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Current and future opportunities for renewable integrated desalination systems in the Brazilian semiarid region

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ABSTRACT

Renewable energy sources for desalination purposes are becoming a reliable and technically mature solution over conventional methods powered by fossil fuels, especially for small-size applications in isolated regions such as the Brazilian semiarid. In this paper, an overview of desalination systems is provided with their respective energy consumption, costs, social needs, environmental assessments, and potential integration with renewable energy sources. The opportunities and challenges for the application of small-scale renewable integrated brackish water reverse osmosis desalination systems in the Brazilian semiarid are provided. In addition, a spatial analysis is conducted for a prior assessment of potential areas for the implementation of photovoltaic-RO-wind (PV-wind-RO) units in the region. Among various hybridization possibilities, PV-RO grid-connected systems are a reliable and cost-effective solution for rural communities due to the high availability of wind and solar resources and previous experience with the technology. The spatial analysis demonstrates that Ceará and Rio Grande do Norte states, as well as the central part of Bahia state, are the regions with highest potential for the implementation of PV-wind-RO systems. Further studies and experimental projects are required to aid decision making and expand small-scale desalination projects in the Brazilian semiarid.

Keywords: Desalination; Brackish water; Reverse osmosis; Renewable energy integration; Brazilian semiarid

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1. Introduction

Even though water covers two-thirds of the Earth's surface, just a slight portion of it is appropriate for human basic needs. Currently, one-fifth of the earth's population is facing drastic water shortages [1]; according to the sustainable development agenda, this statistic might increase to, at least, one-quarter by 2050 [2]. Moreover, approximately 40% of the world's inhabitants, especially those living in remote areas, do not have access to potable water due to the absence of affordable water treatment methods. Future scenarios foresee worsening of the problem reaching two-thirds of the global population by 2050 [2]. World water consumption levels are increasing at a rate of approximately 1% per year, with predictions to keep rising over the next two decades [2].

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Industrial and domestic demands for water will advance much faster than for the agricultural sector, although the latter will continue to have the highest consumption in general terms. Currently, agriculture consumes 69% of the global fresh water, industrial and domestic sectors consume 19% and 12%, respectively [3]. Chronical failure to bring safe fresh water to vulnerable populations leads to hardships, such as decreased life expectancy, spread of diseases and local conflicts. These facts combined with the potential negative impact on fresh water availability brought by climate change, accelerated urbanization, population increase and rising water pollution have sealed the importance of defining water as a top priority in the strategic plans of most governments; as established by Goal 6 of the 2030 Agenda for sustainable development – ensure availability and sustainable management of water and sanitation for all [4].

The adverse consequences of water shortages have promoted the acceptance of non-standard water supply strategies such as water recovery, water imports, and desalination. The latter is the most acknowledged and readily available alternative water resource [5]. Desalination is the process of removing dissolved salt and minerals from saline and brackish water to produce potable water or water for industrial and agricultural use [4]. Saline water can be rated according to the total dissolved solids (TDS) or salinity measured in parts per millions (ppm). For brackish water, the common TDS level is up to 10,000 ppm, while for seawater, the concentration is up to 45,000 ppm [6]. The admissible limit of salinity in drinking water ranges from 500 to 1,000 ppm [7]. Among various desalination technologies, reverse osmosis (RO) currently stands out as the most energy efficient and cost-effective process, representing approximately 65% of the world installed capacity [4,8,9].

In spite of its trending growth, desalination technologies are still considered “chemically, energetically and operationally intensive, focused on large systems, thus requiring a considerable amount of capital, engineering expertise, and infrastructure” [10]. However, the paradigm of high capital expenditures (CAPEX) and large size units is slightly changing, especially in the field of inland desalination in remote areas where decentralized small-scale brackish water reverse osmosis (BWRO) systems have been recently applied with relative success.

Among other technical innovations, integrating renewable energy resources to desalination systems is highlighted as a potential solution to reduce the total energy consumption of the process, as it minimizes greenhouse gas emissions [11]. Despite some technical challenges, such as energy storage, intermittence, and high CAPEX [12,13], the use of small-scale renewable integrated desalination systems may be a feasible solution for remote areas with scarce or no access to the power grid, high water scarcity, and renewable sources availability as well as brackish or saline water sources.

As an intertropical country with a long coastline and high wind and sun radiation levels throughout the year, Brazil is a promising spot for the implementation of renewable integrated desalination systems, particularly in its semiarid region (Fig. 1). The latter is one of the most populous semiarid regions in the world, with 22.6 million inhabitants (12.3% of the Brazilian population) of which 9 million live in rural areas [14], where access to safe drinking water is an ongoing issue. In this region, the lack of access to high quality water significantly affects local economies and commonly causes illnesses and even casualties. Because of poor municipal water management and the absence of contingency measures, the adverse impacts of water shortages are intensified. These continuous negative consequences led several stakeholders, mainly states and cities’ authorities, to consider the implementation of desalination facilities [15]. Therefore, Brazilian government launched in 2004 the “Freshwater Program” (“Programa Água Doce” – PAD), as an alternative solution to establish a permanent public policy of access to high-quality water for human consumption through the implementation of small-scale BWRO desalination systems in semiarid remote communities.

This paper provides an overview of opportunities and challenges for the application of small-scale renewable integrated BWRO desalination systems in the Brazilian semiarid. In this regard, a review of desalination technologies is presented with emphasis on energy consumption, costs, social needs, environmental assessments, and potential integration with renewable resources. The subsequent section reports the Brazilian semiarid water status, demand, and current desalination installed base plants. Then, insights on the potential integration of RO systems with renewable energy sources are discussed, such as solar photovoltaic (PV), wind, and hybrid PV/wind. Since environmental resources, water salinity, and socioeconomics characteristics vary for each site, a method to site selection and support decision making is required. Spatial analysis combines different criteria through map overlay and evaluate several areas according to an established goal. Therefore, in the last section, a spatial analysis for site prioritization assessment is conducted for the implementation of renewable integrated desalination plants in the Brazilian semiarid region.

2. Desalination technologies

2.1. Current status

Desalination technologies have evolved significantly since 1950s. Particularly in the last 20 years, the worldwide installed desalination capacity has risen by around 66 million m^3 [8]. According to the International Desalination Association (IDA), in 2017 more than 300 million persons depend on water produced by 19,372 desalination plants which provide 92.5 million $m^3\ d^{-1}$ in about 150 countries [8]. Middle East countries, China, and the USA are global leaders in desalination contracted capacity [8,16]. Currently, 59% from the total installed desalination capacity derives from seawater, 22% from brackish water and 18% from rivers and wastewater [17]. The utility sector accounts for 60% of all online capacity whilst nearly 30% is covered by industrial demand, especially in the oil and gas industry [18].

Desalination plants vary in size, ranging from small-scale (up to 50 $m^3\ d^{-1}$) to larger plants (larger than 250 $m^3\ d^{-1}$) [19,20]. The Hadera plant in Israel, one of the largest desalination facilities worldwide, produces 127 million m^3 of water per year whereas many remote areas benefit from autonomous small-scale desalination plants which produce only a few m^3 of fresh water per day [21].

Fig. 1. Brazilian semiarid region.

Desalination techniques are usually classified into two major categories: thermal and membrane-based. Thermal technologies, such as multi-stage flash distillation (MSF) and multiple-effect distillation (MED), simulate the natural water cycle of evaporation and condensation by distilling the feed water into water of lower or no salinity. Membrane-based technologies such as electrodialysis (ED) and RO utilize electrical or mechanical power to generate a pressure difference across membranes, retaining salt on one side and allowing water to permeate through the membrane to the other [22]. The most developed desalination methods are (a) RO, accounting for 65% of global installed capacity; (b) MSF – 21%; (c) MED – 7%; (d) ED – 3%; and (e) others – 4% [4,17]. Apart from conventional methods, there are also hybrid processes, which integrate both membrane separation and thermal techniques [23], and emerging technologies, such as nanofiltration (NF), vapor compression (VC), membrane distillation (MD), and forward osmosis (FO) [24]. Al-Karaghouli and Kazmerski [25], Maleki et al. [26], and Shahzad et al. [27] affirm that RO is currently considered the most cost-effective desalination process. Having reached economies of scale, the cost of a small RO unit including maintenance costs is likely to be cheaper compared with other desalination systems with similar capacity. Moreover, the widespread use and availability of RO technology increases the chances of finding local technical expertise for O&M, especially in developing countries and remote areas.

2.2. Energy consumption

The energy consumption for seawater desalination processes has significantly decreased in the last decades, declining from 20 kWh m^{-3} in 1970s [4,28] to 2.5 to 4 kWh m^{-3}, recently [29]. This minimum value was only possible in large SWRO desalination plants due to the addition of among others: new energy recovery devices and better operating conditions, with higher quality membranes, improved pre- and post-treatment processes, higher efficiency pumps [29,30].

Yet, its energy consumption is still considerably high, representing an obstacle for the enhancement and advance in the existing desalination techniques [4,28]. Generally, membrane-based desalination techniques require substantially less energy when compared with thermal-based methods [25,31,32] (Table 1). Among membrane-based systems, RO is considered the most mature process [33]. The RO plant typically incorporates pretreatment, feed water pressurization followed by dissolved salts separation, post-treatment, disinfection, and pH adjustments [34]. In general terms, feed water salinity, water product recovery, energy recovery, pumping energy, operation settings (RO feed-side pressure and feed channel velocity), and unit design (membranes modules arrangements) are the main factors affecting the energy demand of RO plants [35]. The energy consumed in SWRO desalination plants is divided by: water intake (~7%), pre-treatment (~12%), RO-based desalination (~68%), and post-treatment and pumping (13%) [36,37]. Distinct from thermal-based technologies, RO equipment only requires electricity supply to operate. The energy requirement for the SWRO process itself accounts for almost 70% of the total energy employed, ranging between 1.7 and 2.5 kWh m^{-3}. These values will vary according to parameters as the feed water salinity and the pumps and energy recovery efficiency [18]. Extra power used within the plants represents an additional 0.3–1.5 kWh m^{-3}. Hence, the total energy demand in SWRO most developed facilities is 2.0–4.0 kWh m^{-3} [18]. Circumstances such as smaller installations, remote locations, and unskilled operators may elevate the energy demand to 3–7 kWh m^{-3} [38]. BWRO systems, on the other hand, consume less energy than SWRO plants as a result of lower pressure and higher water recovery. Al-Karaghouli and Kazmerski [25], and Shahzad et al. [27] claim that for medium to large-sized BWRO plants, the specific energy consumption varies from 1.5 to 2.5 kWh m^{-3}; the researchers do not mention the recovery ratios or the applied pressure for these specific energy consumption reported. However, Ezzeghni [39] report an energy consumption of 0.64 kWh m^{-3} at a recovery ratio of 65% (15–19 bar; 150 ppm water salinity). Alghoul et al. [40] present a case in Oman in which the energy consumption achieved was of 2.3 kWh m^{-3} at a recovery ratio between 65% and 70% (12 bar; 1,000 ppm water salinity). A recent paper in the United States by Stanton et al. [41] estimated that the theoretical minimum work required to desalt brackish water (500–1,000 ppm) ranges from 0.0084 kWh m^{-3} at 0% recovery ratio to 2.5 kWh m^{-3} at 90% recovery ratio.

Even though the specific energy requirement of RO systems has almost reached the thermodynamic limit, energy efficiency is still considered as one of the most effective manners to minimize desalination cost and dependency on conventional fossil fuel [42]. However, a reduction in the energy demand per m^3 for desalination systems remains achievable, especially when taking into account existing desalination facilities work at three to four times their thermodynamic designed minimum value [36]. There are various strategies to decrease the energy needs of RO technology. These include: (i) enhancement of membrane materials and lifespan [43–46]; (ii) development of energy recovery devices, enabling the reduction of energy intake [47,48]; (iii) improvement of high pressure pumps, increasing its efficiency and reducing the energy requirements [49–51]; and (iv) optimization of operating conditions and configuration in RO processes [45].

Although the integration of renewable energy with RO desalination plants does not reduce the energy needs of the system, it minimizes the demand of fossil fuel sources and electrical consumption from the grid.

In addition, higher water recovery by intermediating chemical demineralization is used to increase water production, however it does not necessarily help reducing the energy need of RO, since more pressure is actually required for higher recovery. Therefore, there is a tradeoff between water recovery vs. energy/cost efficiency. How to take this tradeoff into account for decision making seems an interesting question in future works.

2.3. Economics of desalination

Over the last decades, research and development results have lowered the cost of desalination techniques by reducing the energy consumption and improving the desalination plants design. Energy consumption and capital investment are the major causes affecting the economic feasibility of desalination whereas other aspects as O&M costs are almost at a steady rate, as shown in Table 2 [30]. For example, the energy demand costs in a typical large SWRO facility goes from 38% [35] to 60% [29,52] of the total water production cost. However, this value ranges from 20% to 30% in a BWRO system [35]. In addition to energy use, RO operating costs include chemical cleaners, replacement parts (membranes, pumps, and electrodes), brine disposal, labor and management, and maintenance. High-pressure pumps and membrane replacement represent a significant and consistent maintenance expense in RO systems. Membrane costs for very small-scale units (around 0.5–4.5 m^3 d^{-1}) vary from US$ 100 to US$ 200 per membrane. Units of this size need only 1 or 2 membranes which have typical lifespan of 1–3 years, depending on the intensity of use [9]. Other factors affecting

Table 1
Energy requirements of the main desalination processes

	MED	MSF	SWRO	BWRO	ED
Typical unit size (m^3 d^{-1})	5,000–15,000	50,000–70,000	Up to 128,000	Up to 98,000	2–145,000
Typical electrical energy consumption (kWh m^{-3})	1.50–2.50	4–6	3–7	1.5–2.5	2.64–5.50
Thermal energy consumption (kWh m^{-3})	230–390	190–390	–	–	–
Produced water quality (ppm)	~10	~10	400–500	200–500	150–500

Based on [25,30,34,38].

Table 2
Cost components for a typical SWRO desalination unit

Components	Percentual cost
Energy	38%
Capital investment	34%
Replacement parts	9%
Chemicals	5%
Membrane replacement	5%
Overhead	5%
Labor	3%
Insurance	1%
Total	100%

Based on [35].

desalination cost are (a) feed water salinity, (b) energy source availability and cost, (c) unit size, (d) land cost, (e) managerial skills, (f) environmental considerations, and (g) government subsidies [9,28,38].

Since early-mid 1990s, seawater desalination water production costs have decreased from an average of US $1.25–1.50 m^{-3} [53] to nearly US $0.50 m^{-3} for recent large-scale SWRO plants [54]. More precisely, US $0.45–0.66 m^{-3} for large SWRO facilities (100,000–320,000 m^3 d^{-1}), US $0.48–1.62 m^{-3} for medium size (15,000–60,000 m^3 d^{-1}), US $0.7–1.72 m^{-3} for small-size SWRO units (1,000–4,800 m^3 d^{-1}) [55]. Regarding brackish water desalination, RO and electrodialysis reversal (EDR) are considered the most economic methods. For feed concentrations lower than 3,500 ppm, EDR is generally believed to be a more economical solution whereas for concentrations above 3,500 ppm, RO is presented as the most cost-effective method. For large-scale BWRO plants (40,000–46,000 m^3 d^{-1}), the water production cost varies from US $0.26 to 0.54 m^{-3}, compared with US $0.6–1.05 m^{-3} for EDR [25,56]. This greater cost effectiveness of RO systems arises from technological advances, economies of scale capacity building, and higher economic competition in the field. It is noteworthy that the unit cost of the desalinated water plants increases along with its TDS or concentration, as seen in Table 3.

Considering that along with CAPEX and operational expenditures (OPEX) a realistic and accurate economic assessment for a desalination unit must include the commercialization level of the technology, RO systems will likely prevail in the upcoming future due to their present lower cost and number of units already installed. Nevertheless, no substantial reductions on desalination water cost, construction cost, and energy consumption are projected in the next few years [54].

Table 3
Water production cost in RO systems

Type of feed water	Capacity (m^3 d^{-1})	Water production cost (US$ m^{-3})
Seawater	1,000–4,800	0.70–1.72
	15,000–60,000	0.48–1.62
	100,000–320,000	0.45–0.66
Brackish water	<20	0.56–12.99
	20–1,200	0.78–1.33
	40,000–46,000	0.26–0.54

Based on [25,53–56].

2.4. Social and environmental aspects

Desalination sustainability may be evaluated by four elements which encompass economic, technological, environmental, and social areas [23]. There are many studies covering the economic and technological challenges of desalination techniques while environmental and social aspects are still limited [34].

The main environmental impacts commonly associated with water desalination are (a) the elevated quantity, salinity, and temperature of the concentrated brine and chemical discharges, contributing to eutrophication, water quality changes, and ecological impacts; (b) seawater intake and the entrapment of marine life; and (c) the large amount of air pollutants and greenhouse gas emissions resulting from the intensive energy consumption [18,23,34]. Regarding the latter, replacing fossil fuel by renewable and clean energy sources to power desalination is a promising alternative to overcome the greenhouse gas emission and the carbon footprint of desalination processes; thus, reducing global warming and climate change effects [18,23,34]. Furthermore, inland desalination presents the major environmental challenge of brine management as disposal to the sea is not possible [35].

Concerning the social impacts, the replacement of a traditional water supply to desalination processes results in changes in societal practices and, therefore, its local culture implications should be cautiously assessed. It should be noted that each desalination project presents a specific context for its local community. In general terms, the social aspects involving desalination include concerns over: (a) suspicions regarding the technology performance, (b) water quality, (c) water privatization, and (d) environmental impacts (construction and operation) [18]. In this matter, sustainable behavior of desalination plant designers and policy decision makers may contribute to a project success. A wise path for authorities to create the required trust between people and project proponents is to ensure transparency through effective communication management and to encourage the public participation throughout the implementation of the project as well as to mitigate the negative impacts of the construction [23]. As desalination processes are conventionally related to negative environmental impacts, integrating renewable and clean energy to the technology is a promising way to captivate people on the potential of desalination.

3. Desalination in Brazil

3.1. Brazilian conjuncture and water trends

Brazil is the fifth biggest country in the world covering 8.5 million km^2 (3.2 million mile^2) – 47% of South American territory – and the sixth biggest in population with approximately 208 million people spread unequally through its five regions. Of the total, 84% of population resides in urban areas, mainly in the southeast and northeast regions [57]. The country has several distinct climate regimes, varying roughly from tropical in the north to temperate in the south.

Despite the high-water availability of Brazil, its distribution by region is quite heterogeneous. According to the Brazilian Institute of Geography and Statistics – IBGE, about 68% of the water resources remain in the Amazon basin [58,59], which is inhabited by only 7% of the Brazilian population. On the other hand, northeast, which is the poorest and second most populous region of the country – nearly 54 million inhabitants [59] – has only 3% of the nation's water availability. The southeast and south regions, with 13% of the water availability, are areas of high population density, constantly struggling with pollution problems of urban and industrial origin, while the central west region, with 16% of the water availability, represents the new agricultural frontier [59].

The Brazilian Federal Water Act [60], states the primary water use is for human and animal consumption. Nevertheless, high-quality water in Brazil is still inaccessible for a large part of its inhabitants. In some states of the Northeast, for instance, the treated water supply index does not reach 50% [61]; inhibiting these populations to meet the daily minimum water supply of 20 L $person^{-1}$ d^{-1} for basic food and hygiene needs as stipulated by the UN Agencies and World Health Organization (WHO) [62].

In regard to the national electricity sector, Brazil is distinguished from other countries by its strong reliance on hydroelectric power, which accounts for 60% of the electricity production; followed by thermoelectric, 26%; and on-shore wind, 8% [63]. A commonly accepted view on this matter is that the country has a natural endowment in hydrological resources. Yet, hydropower, mainly run-of-river systems, is vulnerable to climate change effects and rainfall regimes, which can lead to water and energy supply restrictions.

During 2014, Brazil went through its largest water crisis in its recent history. The hydropower electricity production decreased, which forced the activation of fossil fuel thermal electricity generation at higher cost for end consumers. Thus, Brazilian energy regulators are stimulating increases in the participation of wind and solar resources for the base energy loads [64], as indicated by its recent solar and wind energy biddings [65]. As an intertropical country with 7,491 km of coast, Brazil has great potential for wind energy (large areas with at least 6 m s^{-1} of annual average wind speed) [66] and solar PV energy (4.53–5.49 kWh m^{-2} d global horizontal radiation) [67] throughout the year. The exploitation of solar and wind energy offers benefits for the country in the long-term, supporting the development of isolated areas where the electrification of conventional networks is still not practicable. Thus, the use of renewable energy for powering desalination units is presented as a promising solution to increase water and energy supply security for Brazil's most underprivileged citizens: the rural communities of the semiarid.

3.2. Desalination experiences in Brazil: Programa Água Doce

Brazil currently produces 1.7 million m^3 desalted water per day of which 97% corresponds to industrial applications, especially in the oil and gas sector in southern and southeast parts of the country [15]. In contrast, its desalination production for drinkable purposes is still inexpressive with some particular cases involving sea and brackish water RO desalination systems, for example a medium-scale SWRO facility in the touristic island of Fernando de Noronha in the 2000s; requested technical and economic feasibility studies for seawater desalination in major cities in coastal areas of the Brazilian northeast [68]; and with the "Programa Agua Doce" – PAD which joined governmental and civil efforts to bring safe drinkable water to vulnerable communities in northeastern semiarid region [68,69]. The Brazilian semiarid region has low water availability and irregular-distributed annual rainfall, with annual precipitation averages varying from 800 mm to less than 250 mm and potential evapotranspiration of 1,300–2,000 mm $year^{-1}$ [14]. The semiarid region is socially characterized by the lowest income rates in Brazil; it presents a GDP per capita of less than US $2,000 $year^{-1}$, while the Brazilian average rate was approximately US $8,500 in 2015 [69]. The low latitude (proximity to the equator line) and the presence of shallow soils (TDS average of 3,524 ppm), or the absence, does not favor the local population whose efforts to access safe drinking water increase in every new dry season [70].

Among various attempts to cope with the water scarcity, throughout the past decades, the Brazilian Environmental Ministry, in partnerships with federal governments, universities, and civil society, addressed the issue in 2004 by launching the "Programa Água Doce" – PAD [69]. The Program, large-scale actions of which would only take place in 2010, aims to establish a permanent public policy of access to high-quality water suitable for human consumption through the implementation of small-scale RO desalination systems. The PAD was conceived and developed in participatory manner, incorporating technical, environmental, and social precautions along the implementation, recovery, and management of the desalination facilities. Social participation, community empowerment and climate change mitigation are at the center of the program's methodology [70]. The selection of which communities would be benefited occurred according to technical criteria, compiling several social and environmental indicators, such as human development index, percentage of infant casualties, poverty level, presence of salt in groundwater resources and rainfall rates [68–70]. After this procedure, each participating community receives proper training from desalination specialists and the installation of an RO facility. Each RO system is composed of 2–6 membranes with water flows of 400 L h^{-1} at 50% water recovery each, operating 6 h d^{-1} in order to preserve the equipment. The small-scale units produce in average 2.4–7.2 m^3 of potable water per day and present an initial investment cost of nearly US $55,000 (Brazilian Real to US dollar conversion rate: 4.13 taken in September, 18th 2018) (R$230,000). If handled properly, each membrane from PAD program should have a lifespan of 5 years (R. Ferreira, personal communication, October 15–20, 2017). Regarding the sustainability of the entire process, the concentrated brine, a byproduct of the RO desalination system, is rejected to evaporation tanks to be used in agricultural activities, such as fish farming and hay production for cattle herds [70]. If fish farming and irrigation systems are included, each desalination unit receives an additional cost of US $29,000 (R$120,000), presenting a final investment cost of US $85,000 (R$350,000) (R. Ferreira, personal communication, October 15–20, 2017) [71].

Up to July 2017, PAD program promoted sustainable use of groundwater resources in 508 communities in the Brazilian semiarid region, producing more than 2 million L d^{-1} – or 10 L $person^{-1}$ d^{-1} – of drinkable water, benefitting approximately 200,000 people in the most critical conditions [68,69]. By 2019, PAD's objective is to have 1,200 RO desalination operating units, totaling investments of US $62,500,000 (R$258,000,000), assisting approximately half a million people [69]. The current step of the project is to advance in the path of water, food, and energy integrated sustainability expanding the use of solar PV energy and incorporating good soil and water conservation practices [15,70].

4. Potential integration with renewable energy

Conventionally, desalination techniques are powered by fossil fuel energy sources. Besides high operational costs, fossil fuels release large quantities of greenhouse gases (GHG) into the atmosphere. Based on limited data available in literature, the estimated carbon footprint associated with the operation of large RO desalination plants is of 2.33 kg CO^2 eq m^{-3} [72]. For scenarios with current technologies, the World Bank foresees that fossil fuel desalination will release about 400 million tons of CO^2 eq $year^{-1}$ by 2050 [73]. Thus, GHG emissions could be mitigated with the adoption of clean energy from renewable sources such as solar, wind, hydropower, among others [13,74]. In fact, various renewable integrated desalination systems have been proposed in the last 20 years [31,75], either solely or in renewable-conventional hybrid systems [31,76–79] (Fig. 2). In addition to reduced environmental impacts, renewable integrated desalination facilities also have the potential to reduce costs to end-users; enabling fresh water access for inhabitants of low and middle income communities in remote areas [73].

Currently, 130 desalination plants worldwide are fully powered by renewable energy – standing for only 1% of present global water desalination capacity [27,80]. Most of these are small-scale systems based on stand-alone micro-grids [19]. Nearly 43% of these renewable units are power-driven by PV panels, 27% by solar thermal, 20% by wind energy whereas the remaining 10% are hybrid-based renewable energy sources [19,81]. Geothermal, wave, and tidal integrated desalination systems still in a research and development stage [80,82,83]. These configurations, as well as wind applications, usually convert mechanical into electrical energy to power membrane-based desalination systems. Solar power is used in RO desalination systems as electrical or thermal and/or mechanical energy [84]. PV panels directly convert sun radiation into electrical energy through solar cells made from semiconductor materials. Solar energy may also indirectly power RO units by concentrated solar power (CSP) collectors. The thermal energy produced by the CSP collectors or solar ponds is used in a Rankine cycle to power the desalination facility [85,86]. Solar thermal energy is further applied indirectly (solar collectors providing thermal energy) or converted into electrical energy to run membrane desalination systems [4,84,87]. Finally, solar thermal energy is also employed directly in water stills (solar still distillation [SSD]) where thermal absorption and water desalination occurs in the same equipment [88]. SSD is an acknowledged alternative for households applications as it presents low investment and energy cost although its low productivity per unit area (1–3 L m^{-2} d^{-1}) [9]. Fig. 3 illustrates the outlined commercialization status of different renewable integrated desalination systems.

It is noteworthy that finding the most appropriate balance between a desalination system and a renewable energy source to maximize water output and minimize energy consumption is a difficult task. The main factors regarding this decision are location specificities such as renewable energy source availability, water quality, availability of grid electricity, plant size, feed pressure, technical knowledge, and infrastructure [12,13,90].

Despite its environmental benefits and increasing feasibility, integrating desalination with renewable energy faces technical and economic barriers such as constant demand of energy and high capital costs. Solar and wind, the most common renewable integrations, are highly intermittent and weather-dependent technologies, which require energy storage solutions to secure the system reliability. Therefore, battery or thermal storage, hybridization of different renewable sources, or connection to grid are alternatives to overcome intermittence issues [12,13]. Conventional energy storage generally requires stationary batteries. Among various battery types and new emerging technologies, lead-acid batteries are the most cost-effective option [9]. Another alternative is to design an oversized unit to store produced water in a reservoir for later consumption, when weather conditions for energy supply are not favorable. Yet, the storage of potable water in tropical weather presents a higher chance of contamination from biological agents.

Another possibility of energy supply for decentralized desalination systems is hybridization. As previously mentioned, solar PV is the most accepted power source for renewable integrated desalination plants. Moreover, PV-RO combination represents nearly 50% of current installed capacity of solar power desalination systems [91]. This specific integration can be used either as stand-alone systems or through hybridization with wind, diesel, or biodiesel, and grid connection.

4.1. Stand-alone PV-RO

Stand-alone PV-RO plants are composed basically of pre-treatment and post-treatment units, PV panels, and RO membranes. In addition, they might include a bank of stationary batteries to normalize the energy input to the RO system and to counterbalance variations in radiation intensity, as well as a charge controller to secure the batteries from overcharging and deep discharging [80]. Fig. 4 illustrates a schematic of a typical stand-alone PV-RO desalination system. The technical and economic feasibility of such system has been investigated by a large number of experimental studies [77,92–100,101–111], most of them using energy generation systems models such as HOMER, System Advisor Model (SAM), and RETScreen software for pre-feasibility analysis [77]. The efficiency of stand-alone PV-RO desalination plants might be increased by various techniques applied

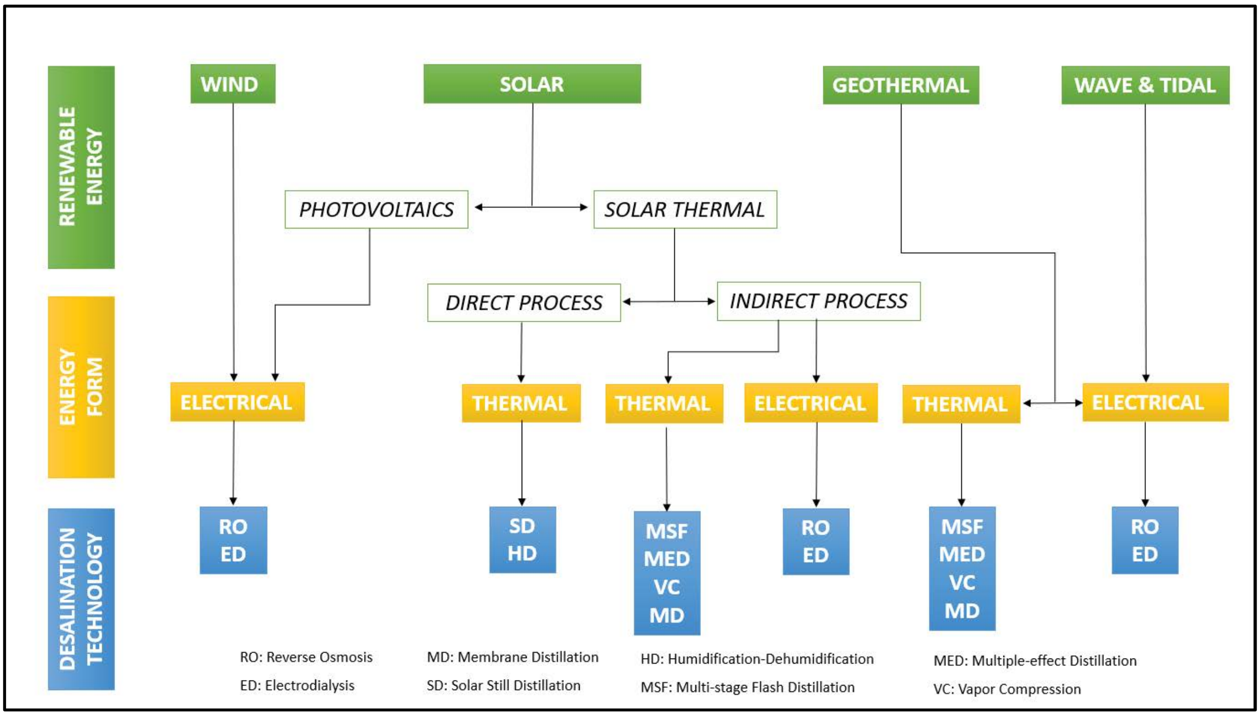

Fig. 2. Possible integrations between renewable sources and desalination techniques.

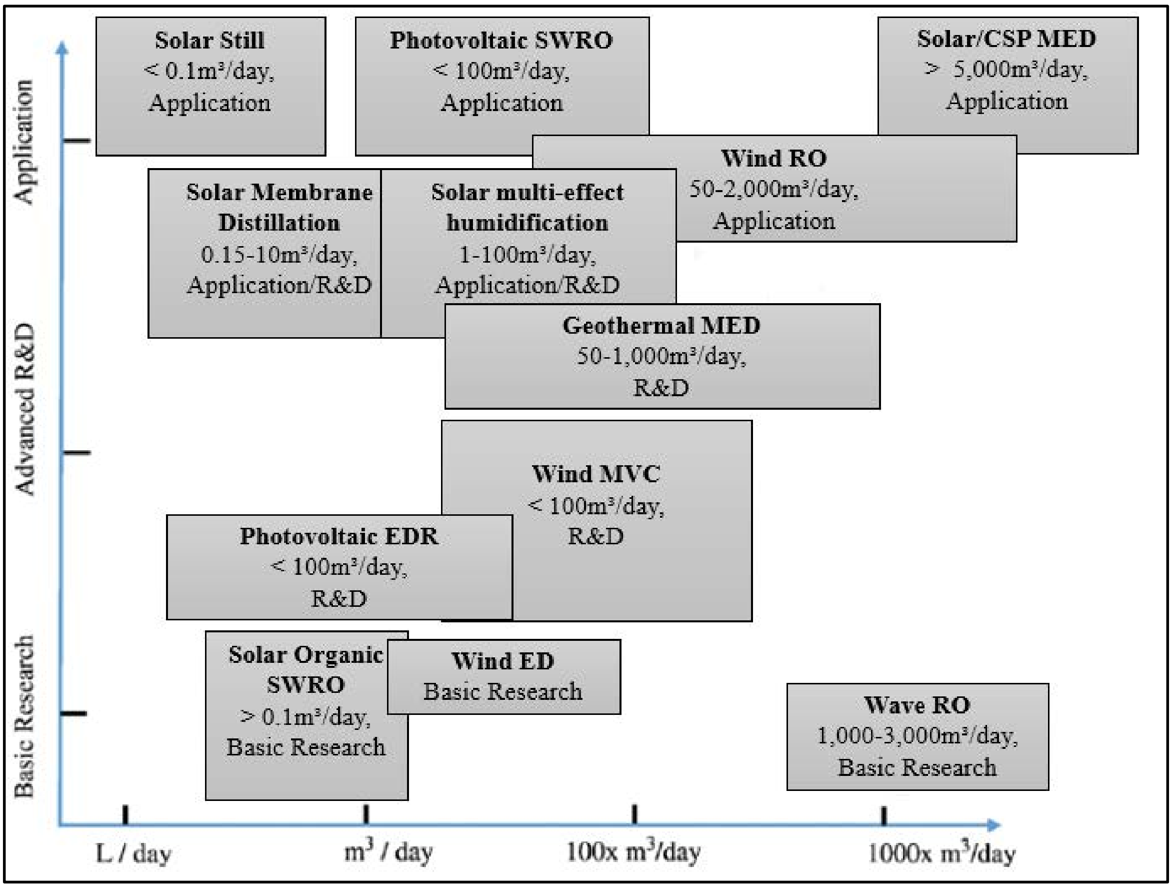

Fig. 3. Commercialization status of different renewable integrated desalination systems. Based on [27,83,89].

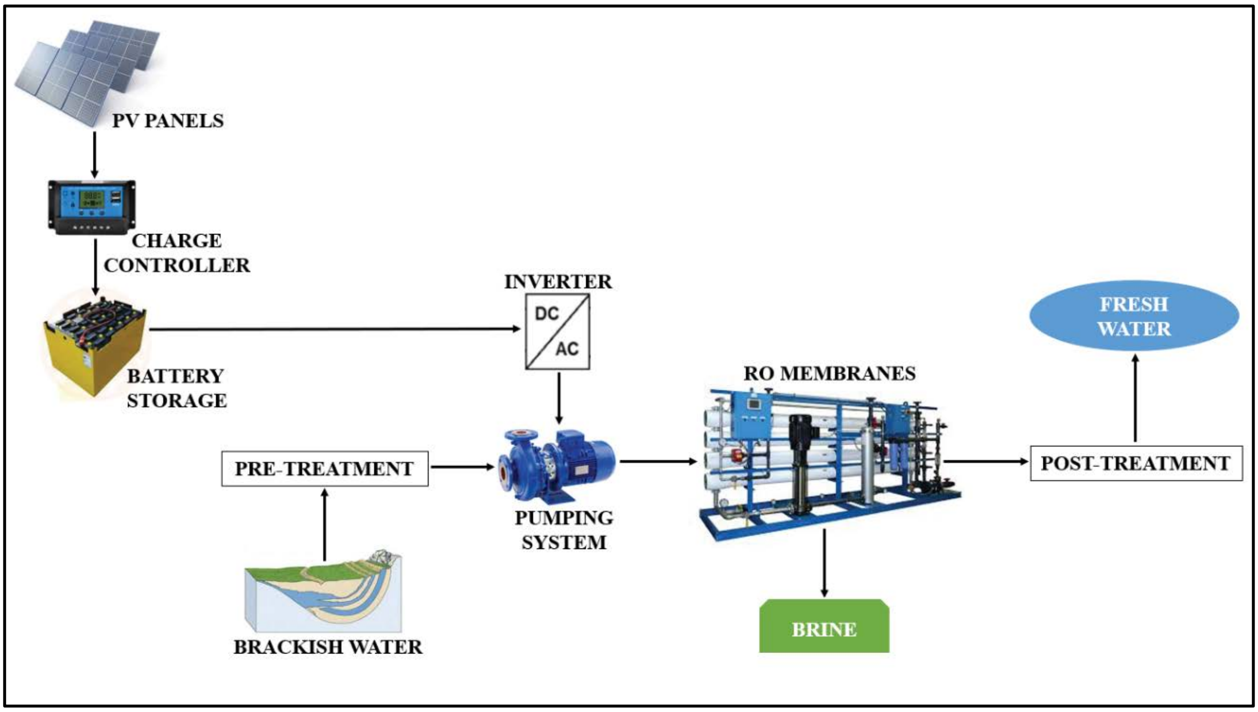

Fig. 4. Schematic of a typical PV-RO desalination plant.

to PV arrays, such as tilt-angle adjustment, solar tracking, and autonomous cleaning [4,112].

The major challenge of stand-alone PV-RO systems is their capability to deal with intermittence and solar radiation variations, which is directly associated with the water production. An autonomous control (passive or active) between PV modules and RO units is strictly necessary since it is more secure and practical than human monitoring. Other challenges of such configuration are (a) relative large surface area required for the PV array (assuming that the energy needs of a desalination facility of 2–5 kWh m^{-3}, 20–50 m^2 of solar panels are necessary to operate a plant producing nearly 10 m^3 d^{-1} [9]), (b) restricted availability of energy recovery equipment, especially for small-sized units, (c) local accessibility of pre-treatment and post-treatment chemicals, (d) water quality monitoring, and (e) limited availability of skilled operators (for pump and membrane maintenance).

Regarding the Brazilian semiarid context, stand-alone PV-RO desalination is a promising technique to secure high-quality water in regions lacking access to the electrical network. Nevertheless, current energy storage systems still represent increased costs in water desalination because of higher CAPEX, shorter operation lifespan, demand of skilled operators, and long distances to urban centers, which might make stand-alone PV-RO systems an unfeasible solution for small-scale applications in some isolated parts of the Brazilian semiarid region. According to Boden and Subban [9], SSD might be a viable small-scale desalination solution for remote communities without access to the grid, as it requires lower initial capital costs, simple maintenance, and can be easily replicated for other locations. However, SSD requires different order of magnitude and land surface for installation than small-scale PV-RO plants. Therefore, more studies are still required, comparing SSD with stand-alone PV-RO systems in the Brazilian semiarid region, including socio-economic aspects, scales of operation, and community acceptance to the system.

4.2. Hybrid PV-RO

In order to compensate interruptions and variations due to solar radiation intermittence and variability, other energy resources are commonly integrated with PV-RO systems. A possible solution to improve energy supply stability to PV-RO units is the integration with wind turbines, diesel and biodiesel generators or grid connection. Fig. 5 describes a few of such configurations.

4.2.1. PV-wind-RO

Wind turbines convert air movement into rotational energy to produce mechanical power or drive a generator to produce electricity. This source is currently one of the cheapest forms of renewable energy worldwide and has received increased consideration in the last decade [113,114]. Wind energy hybridization in desalination started in 1980 [115]. Since then, a large number of small to medium size wind-RO units have been widely designed and tested, being capable of producing up to 10 L kWh^{-1} of nominal wind turbine power [4]. Studies have found that average wind speed on a particular site needs to exceed 6 m s^{-1} for a small wind turbine to be economically viable for desalination purposes [4].

In Brazil, recent centralized energy biddings indicate a steep cost reduction and increase in the use of wind energy, though mostly for large-scale energy supply [116]. The limiting factor associated with wind energy is its unpredictable

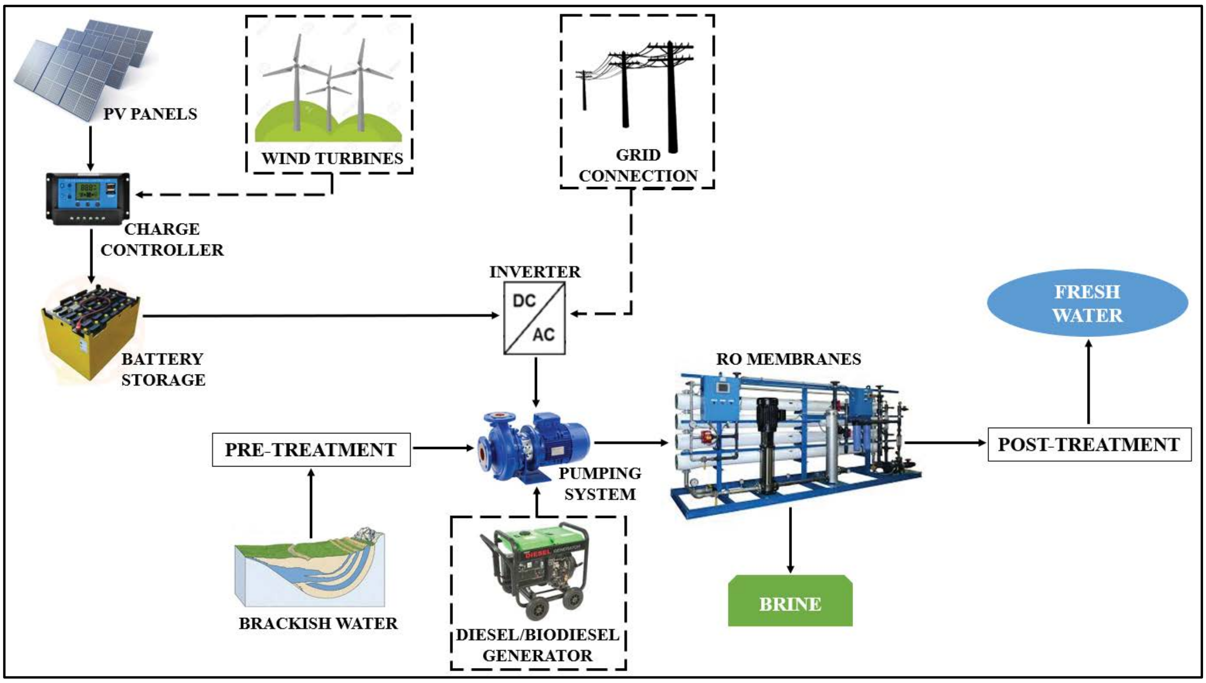

Fig. 5. Schematic of hybridization possibilities for PV-RO plants.
Notes: When grid is connected, storage batteries are not required, PV-RO systems may include different combinations of energy sources.

and intermittent nature. Therefore, a hybrid combination of wind and any other renewable energy sources such as PV panels may be employed for fresh-water production through desalination. PV-wind-RO hybridization has a great theoretical potential in the Brazilian semiarid region, as the area presents high levels of wind speed and solar radiation throughout the year. Although this hybridization enhances system reliability, it increases capital cost and complexity, making it an unlikely alternative to be applied for small-scale applications. Further research is needed in order to select sites with real potential and economic feasibility for such installations.

4.2.2. PV-diesel-RO

Another potential integration for PV-RO systems relies on energy back-up supply through stationary diesel generators. Such configuration presents advantages such as reliability, accessibility, and attractive initial capital cost while disadvantages include GHG emissions, noise pollution, higher O&M costs, and dependence on fuel price volatility. Furthermore, Brazil's energy sector is familiar with operating diesel engines, especially in off-grid areas (isolated communities and islands). In a PV-diesel-RO unit, the diesel fuel consumption might be relatively high to maintain a plant operating continuously, particularly in cloudy days, thus producing elevated amounts of air pollutants. An alternative to mitigate air pollution would be the increase of biodiesel in comparison with the conventional diesel fuel. It is noteworthy that Brazil is the second biggest biofuel (ethanol and biodiesel) producer and consumer worldwide, only behind the United States of America [117], which contributes to the technical feasibility of PV-diesel-RO hybridization. However, local socioeconomics and logistics conditions play a role to determine the real system viability in Brazilian semiarid remote areas. Therefore, more research on economical and long-lasting energy storage solutions and optimization of hybrid PV-diesel-RO systems are required.

4.2.3. Grid connection

Among hybridization possibilities, energy back-up supply through connection to grid stands out as a reliable and cost-effective form of integration for small-scale PV-RO systems. In the specific Brazilian semiarid scenario, this statement is reasonable considering that its transmission lines are widespread and regulations for net metering are ongoing, especially after Federal Program "Light for All" ("Luz para Todos") and ANEEL N°482/2012 normative resolution, which allows decentralized generators to insert energy to grid and compensate it on the electric bills. Furthermore, small-scale BWRO facilities powered by PV grid connected modules have been implemented with relative success by the PAD program since 2017 [70]. Therefore, PV-RO grid-connected systems are a feasible solution for rural communities in the Brazilian semiarid. Once installed, such configuration does not require significant capital expenditure to the unit maintenance. Moreover, energy costs can be significantly lower than solely grid-powered RO facilities as the grid operates as a battery for the system. However, not all rural communities have any or proper access to the grid. Data available to grid connection usually concerns to high voltage transmission lines, which unable proper small-scale PV-RO grid connected planning and installation.

Finally, Table 4 summarizes the reported international experiences with PV-RO configurations in the last decade.

4.3. Spatial assessment for PV-wind-RO implementation

A spatial analysis to prioritize areas in the Brazilian semiarid region for the implementation of small-scale integrated PV-wind-RO desalination systems, stand-alone, or grid connected, is discussed in this section. This analysis is restricted to physical aspects related to the suitability of integration between renewable energy sources and RO desalination technology in the Brazilian semiarid region. Local market, socio-economic and logistic aspects were not addressed in this study, despite their relevance for an in-depth site selection.

The analysis considered three main parameters including local water restrictions, wind speed and solar radiation, and is applied for both, off-grid and grid connected PV-wind-RO configurations. These data were extracted from shapefile layers to be used in ArcGIS.

Data referring to the local semiarid water restrictions are collected from the National System of Information on Water Resources – SNIRH [121], considering five classification ranges of the water exploitation index (WEI), provided by the European Environmental Agency and the United Nations [122]. WEI represents the ratio between the mean annual total freshwater demand and the long-term average freshwater resources, which indicates the pressure of the water demand over the hydrologic resource. The adopted classification ranges were as follows: (a) Class 1: less than 5% – excellent, (b) Class 2: 5% to 10% – decent, (c) Class 3: 10% to 20% – worrying, (d) Class 4: 20% to 40% – critical, and (e) Class 5: higher than 40% – very critical.

Table 4
Reported data from PV-RO systems in the last decade

Hybrid	Feed water	Study	Capacity (m^3 d^{-1})	SEC (kWh m^{-3})	Country	Year	Reference
Stand-alone/battery	BW	Experimental	0.25	1.2	Australia	2007	[95]
Biodiesel	SW	Theoretical	0.5	–	India	2007	[88]
Diesel	SW	Theoretical	20	7.73	UAE	2007	[89]
Stand-alone/no battery	SW	Experimental	0.08	3.8	Greece	2008	[97]
Stand-alone/no battery	SW	Experimental	0.35	4.6	Greece	2008	[98]
Stand-alone/no battery	BW	Experimental	1.11	2.3	Australia	2008	[100]
Diesel	SW	Theoretical	20	7.73	UAE	2008	[89]
Stand-alone/no battery	SW	Theoretical	20	7.33	UAE	2008	[89]
Stand-alone/no battery	BW	Experimental	0.26	1.57	Brazil	2009	[101]
Stand-alone/no battery	BW	Experimental	2.76	2.2	Australia	2009	[99]
Stand-alone/no battery	BW	Experimental	0.4	–	Australia	2009	[102]
Stand-alone/battery	BW	Both	0.2	1.3	Spain	2010	[103]
Stand-alone/battery	BW	Theoretical	0.08	–	Uzbekistan	2010	[90]
Stand-alone/no battery	BW	Experimental	4.8	1.9	Australia	2011	[85]
Wind	BW	Theoretical	57–111	–	Tunisia	2011	[91]
Stand-alone/battery	BW	Experimental	5.7	26	Jordan	2012	[86]
Stand-alone/battery	BW	Experimental	5.7	19.4	Jordan	2012	[86]
Wind-battery	BW	Theoretical	5	9	Egypt	2012	[92]
Wind	BW	Theoretical	45	2.5	UAE	2012	[96]
Wind	BW	Theoretical	45	5	UAE	2012	[96]
Wind	BW	Theoretical	45	7.5	UAE	2012	[96]
Stand-alone/battery	BW	Experimental	1.04	–	India	2015	[84]
Stand-alone/battery	BW	Experimental	1.07	–	India	2015	[84]
Stand-alone/battery	BW	Experimental	1.68	–	India	2015	[84]
Storage of permeate	SW	Theoretical	0.64	–	India	2015	[93]
Stand-alone/battery	BW	Both	5.1	1.1	Malaysia	2016	[87]
Stand-alone/no battery	BW	Theoretical	13–63	6.9–10.5	Jordan	2016	[94]
Wind-diesel-battery	SW	Theoretical	24	4.38	Turkey	2018	[77]
Stand-alone-diesel-battery	–	Theoretical/ optimization	-	–	Iran	2018	[119]
PV-electrodialysis	BW	Both	10	–	India	2019	[120]
Wind/with and without battery	SW	Both	25	–	Spain	2019	[19]
Stand-alone/no battery	BW	Experimental	–	0.98–3.21	Tanzania	2019	[118]

Based on [4,19,77,84–89,91–93,101–110,119–120].

Wind data were taken from the Brazilian Wind Potential Atlas 2013, performed by the Brazilian Electric Power Research Center – CEPEL, based on the mesoscale numerical model (Brazilian developments on the Regional Atmospheric Modeling System), with horizontal resolution of 5 km × 5 km and anemometric measurements network used to adjust the results [66]. Data on annual average wind speed ($m\ s^{-1}$) were considered for wind towers of 30 m tall, and the speed bands were grouped into 10 ordinal classes ranging from class 1 (1.5–2.5 $m\ s^{-1}$) to class 10 (≥11.5 $m\ s^{-1}$), as shown in Table 5. These classes were defined based on wind turbine power curves according to wind speed. Relationship between wind speed and average nominal turbine power were compiled using reported data from the study by Lydia et al. [123] and Brazilian and international turbine suppliers.

Solar radiation data (in $kJ\ m^{-2}\ d^{-1}$) were obtained from WorldClim [124], a set of global climate layers (gridded climate data) with spatial resolution of 1 km^2, grouped in 10 ordinal classes based on the Jenks optimization method (1967)[1] [125].

Finally, all three parameters ratings – water restrictions, wind speed, and solar radiation – were combined in ArcGIS using map algebra. These parameters had the same weight. The class values were multiplied, with results ranging from 1 to 500. The results were then grouped by Jenks optimization method into ordinal classes varying from 1 (low potential for PV-wind-RO implementation) to 10 (high potential for PV-wind-RO implementation). Fig. 6 presents the analysis outcome indicating suitable areas for the installation of PV-wind-RO systems in the Brazilian semiarid region.

Ceará and Rio Grande do Norte states, as well as the central part of Bahia state, are the regions with highest potential for the implementation of PV-Wind-RO systems. On the other hand, northwest and northeast parts of Minas Gerais state and southeast part of Bahia state have the lowest potential. Overall, the west side of the Brazilian semiarid region indicates a moderate potential.

Table 5
Wind speed and turbine power classification

Wind speed ($m\ s^{-1}$)	Classes	% Average nominal turbine power
1.5–2.5	1	1%–5%
3–3.5	2	5%–8.5%
4–4.5	3	8.5%–12.5%
5–5.5	4	12.5%–17.5%
6–6.5	5	17.5%–25%
7–7.5	6	25%–35%
8–9	7	35%–50%
9.5–10	8	50%–65%
10.5–11	9	65%–80%
11.5	10	≥80%

For more precise decision making analysis, further steps would require filtering areas with high implementation potential – classes 8 to 10 – and investigating the existing wells located in those areas for their respective water quality and flow. That information is available in the Brazilian Semiarid Information and Knowledge System (SIGSAB) database (http://sigdados.insa.gov.br/), but is not open to public access. Additionally, a technical and economical assessment of selected municipalities should be provided. Those parameters should include local water cost, population water demand, availability of specialized labor to build and operate the plant, cost of land, best plant configuration and size, amongst others.

Finally, although this section demonstrated the synergy between solar and wind resources, availability in water stressed areas of the Brazilian semiarid region, more experimental research to validate the proposed areas should be addressed. The spatial assessment adopted here, in addition to site specific calculation should be attained in future studies for the Brazilian semiarid region.

5. Conclusions

In this paper, a review of desalination technologies and their possible integration with different renewable energy resources is provided, addressing the opportunities for its implementation in the Brazilian semiarid region. Renewable integrated desalination systems represent a sustainable opportunity to provide safe drinking water through a technically possible, economically feasible, and environmentally friendly solution for areas with lack of infrastructure, restricted access to grid connection, and abundant availability of renewable energy resources.

This work highlights the potential for renewable energy to power BWRO desalination plants in the Brazilian semiarid region. PV-RO grid-connected systems stand out as a reliable and cost-effective solution for rural communities in the semiarid region. Regarding PV-wind-RO plants, the results of spatial analysis show theoretical potential because of the high availability of wind and solar resources in the region. Nevertheless, studies analyzing the economic aspects of small-scale units with this hybridization option should be further investigated. PV-diesel-RO is also a possible configuration; however, this study did not address a full integration of diesel and biodiesel with PV-RO due to the difficulties in defining socio-economic variables for spatial criteria. For isolated areas without grid access, there is still a need of further studies focusing on the Brazilian semiarid region that compares stand-alone PV-RO to small-scale thermal desalination technologies, integrated with renewable energy. These studies should include numerical calculations for land requirement, energy efficiency, installation and maintenance costs, order of scales, community preferences, and environmental aspects.

Moreover, in order to support the expansion of small-scale renewable integrated RO desalination systems in the

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[1] The Jenks optimization method is a data clustering method that seeks to determine the optimum arrangement of values in different classes. This method looks for the minimum average deviation from the class mean, while it maximizes each class deviation from the means of the other groups. Thus, the main goals of the Jenks optimization method are to reduce the variance within classes and to maximize the variance between them [125].

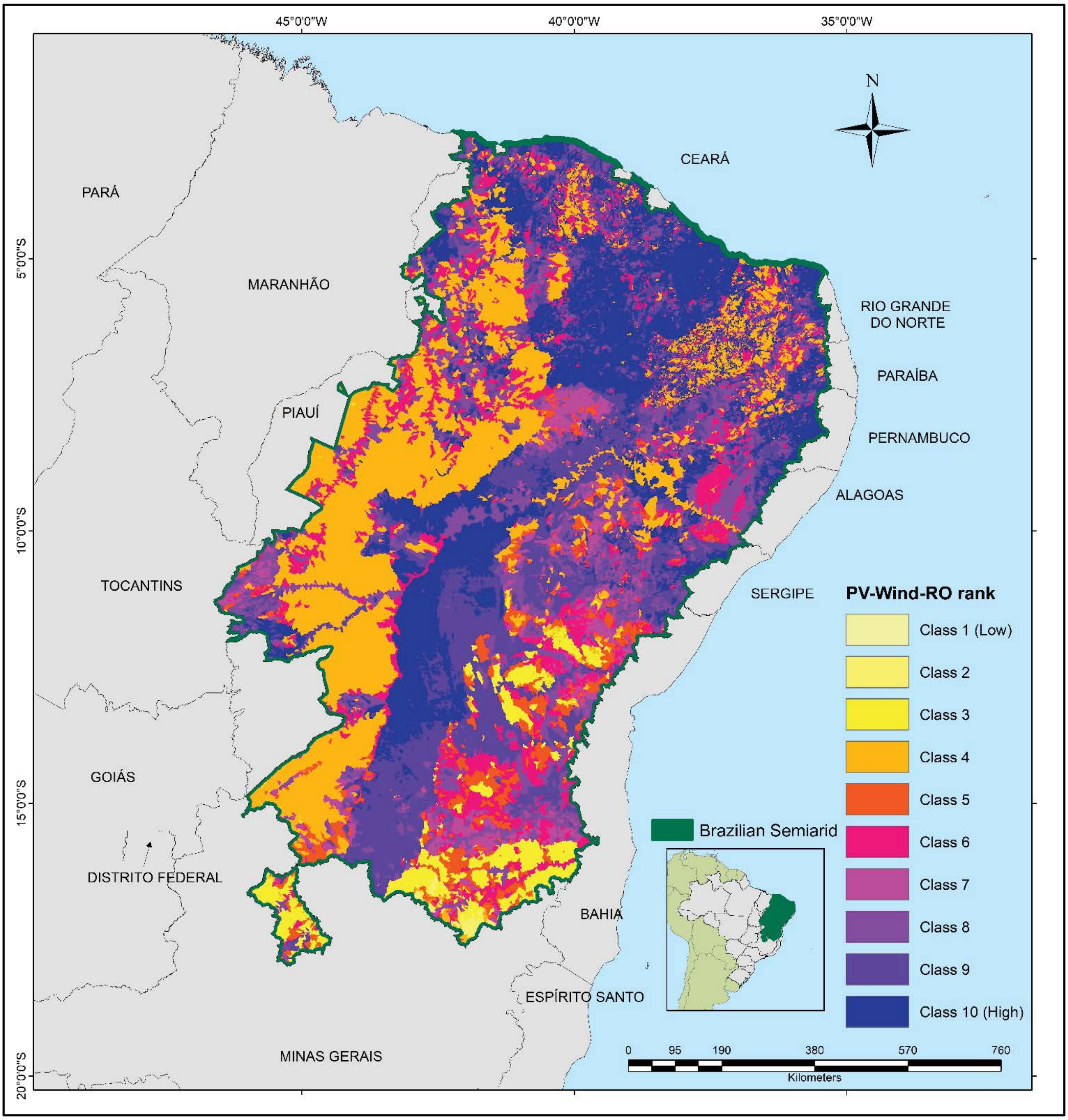

Fig. 6. PV-wind-RO potential implementation sites in the Brazilian semiarid region.

semiarid region, the Brazilian government should intensify subsides and reinforce technology transfer through cooperation with countries that have a long experience of working with renewable integrated desalination systems. The PAD program represents a first step to technology development in the Brazilian semiarid region, however more experimental facilities are still needed.

Further developments will inevitably encourage the competition between market players and stimulate growth and wider acceptability of renewable integrated desalination systems as a significant move towards water sustainability in semiarid regions.

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