Sustainable Desalination: Strategies for a Cost-Effective and Eco-Friendly Water Production Solution

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Introduction

Freshwater scarcity is a global problem affecting millions of people across all continents [1]. With population growth and climate change, droughts and freshwater depletion have intensified, increasing the demand for alternative water sources [2]. A desalination plant is a facility that removes salts and other impurities from seawater, ultimately transforming it into potable water [3]. The process has emerged as a solution for dealing with freshwater scarcity across large parts of the world.

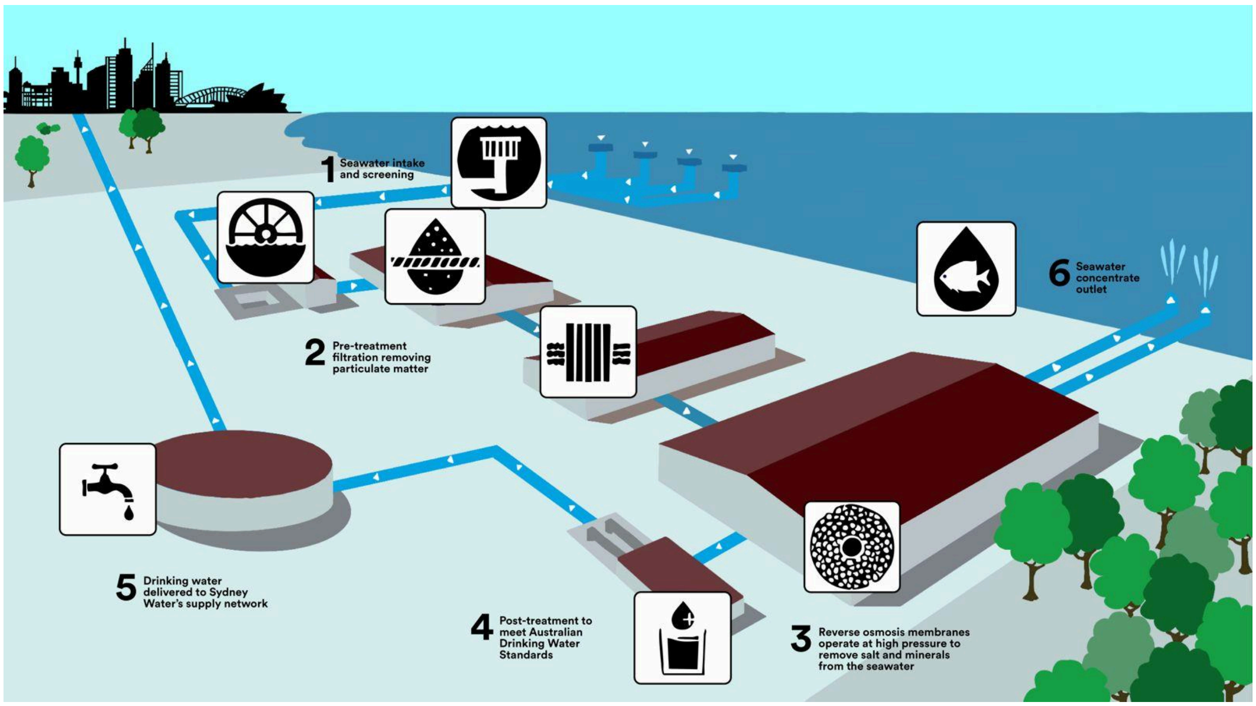

Figure 1. The general desalination process that most plants follow. (image created by author's sister)

In seawater desalination, seawater is transformed into potable water through a series of steps (figure 1). The process begins with seawater intake and screening (Step 1), where large debris and impurities are removed. The water then undergoes pre-treatment filtration (Step 2) to eliminate particulate matter, ensuring it is suitable for further processing. Next, the water passes through reverse osmosis membranes (Step 3), where high pressure forces the water through specialized membranes, removing salt and other dissolved minerals. This step is critical for producing fresh water from seawater. The treated water undergoes post-treatment (Step 4) to meet stringent drinking water standards, ensuring it is safe for consumption. Finally, the clean water is delivered to the supply network (Step 5), while the concentrated brine byproduct is discharged back into the ocean (Step 6), often through systems designed to minimize environmental impact [4].

Desalination appears to be one of the most promising solutions for water scarcity [5]; however, it has its drawbacks, such as reliance on fossil fuels, marine ecosystems disruption, and highly concentrated brine generation [6]. High energy demand within reverse osmosis operations [7] and multi-stage flash distillation [8] consumes tremendous amounts of electricity that primarily originate from non-renewable fuel sources. The reliance produces environmental damage like higher carbon footprint, while raising operating expenses [9,10].

Water intake procedures of desalination plants and their waste discharge operations can cause disruptions to marine ecosystems [11]. Small fish and plankton from the nearby ecosystem can become trapped during water intake, leading to harm of aquatic organisms and disrupting the natural equilibrium of marine habitats [12,13]. The production of highly concentrated brine stands as the most serious environmental consequence of desalination [14]. The mixture of ocean water and discharged saline wastewater increases local salinity levels and decreases oxygen content [15,16]. This presents severe threats to marine biodiversity [13,17]. Desalination has the potential to create environmental problems through improper brine management and fossil fuel consumption. Furthermore, it is only accessible to countries that can shoulder the high operation costs. For example, poorer regions like sub-Saharan Africa and parts of Asia cannot afford this system [18].

This work seeks to understand how desalination plants can be optimized to be cost-effective, energy-efficient, and environmentally friendly. Here I assess four different places, including Victoria, Australia; Dubai, UAE; California, USA; and Mumbai, India; all with their distinct issues and means of desalination. For example, Australia invested in desalination to cope with frequent droughts and a general lack of water [19]. In a desert city like Dubai, the population relies entirely on desalination as its source of water and has installed highly advanced systems within its plant [20]. In contrast, California has been under a water crisis for over a decade [21], and resorted to desalination as supplementary water [22]. Lastly, India has to meet the ever-growing population with regional water deficiencies [23].

One of the goals for this study is to help the upcoming desalination plant in India be more cost and energy efficient, while not degrading the environment with brine and fossil fuel usage. The country has been rapidly urbanizing [24] and increasing its agricultural activities, which have put a lot of pressure on freshwater resources. Agriculture in India uses 80-90% of its freshwater [25]. Coastal regions, where seawater is easily accessible, offer an opportunity to develop desalination plants as a sustainable source of water. However, cost constraints and environmental impacts have limited large-scale implementation [26].

I present a framework with best practices that are tailored for specific regional contexts. My analysis does not only consider technological advancements but also explores how renewable energy sources and environmentally friendly measures can be integrated to enhance the efficiency, cost-effectiveness, and sustainability of desalination plants. Thus, I propose actionable solutions toward the challenges facing desalination, helping make it feasible and accessible on a global scale.

Methodology

I gathered data from various sources, including scientific journals, government reports, and case studies on desalination plants in the selected sites. I combed through existing technologies, energy use patterns, and the environmental impact surrounding desalination. I then looked into the policies and initiatives undertaken by governments and organizations towards the development of desalination as an alternative water resource. I reviewed interviews conducted with experts in water management and renewable energy, which further added to my understanding and provided hands-on insights into current challenges and potential solutions.

I also conducted a literature review concentrating on recent breakthroughs in desalination technologies, including reverse osmosis, multi-effect distillation, and emerging techniques such as forward osmosis. This allowed me to track technological trends and areas for improvement. I also analyzed global databases and reports from international organizations, such as the United Nations and World Bank, to gather statistical data on water consumption, energy usage, and desalination plant efficiency [27,28].

My research also included studying the environmental impact of desalination by examining brine disposal methods and their effects on marine ecosystems. I reviewed studies by environmental scientists to evaluate strategies for mitigating these impacts, such as brine dilution techniques and alternative uses for brine byproducts. This approach ensured that my research addressed both technical and ecological aspects of desalination.

This study compares four sites to evaluate how each method approaches desalination, highlighting key trends and differences among them. By using available operational plant data, the comparative analysis discusses energy consumption costs as well as general environmental impacts. This mixed-method approach allowed me to develop a comprehensive understanding of the factors influencing the efficiency and sustainability of desalination plants.

Results

Desalination plants production and costs

The four desalination plants looked at in this study are located across three continents and produce varying amounts of water per day (Table 1). Table 1 compares some of the biggest desalination plants across the globe, focusing their water production, consumer pricing, and the operational costs.

Table 1. The four desalination plants selected, including the amount of water produced, the price consumers pay and the operational cost of each plant

Plant Name	**Location**	**Amount of water produced** (million liters per day - MLD**)**	**Price paid by consumers per month**	**Operational Cost**

The Jebel Ali Power and Desalination Plant	Dubai, UAE	1000 [29]	AED 300 (USD $81.67) [30]	800 million dirhams ($217.8 million) [31]
The Wonthaggi Desalination Plant	Victoria, Australia	150000 [32]	AUD $50 (USD $31) [33]	$607 million [34]
The Claude "Bud" Lewis Carlsbad Desalination Plant	Carlsbad, California, USA	204 [35]	$75 [36]	$55 million [37]
Manori Desalination Plant	Mumbai, India	200 [38]	Rs 60 (USD 0.70) [39]	Currently unavailable

The Jebel Ali Power and Desalination Plant is the largest facility with its daily output capacity at 1000 million liters per day although the Wonthaggi Plant in Australia pumps out 150 billion liters per day yet its operations cost $607 million. The Claude "Bud" Lewis Carlsbad Plant in California and the Manori Desalination Plant in Mumbai generate less water output despite charging consumers different prices. Households pay more for their water supply across Australia and the United States due to energy-thermally intense desalination operations; however, India keeps water prices low because of its distinct economic framework and government support levels.

The expensive nature of desalination stems from its heavy operational costs because year-round plant operation becomes difficult when financial assistance or other funding options are not available. Access to water needs to maintain balance with financial sustainability because the financial gap is too big. The water-shortage problem uses desalination as a vital solution to provide dependable water supply during freshwater scarcity. Desalination plants must integrate energy-efficient technology and renewable energy sources to make desalination sustainable because this combination will lower expenditure and environmental impact.

Current energy efficiency practises

Each of the locations described exhibits innovative measures customized to its environment and operations, which holds the promise of sustainability for desalination technologies around the globe (Table 2).

Table 2. The current energy-efficiency practices at the four selected plants.captures the various energy efficiency measures deployed in desalination plants located in Dubai, Australia, California, and India.

Plant	Energy-Efficient Features
The Jebel Ali Power and Desalination Plant	CCGT technology, waste heat utilization, AI-based control systems, high fuel efficiency, future renewable integration. [40-45]
The Wonthaggi Desalination Plant	Reverse osmosis, 100% renewable energy offset, energy-efficient compressors, living green roof, ecological reserve. [32][46-48]
The Claude "Bud" Lewis Carlsbad Desalination Plant	Energy recovery devices, energy-efficient membranes, and variable frequency drives on intake pumps.[49-51]
Manori Desalination Plant	Solar-powered, reverse osmosis, eco-friendly design, scalable capacity, cost-effective water production.[38][52-54]

Dubai uses Combined Cycle Gas Turbine (CCGT) technology that said to boost energy efficiency considerably, as it harnesses waste heat from gas turbines and feeds it into electricity generation (Table 2). The integration of Multi-Stage Flash (MSF) technology utilizes this waste heat to desalinate seawater, reducing the overall energy requirement. Advanced control systems, powered by AI and machine learning, optimize operations and improve turbine performance, further reducing emissions. An example of this is Siemens Gamesa's AI-driven wind turbine control system, which uses machine learning to optimize blade pitch and turbine performance, increasing energy output and reducing emissions [55]. Dubai’s focus on high fuel efficiency and plans to integrate renewable energy sources like solar and wind point towards a forward-looking approach to sustainable desalination [56-57].

Australia’s desalination plants emphasize renewable energy and innovative designs (Table 2). Facilities employ reverse osmosis, one of the most energy-efficient desalination methods, while operating entirely on a renewable energy offset model. Energy-efficient compressors and compact, modular plant structures further reduce energy consumption. Additionally, a living green roof not only integrates the plant with its natural surroundings but also lowers maintenance costs by improving thermal efficiency. The surrounding ecological reserve enhances biodiversity, reflecting a commitment to environmental stewardship. California and India have also adopted tailored strategies. The Carlsbad plant in California focuses on energy recovery devices that capture hydraulic energy from the reverse osmosis process, significantly cutting energy use and reducing carbon emissions.

India's upcoming solar-powered desalination plants are designed to integrate renewable energy and emphasize eco-friendly practices (Table 2). The scalable design will provide future capacity expansion, ensuring that resources are utilized efficiently as demand increases. This cost-effective production model by India ensures affordability and sustainability in catering to the growing population. The examples given demonstrate how energy-efficient technologies and innovative practices can make desalination a viable and environmentally friendly solution to global water scarcity.

Current environmental strategies

Each country has taken up measures that address its challenges, showing how the world has been striving for a balance between freshwater production and environmental conservation (Table 3). Some key strategies are brine management, carbon neutrality, and ecological restoration. However, each plant focuses on different strategies.

Table 3. Current strategies implemented for environmental well-being. Summarizes several strategies adopted by desalination plants in Dubai, Australia, California, and India to address their environmental concerns.

Location	Key Strategy	Specific Actions	Impact on Environment
Dubai	Energy Efficiency [29]	33.41% efficiency; uses waste heat.	Lowers fuel use and emissions by 31%.
	Brine Management [29][40]	Controls brine discharge carefully.	Minimizes harm to marine life.
	Standards Compliance [56]	Adheres to strict laws and earns awards.	Ensures low emissions and proper waste.
Australia	Brine Management [47]	Dilutes brine and treats it for reuse.	Reduces hypersalinity, recovers minerals.
	Ecological Restoration [58]	Creates reserves and restores habitats.	Preserves marine biodiversity.
California	Carbon Neutrality [49]	Uses renewables and offsets emissions.	Achieves net-zero carbon footprint.
	Brine Management	Dilutes brine; uses	Protects marine life.

	[49]	fish-friendly systems.	
India	Renewable Energy [38]	Plans solar-powered desalination.	Reduces carbon footprint.
	Coastal Impact [38]	Eco-friendly design, manages thermal output.	Protects habitats, minimizes harm.

Dubai focuses more on energy efficiency and responsible waste management (Table 3). The Jebel Ali plant generates power with an efficiency of 33.41%, which saves fuel and cuts carbon emissions by 31% compared to previous years. By using waste heat from the generation of power, the plant reduces its energy requirements. Also, it follows all environmental regulations and proper management of brine discharge to protect marine life, as Dubai is concerned with sustainable operations.

In Australia, the preservation of marine ecosystems is prioritized in desalination plants (Table 3). Brine is diluted with seawater and treated to recover valuable minerals before it is released, thus reducing the risk of hypersalinity. Ecological restoration efforts, including habitat creation and biodiversity conservation, also ensure minimal disruption to local marine life. These efforts are in line with Australia's focus on integrating sustainability into desalination practices.

California focuses on carbon neutrality and innovative technology (Table 3). The Carlsbad plant incorporates renewable energy and offsets to become net-zero carbon over time. Advanced intake and discharge systems like fish-friendly pumps ensure less damage to marine life while optimizing operation in the ocean.

Likewise, India will seek to open green and solar-powered desalination plants across its coasts to improve water supply without straining on fossil fuels (Table 3). By focusing on renewable energy and reducing coastal ecosystem disturbances, India is striving to achieve water security in a manner that conserves the environment. Altogether, these approaches demonstrate how global desalination is shifting toward environmental sustainability. Each location offers insights into best practices that can be replicated around the world.

General Renewable energy sources

Table 4. Renewable Energy Sources for Desalination. These are the most critical characteristics of renewable energy sources in the desalination processes, based on energy consumption, carbon footprint, water production efficiency, and scalability.

Energy	Energy	Carbon	Carbon	Water	Water	Which plants

Source	Consumption (kWh/m³)	Footprint	footprint (kg CO2 eq/m³)	Production	Production (m³/kWh)	use these technologies
Solar Energy	2.52-3 [61][62]	Low; zero emissions when fully solar-powered.	0.4 [66][61]	Suitable for small to medium-scale plants.	0.33 - 0.44 [67]	None
Wind Energy	3-5 [63][64]	Low; depends on turbine efficiency.	<0.5 [63]	Effective for medium-scale operations.	0.2 - 0.33 [68]	The Wonthaggi Desalination Plant [60][69]
Geothermal Energy	3-5 [62]	Moderate geothermal drilling emits some CO_2.	0.1-0.5 [62]	Continuous; supports medium to large-scale plants.	0.17 - 0.25 [69]	None
Wave Energy	Variable [63][65]	Minimal; emerging technology	0.3 [62]	Limited; suitable for coastal regions.	0.40 [65]	None

In terms of energy consumption, solar energy shows the lowest consumption of 2.52 to 3 kWh/m³, and its carbon footprint is as low as 0.4 kg CO_2 eq/m³, when fully powered by solar energy (Table 4). It is particularly suitable for small to medium-scale plants, offering a water production efficiency of 0.33 to 0.44 m³/kWh, making it a promising option for sustainable desalination.

Wind energy has low carbon footprint requirements of < 0.5 kg CO_2 eq/m³ while consuming 3 to 5 kWh/m³, depending upon the efficiency of the turbine used (Table 4). It will be best applied for medium-sized operations with a water output of 0.2 to 0.33 m³/kWh. Wind energy is excellent for coastal or inland areas.

Geothermal energy features an energy consumption of between 3 and 5 kWh/m³ and a slightly greater carbon footprint at between 0.1 and 0.5 kg CO_2 eq/m³ due to emissions from geothermal drilling (Table 4). It provides continuous energy generation, appropriate for medium to large-sized plants, with water production efficiency in a range of 0.17 to 0.25 m³/kWh. Although it has relatively moderate environmental footprints, it is a reliable source of energy for desalination.

Wave energy is a new technology that has varying energy consumption and a very small carbon footprint of about 0.3 kg CO_2 eq/m³ (Table 4). However, its applicability is limited to coastal areas. Its water production efficiency is 0.4 m³/kWh, and hence it can be used for desalination purposes in areas with regular wave action, but the technology needs to be developed further to make it more reliable and efficient.

Desalination facilities throughout Dubai, Victoria, California, and Mumbai show important distinctions regarding their performance efficiency and environmental effects together with renewable energy capabilities. The innovative waste heat utilization and strict environmental standards make Dubai a leader in water production while reaching high efficiency levels. The carbon emission reduction in Dubai along with stable operational costs and consumer prices became possible through its advanced practices. The city needs additional renewable energy infrastructure because its energy-intensive practices create an urgent need for sustainable power integration.

The environmental sustainability strategy in California emphasizes a thirty-year period to reach carbon neutrality. Such commitment receives support from advanced marine ecosystem protection systems, which also help minimize brine impacts. The implementation of advanced technologies has proven costly for California while also demonstrating restricted capacity to scale up operations thus creating financial hurdles.

Australia implements an appropriate strategy that focuses on brine handling together with strict regulatory systems to safeguard marine biodiversity. The company demonstrates commitment to decreasing environmental interference through programs, which combine brine water dilution and ecosystem healing techniques. The nation's moderate operational expenses coincide with its substantial energy usage since it presents significant potential opportunities to increase investments in renewable power sources such as wind and solar power.

The Indian nation trails behind other nations in their environmental practices and their energy efficiency levels. The desalination plants encounter major operational problems from high energy requirements and chemical contamination together with issues related to brine discharge management. Energy production through desalination remains relatively cost-efficient yet relies on fossil fuels and shows limited adoption of renewable power systems which increases environmental stress. India has enough potential for solar-powered desalination to become a sustainable water treatment approach if proper implementation strategies are established.

Renewable energy acts as a fundamental part in desalination processes. The low-carbon emission characteristics combined with high efficiency of solar energy make it suitable for small to medium-scale power generation facilities. Wind power and geothermal resources represent viable renewable sources with operational constraints that affect their scalability and output efficiency. The emerging nature of wave energy as a prospective resource faces challenges because of its inconsistent output levels as well as its limited deployment areas near coasts.

The research findings support using strategic combinations of cost-efficient measures and environmental protection protocols alongside renewable power implementation for making worldwide desalination procedures effective and sustainable.

Discussion

Table 5. List of possible energy sources for a desalination plant in India. The advantages and disadvantages of the best two energy sources.

Energy Source	Advantages	Disadvantages	Environmental & Energy Efficiency Strategies	Recommendations
Solar Energy	- Abundant and renewable in sunny regions. - Low carbon footprint. - Modular and scalable. [70][71]	- Intermittent energy supply (depends on sunlight). - High initial installation cost. [71][72]	- Pair with energy storage systems (e.g., batteries). - Use solar tracking systems to maximize efficiency. - Incorporate high-efficiency photovoltaic cells. [72]	Best for arid and semi-arid regions with high solar intensity, like Rajasthan.
Wind Energy	- Zero emissions during operation. - Reliable in coastal and windy areas. [73-74]	- Requires significant land/space. - Energy output fluctuates with wind availability. [75][76]	- Install offshore wind farms to reduce land use. - Utilize advanced turbine designs for higher efficiency. - Integrate with energy storage systems for reliability. [76]	Ideal for coastal regions in India like Tamil Nadu and Gujarat.

The sustainable option for desalination technology at present is reverse osmosis (RO) because of its practical implementation (Table 5). The technique stands out as energy-efficient in comparison with MSF desalination since it produces high-quality drinking water while using fewer resources. RO continues to need advancements toward minimizing its waste brine effects and energy usage but remains the prime method for lasting adoption due to its renewable energy compatibility.

Desalination operations need renewable energy systems for reducing their environmental impact. Renewable and scalable properties make solar and wind power the most suitable energy options. The combination of different renewable power sources with storage mechanisms enables stable energy delivery when sunlight or wind speeds are low.

Solar power together with wind energy represent the most practical renewable energy options for desalination facilities because they offer superior scalability with excellent efficiency rates at competitive costs than hydropower, geothermal, and biomass systems. Solar energy proves suitable for desalination operations because spots like India and Middle Eastern locations receive high solar radiation levels. The combination of this energy system delivers both steady power distribution together with decreased fossil fuel dependence. The consistent renewable energy source of wind power works especially well in coastal areas that serve as the usual site for desalination facilities. The extensive applications of solar and wind power surpass hydroelectricity and geothermal systems because they do not need major water supplies and geographical restrictions. The applicability of biomass energy for desalination decreases because it provides unstable power output alongside needing extensive land resources. Solar alongside wind energy provides desalination plants with a sustainable operational system to tackle environmental effects while cutting down future energy expenses.

Solar and wind power prove to be the most suitable renewable energy systems for desalination within the context of India. Solar energy, abundant in states like Rajasthan, offers significant potential with its consistent high irradiance. The combination of energy-efficient technological advancements in photovoltaics together with solar tracking systems produces maximum power output while preserving land resources to the minimum extent.

The states of Tamil Nadu and Gujarat along their coasts benefit from wind energy because they experience continuous wind patterns. Pipelines operating from offshore regions combined with improved turbine technology increase efficiency and minimize environmental impact. The operation of desalination plants depends on storing energy and implementing smart grid systems alongside integrated energy storage elements.

Desalination facilities need to develop sustainability measures combined with operational energy efficiency. The energy requirements of desalination operations decrease when processes are optimized between pre-treatment and post-treatment stages. Brine management systems help plants reduce harmful effects of brine releases on marine environments. Lithium-ion batteries alongside other advanced energy storage systems serve to maintain renewable energy consistency. Through smart grid solutions linked to real-time monitoring facilities optimize energy usage to minimize waste. Desalination plants can simultaneously reach sustainable operation with steady water generation by using these strategic measures.

Conclusion

This research demonstrates the urgent necessity to develop sustainable desalination solutions mainly for India because water shortages are steadily increasing throughout the country. Desalination currently consumes high amounts of energy and money, but when coupled with renewable energy systems from sunlight and wind power, the method can shift toward being practical. India’s abundant sunlight and coastlines make it ideal to utilize solar and wind power for desalination plant operation. The use of renewable sources both reduces dependence on fossil fuels and supports India's effort to decrease its carbon emissions.

Affordable water access through India's economic scheme demands the adoption of budget-friendly energy-efficient technologies. India can solve water scarcity problems and safeguard environmental preservation by leading renewable energy development and working on better brine handling methods and new desalination methods. Strategies that deliver success will create a model suitable for water-scarce regions worldwide while showing how India advances sustainable water management solutions.

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