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Review

Wind-Powered Desalination on Islands: A Review of Energy–Water Pathways

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Abstract: Water scarcity is a global problem that particularly affects islands located in arid regions or regions with limited water resources. This issue has prompted the development of non-conventional water sources such as fossil fuel-powered desalination systems. Concern about the high energy and environmental costs associated with this type of facility has created the ideal framework for the proliferation of desalination projects powered by renewable energies, especially wind energy due to the multiple advantages it offers. This article provides a bibliometric analysis to identify the advances made in wind-powered desalination on islands. While many studies explore wind-powered desalination, none compile references specific to islands. This paper analyses islands' desalination needs and showcases wind-powered systems, exploring their types and uses. Firstly, the most relevant international scientific journals are identified to allow the subsequent selection and quantitative and qualitative analysis of articles directly dealing with wind-powered desalination systems. A total of 2344 articles obtained from the Scopus database were analyzed, of which 144 including 181 case studies were selected. Among the results of this study, an increasing year-on-year trend is observed in the number of published studies tackling wind-powered desalination. Finally, this paper presents a series of maps showing the most relevant facilities, projects, and data in this field, and provides an overview of the lessons learned in the decarbonization of desalination.

Keywords: wind power; off-grid desalination systems; on-grid desalination systems; Canary Islands; energy–water strategies

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1. Introduction

Access to fresh water is a growing problem in many areas of the world, due partly to climate change and partly to other factors such as a rising population [1]. In this context, some research studies have focused on analyzing the influence of climate change on the scarcity of fresh water in traditionally desert-like regions, while others have considered the potential impact on other traditionally freshwater-abundant regions [2,3]. With desalination becoming an increasingly popular option to ensure the supply of fresh water, some studies have looked at the contribution to climate change made by the fossil fuel-based powering of the technologies used to desalt the water [4]. Eke et al. [5] indicate that there is an increasing trend in the cumulative capacity of operational desalination plants worldwide, from just 27,252 m^3/d in 1969 to 97.2 million m^3/d in 2020. The global installed capacity across the world is distributed as follows: 39% Middle East; 3% Oceania; 18% Americas; 8% Africa; 11% Europe; and 21% Asia [5]. The major applications of these desalination systems are for producing drinking water (59% of the fresh water produced) and for industry uses (36%) [5]. Other uses are tourist facilities (2%), irrigation (2%), and military purposes, demonstrations, etc. (1%) [5]. It is well known that reducing the carbon footprint in the desalination sector requires a reduction in the use of fossil fuels and, in the most optimistic of scenarios, their complete replacement with non-polluting renewable energy sources (RESs) [6]. The trend among desalination systems installed during recent years is to use energy recovery devices (ERDs) to reduce the specific energy consumption (SEC) below 3 kWh/m^3 [7].

Water scarcity can be particularly problematic for islands and more and more of them across the world are looking to desalination to cover their water needs [8]. In this regard, there has been a growing interest on the part of the institutions that govern and manage water and energy resources on these islands in projects that use RESs to power desalination technologies. In this sense, the level of technological advancement achieved by wind-based energy systems, readily accessible in the market with a diverse range of rated powers, has resulted in a remarkable surge in their global installation, both onshore and offshore [6,9]. Presently, wind technology stands out as one of the most economically viable renewable energy options, boasting energy prices from newly established wind farms that can rival those of conventional power generation systems. The cost-effectiveness of energy production from a wind farm is significantly influenced by the wind resource at the site and the project's financial structure. Nevertheless, in many regions, wind energy can serve as a cost-effective fuel, even without government subsidies. According to Ali Abdelkareem et al. [10], the majority of studies in the literature have employed wind power in conjunction with desalination systems driven either mechanically or electrically, as these systems prove to be more compatible for integration with wind power. Additionally, in recent years, diverse scientific studies have also been published proposing developments along this line [6,10,11]. Many of these are theoretical and simulate desalinated water production on islands with the participation of renewables [12]. Although to a lesser extent, works have also been published describing actual projects that have been undertaken on islands in which the desalination plant installations are partly or wholly wind-powered [13].

Several of these experimental works have been undertaken in the Canary Archipelago (Spain), classified as an outermost region of the European Union. The islands have commonly endured freshwater shortage issues, with these becoming exacerbated over the past five decades in many of the islands with the development of mass tourism. The climate conditions of the islands, especially the low precipitation levels, and the geomorphological circumstances explain both the absence of exploitable surface waters (a significant factor throughout the inhabited history of the islands) and, indeed, their interest in desalination. Because of the limited water resources, more notable on some islands than others, the first actions that were taken aimed to meet the water demand using whatever desalination or water reclamation technology was available at the time [14]. In fact, the archipelago was a pioneer in Europe in the application of desalination and, over time, the studies undertaken in this field on the islands enabled reductions in SEC and, hence, in water production costs [7,15]. Subsequently, given the particular energy characteristics of the archipelago (no conventional energy sources and a highly oil-centered energy dependency [16]), a historic public and private initiative of sustainable energy–water strategies was embarked upon [17]. The first private actions arose from the need to reduce the electricity bills that were being paid by the owners of plants for energy-intensive desalination processes [18].

In most cases, the use of RESs contributes to lowering fossil fuel-based electricity production. Given the energy structure of the islands, with grids that present stability weaknesses in the event of high renewable penetration, the Canary Islands government published specific regulations [19,20] for the operation of grid-connected desalination systems with renewable participation to ensure their greater integration. This issue was addressed in a recent study that introduced a method for validating the strategies proposed in a planning approach [21]. The study conducted a more specific analysis of the impact on grid stabilization when integrating high levels of RESs into the energy system [21]. The actions that were taken had the prime objectives of reducing external energy dependency, satisfying the water demand of the islands' inhabitants and the very large number of tourists who visit the islands each year, and exploiting the available renewable potential (principally wind and solar) [22]. In this context, R&D efforts began to intensify, considering diverse operating strategies for desalination plants powered by renewables. In most cases, the most feasible renewable option on the islands was wind, given the excessively high costs associated at the time with solar photovoltaic (PV) plants, the limited availability and potential sustainability problems of biomass due to the characteristics of the islands, and topographical restrictions to the use of hydropower on many of the islands. The strategies that have been considered include the exclusive use of renewables to power a desalination plant [23], although always bearing in mind the need to resolve the grid and other problems associated with the generally intermittent nature of these energy sources. In this context, systems have been developed based on different desalination technologies and on the concept of operational flexibility to cover the water demand [7]. Some recent studies have proposed optimizing a hybrid photovoltaic–wind system [24]. Systems have also been considered using water storage and regulation and battery-based energy storage [25,26]. Control systems based on the use of AI have been integrated and the performance of reverse osmosis (RO) membranes tested when operating under fluctuating operating conditions [27,28].

Aim, Novelty, and Key Contributions of This Paper

Although several papers can be found in the literature that analyze wind-powered desalination systems, as far as the authors of the present paper are aware, no study has been made which synthesizes in a single work the major references in the field of island-based wind-powered desalination systems. The present study aims to fill this gap and to analyze island-based desalination needs, showing the importance of desalination in this type of geographic region. In addition, a synthesis is offered of the wind-powered desalination systems that have been implemented, through an analysis of their typology and scale of use.

2. Methods

2.1. Search Procedure Followed

2.1.1. Journal Identification

In this study, an international bibliometric analysis method was applied based on a previous work by Østergaard et al. [29] in the field of energy planning. A purely bibliometric article analysis was carried out. Firstly, international scientific journals were screened using the search term "wind desalination system island" within their indexed data. A more extensive search was then undertaken in which a total of 2344 potential publications of interest were identified. However, it is well known that search engines can generate a significant number of irrelevant publications. For example, ScienceDirect searches all the text of a paper resulting in numerous identifications which only mention the words used in the search term. Manual reading and evaluation of the 2344 initially identified publications was thus undertaken, with 144 finally determined to be valid for selection for the analysis carried out in this study. As some of these 144 articles contained various case studies and could be classified into different categories, the present work differentiates between the total number of selected articles (144) and the total number of case studies (181). These articles were then classified to identify and categorize them by year and type.

The search procedure employed in this work was divided into the various steps described above and summarized in Figure 1.

The search term "wind desalination system island" was selected to identify publications that focused on island-based desalination projects using wind power.

The first step in the process was to identify journals (Table 1) which used the selected search term. The internationally recognized Scopus search engine was used for this purpose, identifying journals which contained studies that included the search term. This database was then used for a more intensive search of relevant articles.

An advanced search and evaluation of relevant articles was performed in this step, ensuring that the bulk of the research described in the article focused on the topic of interest rather than simply mentioning it. The journals' proprietary search engines (ScienceDirect, for example), which allow more detailed searches and may include category selection, were used in this step. Of the articles that were identified, those that contained the search term but in an irrelevant context or without describing or referring to the topic of interest were discarded, along with those that were duplicates (mainly copies of abstracts published separately from the main article).

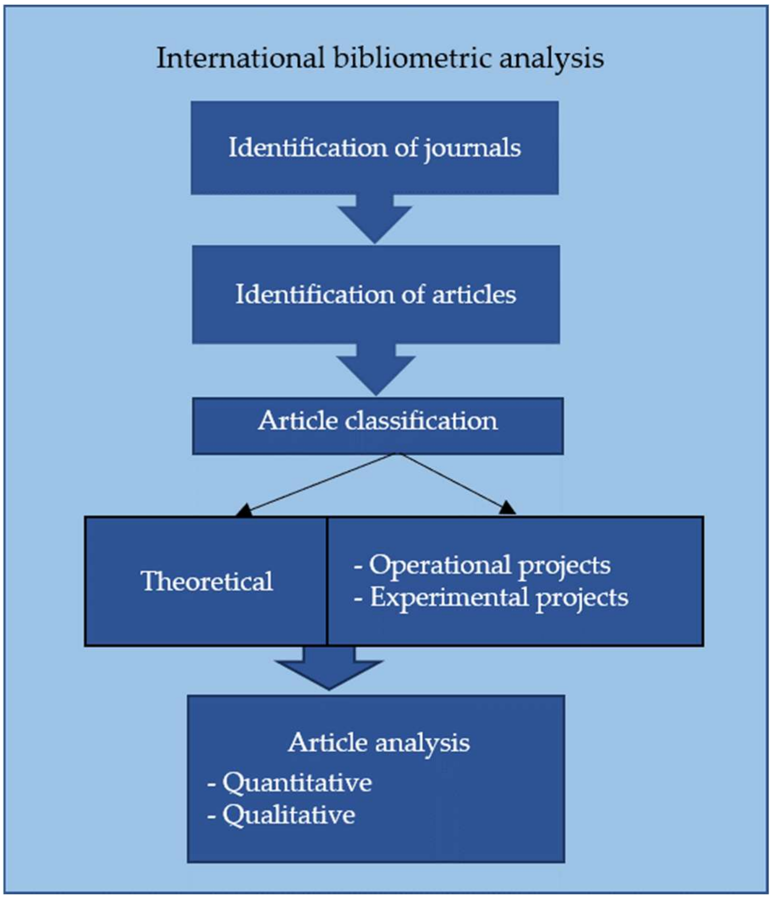

Figure 1. Search procedure followed in this study. Source: adapted from [29], with permission from Elsevier, 2024.

2.1.2. Classification and Quantitative and Qualitative Analysis of the Articles Found

In this step, an initial classification of the articles was made by year of publication and category. Two main categories were considered: on-grid and off-grid wind-powered desalination systems. A more exhaustive classification was then performed, employing the subcategories shown in Figure 2 and differentiating between theoretical analyses and simulations (Tables 2 and 3), projects which are or have been in operation (Table 4), and experimental systems/projects (Table 5). Finally, a qualitative analysis of the most relevant articles in each category was performed.

The classification used corresponds to that published in [30], but on this occasion was applied to wind-powered desalination systems. They are categorized into two main groups, as illustrated in Figure 2. The first group comprises systems where the desalination plants and wind farms are integrated with the conventional power grid, while the second group encompasses standalone microgrids or small-scale systems that operate independently of the conventional grid. Within the first group, two subcategories can be identified:

(a) systems where the entire energy generated by wind turbines is directly injected into the electrical grid, with the desalination plant serving as an additional load on the conventional electrical system;

(b) interconnected microgrids where wind turbines are connected in parallel to the conventional grid but primarily utilize their generated energy to directly power the desalination plant. Any surplus energy is fed into the conventional grid, while any shortfall is supplemented by the conventional grid.

Similarly, three subcategories exist within the second group:

(a) standalone microgrids where the desalination plant is directly connected to the wind power generation system and an energy storage system is employed;
(b) standalone microgrids where the desalination plant is directly connected to the wind power generation system and no energy storage system is employed;
(c) standalone microgrids where the desalination plant is powered by a hybrid energy system.

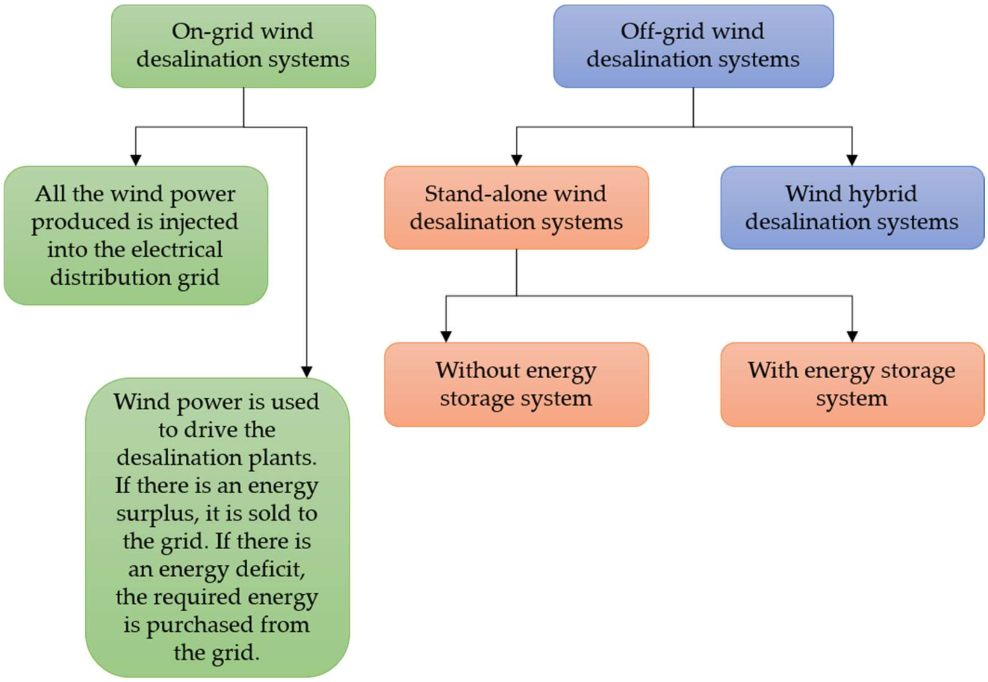

Figure 2. Classification of wind-powered desalination systems. Source: adapted from [30], with permission from Wiley, 2024.

3. Results and Discussion

3.1. Identification of Scientific Journals Selected for the Study

3.1.1. Article Identification

The results of the method employed are described in this section. Firstly, the search results are given, and this is followed by an analysis of the most relevant articles in each category.

The earliest identified use of the search term was in theoretical articles published in 1999, which was the first year used for the classification process that extended up to 2023. As for articles which considered actual wind-powered desalination projects/prototypes, the first identified use of the search term was in 1979, although from 1999 onwards it appears in a considerably more extensive number of publications.

Journal selection was performed using the method described in Section 2.1.1. Table 1 shows the journals grouped by publishing house along with the corresponding publisher's search facility, when available. Elsevier has the most journals considered in the present study (35%), followed by 16 other publishers. Just four of the selected journals (*Desalination*, *Applied Energy*, *Energy*, and *Renewable Energy*) are responsible for 68.7% of the articles considered in this study. *Desalination* alone published 38.7% of the articles, with this attributable to the close relation of the topic with the energy–water nexus and its close alignment to the scope of the journal. The corresponding percentage contributions of

Renewable Energy, *Applied Energy*, and *Energy* are also considerable (11.1%, 9.7%, and 9.7%, respectively). Analogously to the case of *Desalination*, these three journals include in their scope topics related to renewable energy systems, wind power, energy transitioning, etc., which are also in close alignment with the topic tackled in the present analysis.

Table 1. Identification and classification of the journals considered in this study.

Publisher	Journals	Publisher's Full-Text Search Facility
Elsevier	*Energy, Energy Conversion and Management, Solar Energy, Renewable Energy, Energy for Sustainable Development, Applied Energy, Desalination, Filtration and Separation, Sustainable Energy Technologies and Assessments, Energy Reports, Renewable and Sustainable Energy Reviews, Thermal Science and Engineering Progress, Journal of Energy Storage, Science of The Total Environment, Water Science and Engineering*	https://www.sciencedirect.com/ (accessed on 28 February 2024)
Wiley Interdisciplinary Reviews	*Energy and Environment, Energy Research*	https://onlinelibrary.wiley.com/search/advanced (accessed on 28 February 2024)
MDPI	*Energies, Sustainability, Processes, Applied Sciences, Water*	https://www.mdpi.com/ (accessed on 28 February 2024)
Springer	*Solar Desalination for the 21st Century, International Journal of Energy and Environmental Engineering, Renewable Energy Based Solutions, Alternative Energy Sources and Technologies*	https://link.springer.com/ (accessed on 28 February 2024)
Deswater	*Desalination and Water Treatment*	https://www.deswater.com/home.php (accessed on 28 February 2024)
WSEAS	*WSEAS Transactions on Environment and Development*	https://wseas.com/ (accessed on 28 February 2024)
Taylor Francis	*International Journal of Sustainable Energy, Desalination and Water Treatment*	http://www.tandfonline.com (accessed on 28 February 2024)
IEEE	*IEEE Access*	https://ieeexplore.ieee.org/search/advanced (accessed on 28 February 2024)
CET	*CET Journal*	https://www.cetjournal.it/index.php/cet (accessed on 28 February 2024)
IOP Science	*Earth and Environmental Science*	https://iopscience.iop.org/ (accessed on 28 February 2024)
Emerald	*Journal of Engineering, Design and Technology*	https://www.emerald.com/insight/ (accessed on 28 February 2024)
AIP Publishing	*Journal of Renewable and Sustainable Energy*	https://aip.scitation.org/ (accessed on 28 February 2024)
Korea Science	*Journal of Electrical Engineering and Technology*	http://koreascience.or.kr/main.page (accessed on 28 February 2024)
Scientific.net	*Advanced Materials Research, Applied Mechanics and Materials*	https://www.scientific.net/ (accessed on 28 February 2024)
Hindawi	*Computational Science in Smart Grids and Energy Systems*	https://www.hindawi.com/ (accessed on 28 February 2024)
Biomedcentral	*Energy, Sustainability and Society*	https://energsustainsoc.biomedcentral.com/ (accessed on 28 February 2024)
IWA Publishing	*Water Supply*	https://iwaponline.com/ (accessed on 28 February 2024)

3.1.2. Classification of the Identified Works

Table 2 shows the theoretical works identified after applying the previously described search method. The 2344 articles originally identified were filtered to select the most relevant articles in which the search item appeared.

Table 2. Selected theoretical studies.

Year	On-Grid		Off-Grid		
	100% Connected to the Grid	Wind Power Used to Power the Desalination Plant	Without Energy Storage System	With Energy Storage System	Hybrid System
1999		[31]			[32,33]
2000					[34,35]
2001	[36]	[37–40]			[41]
2002		[42,43]			[42,44,45]
2003		[46]	[47]		[48]
2004	[17]	[49,50]			[51]
2005		[52]	[53]		
2006				[54]	[55,56]
2007	[57,58]	[57]	[57]	[57,59,60]	[57]
2008					[61]
2009					[62,63]
2010					[64,65]
2011	[66]	[67]			[68,69]
2012	[70–72]	[73]	[74]		
2013					
2014					
2015	[75]			[76]	[76,77]
2016	[78,79]	[80]			[81–83]
2017					
2018	[84,85]	[86]			[87–89]
2019	[90]	[91]			[92–95]
2020		[96]			[12,97–100]
2021		[23,101,102]	[25,103,104]		[26,105,106]
2022	[107–112]	[108,113]	[108]	[108]	[108,113–116]
2023	[117–123]	[119,120]	[119,120,124]	[119,120]	[119,120,125]

Compared with the initial 2344 articles, only relatively few were finally considered relevant. Many that included the search term were discarded because the actual research study in the article was not related to the topic under consideration. Numerous articles were also discarded that referred only to desalination systems powered with solar PV generation or wave energy converters as unique technology. A significant increase in the number of publications which considered the use of hydrogen as an alternative technology was also observed for the period 2021–2023. These were also discarded as they mentioned wind power or the wind–desalination binomial only in passing without entering into greater detail. Articles which considered the use of any other energy source in addition to wind in off-grid systems are included in the Hybrid category.

Table 3 presents the predominant software/tools utilized in the previously identified theoretical studies. A significant number of these studies constructed their own tools through custom-developed software programming. Additionally, several studies followed a similar approach of developing their own tools using MATLAB. In fewer instances, researchers used HOMER, EnergyPlan, Vensim, or H2RES.

Table 3. Main software and tools applied in the different theoretical studies.

Software/Tool	References
HOMER	[63,73,87,89,92,94,97,112]
ROSA and/or TorayDS2	[87,91]
EnergyPlan	[26]
TIMES, TRNSYS, TRNOPT and/or GenOPT	[67,71,72,76,98,122]
MATLAB	[12,72,77,82,88,100,102,103,105,109,124]
H2RES	[66,75,78]
Vensim	[58]
Custom tool	[17,25,31,32,34,37,39–41,43–46,48–57,59,60,62,64,65,68,69,79–81,83–86,90,91,95,96,98,99,101,104,106,107,110,111,113,114,116–118,121,123,125]
Not specified	[23,33,35,36,38,42,47,61,70,74,93,108,115,119,120]

Table 4 shows only those articles which consider and describe projects that are or have been in operation, and Table 5 those which consider and describe experimental projects.

Table 4. Selected studies which consider projects that are or have been in operation.

Year	On-Grid		Off-Grid		
	100% Connected to the Grid	Wind Power Used to Power the Desalination Plant	Without Energy Storage System	With Energy Storage System	Hybrid System
1979				[126]	
1981				[127]	
1983			[128]		
1988					[129]
1999		[130]			
2000					
2001	[131]		[131]		
2002			[132]		
2003		[133]		[134]	[133,135]
2004	[136]		[13,137–139]	[140]	
2005					[141]
2006					
2007			[142]	[143]	
2008					
2009				[144]	
2010				[145]	
2011	[146]	[146]	[146,147]	[146]	[146]
2012					
2013			[148]		
2014	[149]				
2015			[150]		
2016				[151]	[151,152]
2017				[27]	
2018	[14,153,154]	[14,154]	[14,28,154]	[14,28,154]	[14,154]
2019		[155]			
2020		[156]			
2021			[157]	[157]	[157]

Table 5. Selected studies which consider experimental projects.

Year	On-Grid		Off-Grid		
	100% Connected to the Grid	Wind Power Used to Power the Desalination Plant	Without Energy Storage System	With Energy Storage System	Hybrid System
2003			[158,159]		
2009			[160]		[161]
2015			[162]		
2020					[163]
2021			[164]		
2023					[165]

3.2. Quantitative Analysis of the Results

The quantitative analysis of the results is represented in a series of graphs and maps shown in Figures 3–7.

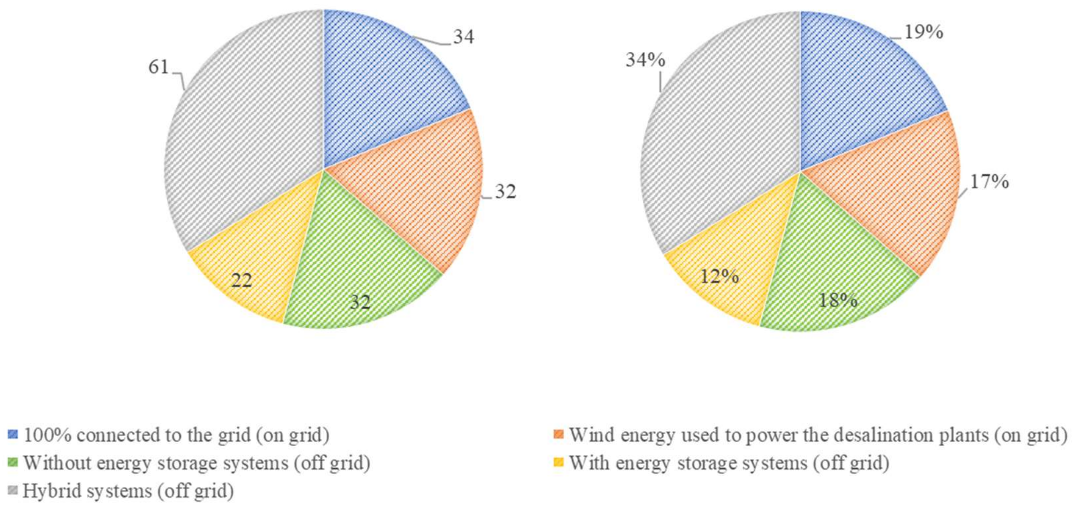

Figure 3. Numbers and percentages of studies by subcategory.

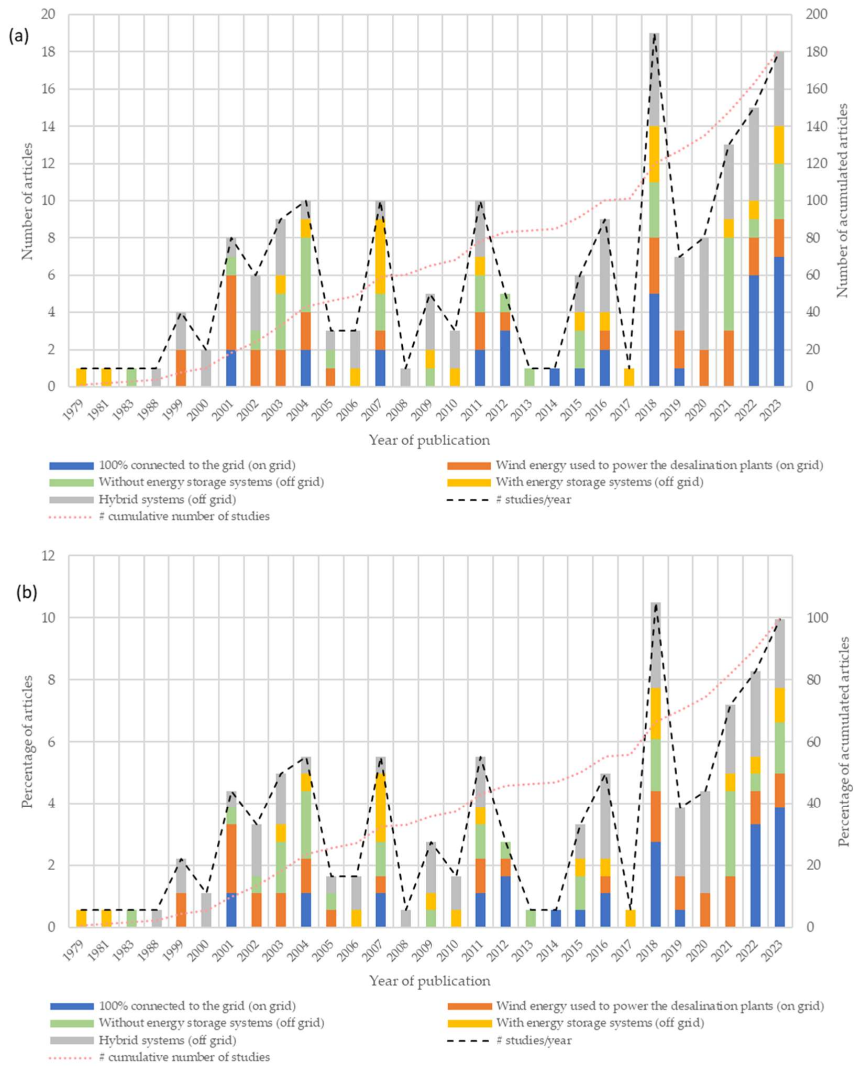

Figure 4. Evolution of the numbers of studies from 1979 to 2023 by year of publication and subcategory: (**a**) in absolute numbers and (**b**) in percentages.

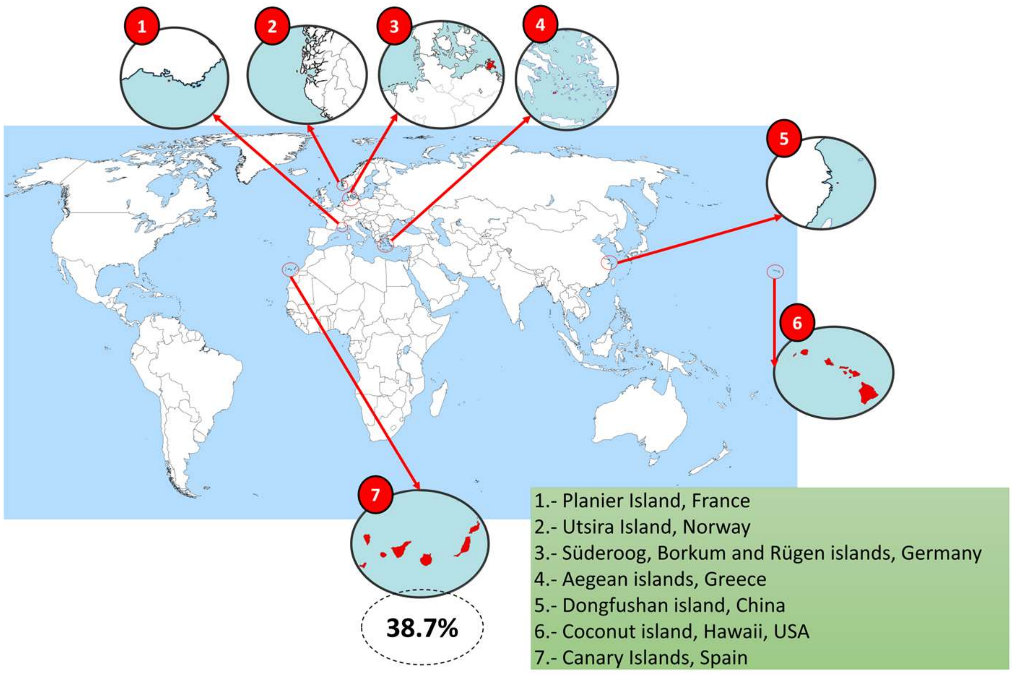

Figure 5. Map of the location of island-based wind-powered desalination projects that are or have been in operation.

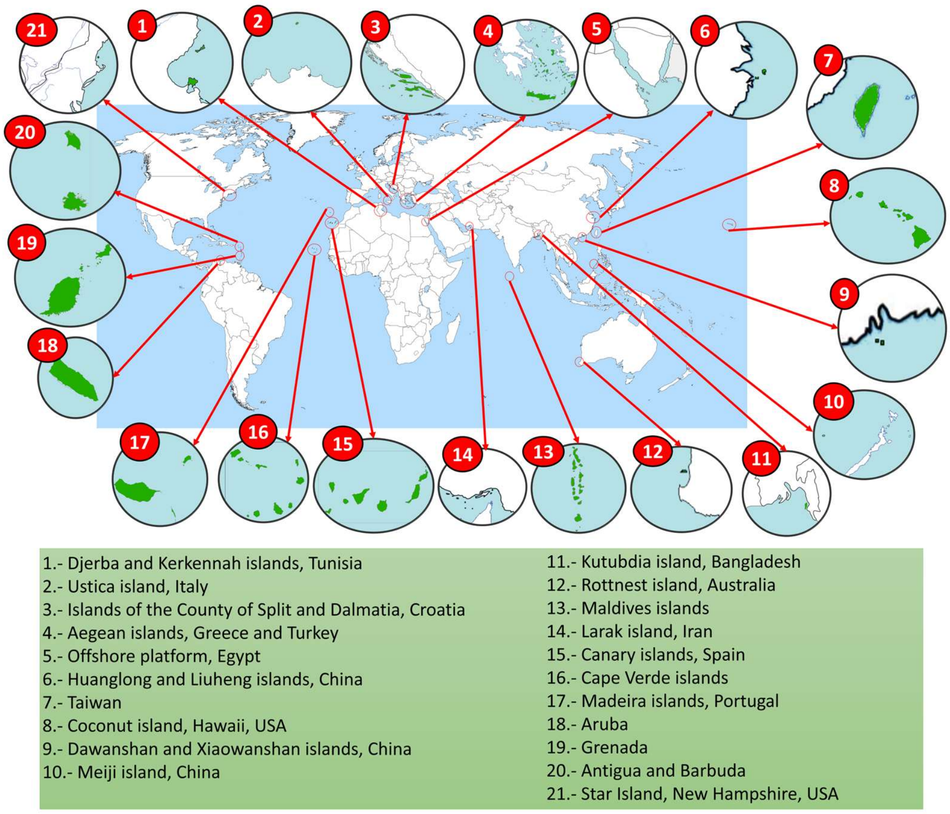

Figure 6. Map of the location of theoretical island-based wind-desalination studies/simulations.

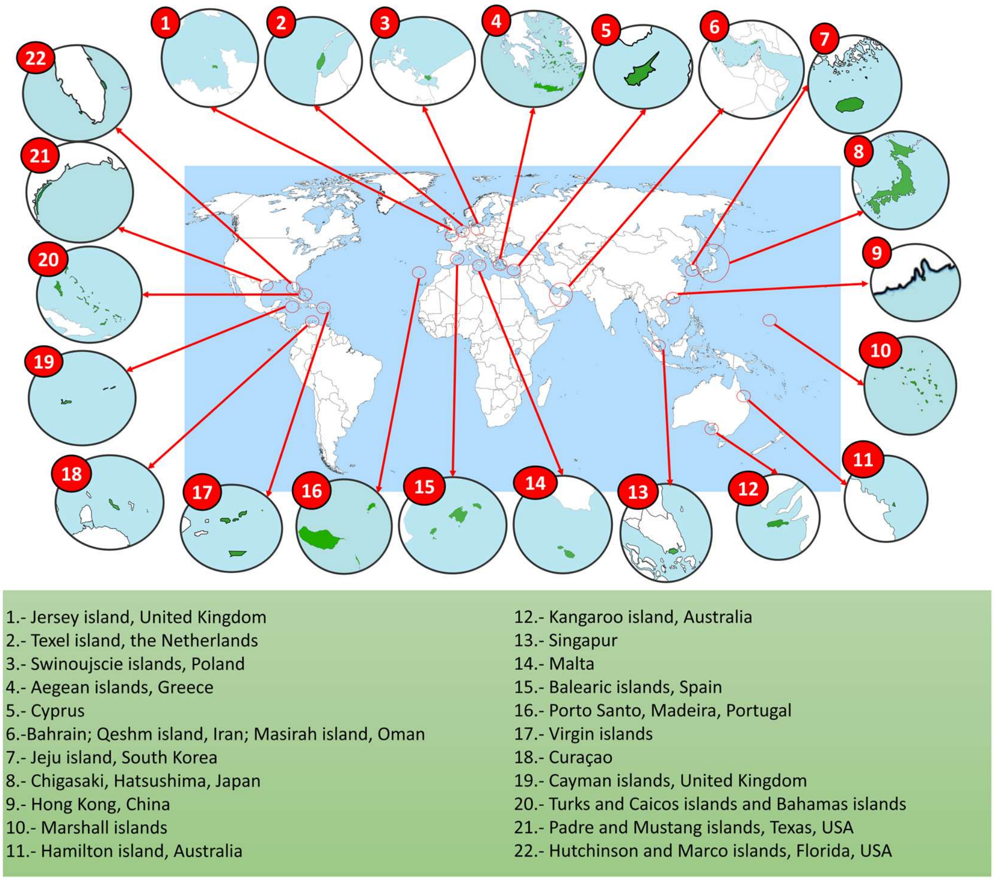

Figure 7. Map of potential island locations for future wind-powered desalination projects. 1.- Jersey island, United Kingdom [166]; 2.-Texel island, the Netherlands [167]; 3.-Swinoujscie islands, Poland [168]; 4.-Aegean islands, Greece [169,170]; 5.-Cyprus [171–173]; 6.-Bahrain; Qeshm island, Iran; Masirah island, Oman [174–176]; 7.-Jeju island, South Korea [177]; 8.-Chigasaki, Hatsushima, Japan [178,179]; 9.-Hong Kong, China [180]; 10.-Marshall islands [181]; 11.-Hamilton island, Australia [182]; 12.-Kangaroo island, Australia [183]; 13.-Singapur [184]; 14.-Malta [185]; 15.-Balearic islands, Spain [186]; 16.-Porto Santo, Madeira, Portugal [187]; 17.-Virgin islands [188]; 18.-Curaçao [189,190]; 19.-Cayman islands, United Kingdom [191,192]; 20.-Turks and Caicos islands and Bahamas islands [8,193]; 21.-Padre and Mustang islands, Texas, USA [194]; 22.-Hutchinson and Marco islands, Florida, USA [195,196].

Figure 3 represents the total number of case studies of the two on-grid and three off-grid subcategories in Table 2, Table 4, and Table 5 and their respective percentages. It can be seen that more studies are dedicated to off-grid than on-grid systems, whether considered numerically (115 vs. 66) or in percentage terms (64% vs. 36%), with hybrid systems the most considered type.

Figure 4 shows the evolution of the five subcategories over time, identifying the number of studies in each of them from 1979 to 2023.

Figure 5 is a map showing the island location of all the wind-powered desalination projects that are or have been in operation. Figure 6 shows the island location of all the theoretical projects that have been undertaken. Finally, Figure 7 shows all the islands where desalination is presently or about to be carried out, but which do not yet use wind as an energy source. This figure was created based on the references indicated in the legend (Figure 7). The relevance of these locations lies in the growing trend for covering electrical energy demand with RESs and, hence, the potential for these islands to be future locations where wind-powered desalination systems are set up.

3.3. Qualitative Analysis and Discussion of Results

In this section, a comparative analysis is made of the results obtained in the search and classification of articles which contained the search term “wind desalination system island”. The analysis is conducted considering some of the studies found in each section.

One of the most notable of the theoretical works is that conducted on the island of San Vicente, in Cape Verde [66]. This study, which used the H2RES tool [197,198] to simulate the use and integration of RESs in the desalination that the island requires, is an example of the on-grid subcategory of 100% connection to the grid, as all the generated energy is fed to the grid and this energy is then used for desalination. This same consumption type can be seen in other studies, with the islands of Antigua and Barbuda using only solar and wind power [107] while a diesel system was added in the study carried out for an island in China [94].

Included among the theoretical works in the second on-grid subcategory is the study performed by Kaldellis et al. [49], which offers an economic and technical analysis of a possible installation on Greek islands in the Aegean Sea (the Cyclades or the Dodecanese islands) using wind and solar energy to power a desalination plant. If the system is unable to generate sufficient energy to meet the demand, energy is purchased from the island’s grid. Another study, also located in the Aegean Sea but this time for the island of Fournoi [86], describes a system with a wind farm, a small hydroelectric plant, and a pumping station. According to the results of the study, 70% of the energy produced would be used for desalination and pumping, with the remaining 30% fed into the grid.

Among the theoretical studies of off-grid systems without energy storage is that by Carta et al. [25] of the island of Gran Canaria (Canary Islands, Spain), in which a simulation was performed of a system comprising a seawater RO desalination plant powered by a wind farm without batteries. To compensate for this lack of energy storage, a flywheel was used to enable the variable operation of the desalination plant. In [60], Kaldellis et al. compared two off-grid systems with battery energy storage, one using wind power and the other solar. The study was carried out for various islands in the Aegean Sea. Georgiou et al. [76] also carried out a comparative study, on this occasion from economic, environmental, social, and technological perspectives, of five proposals for islands in the Aegean Sea, with one of the proposals being an off-grid wind-powered desalination system with battery energy storage. As for the off-grid hybrid system subcategory, a study of a hybrid wind–solar plant for desalination was undertaken for Croatian islands of the Split–Dalmatia region [35]. Kaldellis et al. [55] also designed a hybrid wind–diesel system for the Greek islands of Andros, Naxos, and Kea.

With respect to projects that are or have been in operation, one of the most notable was developed on the island of Rügen [130], with on-grid consumption and the peculiarity that surplus energy is not dumped into the grid but used to raise the seawater feed temperature and thereby obtain greater distillation in the system’s mechanical vapor-compression process. Liu et al. [132] analyzed an off-grid wind-powered RO desalination system without any additional battery energy storage installed on Coconut Island (Hawaii), whereas the off-grid wind-powered desalination system installed on the island of Utsira (Norway) did use such an energy storage device [143]. Cabrera et al. [28] compared two systems in operation on the island of Gran Canaria (Canary Islands, Spain), one with and one without batteries for energy storage. As for off-grid hybrid systems, Zhao et al. [149] studied a wind–diesel microgrid installed on the island of Dongfushan (China) with the peculiarity that the system uses the desalination system to control the increase in renewable energy that is generated.

An example of an actual commercial wind-driven desalination system currently providing water for an island community is the project developed on Milos Island (Greece), commissioned in 2007. It was designed to meet the water needs of the island, which previously relied on water transported by tanker boats from Athens. The seawater reverse osmosis desalination plant is capable of producing 4500 m^3/day, driven by an 850 kW wind turbine and connected to the existing grid. In this manner, the system effectively fulfills the island's water demand even during peak seasons [199]. Table 6 displays this in addition to other commercial systems that are currently operational supplying water to inhabitants.

Table 6. Commercial wind-driven desalination systems currently used by inhabitants of some islands.

Location	Reference	Type	Year
Cañada del Río, Fuerteventura, Spain	[200]	100% connected to the grid	1994
Rügen Island, Germany	[130]	Wind power used to power the desalination plant/standalone	1999
Agragua, Gran Canaria, Spain	[201]	Wind power used to power the desalination plant	2001
Soslaires, Gran Canaria, Spain	[91,202]	Wind power used to power the desalination plant	2002
Milos Island, Greece	[199]	100% connected to the grid	2007
Corralejo, Fuerteventura, Spain	[203]	Wind power used to power the desalination plant	2010
Gorona del Viento, El Hierro, Spain	[204,205]	100% connected to the grid	2014
Díaz Rijo, Lanzarote, Spain	[206]	Wind power used to power the desalination plant	2016
Los Valles, Lanzarote, Spain	[207]	100% connected to the grid	2018
Puerto del Rosario, Fuerteventura, Spain	[208]	Wind power used to power the desalination plant	2019
Conagrican, Gran Canaria, Spain	[209,210]	Wind power used to power the desalination plant	2021

As for experimental systems, Miranda et al. [158] constructed a small-scale prototype to simulate an off-grid standalone system with a 2.2 kW wind turbine connected directly to an RO desalination system and without battery energy storage. A similar prototype was tested by Heijman et al. [160], but in this case a direct mechanical drive was employed meaning that no electricity was required for the transfer of energy between the system's windmill and the RO desalination installation. The system also had low- and high-speed limitations. Among the experimental hybrid systems, Uche et al. [163] developed a prototype that used a small wind turbine and five photovoltaic/thermal collectors to desalinate water using an RO process. The system can be scaled up and was designed for isolated off-grid areas, as commonly found on islands.

The results obtained in the present study reveal a clear year-on-year increase in the number of publications, with this particularly evident in the past 6 years (Figure 4). This may be partly attributable to the growing awareness and importance of the impact of climate change on the scarcity of water resources, and partly to the considerable increase in concern about the use of fossil fuels and the general socioeconomic context which favors the development of RE-based systems. It can therefore be argued that the increase in the types of publications considered in the present study follows a similar trend to studies that tackle the energy transition to renewable sources.

The first studies found in the search, dating back mainly to the 1980s, involved projects that were in operation [126–130]. Nonetheless, theoretical studies dominated overall, representing 62% of the total. This indicates a greater predisposition to the undertaking of studies and simulations in the theoretical sphere, with relatively few works being executed and going beyond the trial stage.

The dominance of case studies focused on off-grid systems was also observed (Figures 3 and 4). This is unsurprising, as many studies seek greater autonomy in wind-powered desalination [13,28,148] and, in addition, the limitations inherent to islands are an influencing factor with regard to the strategies that can be proposed. It is not uncommon on islands for off-grid standalone systems to be the main option, as the grid systems may be very limited or even non-existent [49,127]. These standalone micro-grid systems primarily rely on a combination of wind turbines, RO-based desalination plants, and battery storage, though proposals for hybrid systems (comprising some other additional energy source) have grown in number in recent years.

It can be seen in Figure 5 and Table 6 that a significant percentage of the wind-powered desalination projects in operation or under trial are in the Canary Islands (38.7% of the total). With 24 wind-powered desalination projects undertaken, it could be argued that this region resembles a test facility that confirms the feasibility of this type of project and its potential for transfer to other islands. The projects undertaken on these and other islands will undoubtedly be of interest to those islands shown in Figure 6 where theoretical studies and simulations have been performed (most notably in the Greek islands of the Aegean Sea, with 29 studies corresponding to 24.4% of the total) and, indeed, the islands shown in Figure 7 where desalination systems are up and running but wind power has not yet been scientifically considered as an energy source option.

After analyzing the various studies considered in this research, it is possible to assert that wind power and reverse osmosis desalination systems have been revealed as a relevant combination to reduce emissions in the desalination industry and increase resilience in water supply systems on islands. For large-scale desalination, on-grid wind energy systems are the preferable option [211]. In these systems, the wind turbines feed all their generated energy into the grid. This approach allows desalination plants to operate under stable, consistent conditions, similar to traditional methods. Additionally, with proper design of wind farms, achieving a zero net energy exchange between wind farms and desalination plants is possible [211]. However, in smaller, isolated grids with limited capacity, adding more wind farms can destabilize the system. To overcome this challenge and increase wind energy utilization, the trend is shifting towards large, wind-powered desalination systems connected to the main grid [211]. This solution combines the benefits of on-grid systems with improved stability for weaker grids. The desalination plants utilize most of the wind energy directly, while the system can still draw from or contribute to the main grid as needed. In the case of medium-scale and standalone wind-powered desalination projects, several systems have been built for research purposes, but most have been shut down after their projects ended, despite demonstrating technical viability. However, the interest persists, and companies are exploring off-grid hybrid (conventional–renewable) power systems to provide energy and alleviate water challenges in remote regions [211].

As for the gaps/challenges identified, on-grid systems, with their stable grid support and predictable desalination plant operation, face relatively few challenges. This is because the grid typically buffers the uncertainty introduced by wind energy. However, weak grids limit the penetration of renewables to avoid instability. Conversely, managing and controlling the interconnected components of standalone and hybrid systems presents significantly more complex challenges due to the variable operating conditions and resulting uncertainty in desalination processes.

Some of the main lines of research and trends in this field are related to the key gaps detected:

- The exploration of different energy storage systems to manage the intrinsic variability and intermittency of wind power [212].
- The development of energy management strategies that propose the adaptation of the production (or part of it) of the desalination plant to the available wind power [213].
- The use of artificial intelligence to manage the operating setpoints on the desalination plants [27,212] or to simulate and optimally design the integrated renewable desalination subsystems [6,28].
- The use of dynamic energy-regulation systems based on flywheel or supercapacitor systems to manage the variability/intermittency of wind power [150,212,214].
- The approach of smart energy planning concepts to support the design of the entire energy–water system on the islands, taking into account the synergies between the different desalination and wind power sectors [26].

Additionally, due to spatial constraints limiting onshore wind energy expansion on islands [215], offshore wind farms (WF) have begun to be considered theoretically in very recent research [6]. Despite not yet having identified any actual project that combines offshore wind turbines with desalination systems, standard offshore WF projects for islands present the challenge of bathymetric restrictions [216]. Therefore, the majority of the suggested plans involve deploying floating wind turbines [217,218]. According to [219], in the case of floating offshore WFs, the specific investment cost would be EUR 4200/kW, which is higher than the mean for onshore WFs. It is another challenge to combine this technology with desalination, because the specific cost of the water produced could be EUR 2.57/m^3, which is still six times higher than the cost generated by desalination plants with capacities ranging between 100,000 and 300,000 m^3/day that use conventional energy [6].

4. Conclusions

This article gathers the works that have been published in scientific journals to 2023 that have dealt with theoretical studies as well as experimental projects of wind-powered desalination systems on islands, discarding those based in continental regions of the planet.

All the studies were classified into various categories according to their characteristics: theoretical studies, experimental studies, and projects with both on-grid and off-grid connection. A total of 2344 articles were analyzed, of which 144 were selected, including 181 case studies. The vast majority of the studies analyzed consider it essential to continue with this line of research until the projects proposed in the theoretical framework are implemented, as the particularities of islands and their water–energy dependence give such initiatives strategic importance. Almost all the studies analyzed comment on the high economic cost of the desalination process, mainly due to the high energy consumption of desalination plants. Therefore, the use of wind power can be considered a critical strategy for islands that have this resource, enabling CO_2 emission reductions and contributing to the fight against climate change.

In general terms, the following can be stated:

- Scientific interest in studies dealing with wind-powered water desalination has been growing steadily since the first reviewed publication in 1979.
- The pairing of wind power and reverse osmosis desalination systems has emerged as a noteworthy solution for mitigating emissions in the desalination industry and bolstering resilience in water supply systems on islands.
- On-grid wind energy systems are the preferred choice for large-scale desalination. In these systems, the energy generated by wind turbines is fed into the grid, allowing desalination plants to operate under stable conditions similar to traditional methods. Properly designed wind farms can achieve a zero net energy exchange between the wind farms and desalination plants.
- In smaller isolated grids with limited capacity, adding more wind farms can destabilize the system. To overcome this, there is a shift towards large wind-powered desalination systems connected to the main grid, offering advantages of stability for weaker grids. These systems enable direct harnessing of most wind energy by desalination plants while maintaining flexibility to interact with the main grid.
- Despite the construction of medium-scale and standalone wind-powered desalination projects for research, many were deactivated after demonstrating technical viability. However, ongoing interest has prompted exploration of off-grid hybrid power systems to tackle energy and water challenges in remote regions.

A high level of scientific specialization and a considerable number of theoretical and experimental studies were identified relating to the Canary Islands (Spain) and the Greek islands of the Aegean Sea. This shows that the scarcity of resources (water and energy in this case) of the populations involved can have a favorable impact on the development of knowledge-based strategies to mitigate the negative effects of such scarcity. The technical and administrative knowledge and knowhow generated through the energy–water strategies followed in the Canary Archipelago can be of important use in other islands of the world that have not yet considered the use of renewable energies to cover their water needs or are taking their first steps in this field and wish to undertake climate change mitigation measures and strategies to achieve carbon neutrality in water desalination.

This work also offers the scientific community a series of maps, showing the islands where wind-powered desalination systems have been set up and theoretical studies undertaken. Faced by water scarcity issues, often exacerbated by climate change and a rising population, these islands have opted to pursue solutions that involve strategies that combine wind power and desalination systems.

As future trends in the field, the following can be highlighted:

- Exploring various energy storage systems to manage the inherent variability and intermittency of wind power.
- Developing energy management strategies suggesting the adaptation of desalination plant production to the available wind power.
- Utilizing artificial intelligence to handle operating setpoints for desalination plants and optimize the design of integrated renewable desalination subsystems.
- Implementing dynamic energy regulation systems based on flywheel or supercapacitor systems to handle the variability and intermittency of wind power.
- Applying smart energy planning concepts to design entire energy–water systems on islands, considering synergies between different desalination and wind power sectors.

Additionally, due to spatial constraints limiting onshore wind energy expansion on islands, offshore wind farms have begun to be considered theoretically in very recent studies. The main challenges that this technology presents when combined with desalination systems on islands are the bathymetric restrictions and the higher costs of floating offshore wind farms, with specific investment costs higher than the mean for onshore wind farms.

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