water

Review

Possibility of Implementing Large-Scale Solar Desalination System in the Republic of South Africa

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Abstract: This paper examines the viability of introducing solar thermal desalination technology as a means to supplement existing water production methods in the Republic of South Africa (RSA). The study provides an overview of the current state of desalination technology in the country. A key aspect of this study involves comparing the RSA with the Middle East and North Africa (MENA) region, using publicly available studies and reports. The focus of this comparison is to highlight the potential implementation of large-scale solar desalination in the RSA by evaluating the respective resources and environmental data that directly impact the input and output of a thermal desalination system. The study comparatively analyzes the environmental conditions and seawater salinity of the RSA and the MENA region. The RSA receives a higher solar irradiation range of 4.5–6.5 kWh/m^2, whereas the MENA region experiences a range of 3.5–5.5 kWh/m^2. Additionally, the salinity of the RSA's seawater ranges between 35 and 35.5 parts per thousand, which is lower than the MENA region's range of 36–40 parts per thousand. The study also reviews and proposes the adoption of an emerging thermal desalination method that has been successfully tested in the MENA region and other countries, based on its performance.

Keywords: desalination; water purification systems; solar radiation; MENA region

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1. Introduction

Water and energy are crucially interconnected resources that drive the daily economic activities of the Republic of South Africa (RSA). The RSA, a semi-arid and water-stressed country, is bordered by a coastline spanning over 2500 km, encompassing the Indian and Atlantic Oceans [1–3]. With an average annual rainfall of 450 mm, the RSA falls significantly below the global average of 860 mm per year [4]. This low rainfall average has led to water shortages in several water management areas, as the RSA struggles to meet the increasing water demand [5]. The ongoing water crisis, characterized by declining water levels in the RSA dams [6], is partly attributed to inadequate water management practices and associated factors. To address the growing water demand, various solutions have been proposed. One major proposal involves constructing additional dams in different parts of the country. Other methods, such as implementing water monitoring devices to discourage excessive water usage and launching educational initiatives to promote water conservation, have also been suggested as potential solutions [7].

The primary concern with this solution lies in its high cost and negative environmental impact. Additionally, implementing this solution could potentially disrupt the ecosystem in the targeted location of the proposed dam. Desalination is a widely used technology globally to address water demand, and it has been partially employed in certain areas of the RSA. There remains significant potential for the growth of the desalination industry in the country. However, implementing large-scale desalination technology requires an initial assessment to determine the most suitable desalination method for each specific region. This preliminary evaluation is crucial for understanding the performance of the chosen desalination technology, particularly when it is dependent on environmental conditions. To facilitate this preliminary assessment, mathematical equations need to be formulated, enabling the prediction of desalination system performance based on influential factors such as solar intensity, wind speed, and more [8–12]. It is also crucial to understand that there are numerous factors that are contributing to the cost of water supply. This includes the maintenance, which is calculated based on cubic meters [13]. There are also factors that are directly or indirectly involved in the performance of desalination systems, and these factors need to be considered during the planning phase of the implementation of the desalination system. Those factors include useful heat loss, and these kinds of factors have been studied extensively by various researchers, which then led to the formulation of prediction methods [14–17].

The interconnection between water and energy has gained significant global attention from governing bodies and the academic community. The Department of Energy (DoE) in the RSA projects that the total annual electricity consumption will exceed 300,000 GWh by 2050 [18]. This rising energy demand necessitates the exploration of alternative methods to supplement the predominant fossil fuel-based energy supply. The RSA ranks as the seventh-largest global coal producer, with approximately 77% of its electricity generated from fossil fuel combustion [19]. However, this approach is both environmentally and economically unsustainable, leading to stringent regulations imposed by local and international legislative bodies to mitigate excessive carbon emissions and protect the environment. The heavy reliance on fossil fuels in the RSA not only contradicts decarbonization initiatives but also presents challenges for large-scale desalination implementation. Existing desalination methods and water production infrastructure heavily rely on grid electricity generated from fossil fuels. Moreover, fossil fuel-based energy production requires significant water supplies for operational and plant cooling systems, further exacerbating the RSA's water scarcity challenges [3]. The limited utilization of renewable and sustainable energy systems in the RSA has resulted in the disregard of various thermal-based desalination methods, leaving reverse osmosis (RO) as the predominant desalination technique due to its energy efficiency [20]. Thermal desalination involves utilizing direct or indirect thermal energy to separate freshwater from saline water. On the other hand, RO desalination utilizes a semi-permeable membrane to separate water from salt [21]. While RO has advantages in terms of energy consumption, it faces challenges in membrane maintenance. Avlonitis [22] highlighted the costs associated with maintaining RO membrane filters in desalination plants, averaging around 0.11 USD/m^3. These maintenance costs are considerably high. Despite these limitations, the energy efficiency of RO has often overshadowed these concerns, leading to its widespread use compared to thermal desalination methods.

In the RSA, there are approximately 8 to 10 h of daily sunshine available for harnessing as a valuable energy source, including for desalinating seawater. Solar thermal desalination systems have the potential to make a positive contribution to ongoing decarbonization efforts. However, there is still much work to be conducted by South African legislative bodies to accelerate the adoption of solar energy technologies [23]. Creating an environment conducive to the implementation of solar energy-based systems, such as renewable energy-powered desalination, would inspire investor confidence. This, in turn, would stimulate economic growth, mitigate excessive carbon emissions, and foster the development of energy-efficient and sustainable water supply methods.

This article highlights the significance of implementing desalination technologies in the RSA to address water supply challenges. Specifically, it proposes the utilization of solar thermal desalination as a viable solution to enhance the availability of clean drinking water. The comparison of seawater salinity and solar irradiation between the MENA region and the RSA is presented to support the selection of this technology. The rationale for choosing solar thermal desalination is further explained in subsequent sections of this review. Additionally, the study proposes the adoption of an emerging adsorption desalination technology for the RSA based on the comprehensive review and analysis conducted in this study.

2. Data Analysis

The implementation of desalination systems in the MENA Region has experienced consistent growth over time. The region's climate and available resources serve as key factors for analysis and comparison with RSA to evaluate the feasibility of implementing similar systems in RSA. In this study, the MENA region was used as a benchmark for the feasibility assessment. The study conducted a comprehensive review by examining the historical literature from published research articles, technical reports from academic journals, and research institutions in the government and private sectors. The conceptual framework of the review article is depicted in Figure 1. Table 1 presents a data collection table indicating the number of documents reviewed for this study.

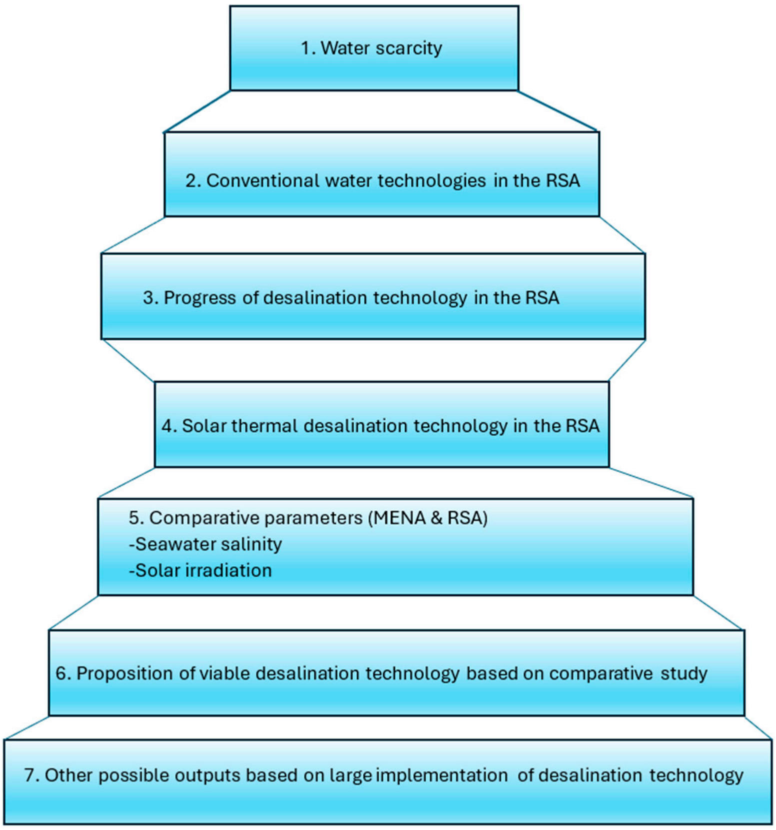

Figure 1. Flow chart of article framework.

Table 1. Data collection.

Review Aspects	Number of Documents	Refined Documents
Background to study	70	23
Water scarcity in the RSA	33	13
Conventional water systems in the RSA	20	6
Desalination progress in the RSA	35	20
Adsorption desalination	35	10
Solar tensity and seawater salinity	60	26
Social and environmental	15	6

First and foremost, it was crucial to provide an overview of the current state of the water crisis in the RSA and the measures taken thus far to address the water demand. This was achieved by conducting a review of publicly available articles and reports. The review process included a comprehensive examination of the progress made in desalination technology within the RSA. Technical data from existing desalination plants were thoroughly analyzed. Furthermore, a more focused review was conducted specifically on solar thermal desalination technology. This review extensively covered technical information and data pertaining to solar-based desalination technologies from various countries, with a particular emphasis on the MENA region, which served as a benchmark for the study's analysis.

In this study, a comparative feasibility approach was adopted to assess the viability of desalination implementation in the RSA in comparison to the MENA region. The natural resources available in both locations, namely solar irradiation and seawater salinity, were presented and thoroughly analyzed. These parameters play a significant role in the performance and efficiency of thermal-based desalination systems. Based on this analysis, an emerging thermal desalination method was recommended for large-scale implementation. The recommended thermal desalination method was briefly reviewed, and its technical aspects were comparatively analyzed in comparison to reverse osmosis, which is a desalination method that has been explored in the RSA.

To advocate for the implementation of large-scale thermal desalination, this study examined the potential social and environmental implications associated with its implementation. The approach employed to present this information involved reviewing previous studies that investigated the social and environmental outcomes of large-scale desalination projects. By synthesizing the findings from the literature review, the study drew a conclusion challenging the status quo of solar thermal desalination in the RSA.

3. Factors Contributing to Water Scarcity in the Republic of South Africa

The Republic of South Africa primarily relies on water stored in dams as its major water source [5,6]. However, the replenishment of these dams is heavily dependent on the amount of rainfall received in each area. The study established in the initial section that the current rainfall levels are insufficient to meet the daily water demands of the country, highlighting the significant role of climate conditions in contributing to water scarcity in the RSA. Despite being surrounded by the Indian and Atlantic Oceans, the RSA still faces challenges as a water-scarce country [24]. The Department of Water Affairs and Forestry (DWAF) of the RSA forecasted that the water demand may surpass the available water supply if the alarming water crisis is not addressed (see Figure 2 for sectorial demands) [5,25]. Numerous reports over the past decade have echoed the ongoing water crisis in the RSA, proposing various solutions to mitigate water scarcity [25–28]. One proposed solution is the implementation of a water management system, which includes the installation of monitoring systems to reduce household water usage [29]. Other works suggest that the RSA currently has enough water to meet immediate needs, but contamination from air pollution necessitates additional purification processes. It has been reported that 25% of the rivers in the RSA are contaminated due to a combination of pollution sources, resulting in higher costs for water delivery due to additional purification measures. With economic growth contributing to industrialization and air pollution, water contamination is expected to increase. The construction of additional dams is critiqued in this study due to its potential disruption of the ecosystem [6]. Reports also indicate that a lack of public awareness and knowledge regarding water conservation and management contributes to the water crisis. It is suggested that the government should initiate awareness campaigns to educate society on water management and promote responsible water usage, with the aim of changing societal attitudes and reducing water infrastructure vandalism, which adds to maintenance costs [30]. The causes of water scarcity in the RSA are multifaceted, not only involving climate change and the imbalance between water demand and supply but also poor water management practices and a lack of skilled personnel to implement and maintain efficient water supply infrastructure [31]. Furthermore, in rural areas, the lack of proper drainage infrastructure for wastewater recycling perpetuates the water crisis as water is hardly reused.

The primary dams situated within the designated Water Management Areas (WMAs) in the RSA serve as reservoirs for capturing rainwater and water from other sources [32]. The stored water undergoes further treatment using diverse conventional methods to produce drinking water. However, due to the inevitable decline in water levels in these dams, RO technology has been implemented in several regions of the country. As a result, the production of freshwater in the RSA is primarily reliant on two methods: reverse osmosis (RO) and water softening [33].

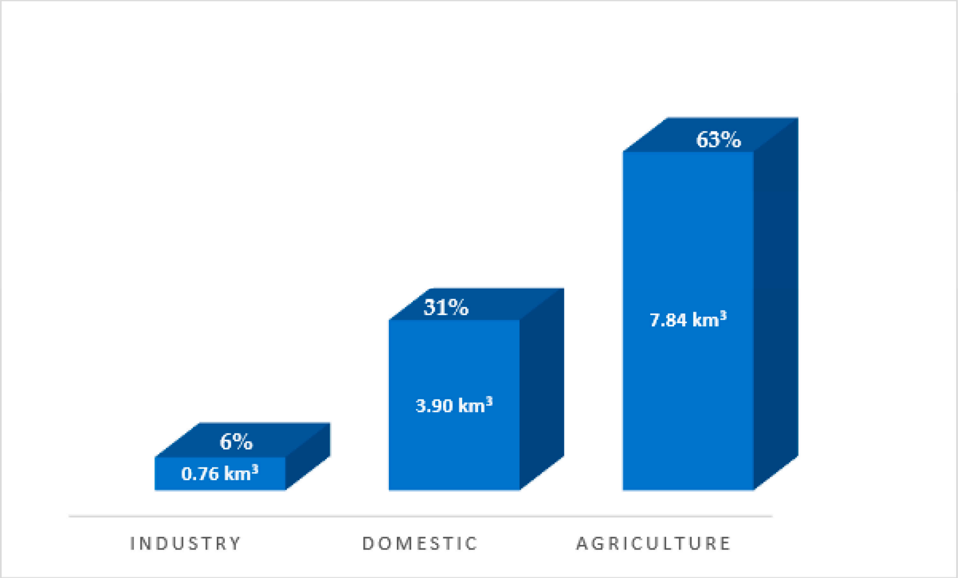

Figure 2. Water withdrawals in the RSA [3].

4. Desalination Technology in the Republic of South Africa

The desalination industry is still in its early stages in the RSA, and the government has taken steps to invest in this sector to meet the growing water demand [34,35]. There is a wide range of desalination technologies available in the market, including reverse osmosis, multi-stage flash, multi-effect distillation, and other emerging methods. However, it is crucial to select the most suitable technology for a specific location based on the available resources in that area [36–39]. Each type of desalination method has its own limitations [40], but ongoing research and development efforts have been improving these technologies over the years. In the past, thermal desalination was deemed unsuitable for the RSA due to its high energy requirements, making reverse osmosis the most viable option at the time. However, it is important to note that while RO has lower energy costs, it comes with expensive membrane costs. A study on three seawater reverse osmosis (SWRO) desalination plants in the RSA revealed significant maintenance costs, as depicted in Figure 3. For instance, the smallest plant analyzed, the Albany Coast Plant, had a maintenance cost of R1.97 per cubic meter of water produced [28]. These data highlight the economic challenges faced by small communities in coastal areas with fewer than 1000 residents, as large-scale desalination plants like the one in Mossel Bay (Figure 3) are not suitable for such communities. The maintenance aspect of small-scale RO desalination plants needs further improvement to ensure economic sustainability, as this has significant implications for the South African community, which faces a high demand for potable water.

The implementation of reverse osmosis (RO) systems in various parts of the country was primarily driven by the combination of low energy costs and high water demand. This desalination method relies heavily on grid electricity for its operation. However, the detailed discussion of the energy aspect is beyond the scope of this article. Figure 3 illustrates several seawater reverse osmosis (SWRO) plants in the RSA, demonstrating the relationship between maintenance costs and daily water production for these plants. The trend suggests that larger SWRO plants have lower maintenance costs. However, this poses a challenge for remote areas with smaller populations, as the requirement for a smaller plant leads to higher maintenance expenses.

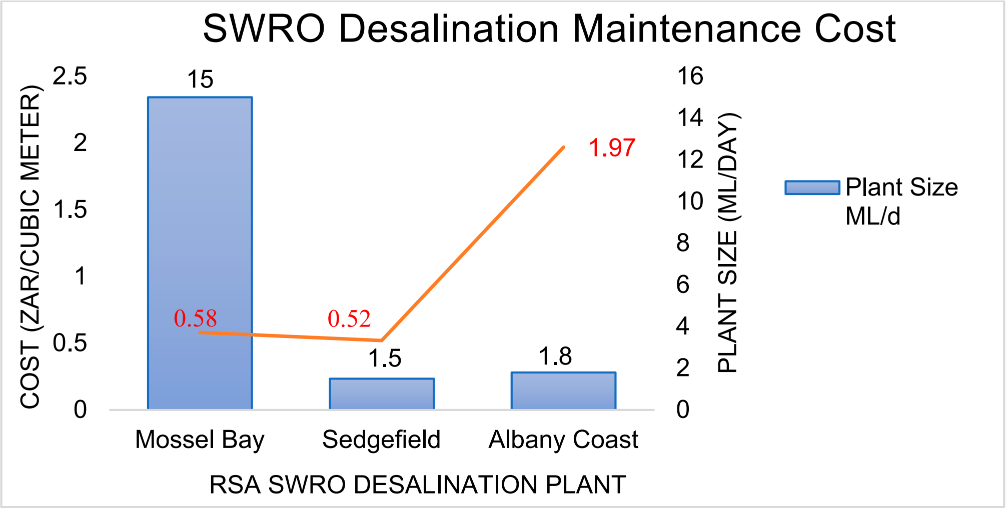

Figure 3. Desalination maintenance cost and daily water production of three RSA plants [27–29].

Efforts have been made to expand the desalination industry in the RSA, despite some local entities expressing reservations about its growth [41–43]. While there are pilot plants and ongoing studies on desalination in certain provinces, the literature on the subject is lacking across the nine provinces of the RSA [44–47]. Goga et al. [48] conducted a comparative theoretical study in the eThekwini Municipality, comparing the life cycle assessment of wastewater reclamation with that of desalination. The study revealed that greenhouse gas emissions pose a challenge, given the RSA's reliance on unclean energy sources. To address the water scarcity issue, the suggestion was made to construct two environmentally friendly water supply plants. Additionally, Moorcroft [49] and Ngobese [50] reported on a mobile seawater membrane desalination plant, capable of producing ten million liters of potable water daily for households in the KwaDlangezwa to Madlazini area of the KwaZulu-Natal province in the RSA. It is important to note that all the desalination methods discussed in this section were membrane-based and reliant on electricity.

5. Solar Thermal Desalination Technology

This section provides an overview of solar thermal desalination technology in the context of the RSA. Thermal desalination involves the process of reducing salinity or desalting brackish or saline water using thermodynamic principles. This temperature-sensitive technology can be categorized into two main types: thermal distillation, which involves adding thermal energy to saline water to produce distillate, and crystallization, which involves removing thermal energy from saline water until it crystallizes into pure water [51–54]. In recent years, there has been significant exploration of the idea of utilizing renewable energy resources such as wind, geothermal, and solar energy to power conventional desalination technologies, moving away from non-renewable energy sources. Extensive research has been conducted on how these renewable energy resources can be harnessed to provide the energy required for thermal desalination technologies [55–60].

Recent studies have highlighted various hybrid configurations of traditional thermal desalination processes combined with renewable energy resources. Sarbatly and Chaim [61] conducted a study on the use of warm geothermal water as a feed in a cross-flow vacuum membrane desalination system. They found that this energy source resulted in a remarkable energy consumption reduction of 95% (equivalent to 87–89 kWkg h^{-1}). The water produced met the acceptable standards set by the World Health Organization (WHO), which specifies a total dissolved solids (TDSs) level below 500 ppm for potable water. Mohammadi et al. [62] reviewed concentrated solar power (CSP) desalination systems and examined different configurations of CSP coupled with desalination plants. They presented the concept of co-generating plants that produce both potable water and power and proposed CSP–humidification–dehumidification (HDH) hybrid as the most promising CSP-coupled desalination technology for the future. The study also suggested three research modes to enhance the efficiency of CSP hybrid desalination systems: improving solar collectors, optimizing desalination systems to reduce costs and increase efficiency, and advancing integration schemes for improved performance and economics of hybrid configurations. The combination of CSP parabolic troughs or dishes with photovoltaic systems for desalination technology has garnered significant interest and investment from governments and researchers worldwide. Extensive research has been conducted on various hybrid co-generating plants [63,64].

As demonstrated earlier, solar energy can be harnessed in various ways to facilitate water desalination. Previous studies have focused on indirect solar desalination methods. Indirect solar desalination involves separating the solar energy collection unit from the actual desalination unit, contrasting with direct solar desalination technologies. Direct solar desalination encompasses various types of solar stills commonly used in remote rural areas and farms where there is both water scarcity and abundant solar energy [65–68]. Solar stills represent the simplest form of desalination devices, consisting of a basin filled with saline water and covered by a slanted transparent material that allows solar radiation to penetrate and heat the water within the basin. The heat causes the pure vapor to separate from the saline water, condensing on the sloping material and collecting in external troughs. Traditional solar stills have no moving parts, making them ideal desalination devices, although they face the challenge of meeting higher water demands [69,70]. Recent studies have explored advancements in solar still technology to increase daily water production. These developments involve exploring different shapes and transparent materials for the solar still panel. Additionally, hybrid configurations have been investigated to enhance solar irradiation collection, leading to higher distillate yields [71–75].

Although there have been significant advancements in the implementation of solar thermal desalination systems worldwide, there is a lack of reports detailing progress specifically related to solar thermal desalination plants in the RSA. However, in 2018, the first solar thermal-based desalination technology was commissioned in the RSA. This plant, located in the Hessequa Municipality at Witsand in the Western Cape province, has a daily production capacity of 150 kiloliters of potable water. It is important to note that this desalination plant was not locally developed but is a foreign design provided by Mascara. This highlights the need to strengthen local research and development efforts in order to implement thermal desalination technology and foster the growth of the desalination industry for alternative water supply systems as well as to provide other benefits such as youth employment [76,77].

6. Feasibility of Thermal Desalination in South Africa

The desalination of seawater is increasingly being recognized as a crucial solution to address global water scarcity [78–81]. This section aims to justify why thermal desalination could be a viable option for addressing water scarcity in the RSA. Firstly, a review of various methodologies and parameters considered by previous researchers that influenced the selection of thermal desalination will be presented. Secondly, this study will highlight and compare the daily solar irradiation and seawater salinity of the MENA region with that of the RSA as a means to motivate the suggestion of thermal desalination for the RSA. The choice to compare MENA with the RSA is based on the successful implementation of thermal desalination methods in the MENA region [36,82]. Over the years, advancements in thermal desalination systems have ensured that minimal solar irradiation is required for the desalination process to occur [83].

In general, the selection of the most suitable desalination technology for a specific area follows various criteria, including geographical characteristics, water quality, water demand, and other factors [20,36]. These criteria are prioritized in an assessment process to determine the feasibility of different desalination methods. For instance, the evaluation matrix for selecting a desalination method in a small community without electricity would differ from the selection process for desalination technology in a city. Wang [84] proposed a new selection process that considers hybrid information scenarios. There is a wealth of literature available that highlights the factors influencing the selection of desalination technologies. Regarding desalination cost, Advisian [85] identified several major factors, such as the type and location of the desalination plant, raw water quality, distance between the plant and the water source, pretreatment requirements, energy recovery methods, power supply, post-treatment processes, local infrastructure costs, and environmental regulations. Alhaji et al. [86] evaluated various assessment criteria and developed additional criteria for selecting an optimal desalination technology to replace decommissioned plants. Their evaluation encompassed six main domains: environment, economy, technical aspects, social factors, safety considerations, and policies and regulations. These considerations align with those of other researchers previously reviewed in this study [87–91].

Returning to the criteria used to justify the recommendation of thermal desalination for the RSA, it is important to compare the solar irradiation levels in the MENA region and the RSA. The MENA region experiences daily solar irradiation ranging from 3.5 to 5.5 kWh/m^2, while the RSA receives a higher range of 4.5 to 6.5 kWh/m^2 [92]. This is depicted in Figure 4, indicating that the RSA benefits from higher solar irradiation, giving solar-based desalination technology a significant advantage over the MENA region. Higher solar irradiation translates to greater availability of thermal energy, which is a renewable energy source that aligns with the global decarbonization initiative. Numerous studies on desalination technologies have been conducted in the MENA region, including countries like Egypt and Iran, where the desalination industry plays a prominent role in water supply [36,82,83,93].

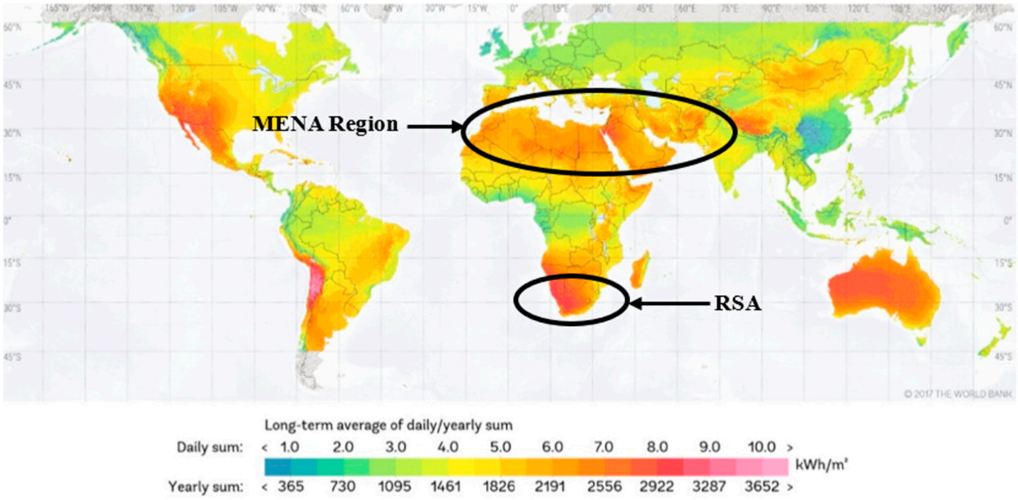

Figure 4. Global map of direct solar irradiation [93].

The MENA region is responsible for the majority of desalination systems worldwide [94]. The salinity of seawater in these regions, exceeding 40 parts per thousand (ppt), is considerably higher compared to the RSA, where the salinity ranges up to 35.8 ppt [38,94–97]. Considering that thermal desalination has been successfully implemented in the MENA region despite its higher salinity, it suggests that the RSA, with its lower salinity and higher solar irradiation, would face fewer challenges in implementing thermal desalination systems. This highlights the potential for the latest thermal desalination technologies to perform even better when tested under South African conditions, specifically the adsorption-based thermal desalination system. Table 2 provides a comparison between the acceptable Total Dissolved Salt (TDS) levels set by the World Health Organization (WHO) [32] and the TDS levels observed in the MENA region and along the coast of the RSA. This comparison further strengthens the case for considering an adsorption-based thermal desalination system.

Table 2. Comparison of seawater salinity of MENA region and the RSA [20,97].

WHO-Acceptable Salinity in Potable Water (in ppt)	MENA Coast Average Seawater Salinity (in ppt)	RSA Coast Average Seawater Salinity (in ppt)
0.5	36–40	35–35.8

A total of 1 mg of TDS/L of saline water = 1 ppm = 0.001 ppt (ppm—parts per million; ppt—parts per thousand).

The slow progress in implementing renewable energy sources is hindering the growth of the renewable energy-based desalination industry in the RSA [28]. Currently, the RO desalination systems operating in the RSA rely on electricity from the grid. The electricity consumption of RO systems ranges from 3.5 to 8 kWh/m^3 of water produced, which is more cost-effective compared to thermal-based desalination methods such as multi-effect distillation (MED) and multi-stage flash (MSF) systems, which consume 14.45 to 21.35 kWh/m^3 and 19.58 to 27.5 kWh/m^3, respectively [32,37,96]. In contrast, adsorption desalination, when powered by renewable energy sources, is the most economical thermal desalination method. It operates at a lower temperature of 55 °C, which can be achieved with lower solar irradiation. This results in reduced scaling and fouling, leading to lower maintenance costs [39,82,95,97,98]. Table 3 provides a comparison of solar irradiation and renewable energy consumption between membrane-based desalination methods and desalination methods employed in the MENA region. Adsorption desalination demonstrates superior energy consumption, excluding the costly maintenance expenses associated with RO. Despite the favorable environmental conditions in the RSA, there have been no reports of large-scale renewable energy-based desalination systems being implemented.

Table 3. Available solar irradiation and energy consumption of desalination methods [32,34,97].

MENA Solar Irradiation (kWh/m^2)	RO Desal. Energy Consumption Electrically Driven (kWh/m^3)	Adsorption Desal. Energy Consumption Thermally Driven (kWh/m^3)	MED Desal. Energy Consumption Thermally Driven (kWh/m^3)	MSF Desal. Energy Consumption Thermally Driven (kWh/m^3)
3.5–5.5	3.5–8	38.8	40.3–63.9	52.8–78.3

7. The Proposed Sustainable Desalination Method for the Republic of South Africa

The suitability of solar thermal desalination for the RSA has been established in previous sections, and it is important to propose a suitable desalination method in this stage of the review. Among the various desalination technologies available, a newly developed method called adsorption desalination is recommended for the RSA in this article. This method combines traditional desalination, which involves boiling saline water at controlled pressure, with an adsorption desorption cycle. The adsorption desalination method operates at low temperatures ranging from 50 to 85 °C, resulting in lower thermal energy requirements for the production of potable water. The system consists of three sub-systems: the evaporator, adsorbent beds/chambers, and the condenser [99].

During the first stage of the adsorption desalination process, the evaporator is responsible for boiling saline water at a low pressure, typically at temperatures ranging from 50 to 85 °C. The water vapor generated during this process is then captured in adsorbent beds, which contain physical granular porous adsorbents such as silica gel, zeolite, or activated alumina. Subsequently, the captured water vapor is released and condensed in the condenser to produce potable water [81,99].

The adsorption desorption cycle functions as an independent refrigeration cycle, consisting of two main components: the adsorbent (silica gel) and the adsorbate (water vapor). The adsorbent possesses both hydrophilic and hydrophobic properties that are activated by temperature variations. When the hydrophilic property is triggered, cold water is circulated through the adsorbent bed, causing the hydrophobic silica gel to attract and retain the low-temperature water vapor (adsorbate) on its external surface until saturation is reached. Conversely, when the hydrophobic property is activated, the water circulation through the adsorbent chamber is switched to hot water (not exceeding 50–85 °C), and the captured water vapor is released and directed to the condenser for the final stage of potable water production. Unlike conventional desalination processes where water vapor from the evaporator goes directly into the condenser, adsorption desalination incorporates pairs of adsorbent beds, as depicted in Figure 5. The system includes two pairs of adsorbent beds, which enhances the rate of potable water production, resulting in increased daily water output for the desalination system. Given its advantages, this desalination method is highly recommended for addressing water scarcity issues in the Republic of South Africa [100–104].

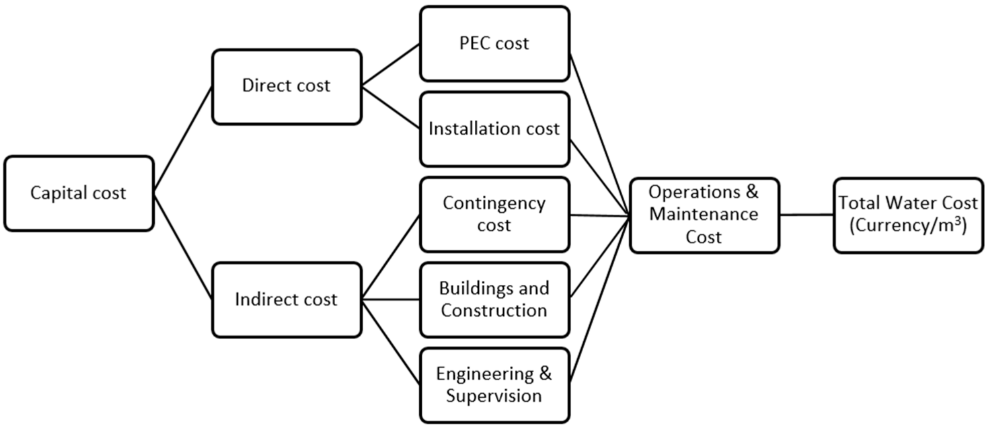

Figure 5. Total water cost components [105].

The minimum theoretical energy requirement for seawater desalination is estimated to be 0.78 kWh/m^3 [104]. While this provides a basis for calculating the cost of desalinating seawater, it is not a practical approach to determining the overall cost of water production. Various other factors need to be considered when implementing a desalination plant, as illustrated in Figure 5. Sarai Atab et al. [105] graphically summarized the total cost per quantity of water produced for a reverse osmosis (RO) desalination plant (Figure 5).

Table 4 provides a comparison between adsorption desalination and reverse osmosis (RO) desalination, aiming to highlight their respective performances. It is important to note that the data presented in the table do not specifically represent the desalination systems available in the RSA, as there is a lack of published data for the RSA's RO desalination systems. However, the inclusion of the proposed adsorption desalination system for the RSA serves as a point of contrast to emphasize its potential benefits and justify its implementation in the country.

Table 4. Comparison of adsorption desalination to RO desalination.

Parameters	Adsorption Desalination	RO Desalination	Ref.
Max TDS in feed water $\times 10^3$ (ppm)	67	45	[32]
Min TDS in Water produced (ppm)	10	10	[32]
Electrical energy required kWh/m^3	$\leq$1.38	3.5–8	[32,104]
Thermal energy required kWh/m^3	$\leq$38.8	n/a	[104]
Daily water production (L/day)	3.9–7.7	26,000–50,000	[106,107]
Cost of water production (USD/m^3)	0.2	0.49–0.75	[32,105]

The summarized data in Table 4 provide insights into the capabilities of both desalination systems, highlighting the strengths and weaknesses of each. It is evident that RO desalination is capable of producing large volumes of water, assuming factors like energy requirements and carbon emission regulations are not significant concerns. However, it should be noted that the data presented in Table 4 represent desalination plants from other countries, which are analyzed within the South African context with the objective of producing potable water for the RSA [32,104–107].

The power consumption associated with operating a typical large-scale RO desalination system, ranging from 26,000 to 50,000 m^3/day, using electricity from the grid is prohibitively expensive. This is particularly concerning given that the RSA relies heavily on fossil fuel burning for electricity generation. While there are limited pieces of literature available on large-scale adsorption desalination systems directly comparable to large-scale RO desalination, the data indicate that adsorption desalination holds great promise as a system that can be operated entirely on solar thermal renewable energy. Moreover, the water production cost of adsorption desalination is more than 50% lower compared to that of RO desalination. This analysis aligns with and supports the findings presented in previous sections of this work, which emphasize the role of the desalination industry in addressing the growing water demand in the RSA.

The adsorption desalination method is considered to be an excellent choice among various thermal desalination technologies available for large-scale implementation. It stands out for its ability to effectively desalinate seawater at lower temperature requirements. This particular desalination method has garnered significant attention and research interest worldwide, as it can achieve desalination at a minimum temperature of 50 °C.

8. Social and Environmental Impacts of Employing Thermal Desalination

Desalination has been widely recognized as a sustainable solution to address water scarcity on a global scale. This industry not only improves access to drinking water but also creates job opportunities that contribute significantly to the economy. Although there is limited academic research available on the social impact of desalination technology, efforts have been made to assess the environmental aspects of using desalination to supply water to communities worldwide. One major challenge associated with the desalination process is the management of brine discharge. Disposing of brine can have detrimental effects on ecosystems and marine life in the discharge area [108].

Ihsanullah et al. [109] conducted a comprehensive review study to assess the environmental impact associated with desalination technology. They analyzed data collected from operational desalination plants and compared with information available in the literature. The study supported the use of renewable energy-based desalination methods, emphasizing the importance of environmentally friendly approaches. Another study by Balfaqih et al. [110] focused on evaluating the economic and environmental impact of the water desalination supply chain (WDSC). The research revealed that among the components analyzed, airborne emissions had the greatest environmental impact.

In order to address the environmental impact of brine discharge from thermal desalination systems, this study proposes a solution that involves managing brine within the desalination process itself. By reducing the temperature difference in the desalination process, brine can be recirculated and diluted with fresh seawater feed, making it compatible with the RSA's solar irradiation and enabling further desalination. This approach eliminates the need for external disposal of brine discharge, particularly when the feed seawater has high salinity levels. Previous reviews and technical studies have explored various management tools for brine discharge, but some of these tools had limitations that overlooked important technical aspects affecting the operations of thermal desalination systems [111–113].

The proposed strategy not only mitigates the environmental impact and protects ecosystems, but it also safeguards the desalination system itself from fouling and scaling issues. By maintaining a low temperature difference within the desalting process, the occurrence of fouling and scaling is prevented. This ensures the optimal performance and longevity of the desalination system.

9. Conclusions and Future Work Recommendations

The objective of this review study was to propose the implementation of a large-scale solar thermal desalination technology, specifically the adsorption desalination system, in the RSA to address the increasing demand for potable water in the country. The effectiveness of the existing RO desalination method in the RSA was questioned, leading to a call for its reconsideration. Concurrently, the adsorption desalination system was proposed as a complementary method to alleviate water scarcity. By conducting a comparative analysis of the environmental conditions between the RSA and the MENA region, the feasibility of implementing adsorption desalination in the RSA was assessed. It was found that the RSA not only had more favorable environmental conditions but also met and exceeded the minimum operational requirements for the adsorption desalination method.

It is recommended that the RSA transition to sustainable renewable energy sources for operating its existing desalination systems. The implementation of sound regulations that support sustainable and renewable energy systems will not only contribute to financial gains but also foster a healthier environment. In addressing water scarcity issues, it is proposed that the RSA adopts renewable energy-based desalination methods, particularly thermal desalination. This recommendation is based on the favorable environmental conditions in the RSA, including the abundant seawater with a salinity level of 35–35.8 ppt, which is lower than that of the MENA region where thermal desalination has been successfully implemented. Additionally, the RSA benefits from a higher daily solar irradiation range of 4.5–6.5 kWh/m^2 compared to the MENA region. Considering these factors, it can be concluded that implementing thermal desalination has the potential to effectively meet the water demand in the RSA.

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