market is currently dominated by the use of reverse osmosis (RO) [4]. Although desalination techniques, in general, have undergone improvements in terms of efficiency [5], they consume significant amounts of energy which tend principally to be obtained from fossil fuel sources [6]. The high correlation between the use of fossil fuels and climate change is widely recognised in the scientific world [7]. In this context, governments in many regions of the world have established roadmaps for the elimination of the carbon footprint left behind when such fuels are used [8]. The strategies that have been put forward in this regard include, among many others, a transition to the use of low cost, non-polluting and technologically mature renewable energies (REs) [9,10]. Given the significant energy consumption associated with current desalination technologies [11–13] and, in consequence, its potential impact on the carbon footprint [12,14], the replacement of fossil fuels with REs in this sector is of crucial importance [9]. As pointed out in [15], sustainable development in this field is dependent on the availability of efficient and reliable designs of medium and large capacity RE-powered RO desalination plants. However, as reported by Ghaffour et al. [16], currently only about 1 % of total desalinated water is based on energy from renewable sources. In addition, in terms of roadmaps, specific consideration needs to be given to the considerable number of inhabited islands in the world which either urgently require or will soon require water desalination to cover their consumers' needs [17]. This specific consideration is required because of certain characteristics that are particular to islands, including the fact they tend to have weak electricity grids. While an analysis of the literature reveals a large market potential for RE-powered desalination systems worldwide [16], the studies that have been undertaken on their implementation in islands have been largely theoretical in nature [18,19]. Very few papers have been published on island-centred strategies for the implementation of RE-driven desalination systems or on the lessons learned in practical trials of such systems at diverse scales, and those that have been published have tended to focus on particular cases [20,21]. Among the

* Corresponding author.
E-mail address: pedro.cabrerasantana@ulpgc.es (P. Cabrera).

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many islands of the world with a growing need for desalinated water are those found in the Canary Archipelago (Fig. 1).

1.1. The water-energy nexus in the Canary Archipelago

As a consequence of the limited water resources that were available in the islands, the use of desalination technologies was first considered in the mid-1960s [22]. Indeed, in terms of the deployment of water desalination, the archipelago was a pioneer in Europe [23,24]. The generalized use in the islands over the last 50 years of the different desalination techniques has meant a high degree of specialization in water treatment sectors and the accumulation of a considerable amount of know-how in terms of the installation, exploitation, maintenance and operation of desalination systems at different scales [25–28]. By the end of the last century, the archipelago was considered a worldwide reference with respect to desalination plants [22,29]. In 2018, 54.12 % of the 501,735,000 m^3 of water available for human consumption or agricultural use came from desalination (Fig. 2) [30].

The energy structure of the archipelago is characterized by the existence of seven small-sized independent insular generation systems (Fig. 1 and Fig. 3) [31].

The association between the energy and water sectors has long been recognised in the archipelago and is contemplated in detail in the Canary Islands Energy Plan (PECAN by its initials in Spanish) [32]. The particular characteristics of the islands led to the initiation, at the end of the 1980s, of historic proposals, involving both the public and private spheres, for sustainable energy-water strategies [33]. One of the objectives of the actions undertaken by public bodies was the rational use of energy to ensure the maximum possible exploitation of endogenous REs (principally wind and solar) associated to water cycles.

R&D efforts on the islands began to intensify, headed by Las Palmas de Gran Canaria University (ULPGC) and two research centres which were set up for this purpose, the Canary Island Institute of Technology (Spanish initials: ITC [34]) and the Institute of Technology and Renewable Energies (Spanish initials: ITER [35]). The strategies considered to deal with the challenge of meeting water demand can be classified into three basic types: the integration of desalination and wind generation systems in conventional electricity grids (on-grid systems), the use of hybrid generation systems, and the direct use of wind energy to power desalination plants (off-grid systems) (Fig. 4). Attention at that time focussed on wind energy.

The first actions were taken after the areas with the highest wind potential in each island were determined and analysed by the ULPGC and the results published [33]. At this point, awareness began to grow in the business sector of the potential profitability of these systems. These initial actions were undertaken by the owners of large desalination plants and comprised the use of on-grid wind energy systems for water desalination [36] (Fig. 4). Wind farms (WFs) situated in sites with high wind potential dump all the energy they generate into the conventional grid and the desalination plants are treated by the energy system as one more load. For the purposes of the present paper, this is henceforth referred to as Strategy A. The aim was to reduce the electrical energy consumption costs of the plants, which were heavy energy consumers, by trying to balance their annual energy consumption with WF production. Such actions in general can contribute to lowering annual production in fossil fuel-based power plants.

The particular characteristics of wind energy have repercussions for power system generation, energy storage requirements, conventional generation capacity, generation reserves capacity and the transmission and distribution networks [37]. Because of the particular characteristics of insular electrical systems their electricity grids display certain weaknesses when managing high RE penetrations in terms of system stability, with the consequence that limitations on wind energy generation may need to be imposed. In the Canary Islands, with its high RE potential, this can mean that the wind resource cannot be fully exploited and that the amount of RE that can be used for water desalination needs to be limited. To mitigate this drawback, proposals have been made to increase energy storage systems and allow temporary suspension of the energy supply to desalination plants in emergency situations or, in other words, load shedding. In this context, the Canary Government has published specific regulations for the operation of on-grid desalination systems with the participation of renewables to allow the greater integration of the latter. One option contemplated in the regulations is the use of on-grid wind energy-desalination systems in which the WTs are permanently coupled to the desalination plant via a direct connection that is independent of the conventional grid. The electrical energy generated by the WTs is used, firstly, to meet the instantaneous power demands of the desalination plant. Any shortfall or surplus imbalances between the instantaneous power generated by the WTs and the power consumed by the plant are resolved by either acquiring power from the conventional grid or injecting power into it [6]. For the purposes of the present paper, this is henceforth referred to as Strategy B (Fig. 4).

Another of the operating strategies investigated concerns the use of off-grid wind energy-desalination (Fig. 4). In this regard, both wind-diesel systems and isolated systems that totally discard the use of fossil fuel sources have been developed [38,39]. With the latter type, the

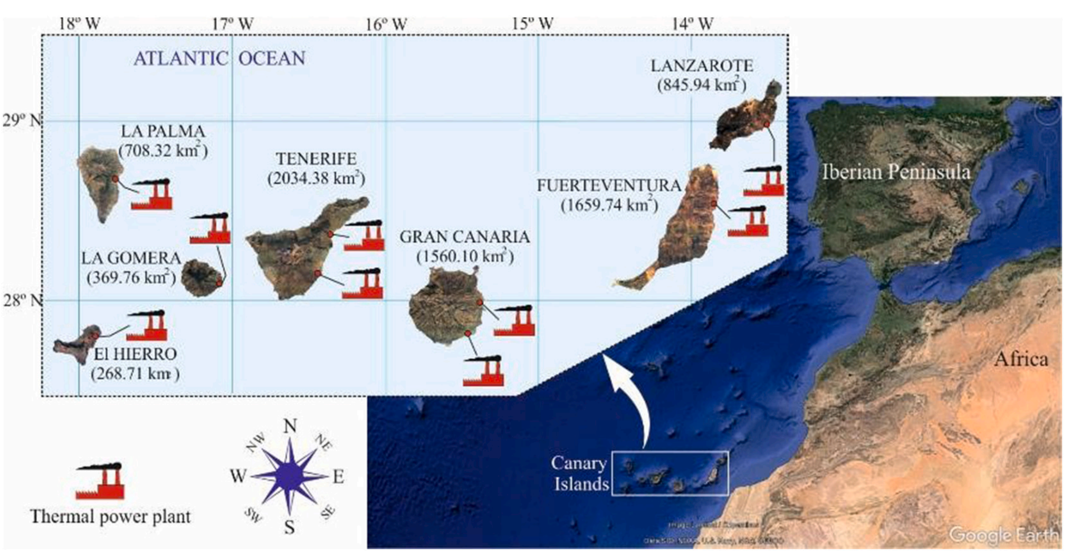

Fig. 1. Location of the reference case.

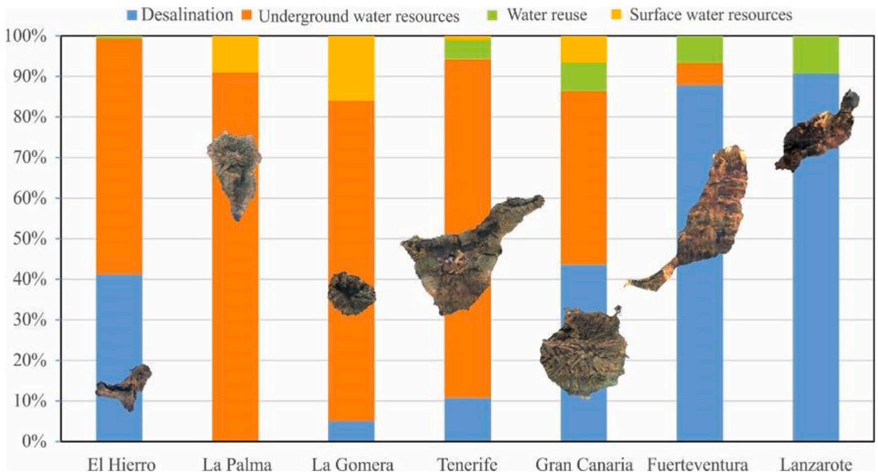

Fig. 2. Percentages of water resources in the different islands of the Canary Archipelago.

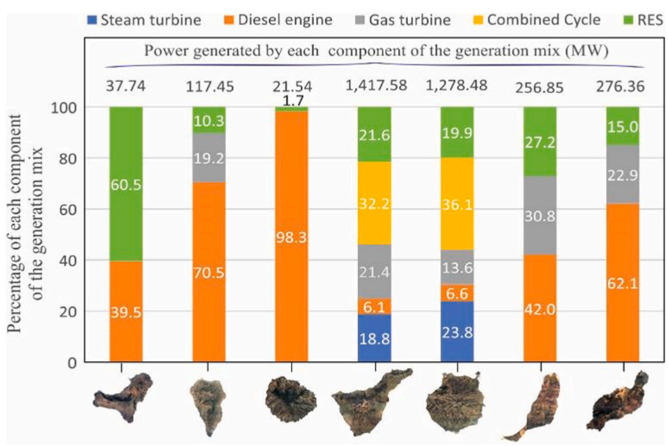

Fig. 3. Configuration in 2021 of the generation park of each island by electrical power.

aim has been to resolve the problems associated with the variable nature of wind energy. In this context, the testing and development have been undertaken of systems designed with the aim of adapting the energy consumption of the plant to the electrical energy (or mechanical in some of the patented and tested prototypes [40,41]) produced by the WTs in each instant. For this purpose, these systems have been designed with flexible operating criteria; through dynamic modification of the desalination capacity [42,43], dynamic variation of operating parameters [41,42,44–47], or joint use of the two techniques [48–52].

Given the large number of experimental works developed on the islands, the Canary Archipelago can be considered a veritable RE-desalination laboratory. In this context, and with the joint aims of promoting the use of RE for desalination in the islands and other nearby island systems, increasing public awareness of the importance of the water-energy nexus, training young adults in the installation and maintenance of RE, desalination and water reuse systems, and promoting entrepreneurial interest in these fields, via its Department of Process Engineering and Mechanical Engineering, the ULPGC provides education on wind-powered desalination at various levels [22]. The ULPGC is also a member of the DESAL+ LIVING LAB platform [53], an initiative of the DESAL+ project, which is a fully equipped public-private ecosystem located in the Canary Islands where researchers, managers, technicians, businesses, water bodies and knowledge institutions can cooperate and research, develop, test and validate water desalination solutions from the water-energy nexus perspective and an RE-based approach.

1.2. Aim, novelty and key contributions of this paper

The aim of the present paper is to provide detailed information about the numerous lessons that have been learnt from the many experiments and projects that have been developed in the Canary Archipelago since 1984 in the field of wind energy-desalination. We believe that the knowledge that has been acquired may be of use in many islands of the world without access to drinking water but where brackish water or seawater could be converted into potable water by using the available wind as an energy source. The novelty of this work lies in the timeline-based analysis and description of the research experiments and projects that have been undertaken, the aims that have been pursued and the projects that have been undertaken involving wind-powered desalination systems in the Canary Archipelago with a view to alleviating the problems associated with a scarcity of drinking water. One of the study's key contributions is to explain the critical factors that led to the expected or unexpected results that were obtained. The evidence that explains the possible causal relationship between the factors that contributed to the outcome is set out, and various recommendations are provided that would allow resolution of the problems that have been identified, the mitigation of other risks, and the repetition or enhancement of successful outcomes.

2. Method

There are diverse methodologies that can be used to facilitate the generation and capture of knowledge in organizations with the aim of identifying lessons learned [54–58].These methodologies include the use of case studies. The method that is proposed in the present paper to document the lessons that have been learned and to specify the acquired knowledge which it is hoped to disseminate for replication in other islands comprises three stages (Fig. 5). As can be seen in the block diagram of Fig. 5, in the first stage, we provide a timeline of the experiments and projects that have been developed in the Canary Archipelago in the field of wind energy-desalination and a description is given of the background to identify the lessons learned. Explaining the background entails describing the experiments being analysed, their aims, the context in which they are taking place and the moments and/or critical factors that led to obtaining or not the expected results. Of the two main approaches that can be employed (reactive and scheduled) to identify lessons learned, it was decided in this work to use the reactive type [54]. This approach requires the identification of specific successes and failures from which to learn. Given the participation of the authors in the identification of the areas with the highest wind potential in each island, as well as in some of the stages (design, construction, setting up, testing, maintenance, assessment, etc.) of many of the projects described in this

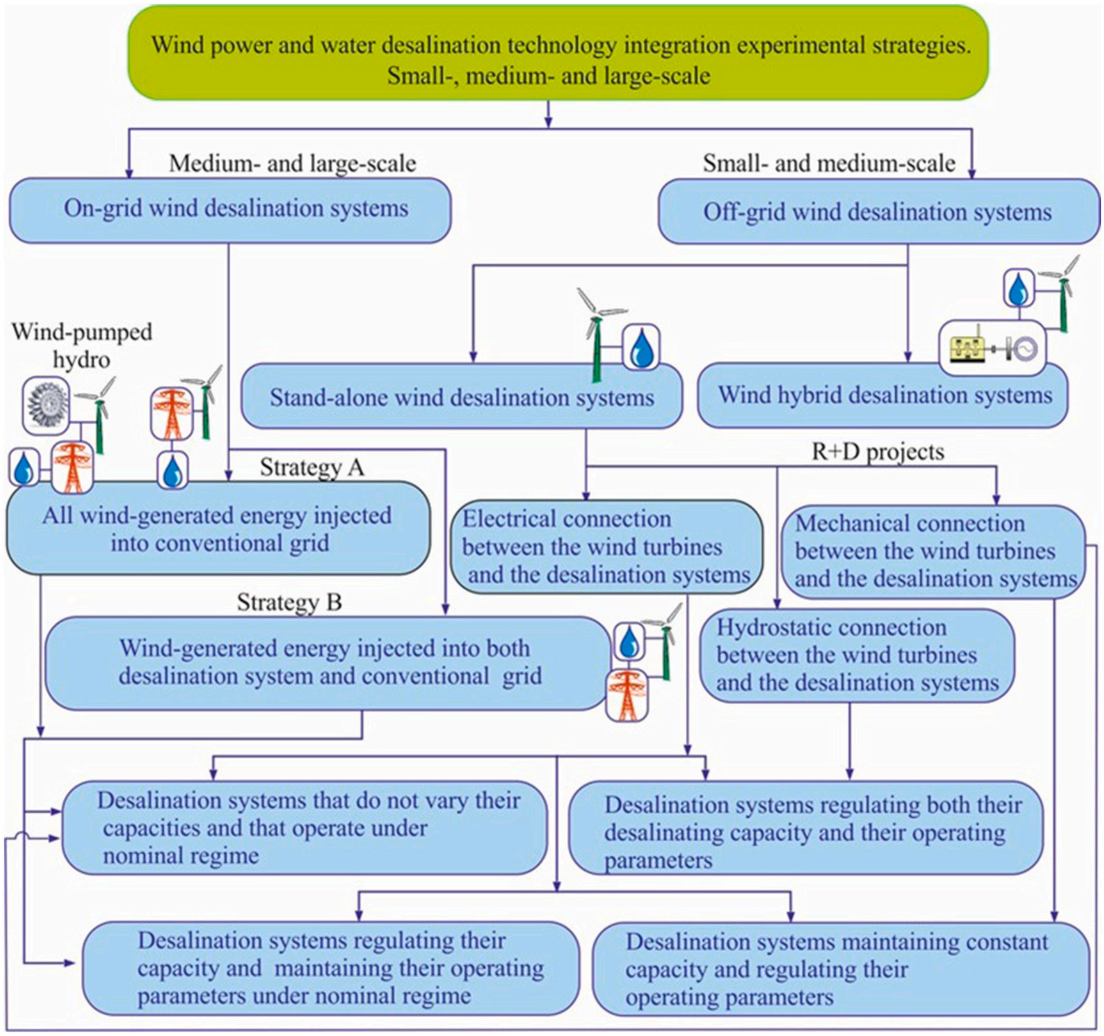

Fig. 4. Classification of wind-powered desalination systems.

work, in these cases the authors have taken on the role of main identifiers. In the case of projects in which the authors were not involved in any of the stages, in most cases one or more visits was made to the installations and information about them was obtained in situ. Most of these latter projects pertain to strategies A and B and the intention was to identify lessons learned in relation principally to the technologies employed (both in the WFs and in the designing and retrofitting of the desalination plants) and the sites where they were installed. For a few of the projects, the information was gathered from publications which are duly referenced in this work. In the second stage, we analyse the lessons that have been learned, with the aim of expressing the relation between the results obtained in the different projects with the different strategies employed and the conditions or causes that impacted those results. Based on the lessons learned, we then present, in a third stage, a series of recommendations to, under similar circumstances, correct certain problems, mitigate risks, and repeat or improve on successful outcomes.

3. Results of the identification of lessons learned, analysis undertaken, discussion of the results and recommendations made based on the analysis

This section describes, analyses and discusses the information gathered from the lessons learnt in the different projects undertaken in the Canary Islands, following the structure indicated in section 2 (Method).

3.1. Identification of the lessons learned

As shown in Fig. 6, the experimental projects implemented within the framework of water desalination with wind energy began in the islands in October of 1984.

3.1.1. Experiences of on-grid installations with Strategy A

Lanzarote in 1993, 2006 and 2018. The first Strategy A-type system was established in the islands in Lanzarote in 1993. The company INALSA (Insular de Aguas de Lanzarote S.A) installed a WF in an area called Los Valles (Fig. 6). INALSA is a publicly owned company responsible for the production and supply of water for human consumption in the entirety of Lanzarote and the small neighbouring island of La Graciosa. The WF, with a rated power of 5.28 MW (Fig. 7A), was sized so that the annual energy produced would be able to meet a specified percentage of the total energy demand of the desalination plants available at that time. It was not possible at the time to increase the capacity of the WF because of grid wind energy penetration limits. The WF comprised 48 WTs, 6 with MADE technology [59] (AE-23 model with 180 kW rated power) and 42 with AWP technology [60] (AWP 56–100 model with 100 kW rated power). In the period 1993–1996, the energy produced by the WF was estimated to have covered 27.4 % of the energy consumed by the desalination plants installed in the areas, called Janubio and Díaz Rijo (Fig. 7C), considering a SEC of 5 kWh/m^3 [24,29]. In the same period, the mean water production of INALSA, whose energy

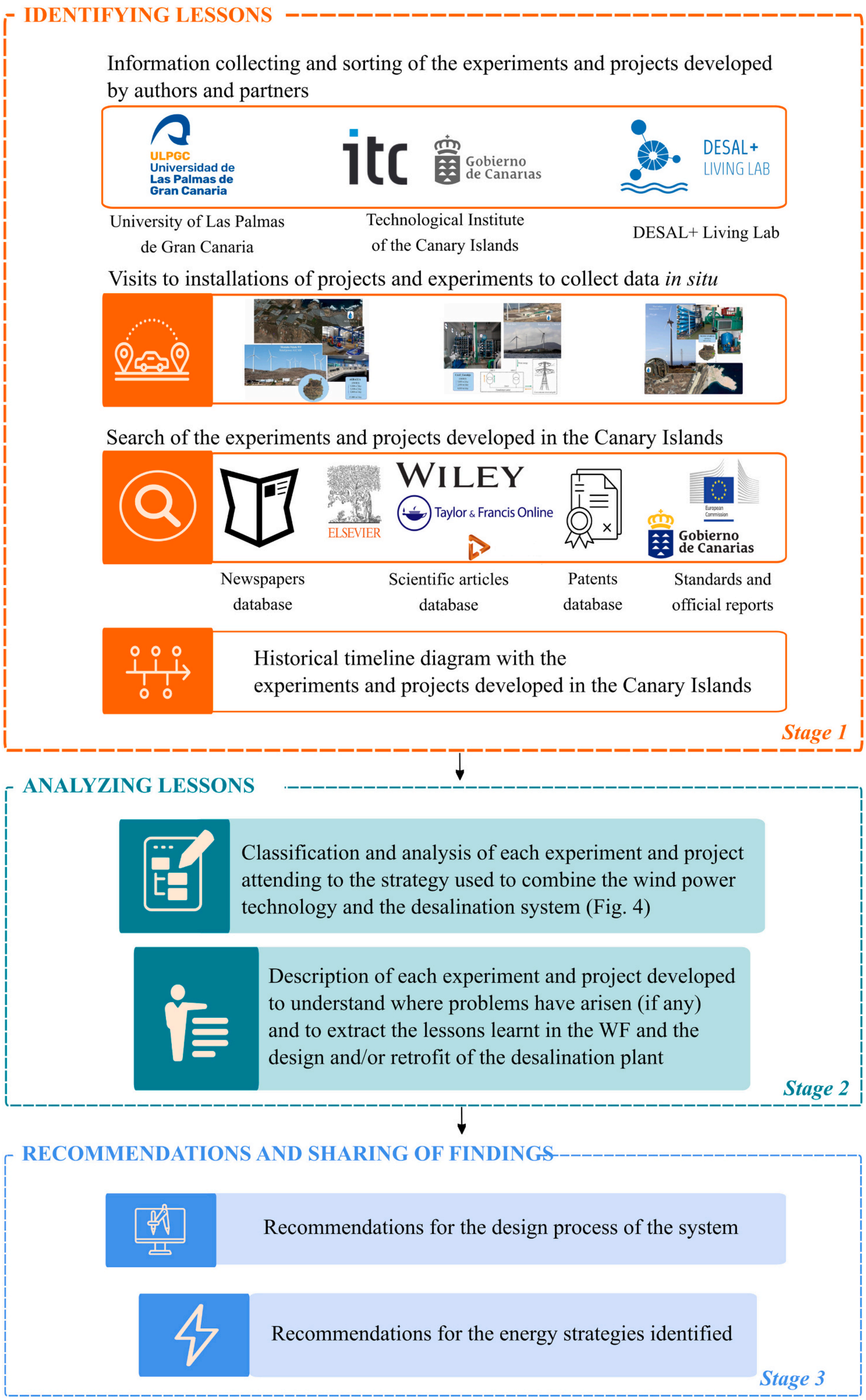

Fig. 5. Method used for the elaboration of the research, based on the lessons learnt procedure recognised in the literature [54–58].

costs it was hoped to reduce with the project, was 8.62 Hm^3/year. (Fig. 7D). Because of the increase in freshwater demand, the capacities of the desalination plants gradually increased over the years, reaching 24.7 Hm^3 by 2018 (Fig. 7D). Currently, the desalination capacities are 73,000 m^3/day and 18,000 m^3/day in the Díaz Rijo and Janubio production centres, respectively. As a result of the increases in production and the obsolescence of the WTs that were initially installed, the percentage of energy consumed by the desalination plants and covered by wind energy fell substantially over the 1998–2005 period.

For this reason, a repowering of the WF was undertaken in 2006 with the installation of 9 GAMESA WTs (model G52/850 [61]), each with a rated power of 850 kW (Fig. 7B). The total installed power was thus raised to 7.65 MW, and the mean energy consumption of the desalination plants in the period 2007–2017 covered by the WF was 20.4 % (Fig. 7C). It was also possible with the new technology to increase the mean interannual capacity factor (CF) of 23.7 % and the interannual

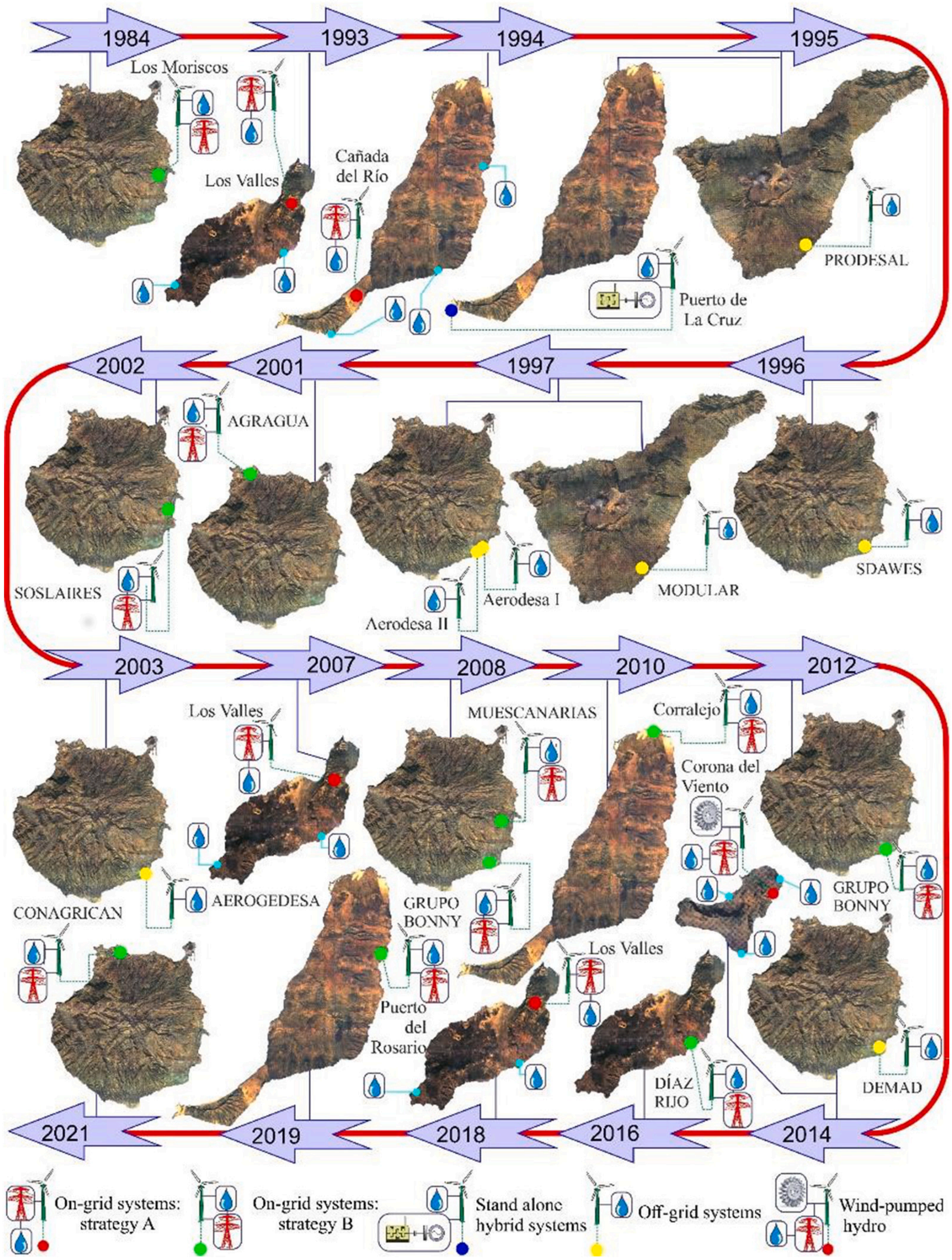

Fig. 6. Timeline history of wind energy systems for water desalination in the Canary Archipelago.

mean equivalent full-load hours value of 2072 h, calculated for the period in which the first WF was in operation (Fig. 7D). The term 'equivalent hours' represents the energy produced in a specific period per unit of installed wind power (kWh/kW). The CF is simply the percentage of the number of equivalent hours with respect to the reference number of total hours. With the new WF, these values were 36 % and 3154 h, respectively, for the period 2007–2017, as the energy efficiency of the WTs was substantially increased (Fig. 7D). The rated power of the WF was raised once again in April 2018 with the installation of another WT of the same model, reaching a capacity of 8.5 MW. This infrastructure corresponds to a desalinated product water of 6,286,820 m^3/year.

Fuerteventura in 1994. In February 1994, after publication of the results of a study to estimate the areas of the archipelago with the best wind resource potential [33], the CAAF (Consorcio de Abastecimiento de Agua de Fuerteventura), a publicly owned company responsible for freshwater production and distribution on the island, installed a WF in Cañada del Río, an area connected to the island's distribution grid (Fig. 6). This WF can be considered to operate with Strategy A as the seawater desalination centres are situated at relatively large distances from the WF. The aim being pursued was to reduce the high energy bill that resulted from the high SEC of some of the technologies used in the 1990s (vacuum vapor compression (VVC) technologies had SEC values in the range of 18 kWh/m^3 to 20 kWh/m^3 [62]).

Fig. S1 shows the annual mean CF (24.76 %) and the annual mean equivalent full-load hours (2169 h) for the period 1995–2014. When the WF began operating the desalinating capacity of the CAAF, whose energy bill it was hoped to reduce, was 16,800 m^3/day (Fig. S1). However,

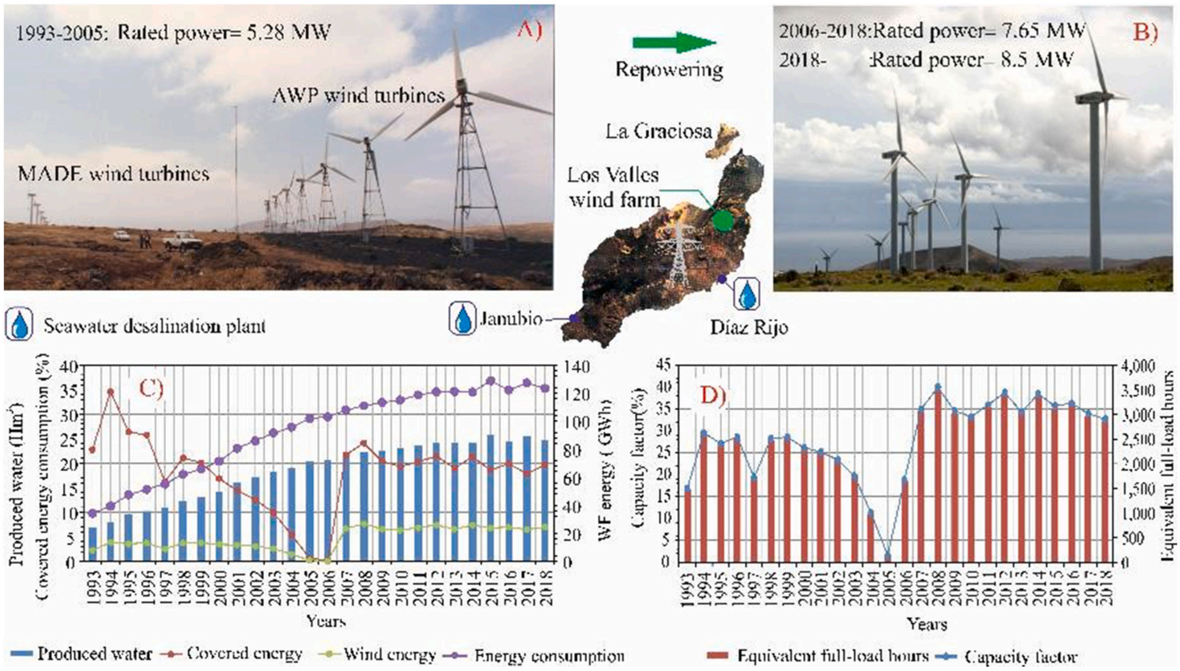

Fig. 7. Los Valles project: A) WF initial installation, B) WF repowering, C) Evolution of water production and WF-generated energy production, D) Capacity factors and equivalent full-load hours of the WF.

this capacity was modified over the course of time, amounting to 23,800 m^3/day in 2014 (Fig. S2). Over the course of the period 1994–2014, SWRO technologies were implemented, the VVC technologies were abandoned because of their high SEC, the Morro Jable plant ceased to be a part of the CAAF and, from 2011, the Corralejo plant began to operate using Strategy B (see Section 3.1.2).

Fig. S3A shows the annual desalinated water flow, the SEC of the desalination plants, and the percentage of desalted water that is considered covered by the energy generated by the Cañada del Río WF for the period 1993–2014. Note that until 1998 the energy consumption of the CAAF centres was relatively high, despite the relatively low desalinated water production (Fig. S3B). This was due to the high SECs (Fig. S3A) of the VVC technologies used until that time. When the VVC technologies were replaced with SWRO technologies there was a reduction in energy consumption, with the energy generated by the Cañada del Río WF in 1999 easily able to cover the CAAF's energy needs (Fig. S3A). In subsequent years, the CAAF carried out modifications to the SWRO technologies to reduce their SECs (Fig. S3A), with the result that in the last years of the study period the SEC was slightly below 5 kWh/m^3. However, due to the considerable increase in desalinated water flow and the growing obsolescence of the WF, it was unable to cover the CAAF's energy needs from 1999 onwards, even when the financial crisis of 2008 caused a desalinated water demand reduction from 2009 to 2011 (Fig. S3A). Despite this, it should be noted that the wind energy generated by this WF between 1994 and 2014 covered 63.66 % of the energy needs of the CAAF centres (Fig. S3A). According to the CAAF [63], the Cañada del Río WF was the driving factor behind the ability to maintain water prices and facilitated societal water consumption (responsible for the highest percentage of consumption). In addition, it is estimated that installation of the Cañada del Río WF resulted in achievements in line with the goals of the PECAN, namely a reduction in CO2 emissions of 364,300 t and the saving of 39,860 t of oil equivalent (TOE) (Fig. S3C).

Given that the Cañada del Río is currently obsolete, it is, according to [64], in a repowering stage with a planned reduction from the 45 units presently found there to 8 WTs of 2 MW rated power each to obtain a total installed power of 16 MW. This project includes the incorporation of a new substation of 20 kV to 66 kV for interconnection with the island's 66 kV transmission network.

El Hierro in 2014. In June 2014, a wind-pumped hydro power plant began operating on the island of El Hierro working in parallel with a thermal power generation system. The thermal system comprised ten diesel engines with a total power of 6 MW. The renewable system comprised a WF with a rated power of 11.5 MW (comprising 5 × 2.3 MW Enercon E-70 WTs [65]) and the pumped hydro system which had 4 × 2830 kW Pelton turbines and a pumping system with eight centrifugal pump units with a total installed capacity of 14.9 MW. The upper reservoir, with a capacity of 380,000 m^3, is connected to the Pelton turbines via a steel penstock of 2350 m in length. The lower reservoir, with a storage capacity of 149,000 m^3, is connected to the pumping system via a 3015 m long steel pipe. When the energy from the WF and pumped hydro system is sufficient to satisfy demand, the diesel groups are disconnected and frequency control is provided exclusively by the pumped hydro system [44].

Three SWRO desalination centres (El Golfo, La Restinga and Cangrejo) are connected to the electrical grid of the hybrid generation system. The location of these plants and their desalination capacities are shown in Fig. 8.

Fig. 9A shows the monthly energy demand of the island in 2018, and the percentage of this demand that is consumed by the three desalination plants. The energy demand and the energy generated by the different sources (diesel, wind, hydraulic) were obtained from the 10-min data published by REE (Red Eléctrica de España [66]), Spain's transmission system operator (TSO). The electrical energy consumption of the desalination plants was obtained considering a SEC of 5.44 kWh/m^3 [24] and the water flows (Fig. 9B) generated in 2018 [67], which totalled 1,125,913 m^3. Fig. 9C shows the monthly consumption of the desalination plants, indicating the percentages that it is estimated were covered by RE-sourced and by fossil fuel-sourced energy. Total annual energy consumption on the island in 2018 was 43.53 GWh, while desalination plant consumption, without considering the full water cycle, was 6.12 GWh, meaning that the total percentage of energy used for water desalination amounted to 14.06 %. As a result of the particular intensity in the summer months of the NE trade winds which cross the Canary Archipelago almost all year round [68], the percentage consumed in July by the plants that was RE-sourced was 95.32 %. The

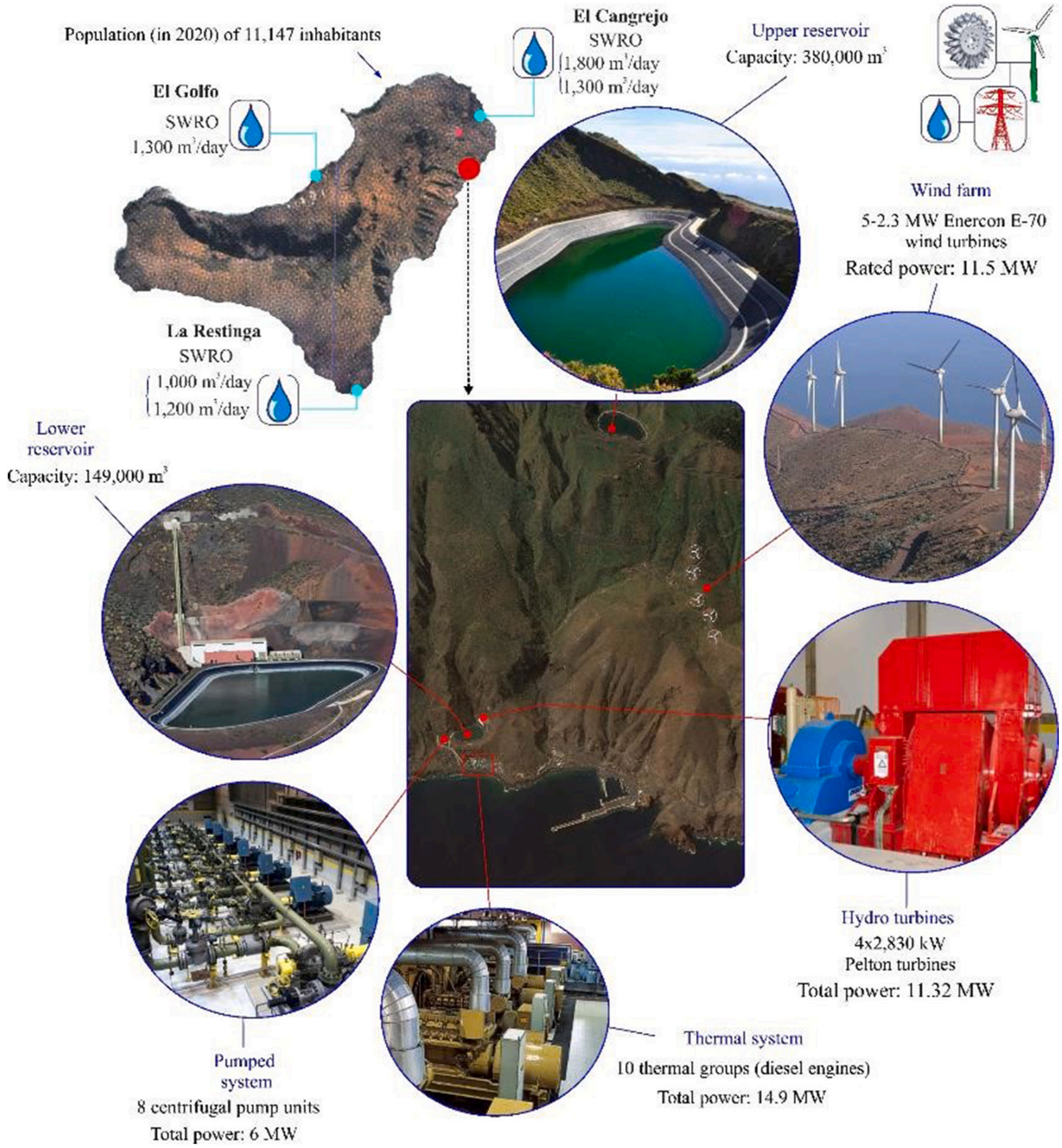

Fig. 8. Desalination plants connected to the hybrid energy system of El Hierro.

annual wind speed histograms, measured at nacelle height, were relatively high [69]. In summer, the frequency of the trade winds regime is very high. This means that although the desalination electricity demand in the summer months is also very high (Fig. 9A), so too is renewable penetration (Fig. 9C). According to [67], there is presently a surplus wind energy that cannot be injected into the grid and, according to [70], in order to provide electrical system stability the grid operator allows wind penetration up to a certain limit, and so the wind power is curtailed. In this context, to improve operation of the system, modifications have been made to the control system [44], and changes have been proposed to the system's operating strategies [71] and to increase the capacity of the storage tanks [70].

3.1.2. *Experiences of on-grid installations with Strategy B*

This type of installation has only been carried out in the islands of Gran Canaria, Lanzarote and Fuerteventura. To date, the Gran Canaria installations have been done by enterprises owned privately, and their aim has been to reduce energy purchase costs for seawater or brackish water desalination, mainly for agricultural use. In Lanzarote and Fuerteventura, the installations are publicly owned and for urban supply.

Gran Canaria in 1984. The first trial of on-grid installations with Strategy B was set up in 1984 at the Experimental Agriculture Farm in Los Moriscos, in Gran Canaria (Fig. 10). The system was developed with the aim of providing guidance to farmers on the island in relation to crop-growing and technical innovations.

The WT used in the system, a GA/WM-14S model [72] Spanish manufactured with a Danish patent [73] and a rated power of 55 kW (Fig. 10), was the first WT installed in the archipelago and connected to the grid using Strategy B. The WT was in operation until 1991. Its purpose was to supply electrical energy to, among other loads, a brackish water desalination plant with a capacity of 75 m^3/day and EDR technology, which was also inaugurated on the same day. A 200 m^3/day capacity desalination plant was already in operation at the experimental farm that employed brackish water RO (BWRO) technology. This plant, which was also used in the system, was installed in 1979 and had seven pressure vessels working in parallel, each fitted with seven TFC 4600 4"

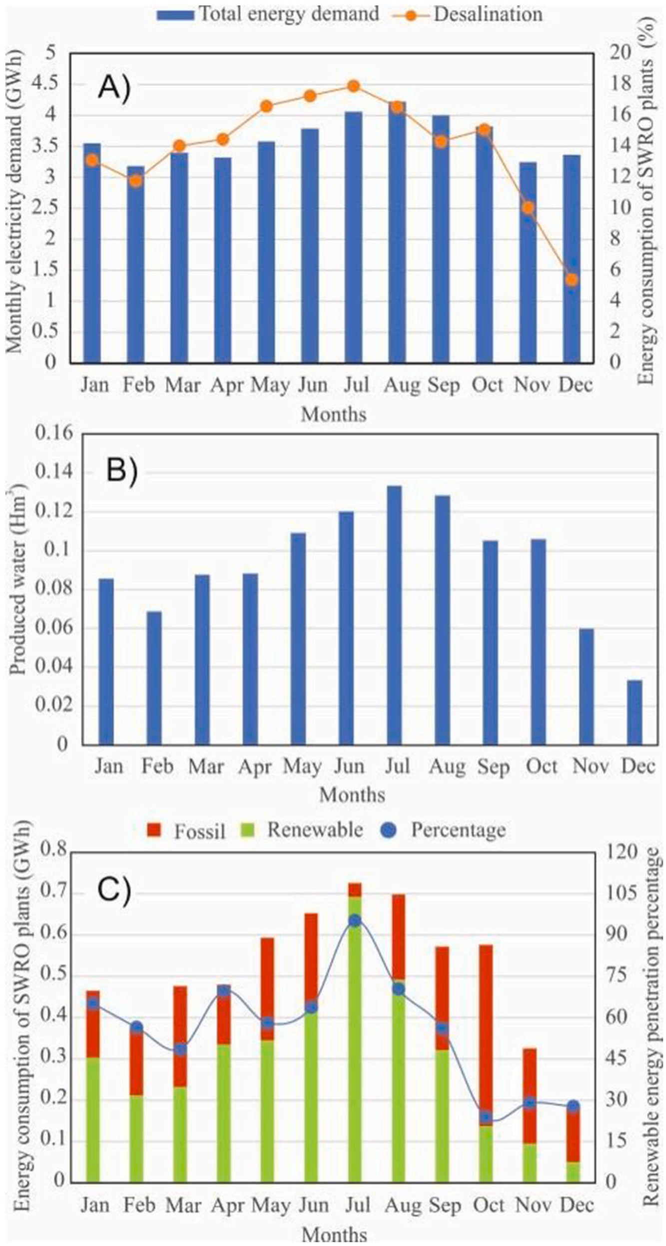

Fig. 9. A) Monthly energy demand in 2018, B) Monthly product water flow, C) Monthly energy consumption of the desalination plants.

spiral-wound membranes manufactured by Fluid Systems. This BWRO plant, which operated with a recovery rate of 50 % and a pressure of 30 bar, had replaced another BWRO plant installed in 1973 with an 80 m^3/day capacity. This latter plant was the first example of the employment of RO technology in the islands. It was replaced because the high colloidal silica content in the feedwater resulted in clogging of its aromatic polyamide hollow fibre membranes (PERMASEP B-9 model manufactured by DUPONT). The plants treated feedwater that was stored in a tank and extracted from a well at the site with an approximate salinity of 10,000 $\mu S/cm$. The permeate was stored in another tank before being used for the different crop trials that were carried out in the greenhouses of the experimental farm (Fig. 10).

The mean annual wind speed was 5.55 m/s and, except for the summer months when the trade winds blow strongest, the monthly mean wind speeds were very close to the cut-in wind speed of the WT (4.5 m/s). In this context, the importance of the correct siting of wind-powered desalination installations is fundamental [48]. In this case, the site selected for the installation of the WT did not have sufficient wind resources and cannot be considered an optimal site for the installation of systems based on Strategy B.

Gran Canaria in 2001. In March 2001, a company going by the name of AGRAGUA inaugurated a WF with a rated power of 4.62 MW (Fig. S5) for the supply of electrical energy to a 15,000 m^3/day capacity SWRO plant. The WF, situated between 95 m and 165 m above sea level on Montaña Pelada, has 7 MADE WTs (AE-46 model [74]), each with a rated power of 660 kW. Installation of the WF was carried out with the aim of reducing the mean annual energy consumption bill of the desalination plant.

The WTs generate AC energy at 690 V, which is raised to the distribution voltage of the farm (20 kV) through 700 kVA transformer stations situated inside the towers. At 20 kV, the energy that is produced is conducted over a 3.5 km underground line (in this way avoiding the visual impact of the cable) to the energy distribution centre in the desalination plant. The plant itself is situated in an area called Playa de Bocabarranco and comprises 3 × 5000 m^3/day lines working at a pressure of 63 bar. The desalination system has kinetic energy exchangers to reduce the energy consumption of the process (Fig. S5).

Fig. 11A shows the monthly energy produced by the WF in the period 2002–2003 [75]. Table 1 shows the mean annual energy production and management values of the WF and the product water flow. The mean equivalent full-load hours of the WF were slightly lower than the mean overall WF values in Gran Canaria in this period according to the 2012 Canary Islands Energy Statistics Yearbook [76]. It is considered that this difference is fundamentally due to the wind potential of the area in which the WF is installed being lower than that in other areas of the island, where equivalent full-load hours above 4500 are achieved. The various devices of the SWRO process are fed the electrical energy produced by the WF and any surplus energy is dumped into the island's grid (Fig. 11B). In the period considered, only 6 % of the energy produced by the WF was dumped into the grid and in neither of the two years analysed was the energy produced by the WF able to match the energy consumed by the desalination system. The energy dumped into the grid in 2002 and 2003 corresponded to 28.32 % and 20.59 %, respectively, of the energy that was purchased. In this context, repowering of the WF would allow an increase in the percentage of wind energy that could be used to cover the demand of the desalination system.

The desalinated water is mainly used for irrigation of banana plantations, a crop which is highly sensitive to seawater salts, and as supply for public consumption.

Gran Canaria in 2002. In June 2002, the Soslaires company inaugurated a WF with a rated power of 2.64 MW to supply electrical energy to a 5000 m^3/day capacity SWRO desalination plant and to other loads [77]. The WF comprises 4 G46/660 GAMESA 660 kW WTs [78]. The plant comprises two lines, each with a capacity of 2500 m^3/day, fitted with SWC3 spiral wound membranes manufactured by Hydranautics. Each line has 17 pressure vessels and each vessel 7 membranes, operating in a pressure range of 57–58 bar. The desalination system has a pressure exchanger (PX) from Energy Recovery Inc. (ERI 120–240), and the pump motors have frequency control, except for the pumps which raise the product water. The desalted seawater, with below 400 mg/l of total dissolved salts (TDS), is used for the irrigation of diverse crops (Fig. S6). The SEC in 2002 and 2003 was 2.8 kWh/m^3, which includes feed consumption (0.4 kWh/m^3), process consumption (1.9 kWh/m^3), consumption in the desalted water elevation process to a height of 90 m (0.3 kWh/m^3) and other loads consumption (0.2 kWh/m^3) [79].

Fig. 12A shows the monthly energy produced by the WF in the period 2003–2005 [75], while Fig. 12B shows the surplus energy dumped into the island's grid [75]. The highest percentage of energy is produced between June and August, due to the strong trade winds that blow in the area with a prevailing NE direction. Fig. 12C shows the annual management of the energy generated by the WF and the energy consumed by the desalination plant in the period 2003–2008 [79]. Fig. 12D shows the equivalent full-load hours and the CFs for the same period. The

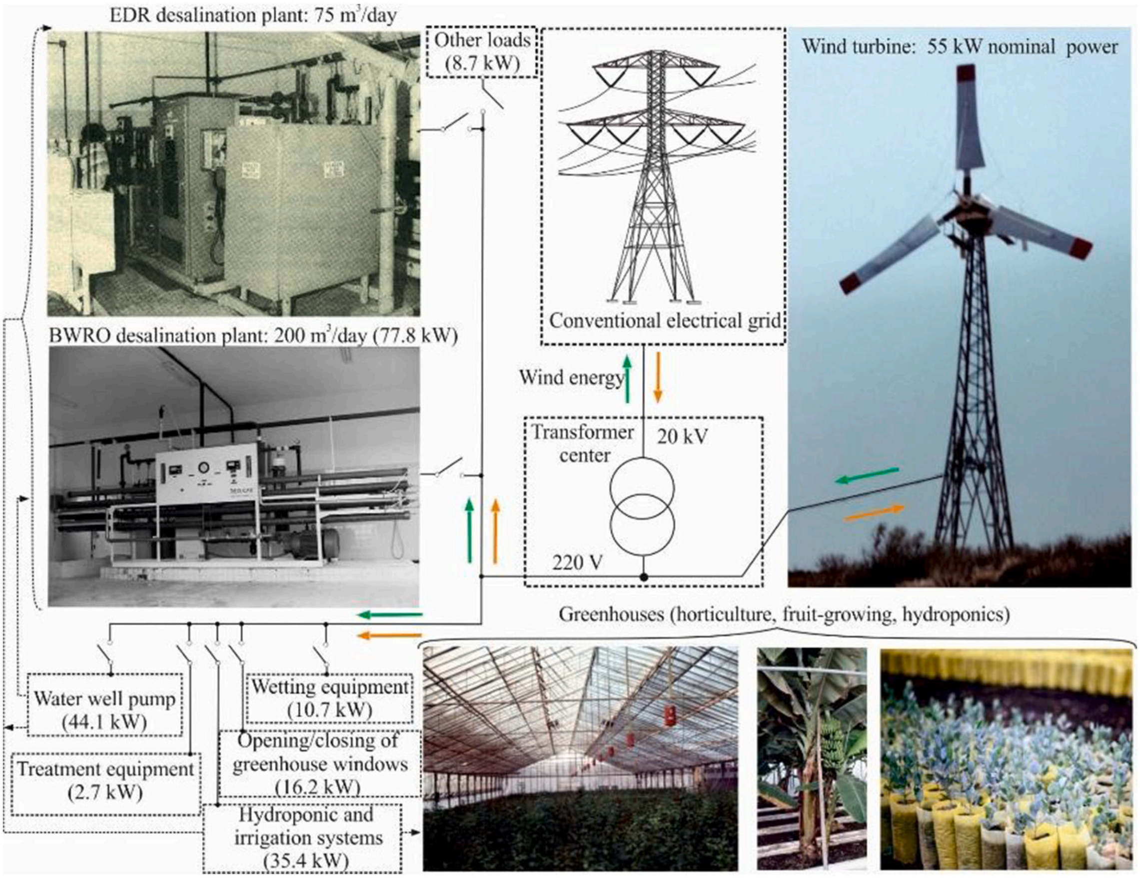

Fig. 10. Los Moriscos Experimental Farm in Gran Canaria.

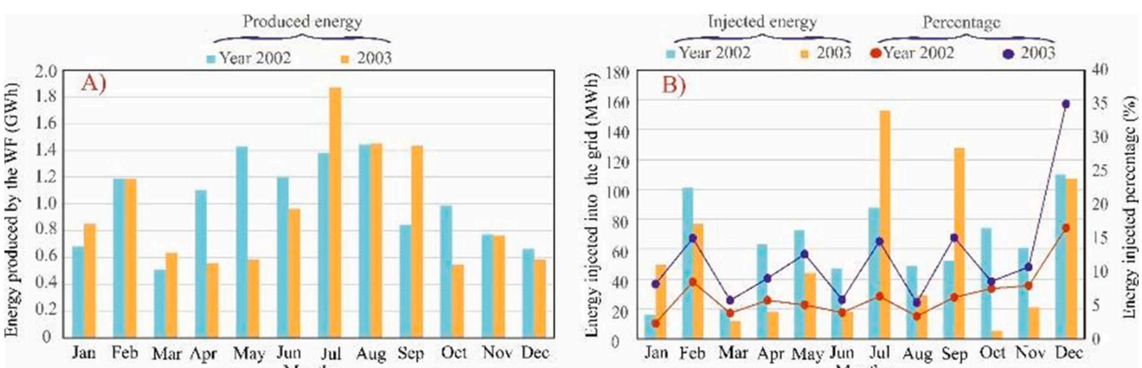

Fig. 11. A) Energy produced by the AGRAGUA WF, B) Energy dumped into the grid.

Table 1
AGRAGUA wind farm energy production values in the period 2002–2003.

	2002	2003
Energy produced by the WF (kWh)	12,205,987	11,424,578
Energy dumped into the grid (kWh)	756,011	664,615
Energy consumed by the plant (kWh)	14,119,484	13,987,581
Energy purchased (kWh)	2,669,508	3,227,618
Product water flow (m^3)	4,782,721	4,691,509
Equivalent full-load hours of the WF	2642	2473
Equivalent full-load hours of WFs in Gran Canaria	2728	2518
CF (%)	30.20	28.20
Mean CF of WFs in Gran Canaria	38.00	38.75

equivalent full-load hours of the WF were again slightly lower than the mean overall WF values in Gran Canaria in this period according to the 2012 Canary Islands Energy Statistics Yearbook [76] (Fig. 12D). Likewise, it is considered that this difference is fundamentally due to the wind potential of the area in which the WF is installed being lower than that in other areas of the island, although WF operating efficiency may also be a relevant factor. In the study period, 71.74 % of the energy produced by the WF was dumped into the island's grid and 28.6 % was used for self-consumption. Of the energy consumed by the plant, 34.71 % was purchased and 65.29 % was supplied directly by the WF. Production was closely related to the freshwater needs of the local population. In 2003, total annual permeate production was 768,395 m^3, whereas in 2004 it reached 1,466,480 m^3 [77]. In the study period, the energy produced by the WF was always greater than the energy

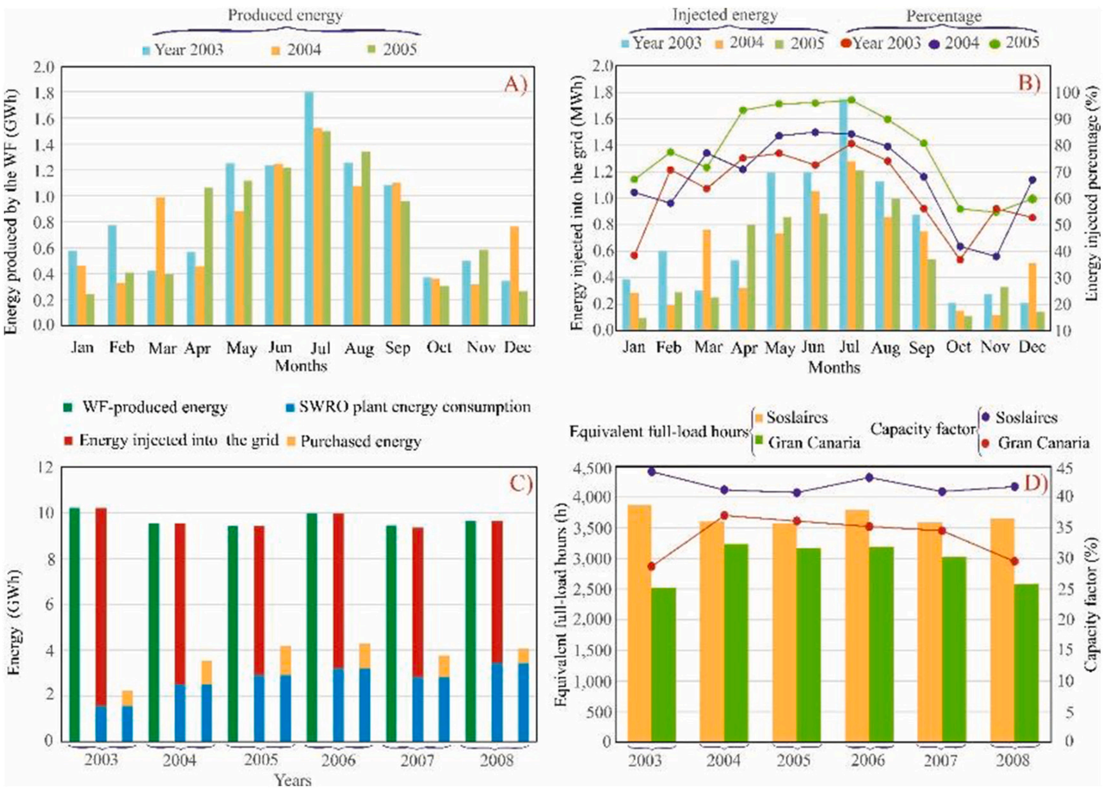

Fig. 12. A) Energy produced by the wind farm, B) Energy dumped into the grid, C) Annual energy management, D) Equivalent full-load hours and capacity factors of the SOSLAIRES wind farm and all Gran Canaria wind farms.

consumed by the desalination system.

Gran Canaria in 2008 and 2011. In 2008, the company Grupo Bonny inaugurated a WF with a rated power of 1.7 MW in the area called Las Salinas del Matorral (Fig. S7). The WF supplies electrical energy to, among other loads, an SWRO desalination plant. The product water is used for crop irrigation (mainly tomatoes and cucumbers, but also bananas and blueberries, among others [80]). In 2008, the WF comprised two GAMESA WTs (model G52/850 [81]), each with a rated power of 850 kW. Subsequently, in 2012, the WF was repowered to a rated power of 2.55 MW through the installation of a third WT of the same model and technology as the original two. The SWRO plant comprises nine lines, each with a nominal capacity of 750 m^3/day. Each line has 10 pressure vessels and each pressure vessel 6 spiral-wound membranes. As a result of the improvements that were gradually implemented in the desalination plant, the SEC values were reduced to 2.2 kWh/m^3 [82]. The technology employed allows a product water with TDS values below 200 ppm [82].

In 2008, the company MUESCANARIAS put into operation an ENERCON WT (model E33 [83]) with a rated power of 330 kW for the supply of electrical energy to a BWRO plant with a capacity of 800 m^3/day and other loads (Fig. S8). The product water is used for the irrigation of diverse agricultural products which require varying water qualities.

Fuerteventura in 2010. With the aim of further reducing its energy bill for potable water production, the CAAF installed a new WF (Strategy B) in the tourist area of Corralejo, in the north of the island. More specifically, the WF was sited beside the Corralejo desalination plant. The WF, with a rated power of 1.7 MW, was put into service on April 14. It comprises two GAMESA WTs (model G52/850 [81]), each with a rated power of 850 kW (Fig. S9).

From 2007, the capacity of the desalination plant, in operation since 1993 and with an original capacity of 1500 m^3/day (Fig. S4), was 4000 m^3/day (Fig. S2). With a mean SEC of 5.11 kWh/m^3, the plant comprises two SWRO lines with a 2000 m^3/day capacity, each with Pelton turbines as energy recovery systems [84] (Fig. S9).

Fig. 13 shows the evolution of monthly electrical energy production of the WF, and the percentages of that energy directly consumed by the desalination plant and dumped into the island's grid. In the study period of 2010–2014, 63.05 % of the WF-generated energy was consumed directly by the plant and 36.95 % was dumped into the grid.

Fig. S10 shows the monthly product water flow, as well as the percentage of desalted water produced directly using WF-generated energy and the percentage produced with energy purchased from the grid. In the study period of 2010–2014, 48.65 % of the product water flow was produced using energy directly from the WF and 51.35 % with energy purchased from the grid.

It can be seen in Fig. 14 how on some days (in the months of July and November 2012) desalted water production was completely covered by the WF-generated energy, but also how on some days the energy required had to be taken fully from the grid.

Fig. 15 shows the equivalent full-load hours and the CFs of the WF. The mean values of these parameters in the study period were 2072 h and 23.66 %, respectively, in the Corralejo complex WF. These values were higher than the mean overall values for WFs operating in the island in this period according to the 2014 Canary Islands Energy Statistics Yearbook [76]. Also shown in Fig. 15 are the tonnes CO2 equivalent not emitted into the atmosphere. The cumulative value of this latter parameter for the 2010–2014 period was 12,951 teq CO2.

Lanzarote in 2016. In November 2016, the island's authorities inaugurated a 4.6 MW WF at the site of the Díaz Rijo desalination complex with the aim of covering part of the energy consumption of the desalination plants that provide water for the population. The WF comprises 2 ENERCON E70 WTs [65], each with a rated power of 2300 kW (Fig. S11).

The annual energy generated by the WF in the period 2018–2021 could only cover 13 % of the energy consumed (Fig. 16A) by the three SWRO plants available (Fig. S11) to produce the flows indicated in Fig. 16B [85]. The equivalent full-load hours and CFs of the WF are shown in Fig. 16C. These parameters were lower than the mean overall

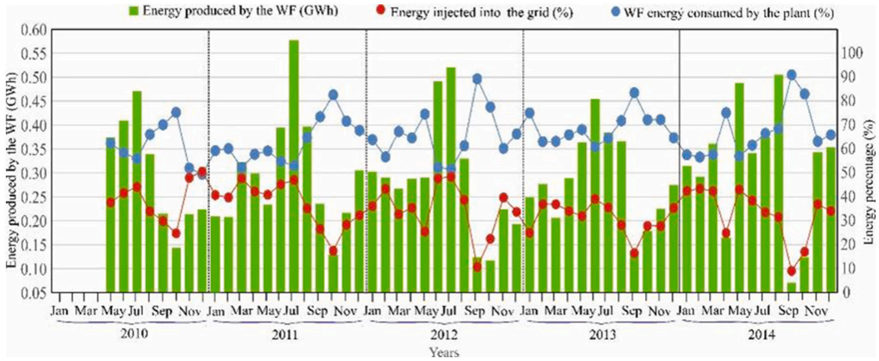

Fig. 13. Monthly electrical energy produced by the wind farm (WF) in the Corralejo complex in the period 2010–2014.

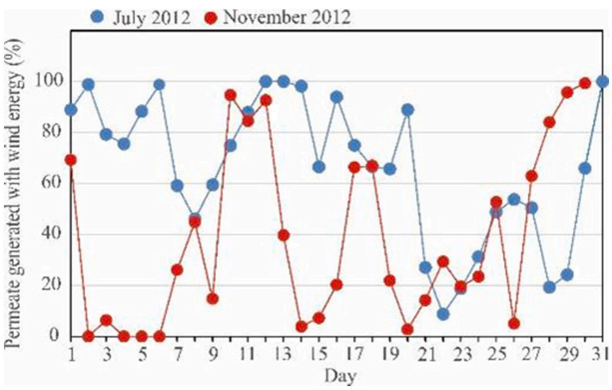

Fig. 14. Percentage of desalted water production in July and November of 2012 covered by energy directly obtained from the Corralejo complex wind farm.

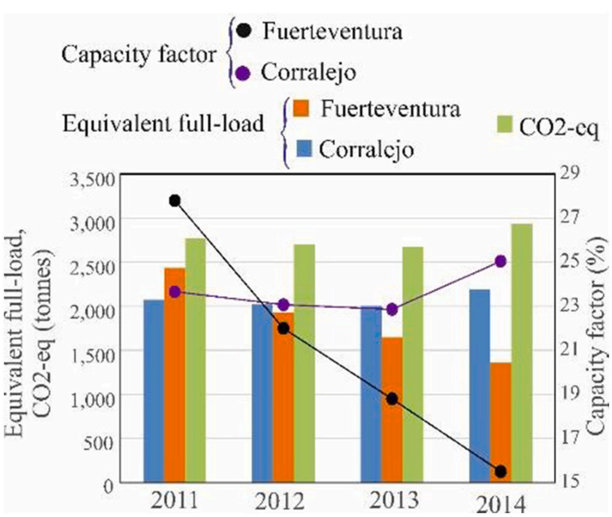

Fig. 15. Equivalent full-load hours and capacity factors of the Corralejo complex WF and Fuerteventura WFs, and CO2 emission savings.

values for WFs operating in the island in the same period according to the 2021 Canary Islands Energy Statistics Yearbook [76].

The tonnes CO2 equivalent not emitted into the atmosphere in the period 2017–2021 amounted to 352,501 teq CO2.

Fuerteventura in 2019. In view of the results obtained with the Corralejo system, the CAAF installed in 2019 a WT in the CAAF premises in Puerto del Rosario (Fig. S12). This ENERCON WT (model E82/2350 [86]) has a rated power of 2350 kW. For the moment, due to restrictions on the power that can dumped into the grid related to the proximity of the WT to the island's conventional power plant (Fig. 1), its rated power is limited to 2 MW. The main aims are to lower the cost of the electrical energy consumed by the desalination plants and reduce the emissions of greenhouse gases in relation to the energy generated by power plants that use fossil fuels. The Puerto del Rosario desalination complex has a rated capacity of 27,000 m^3/day, consuming on average presently 4.5 MWh, between 14 % and 15 % of which is covered with wind energy.

Gran Canaria in 2021. Conagrican S.L. is one the largest banana and papaya producers in the islands [87]. It also grows, though in lower amounts, tropical pineapples, avocados, oranges, mangos, coffee beans and other products. In February 2021, the company installed an ENERCON WT (model E-82 [88]), with a rated capacity of 2300 kW, to supply energy to its 5000 m^3/day capacity SWRO plant in Roque Prieto in the north of Gran Canaria (Fig. S13). An annual energy production of 5773 MWh is estimated, along with self-consumption of above 65 % of the generated energy.

3.1.3. Experiences of off-grid installations with wind-diesel systems

In 1995, to fully cover the energy and potable water needs of a fishing village and ensure an adequate quality of life, the installation of a hybrid wind-diesel system was undertaken on the island of Fuerteventura. The goal was to meet the energy needs of an area that was not covered by the conventional grid (Fig. 6 and Fig. S14).

The design specifications established: a) the need for potable water production to be entirely carried out through the use of wind-sourced electrical energy; b) the need for maximum supply reliability but minimum diesel group activity. Therefore, one of the loads of the system [38,39] comprised an SWRO desalination plant. A multi-stage submersible vertical centrifugal pump was responsible for supplying the feedwater of the plant at a pressure of 0.3 MPa. The SWRO plant had a recovery rate of 35 %, a 65 m^3/day production capacity of water with a TDS concentration of 350 ppm, and a mean electrical energy consumption of 7 kWh/m^3 of product water (Fig. S14). The plant was designed, in principle, to operate only during the summer months (July and August) powered exclusively (from the seawater pump to product water storage) by wind energy, as this is the period of the year with highest wind intensity. Mean wind speed in the period 1988–1990 was 7.07 m/s at 10 m a.g.l.

A storage device was designed to regulate the water supply to the population the rest of the year (Fig. S14). The rated power of the VESTAS WT (model V27/225 [89]) was 225 kW, and the power plant comprised two diesel generators of one diesel motor each connected by clutch to a 120 kg m2 flywheel and a brushless 60 kW synchronous generator. The system had dump loads comprising 390 W to 50 kW resistance generators connected to balance electrical energy consumption with power generation. The hybrid wind-diesel system was designed to operate in the following three modes: diesel-only, diesel and wind, and wind-only. The last of the three modes was the only one with desalination plant busbar connection. Fig. 17 shows, by way of example, the operating

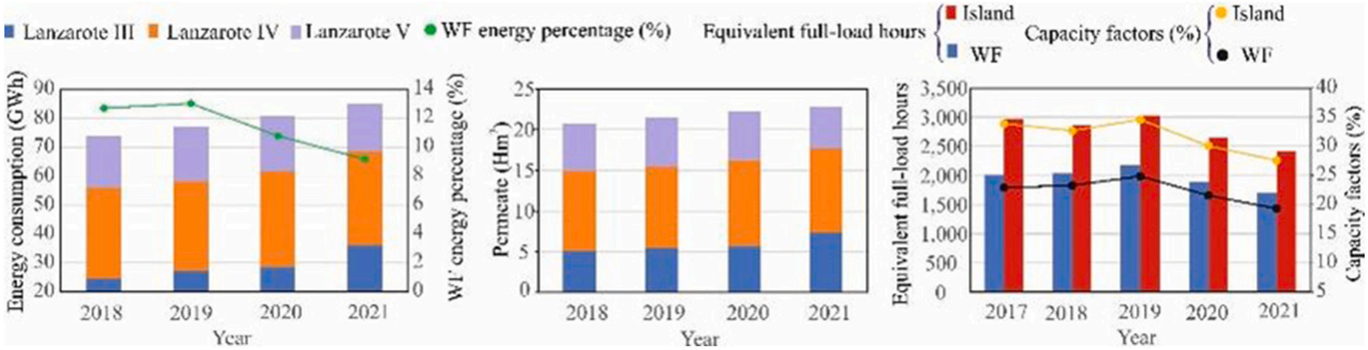

Fig. 16. A) Energy consumed by the Díaz Rijo desalination plants and energy percentages that could cover directly or indirectly the energy demand of the plants, B) Product water flow of the desalination plants, C) Equivalent full-load hours and capacity factors of the Díaz Rijo wind farm (WF) and the WFs of Lanzarote.

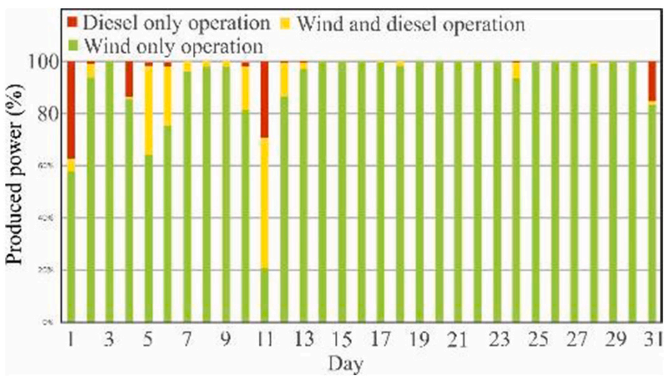

Fig. 17. Operating percentages of the Fuerteventura hybrid wind-diesel system during July 2001.

percentages of the system over the course of July 2001. Note the high frequency with which the system operated in wind-only mode, with entire days of operation in this mode which, therefore, could be used for desalination, Even on days, such as July 9, during which the system was not in wind-only operation 100 % of the time, there were still sufficiently long periods of continuous operation in this mode to allow the operator desalination plant busbar connection (Fig. 18A). Given the slowness of the WT blade control system, the dump loads functioned as a generation-consumption balancing method in steady-state conditions (Fig. 18B), which entailed a loss of generated wind energy in addition to the energy spent on turning the flywheels coupled to their respective synchronous generators which acted as motors connected in parallel.

The operation of the system demonstrated its technical viability to satisfy energy and freshwater demands with a high wind energy penetration [39].

3.1.4. Experiences of off-grid installations with stand-alone wind systems

This type of installation consists of research prototypes undertaken fundamentally on the island of Gran Canaria by the ITC and the ULPGC. The prototypes that were developed pursued the direct exploitation of wind energy to power small-and medium-sized desalination plants and were designed to adapt their consumption to the intermittent nature of this RE resource. Only two prototypes, both developed by the company ENERCON, were tested at the ITER facilities in Tenerife.

Tenerife in 1995 and 1997. In January of 1995, as part of the PRODESAL project, the development of a pilot desalination system fed with the energy provided by a WT and which operated in autonomous mode was initiated at the ITER facilities [52] (Fig. S15A). The prototype combined a 200 kW ENERCON WT (model E-30/200 [90]) with an SWRO plant which had a Pelton turbine-based energy recovery device

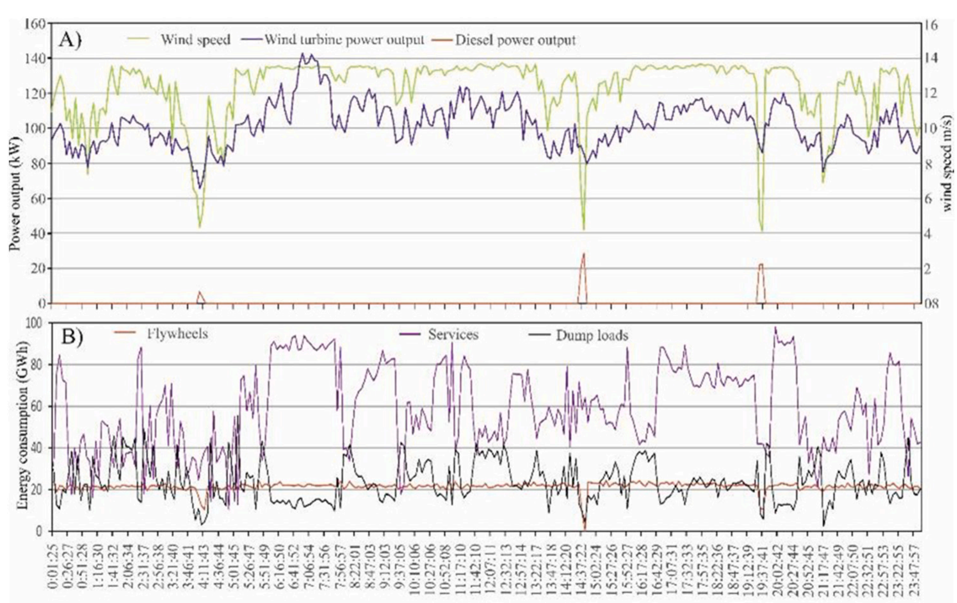

Fig. 18. Power of the Fuerteventura hybrid wind-diesel system on July 9 of 2001. A) Power generated, B) Power consumed.

(ERD). The SWRO plant had various modules which could be connected in parallel, with variable operating parameters (pressure and flux) and a capacity range of 100–250 m^3/d. The plant was designed expressly for this purpose and combined the benefits of spiral wound and flat membranes [52]. Pressure control was achieved by acting on the inlet nozzle of the Pelton turbine, varying the needle position. An uninterrupted power system (UPS) unit was used to provide energy to the control system. The components of the desalination system were installed next to the WT (Fig. S15A) and included tanks to store the seawater and product water, filtering elements and a pre- and post- water treatment system.

In 1997, as part of the Modular Desalination project under the framework of the EC DG XII JOULE III programme [91], a desalination system prototype fed with the energy provided by a WT and which could operate in autonomous and grid-connected mode was installed at the ITER facilities (Fig. S15B). The prototype combined a 30 kW ENERCON E-12 WT [92] and a single-line SWRO plant with a pressure vessel of varying capacity between 60 and 110 m^3/day and a product water conductivity of 0.85 mS/cm. In autonomous (stand-alone) mode, the power generated by the WT had variable frequency and voltage [47]. The SWRO plant, which included a piston accumulator-based ERD developed by ENERCON [93], was installed in three container modules (Fig. S15B). Housed in one were the filtering system, the SWRO module, a membrane-washing system for when the plant was not operating, a pump for product water distribution and the control system. A seawater storage tank and product water storage tank were housed in the second container. The third container, smaller in size, housed the chemical water treatment system. The energy consumption of the high-pressure pump varied between 5.5 kW and 15.3 kW.

Gran Canaria in 1996. The SDAWES (Sea Desalination Autonomous Wind Energy System) project was initiated in 1996, co-funded by the EU (JOULE III Programme, Contract JOR3-CT95-0077). The system installed in the ITC (Fig. 19), aimed to verify the feasibility of the stand-alone operation of a WF without the auxiliary need for batteries for energy storage or supporting diesel generators, and to analyse the problems that might arise in the management of desalination loads of different technologies (SWRO, VVC and EDR) [42].

The WF comprised two ENERCON 230 kW WTs (model E-30 /230 [90]). The generation system also comprised a 100 kW synchronous motor (mechanically coupled to a flywheel), a 22 kW asynchronous motor (whose shaft was connected, via a power transmission belt, to the rotating shaft of the flywheel and provided the necessary torque for

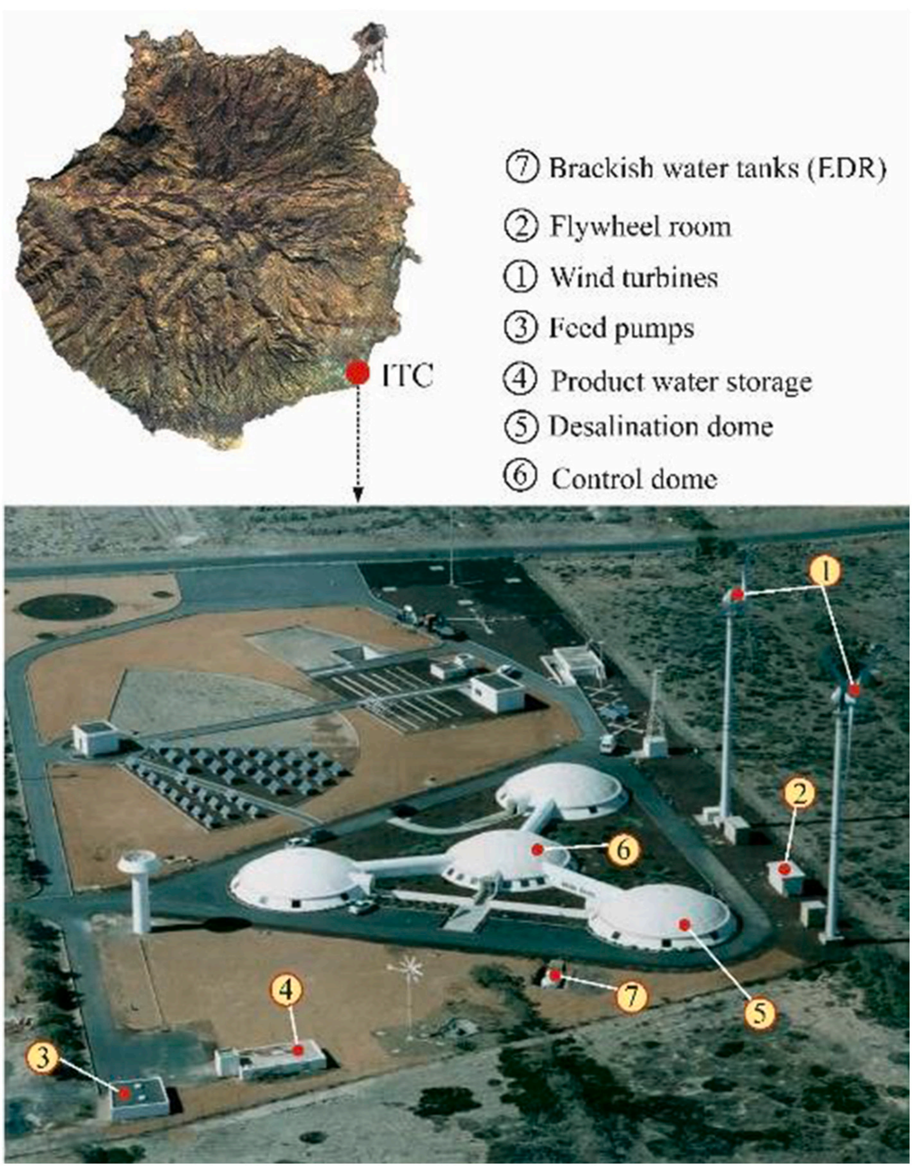

Fig. 19. Location of the SDAWES project.

start-up) and a 10 kW UPS to provide the control system with energy autonomy. The generation system supplied energy to the desalination processes, from the seawater pump to product water storage (Fig. 20).

In the case of the SWRO technology, which had no ERDs and operated under constant pressure and flow conditions (mean conversion rate of 35 %, nominal production capacity of 1 m^3/h, nominal working pressure in the range of 60–70 bar, and SEC of 7.2 kWh/m^3), plant modularity was exploited by connecting and disconnecting modules so that the variation in desalination energy demand would be in synchrony with wind generation [43] (Fig. 21). The pump station comprised two pump-motor units, each with a rated capacity of 13 kW (at 50 Hz), capable of providing a 40 m^3/h flow, operating alternately every 30 min. These pumps had no frequency regulators and, whenever there was energy available for them and at least one SWRO module could operate, were connected and pumped all the water necessary for operation of all the SWRO modules simultaneously.

The hydraulic circuit that was designed had a solenoid valve that allowed unused water (if all the SWRO modules were not operating) to be returned to the sea through an underwater outlet pipe [43]. With respect to the VVC [20,42] and EDR [45,46] technologies, their performance in a regime allowing variable operating parameters was investigated. The VVC plant had a nominal production capacity of 2 m^3/h, a conversion rate of 50 %, a nominal working pressure (at 62Â°C) of 0.2 bar, a SEC of 16 kWh/m^3, and a variable compressor speed range of 8000 to 12,000 rpm. The EDR plant, with a feedwater salinity ranging between 2500 and 7500 νS/cm, had a nominal production capacity of between 3 and 7.9 m^3/h, a conversion rate in the range of 35–75 %, and a nominal working pressure of 1 bar.

Gran Canaria in 1997. In 1997, two prototype wind-powered desalination systems were installed at the facilities of the ITC: AERODESA-I and AERODESA-II. The AERODESA-I prototype comprised a 3-bladed vane-oriented WT, designed, patented [41] and specifically constructed to be mechanically coupled to the high-pressure pump of an SWRO plant (four membranes in series) with a 10 m^3/day capacity. Therefore, the prototype does not supply energy for the seawater pump. The kinetic energy of the wind is transformed into mechanical energy in the rotor (9 m in diameter) of the WT (operating range of 6–21 m/s and a rated power of 10 kW) and transmitted via a power system to the high-pressure pump which is situated in a room that comprises the base of the tower (Fig. S16).

The rotor transmits its rotation to the main shaft where a disc brake and centrifugal speed regulator limit its rotation to 60 rpm (Fig. S17). The main shaft is connected via bevel gearing to a vertical shaft (of four sections with flexible couplings) which is inside the 14 m high tower of the WT.

Another pair of bevel gears is found at ground level, with a

Fig. 20. Components of the SDAWES project.

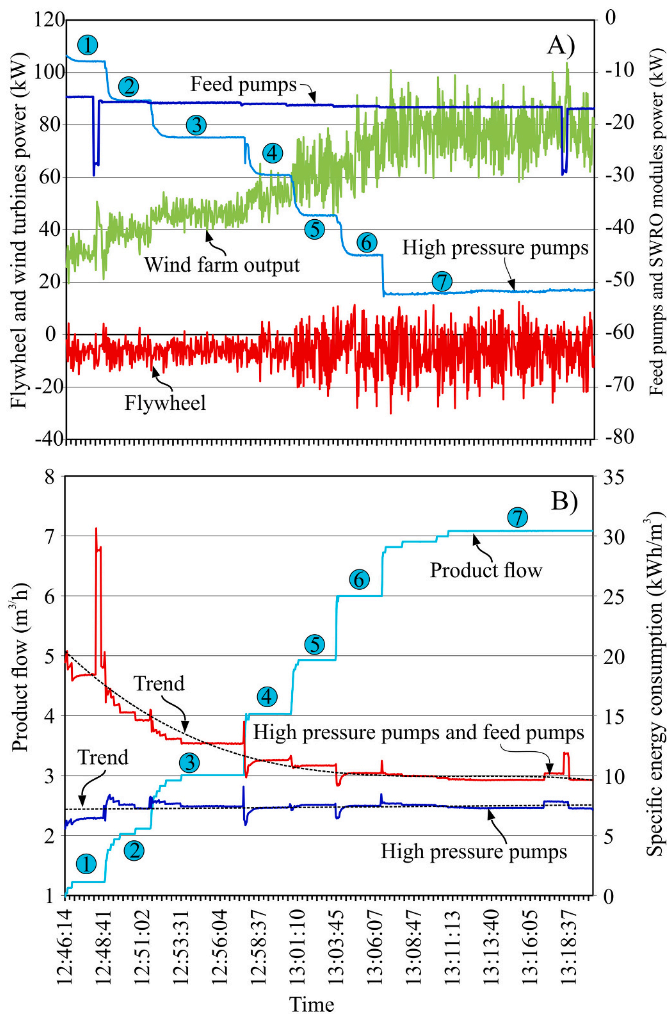

Fig. 21. SDAWES project: Sequential connection process of seven SWRO modules (13/10/2000, from 12:46:14 to 13:20:09. A) Power, B) Product flow and specific energy consumption.

multiplication ratio equivalent to that of the first pair, which transmit movement to the high-pressure pump via V-belt transmission (Fig. S17).

The hydraulic circuit of the desalination plant acts as an auxiliary fluid control of the system, using for this purpose hydraulic valves of standard operation with drainage tolerances and manufacturing materials suitable for operation with seawater (Fig. S17).

The AERODESA-II prototype comprises a 2-bladed 15 kW WT with a passive downwind orientation system. The WT was designed, patented [40] and constructed specifically to be coupled via a hydrostatic transmission with the high-pressure pump of a 2-module 15 m^3/day capacity SWRO plant (Fig. S18). Therefore, the prototype does not aim to supply energy for the seawater pump. An oil-hydraulic system was designed and developed to act as a control system.

Gran Canaria in 2003. A wind-driven desalination system prototype called AEROGEDESA was installed at the ITC facilities in 2003. The seawater pump for the plant was not powered by the VERGNET 15 kW WT (model GEV10/15) used in the system. The SWRO plant comprised two pressure vessels arranged in series, each with 3 spiral wound membranes (FILMTEC SW 30–4040 HR). The capacity of the SWRO plant was 18 m^3/day when operating at a pressure of 60 bar and with a recovery rate of 24 %. The SWRO plant had no ERD and its SEC was 8.4 kWh/m^3. The system also had a battery-based energy storage system [49] (Fig. S19).

The wind regime and battery-based energy storage capacity conditioned the shutdown frequency of the system. Therefore, there were periods in which the SWRO plant was not operational because there was insufficient energy available in the batteries (and the wind speed was insufficient for the WT to charge them) for its setpoint operation [94]. Fig. 22 shows an example of system operation on a day with low wind speed and a day with high wind speed.

Gran Canaria in 2014. In 2014, based on use of the components of the AEROGEDESA project, research began on a new SWRO plant prototype designed to continuously adapt its energy consumption to the variable power supplied by the WT, discarding the massive battery energy storage of the original project. In the new prototype, named DEMAD, the SWRO plant and WT were redesigned. In addition, a supercapacitor bank was designed and developed to act as a dynamic regulation system, given its advantages [49] (Fig. 22). This supercapacitor bank, comprising 33 plates in series (each with 6 supercapacitors of 350 F and 2.7 V connected in series) allows working with voltages of up to 534.6 V. Given the problems associated with the self-excited squirrel cage induction generator of the WT of the AEROGEDESA prototype [49], this was replaced with a permanent magnet synchronous generator (Fig. 23). The most important changes undertaken in the SWRO plant were: a) use of the arrangement in parallel of the two pressure vessels, which in the AEROGEDESA prototype had been arranged in series, b) replacement of the six original membranes with six new ones (Toray TM810), c) replacement of the high-pressure pump and its electric motor with a system of higher capacity, d) resizing of the hydraulic circuit for its adaptation to new flow rates, and e) the installation of various valves and sensors that would allow the dynamic connection/disconnection of one or two pressure vessels and variation of the operating parameters (pressure and flow) [49].

Artificial neural networks (ANNs) were implemented in the control system to manage operation of the SWRO plant. These ANN models, based on the available electrical power and the temperature and conductivity of the feedwater (Fig. 24 A), enabled selection of the flow rate and operating pressure while maintaining the permeate recovery rate practically constant [50] (Fig. 24 B). From a theoretical perspective, and

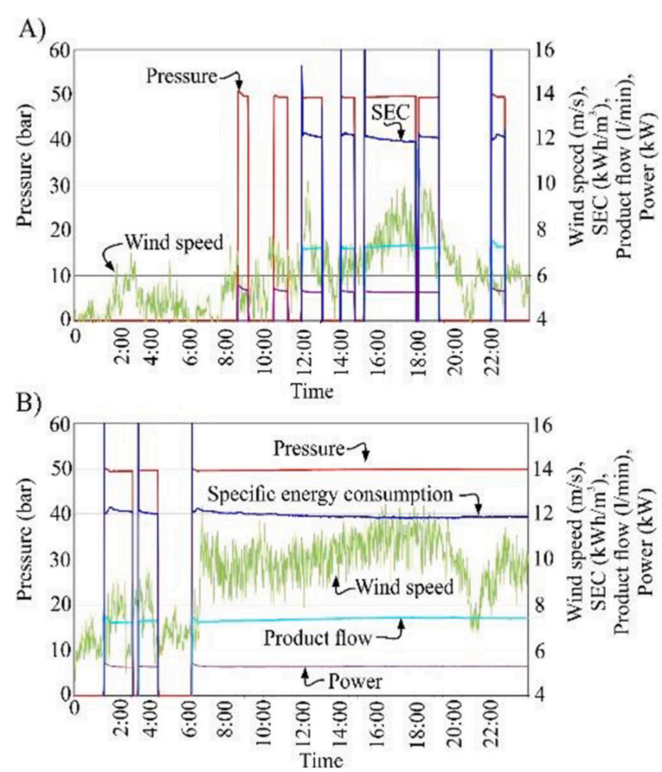

Fig. 22. AEROGEDESA project system operation at a pressure of 50 bar and feed flow of 3.1 m^3/day in February of 2005. A) Day with mean wind speed of 5.9 m/s, B) Day with mean wind speed of 9.2 m/s.

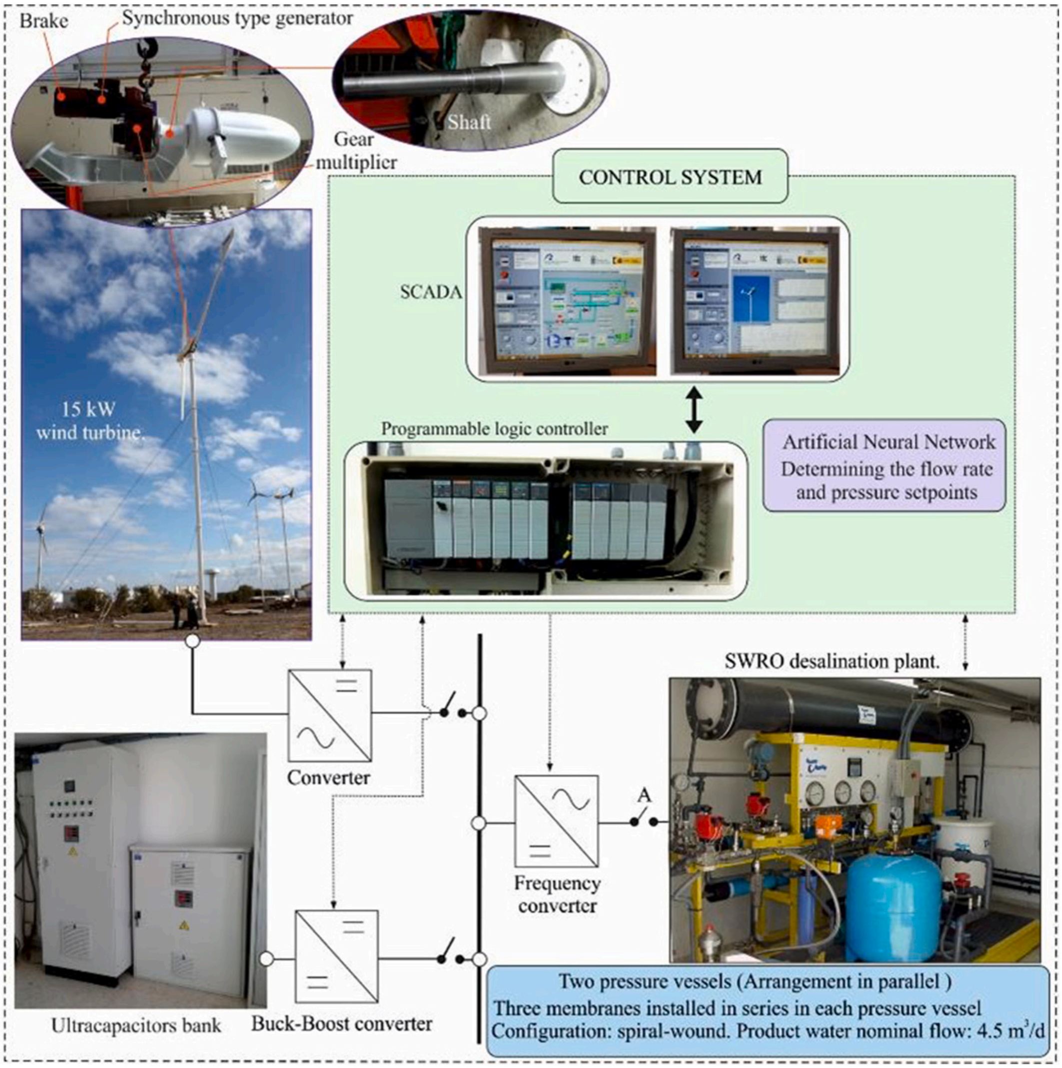

Fig. 23. DEMAD prototype.

as an alternative to plant shutdown, this strategy offers the best alternative for the operation of an SWRO system with heavily fluctuating wind energy, given the wide load range [95], even allowing SWRO plant operation with low wind speeds. The SEC is dynamic and is fundamentally a function of the number of pressure vessels which are connected (Fig. 24 C).

3.2. Analysis of the lessons learned

A description is offered in this section of the lessons learnt from the experiences previously detailed, showing the relationships between the results obtained in the various projects with respect to the different strategies employed and the conditions or causes that impacted those results.

3.2.1. Designing and retrofitting desalination plants

Since, in 1964, the Canary Archipelago turned to desalination to mitigate the freshwater shortage problems it was facing, all the concerned sectors (including the public sector [32]) have become increasingly aware of the water-energy nexus and its fundamental importance in the advancement of desalination. Energy consumption and carbon emissions are costs associated with desalination. Public desalination plant energy consumption corresponds to around 5–10 % of the electrical energy generated in the islands' power plants and injected into their grids [24]. In the archipelago, the cost of that energy can represent between 40 % and 60 % of desalinated water production costs. In this context, given the very high number of desalination plants (density ratio of 22.73 km^2/plant [29]), the prime objective pursued over the years, in practically all the medium- and large-sized plants, has been, in addition to improving product water quality, to gradually increase their energy efficiency. For this, already installed plants have been redesigned and the most up-to-date technological innovations have been used in newly installed plants. The first actions in this regard involved implementation of ERDs [24,25,29]. The first ERDs implemented in SWRO plants, which had recovery rates in the 43–57 % range [24], were centrifugal in type and based on the Francis turbine [29], achieving SECs in the range of 4–5 kWh/m^3 [24]. These ERDs were later replaced with Pelton turbine-based centrifugal devices [28], resulting in maximum efficiencies of between 85 % and 90 % [96] and SECs of 3–4 kWh/m^3 [24]. In recent years, there has been a growing trend towards the replacement of the centrifugal devices of medium- and large-sized plants with isobaric chambers.

In the case of the desalination plants with on-grid operation under Strategies A or B, as shown in Sections 3.1.1 and 3.1.2, except for the BWRO plants installed in Gran Canaria (Fig. 10, Fig. S8), all the plants (SWRO-type) have used ERDs. Although Pelton turbine-based centrifugal-type ERDs continue to be used (Fig. S9), most SWRO plants, either from their inauguration (Fig. S6, Fig. S13) or as the result of a

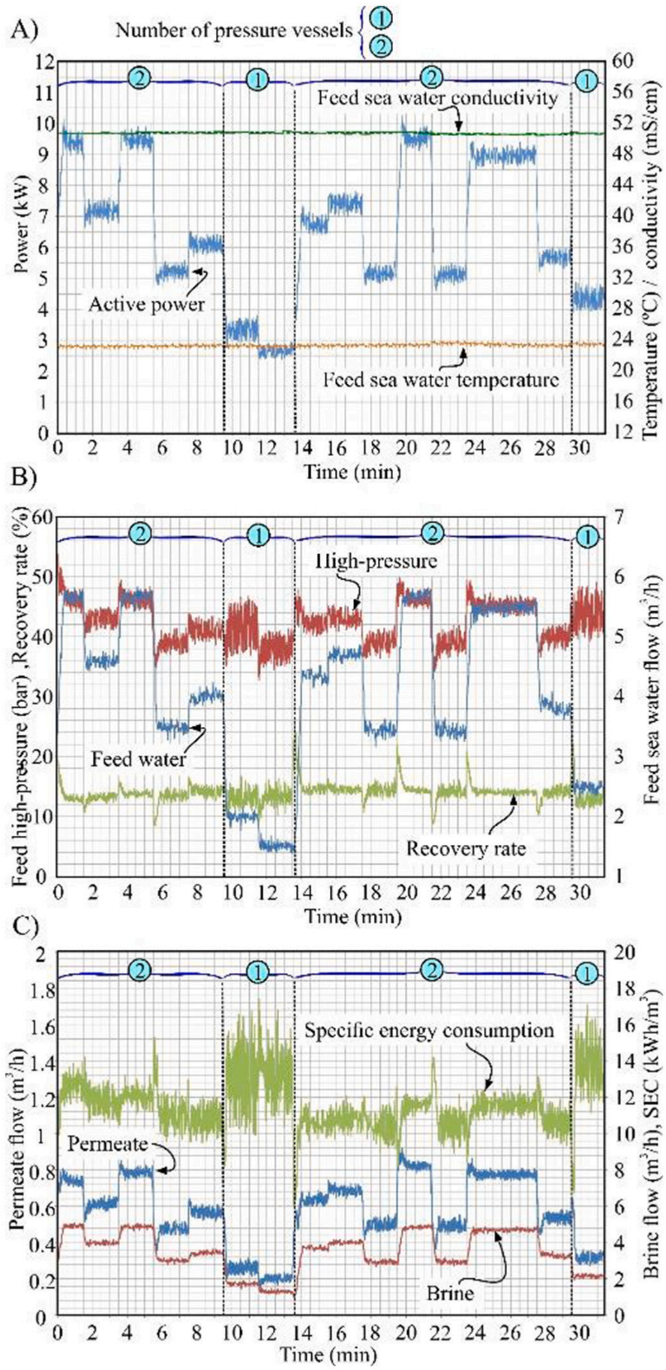

Fig. 24. DEMAD project: A) Power consumed by the seawater reverse osmosis (SWRO) desalination plant vs. time of operation, B) operating pressures, feed flows and recovery rates in the SWRO plant vs. time of operation, C) Permeate, brine flows and specific energy consumption (SEC) vs. time of operation.

retrofitting, (Fig. S5), have isobaric chambers. Of the types of isobaric chamber commercially available, the one used to date in the islands has been the pressure exchanger (PX) from Energy Recovery Inc., a device based on rotary displacement. In addition to the incorporation of more efficient ERDs [24], which is the main driving force behind SWRO plant energy consumption reduction, other methods include the installation of particular membrane types, high-pressure pumps and high-efficiency variable speed drives [77,79]. Pump speed control allows adaptation of operating flows and pressures to the needs of the installation at any given moment, enabling the system to work at its optimal point and thereby facilitating maximum efficiency.

According to Arenas-Urrea et al. [24], from the studies undertaken in diverse SWRO plants in the islands operating with recovery rates in the 43–53 % range and using ERDs based on isobaric chambers, SECs of between 2.10 kWh/m^3 and 4.08 kWh/m^3 are being obtained (considering only data associated with the high-pressure lines). However, the authors [24] stress that these values are not solely the result of using the aforementioned ERDs, and that the impact of state-of-the-art membranes, which allow the use of lower operating pressures and increase membrane flow, should not be underestimated.

The lessons learnt from the actions that have been undertaken in the desalination industry to reduce the SEC of on-grid SWRO plants, operating under both Strategy A and Strategy B, effectively confirm the very positive impact that their gradual modernization has had on improving their energy efficiency. In this context, we recommend that the knowledge and know-how generated in the Canary Archipelago through these successful actions, namely the use of ERDs based on isobaric chambers, high-pressure pumps, high-efficiency variable speed drives and state-of-the-art membranes, be replicated in future designs of on-grid SWRO desalination systems.

In the case of off-grid desalination plants, as indicated in Sections 3.1.3 and 3.1.4, except for the prototypes tested at the ITER facilities which used Pelton turbine-based ERDs [52] and a piston accumulator-based ERD developed by ENERCON [47,93] (Fig. S15A and Fig. S15B, respectively), none of the wind-driven desalination systems tested in the islands has employed ERDs. This and the low recovery rate (below 35 %) are two of the reasons why the SECs of the plants that have worked with constant operating parameters (at the point of best efficiency), including the wind-diesel system of Fuerteventura and the AEROGEDESA prototype, reached values above 7 kWh/m^3. As for the wind-driven desalination systems that operated with step-type variation of flow, as in the case of the SDAWES project, the SECs associated to the high-pressure lines were practically constant at a value of around 7 kWh/m^3 (Fig. 21B). However, when consideration was also given in SEC calculations of the feed pump consumption, the SEC values depended on the number of SWRO lines connected (Fig. 21B). Given that there were no frequency regulators to adapt feedwater flow to the number of SWRO lines connected, the SECs were high when the number of connected lines was low, but tended to fall when the number was increased (Fig. 21B). In the case of wind-driven desalination systems which varied flow and operating pressure continuously, as in the PRODESAL, MODULAR and DEMAD prototypes, the SECs associated to the high-pressure lines were dynamic, with their values depending on the magnitudes of the operating parameters and on the strategy adopted for their variation. With the DEMAD prototype, for which the strategy of maintaining a constant permeate recovery rate of 13.5 % was adopted as an alternative to plant shutdown, mean SEC values were obtained in the range of 10–12 kWh/m^3 when operating with two pressure vessels. When only one pressure vessel was used, the same parameter was in the range of 12–16 kWh/m^3 (Fig. 24). In the case of the MODULAR prototype, given the incorporation of an ERD, energy efficiency was high [47].

The lessons learnt from the actions undertaken with the various projects and prototypes that have been in operation in the islands since 1995 have enabled documentation of the learning in terms of the strategy adopted to operate stand-alone off-grid plants with low recovery rates. This strategy was accepted, given the limited experience at the time of the performance of SWRO membranes when working with intermittence and/or under variable operating parameters. The aim with this strategy was to reduce the probability of failure of the final membranes of the pressure vessels due to incrustation issues and/or incorrect operation of membrane rinsing systems. That is, low recovery rates were used to avoid, with increased water TDS of the final membranes, the least soluble minerals starting to form scales on the membrane surface through precipitation in the event of a pre-treatment (either in the form of a water deionizer or chemical anti-scaling reagents) ceasing to work or the rinsing systems no longer working adequately. However, the results obtained in tests undertaken in the islands with SWRO plants working under variable pressure and flow conditions showed that they can operate satisfactorily with high recovery rates (up to 50 %) without problems arising [97]. According to García-Latorre et al. [95,97], the 18.9 m^3/day capacity pilot SWRO plant used in the tests had 6 SWRO membranes (Koch Fluid Systems TFC 2822-SS) installed in series in a 6 m long pressure vessel and an automated cleaning tank. Different pre-treatment products were tested.

According to [97], no membrane deterioration was observed over the test period as a result of operating with variable pressure and flow. The SWRO plant, with no ERD, operated discontinuously with a wide range of powers that affected the operating pressure (35 to 80 bar), the recovery rate (20 % to 50 %) and the SEC (5 kWh/m^3 to 4 kWh/m^3), without detection of membrane fouling or damage problems. In this context, and given the knowledge acquired, it is recommended to avoid the strategy of using low recovery rates in future designs of off-grid SWRO plants with a view to obtaining lower SECs. However, special attention should be paid to the pre-treatment and the reliability of the automated membrane rinsing system. Likewise, and with the same objective, as recommended by García-Latorre et al. [97], given the high kinetic energy contained in the reject flow, ERDs should be installed in future designs of SWRO plants in the brine discharge line instead of eliminating this energy through the reject valve, as has been the case in wind-driven desalination system prototypes tested in the archipelago to date, with the exception of the prototypes tested at the ITER facilities. According to Arenas-Urrea et al. [24], in the case of SWRO plants with very small capacities, the experience of the Canary Islands indicates that the employment of pressure intensifiers as ERDs, such as the axial piston pump and axial piston motor (APP/APM) from Danfoss, gives adequate results, achieving relatively low SEC values.

Although SWRO plants have gradually incorporated adequate ERDs, high-pressure pumps and high-efficiency variable speed drives as well as state-of-the-art membranes to minimize energy consumption, there are signs that further SEC reduction will be complicated given that it is now approaching the theoretical thermodynamic limit of desalination. Future challenges should therefore be focused on replacing fossil fuels with renewable energies and on defining the optimal operating strategy of wind-driven desalination.

3.2.2. On-grid wind-driven desalination systems with Strategy A

The knowledge acquired from the experiences with this strategy, through an analysis of the factors that most impacted the results, suggests some positive and some negative aspects. The decision to use this strategy was correct in the sense that it enabled optimal selection of the installation sites of the Cañada del Río WF (Fig. S4) and the Los Valles WF (Fig. 7). From the perspective of technical, economic and environmental impact considerations, the strategy facilitated the suitable siting of the plants in the two islands concerned (Fuerteventura and Lanzarote). The WFs were installed in areas which met the conditions of sufficient space and high wind resource availability. One of the negative aspects that should be highlighted is that the type of WT used affected the equivalent full-load hours. This is reflected in the increase of this parameter when the WF was repowered, as seen in the WF of Los Valles (Fig. 7). In this context, optimal selection of both the WF site and the technology employed is vital. A fundamental question to bear in mind when considering use of this strategy concerns the restrictions that may be imposed on grid penetration of large amounts of renewable energy, especially on small islands. It should also be noted that a zero-carbon footprint is not possible with this strategy as long as fossil fuel-sourced energy continues to be used in the conventional grid. Lower carbon footprints, however, are possible when the percentage of renewable energy circulating in the conventional grid increases, as has occurred in the case of the island of El Hierro [44].

3.2.3. On-grid wind-driven desalination systems with Strategy B

As can be deduced from the timeline shown in Fig. 6, there has been a growing trend towards implementation of this strategy in the easternmost islands of the archipelago. The knowledge and know-how acquired for the tests that have been undertaken show that the level of success of a system is closely associated to the characteristics of the area in which it is implemented. That is, to an optimal wind resource and optimal WF and desalination plant siting, as the WTs should be installed as close as possible to the desalination plant. The longest distance between a WF and desalination plant can be seen in the AGRAGUA system (Fig. S5), where the energy produced (with a voltage of 20 kV) is taken to the plant via a 3-phase line approximately 3 km in length which is buried underground to avoid any visual impact. The distance factor affects energy transport losses and costs and the difficulties related to installation of the transmission line. In this regard, the SOSLAIRES WF was sited at a very short distance from the desalination plant and in an area with high wind resource potential (Fig. S6). As a result of this action, along with the efficiency of the WF, it was possible to obtain notable equivalent full-load hours. The success of the project was also due to the SWRO technology employed, which enabled a signification reduction of the SEC of the plant. However, the fact that the wind resource may not be particularly high, as in the case of installations in Lanzarote (Fig. S11) and Fuerteventura (Fig. S12), does not necessarily mean the failure of this type of installation, as the advantages associated with this strategy can be sufficient compensation. In fact, the companies which began installing on-grid systems with Strategy A on the islands of Lanzarote and Fuerteventura (Fig. 7 and Fig. S4) subsequently undertook the installation of on-grid systems with Strategy B. The knowledge and know-how generated allow us to recommend, given the benefit they have of reducing the problems associated to the penetration of electrical energy of renewable origin in weak electrical systems, the replication of such successful actions in future interventions in similar contexts. It should also be noted that with this strategy, if the wind-driven system is isolated from the conventional grid and energy storage systems are included, a low carbon footprint can be achieved if considering only the operating life of the system [98,99].

3.2.4. Off-grid wind-driven desalination systems. Hybrid systems

The lessons learnt from the tests conducted with this type of system on the island of Fuerteventura (Fig. S14) reveal both successes and errors that need to be avoided in similar future projects. With respect to the errors that were committed, these can be categorised in two types. Firstly, those committed in the technical planning of the project. One of the most important of these is related to the specifications for production of all potable water during the summer months and imprecisions in the estimation of demand for the same period [38,39]. As a result of such errors the generation system was oversized, generating frequency and voltage variations in the order of ±5 %. It was therefore necessary to reduce the rated power of the WT from 225 kW to 130 kW and to carry out changes to the dump load management strategy. The dump loads were initially designed to operate only in dynamic periods of transition and had to be subsequently modified to allow their operation as a system balance in stable conditions, The modifications that were made reduced frequency and voltage variations to the order of around ±1 %. Another of the limitations that was detected after implementing the system was the difficulty in finding specialist technicians to carry out the management and maintenance of a system that had a high degree of technological sophistication. It is recommended that the staff in charge of the system be fully trained before responsibility for its correct operation is handed over to them [100].

As for successes, most importantly the implementation of the wind-diesel system and the modifications made to it benefitted enormously the inhabitants of the village given that, from the technical perspective, the system considerably improved the quality of life of the community, especially bearing in mind the limitations of the technology available at the time.

3.2.5. Off-grid wind driven desalination systems. Stand-alone systems

From the lessons learnt from the various projects that were developed with this type of system, it is recommended that various aspects be taken into account in future plans and developments.

With respect to the desalination technologies that have been proposed for operation under variable and/or intermittent operating conditions, it should be noted that the VVC plant was able to operate in a compressor speed range of between 8000 rpm and 12,000 rpm, with adequate adaptation to a variable energy consumption, However, the VVC plant did present a series of issues [18], one of the most notable of which was the length of time required to create start-up conditions. Another negative aspect was the problem caused by calcareous deposits which formed when the plant was inactive for more than 24 h because of low wind speeds. This considerably increased maintenance tasks and the time that the plant was consequently unavailable for operation [40]. In this context, a redesign of the VVC plant was proposed to avoid the problems caused when its operation was interrupted [18]. However, the high SEC values of this type of technology place it at a disadvantage in terms of energy efficiency rankings compared to SWRO technology. The EDR technology operated adequately with a variable energy consumption and very short start-up and shutdown times [46]. The negative aspects to be highlighted include the EDR technology being limited to brackish water desalination [20,42] and the generation of electrical harmonic distortions. With respect to the latter, more detailed research is recommended to evaluate the effect on the local grid, along with the design of an effective harmonic filtering system suitable for the installed rectifiers [46].

With respect to the SWRO technologies that were designed to operate under variable or intermittent operating conditions, it should be noted that the lessons learnt with the systems that used mechanical (Fig. S17) or hydrostatic (Fig. S18) interfaces in the coupling between WT and desalination unit suggest that certain design aspects need to be studied in greater depth. The aim being pursued, namely the need for the system to have only standard and minimum maintenance so that it could be used in isolated areas or developing countries, was not fully satisfied. In the case of the AERODESA-I system, the tests performed indicated that the design of the mechanical system required certain modifications, especially in the rotor, to achieve more adequate starting torque. In the case of the AERODESA-II project, the most notable difficulties were found in the control system, which had a high degree of automatism and was based on an oil-hydraulic system, as elements of the latter system did not respond optimally to the dynamic signals. In this context, further investigation is recommended in this area when considering the implementation of this type of system in the future.

The systems that employed an electrical interface in the coupling between the WT and the desalination unit (Fig. S15) can be considered successes. In the case of the MODULAR project, the desalination plant produced high quality product water with a typical conductivity of 0.85 mS/cm (seawater conductivity was around 41 mS/cm), with the system able to operate in stand-alone, grid-connected or hybrid mode [47]. In stand-alone mode, SWRO plant production followed available wind power and the change-over processes were correctly executed [47]. Given the test results obtained, these systems, which are based on the use of a single WT, can only be implemented in areas with a low or medium local water demand [47].

The lessons learnt from the SDAWES project indicate several successes, the replication of which is recommended, and a set of errors that should be avoided in future developments. Most notably, this was the first successful operation of a WF isolated from the conventional grid and supplying energy to diverse desalination technologies throughout the desalination process (from the pumping of seawater to the storage of the product water) (Fig. 20) [42]. That is, this constituted a considerable advance in the field of wind-driven desalination, from the use of a single WT to a WF. As can be deduced from the descriptions offered in this section, until that time the installations had comprised microgrids configured to handle mostly small-scale desalination. The SDAWES project took the first steps in the advance from wind-driven small- or medium-scale desalination to large-scale desalination. The use of a flywheel, which allowed generation of the isolated electrical grid, along with the start-up process of the system, were the critical factors that led to the desired result [43]. The evidence that justifies the description of the project as a success include the facts that, once the start-up process had conclude: a) system frequency remained within the established range without the need for battery intervention, load dumping or diesel support generator sets; b) the connections of the SWRO plants were executed as planned (Fig. 21); and c) the results obtained did not reveal any significant variation in mean product water volume or quality, or any physical deterioration in the main components of the system as a consequence of the shutdowns and start-ups provoked by variations in the wind energy supply or oscillations of the voltage and frequency parameters.

As a result of the knowledge and know-how acquired, a series of problems were identified that need to be taken into account in future developments of this type [20,42]. However, there were five main factors that contributed to some of the results not being optimal: a) the non-use of ERDs was a cause of the high SECs of the SWRO plants; b) the non-use of frequency regulators caused a substantial increase in the SEC of the desalination system; c) non-implementation of a variable operating regime of the SWRO plants resulted in non-optimal wind energy exploitation; d) inadequate analysis of the size of the UPS needed to cover the energy needs of the control systems of all the devices became evident during lengthy periods of low wind speeds; and e) non-optimization of WT rated power for various reasons led to the erroneous establishment of a rated power of 460 kW [43]. We therefore recommend that such errors not be repeated in future actions of this type to ensure more successful outcomes.

In terms of lessons learnt, various problems were identified in the AEROGEDESA prototype (Fig. S19). Among the critical factors that impeded optimal results being obtained was battery energy storage capacity. It was found that the capacity employed had a causal relation with the frequency of system shutdowns [51]. In this context, it is recommended that in-depth analyses of optimal battery capacity be undertaken to reduce system shutdown frequency. A further recommendation is that consideration be given in future designs to the possibility that the seawater feed pump and control system be supplied with WT and battery bank energy, or in other words that the energy system supply the energy to all the devices that participate in the entire desalination process.

As a result of the lessons learnt to date from the DEMAD prototype (Fig. S19) various recommendations can be made for future projects of this type. The ANN models were able to manage the operating setpoints of the SWRO plant and successfully adapt the energy consumption of the plant to the widely and randomly varying available electrical power. However, some instantaneous permeate recovery rate values were observed which pushed the membrane system beyond its acceptable operating limits. It was found that these atypical values were due to the feed flow regulating algorithm and the proportional-integral-derivative control algorithm which controlled the operating pressure regulating valve [50]. It was additionally observed that the support vector machines and random forest models were significantly better predictors of SWRO plant performance than the ANN models [51]. Simulations carried out with one year's worth of data indicated that the DEMAD prototype operated more continuously (with higher operating frequencies and lower shutdown/start-up frequencies) than the AEROGEDESA prototype [51]. As with the AEROGEDESA project, it is recommended that in future developments of this type consideration be given to the possibility that the energy system supply the energy to all the devices that participate in the entire desalination process. It should be noted that system tests using the supercapacitor bank have not yet been finalized and that, therefore, there are no publications yet describing the lessons learnt in this regard. It should additionally be noted that a further project is underway within the DEMAD framework called INERTIA which will investigate the intelligent management of a flywheel for its integration in an isolated wind-powered desalination system [101]. The results of the INERTIA project will be compared with those obtained with the supercapacitor bank and publication of the lessons learnt will ensue.

3.3. Common issues and challenges identified with the recommendations and sharing of findings

Based on the lessons identified and analysed, we present in Table 2 the common issues and challenges identified, and a series of recommendations to, under similar circumstances, correct certain problems, mitigate risks, and repeat or improve on successful outcomes.

4. Conclusions

This work presents the lessons learnt from the prototypes and projects undertaken in the Canary Archipelago in the field of wind-driven desalination from 1984 to the present day. The Canary Archipelago can be considered a true wind energy- desalination laboratory. The paper chronologically identifies the different works undertaken and analyses the lessons learnt in each case. Several common issues and challenges were identified and recommendations are also made to resolve the problems identified, mitigate other risks, and repeat or improve on successes. The aim is for the lessons that have been learnt in this field to be of use in other islands interested in the water-energy nexus and the need for mitigation measures in the face of climate change. The most important of the conclusions that can be drawn from the different strategies employed are as follows:

1. Modernization of the SWRO plants with on-grid operation was a factor which very positively affected energy efficiency.
2. When implementing on-grid systems, optimal selection of the WF site and WT technology is of fundamental importance.
3. The success of on-grid systems is dependent principally on the existence of optimal wind resources and optimal desalination plant characteristics.
4. The outcomes of studies aimed at estimating the areas within the archipelago with optimal wind resource potential have proven advantageous for diverse local stakeholders.
5. With respect to the desalination technologies that have been proposed for use with variable and/or intermittent operating conditions, the SWRO technology presents considerable advantages over others.

The results obtained in this research also allow to obtain the following conclusions:

1. While the implementation of a wind-diesel desalination system on remote islands (as in the case of Fuerteventura) can be of major benefit for its inhabitants, any future similar systems should take into account the availability of sufficient technical and human resources to ensure the system's correct operation and maintenance.
2. For systems that use mechanical or hydrostatic interfaces in the coupling between the WT and desalination unit, more in-depth research should be undertaken before their implementation.
3. Systems which employ an electrical interface in the coupling between a WT and the desalination unit can only be implemented in areas with a low or medium local water demand.
4. The SDAWES project saw the first use of a WF isolated from the conventional grid, taking the first steps in the advance from small- and medium- to large-scale desalination.
5. The power system should be designed in such a way that it can supply the energy required to run all the devices that intervene in the entire desalination process, thereby avoiding the drawbacks of requiring conventional grid energy when, for example, the system only supplies energy to the high-pressure pump of the SWRO plant. Likewise, optimal battery capacity sizing is important due to its causal relationship with the frequency of system shutdowns.

Table 2
Common issues and challenges identified and recommendations made.

Common issues/challenges identified	Recommendations
The WTs were not installed in an optimal location.	Optimal selection of the WF site is of fundamental importance. Firstly, the success of Strategy B on-grid systems is dependent principally on the existence of optimal wind resources. Additionally, the WTs should be installed in an area as close as possible to the desalination plant to reduce energy transport losses, lower line installation and maintenance costs, and avoid the difficulties related to the installation of longer lines.
The WT technology used is not optimal or becomes obsolete over time	In the planning stage, shorter lifetimes for wind technology than those traditionally considered should be taken into account. Furthermore, as technology advances, repowering should be considered to maximize wind resource exploitation in the area, both to increase the mean interannual capacity factor and to augment the interannual mean equivalent full-load hours value.
Wind farms experience curtailments due to stability issues, particularly in small and weak grids such as those found on islands.	This can be partially offset by selecting the optimal technology and location for wind farms for Strategy A. Additionally, choosing the on-grid or off-grid configuration that best suits the available electrical grid type can help mitigate these issues. Incorporating stability compensating equipment or inertia mechanic systems, such as flywheels, can also contribute to smoother exploitation of the inherent wind variations.
Desalination plants have a very high energy consumption, necessitating large-scale wind installations.	Modernization of the SWRO plants should be ensured through the implementation of ERDs based on isobaric chambers, modern membrane technology, high-pressure pumps and high-efficiency variable speed drives.
A zero-carbon footprint is not possible with on-grid operating strategies as long as the conventional grid remains reliant on fossil fuel generation	Lower carbon footprints are achievable when the proportion of renewable energy integrated into the conventional grid increases, as observed in the case of the island of El Hierro. Furthermore, if the wind-driven desalination system is isolated from the conventional grid and energy storage systems are incorporated, a residual carbon footprint can be achieved if considering only the operating life of the system. This residual footprint may be eliminated in the future as manufacturing processes for wind turbines, batteries, and desalination plants benefit from carbon-neutral societies.
Operating and maintenance costs may be higher in some of these proposals compared to traditional fossil fuel-based desalination systems or directly connected conventional grid desalination systems.	Installing wind turbines close to the desalination plant offers several advantages. It helps minimize energy transport losses, lowers line installation and maintenance expenses, and addresses challenges linked to the installation of longer transmission lines. The increased use of green energy and the elimination of CO2 emissions also contribute to cost reductions in desalination operations. Though often overlooked, these benefits effectively reduce the typical operating costs associated with wind-powered desalination systems.
The success of completely off-grid systems may be affected by the technical challenges posed by remote sites.	For these off-grid systems, consideration should be given to the availability of sufficient technical and human resources to ensure the system's correct operation and maintenance. It is also extremely important that the staff who will oversee

(*continued on next page*)

Table 2 (*continued*)

Common issues/challenges identified	Recommendations
	the system have been fully trained before responsibility for its correct operation is handed over to them. In such cases, wind-diesel systems should be considered highly beneficial.
Very interesting proposals analysed through simulations or theoretical studies are often never implemented.	In this regard, it is essential to involve all stakeholders throughout the entire process, from planning to implementation. This includes energy planners and politicians, as well as public and private entities responsible for freshwater production and distribution on the islands.
Some seawater desalination technologies that have been proposed for use with variable and/or intermittent operating conditions have not been successful.	In this regard, it is important to note that the SWRO technology presents considerable advantages over VVC.
Despite the success of systems which employ an electrical interface in the coupling between a WT and the desalination unit, it should be noted that these can only be implemented in areas with a low or medium local water demand.	The SDAWES project saw the first use of a WF isolated from the conventional grid, taking the first steps in the advance from small- and medium- to large-scale desalination. It could serve as an example of use and an implementation model.
Mechanical and hydrostatic interfaces in the coupling between the wind turbine and desalination unit have not been sufficiently developed and expanded commercially.	It is recommended that more in-depth research be undertaken on certain design aspects before implementing such types of system. It is also recommended in future projects of this type that consideration be given to the energy system supplying energy to all the devices that intervene in the entire desalination process.
Off-grid small electrical batteries-based systems have found some difficulties to cover all energy consumption.	It is also recommended that consideration be given to the energy system supplying energy to all the devices that intervene in the entire desalination process. Likewise, optimal battery capacity sizing is recommended for future projects of this type as it was found that battery capacity had a causal relation with the frequency of system shutdowns.

CRediT authorship contribution statement

Pedro Cabrera: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Investigation, Formal analysis, Data curation, Conceptualization. **José A. Carta:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Carlos Matos:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Henrik Lund:** Supervision, Investigation, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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