Journal of Engineering Research

Volume 7
Issue 5 *This is a Special Issue from the Applied Innovative Research in Engineering Grand Challenges (AIRGEC) Conference, (AIRGEC 2023), Faculty of Engineering, Horus University, New Damietta, Egypt, 25-26 October 2023*

Article 12

2023

A Comprehensive Review on Hybridization in Sustainable Desalination Systems

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Journal of Engineering Research (ERJ)
Vol. 7 – No. 5, 2023
©Tanta University, Faculty of Engineering
ISSN: 2356-9441 https://erjeng.journals.ekb.eg/ e ISSN: 2735-4873

A comprehensive review on hybridization in sustainable desalination systems

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***Abstract*- The contemporary era underscores the paramount significance of the water sector, largely due to dwindling resources and the exponential growth of the global population. Consequently, there is a pressing need to emphasis the vital role of desalination processes in addressing these challenges. In recent times, nations worldwide have shifted their focus towards optimizing treatment facilities. This optimization is pursued through the enhancement of plant efficiency and the amalgamation of diverse desalination technologies. The latter strategy has demonstrated its efficacy in augmenting on-ground productivity. Within this context, we embark on an exploration of the world's foremost desalination facilities, delving into their production capacities and their hybridization status. Furthermore, we delve into the pivotal dimension of integrating renewable energy sources into these processes, acknowledging the substantial energy demands that desalination inherently entails. It is evident that countries in the Middle East have showcased a noteworthy inclination towards hybridization endeavors, which have yielded substantial improvements in station productivity. Notably, the RO-MSF hybrid system has emerged as a highly reliable choice among the various hybridization schemes employed in operational plants. The Middle East, in particular, has substantially bolstered its presence in the global landscape of operational hybrid plants, amassing a staggering total production capacity exceeding 17 million cubic meters per day. This attests to the region's remarkable commitment to securing sustainable water resources through innovative desalination approaches.**

Keywords- Hybridization, Operational Desalination plant, Renewable Energy Integration, Sustainability

I. Introduction

The depletion of freshwater reservoirs is accelerating due to the growing global need for water resources. This heightened demand arises from increased requirements for natural resources and is exacerbated by the influence of climate change, particularly impacting arid, coastal, and inland regions. It is crucial to acknowledge that water and energy represent indispensable assets for sustaining life on our planet. These resources have played a pivotal role in facilitating progress and advancement in numerous regions of the developed world. However, it is important to note that a considerable number of regions in developing countries grapple with acute shortages of both freshwater and energy resources [1]. In one of its 2012 reports, the United Nations Environmental Program (UNEP) highlighted a significant finding. According to the report, approximately one-third of the global population currently has access to freshwater resources essential for their livelihoods. However, the prognosis is alarming as it suggests that the majority of the world's population will face severe water shortages by the year 2025. [2].

Within this substantial volume of water, approximately 97% constitutes saltwater, leaving a mere 3% as freshwater. Furthermore, within this limited freshwater fraction, a significant portion, approximately 68.7%, exists in frozen form within icecaps or is bound as soil moisture. Figure (1) gives a summary for distribution of various water resources across the globe.

The Desalination processes can be categorized based on their separation methods into two primary groups: membrane-based processes, which encompass RO and ED, and thermal-based processes, which include MSF, TVC, MED, and HDH. Figure (2) shows the percentage of global desalination capacity by process.

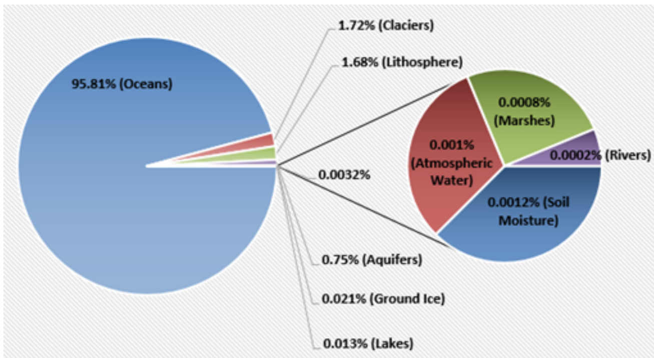

Figure 1. Distribution of water resources across the globe [4].

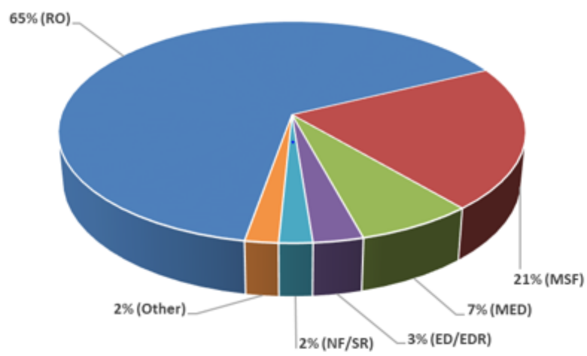

Figure 2. Global desalination capacity by process [5].

doi: 10.21608/erjeng.2023.235480.1238

Journal of Engineering Research (ERJ)
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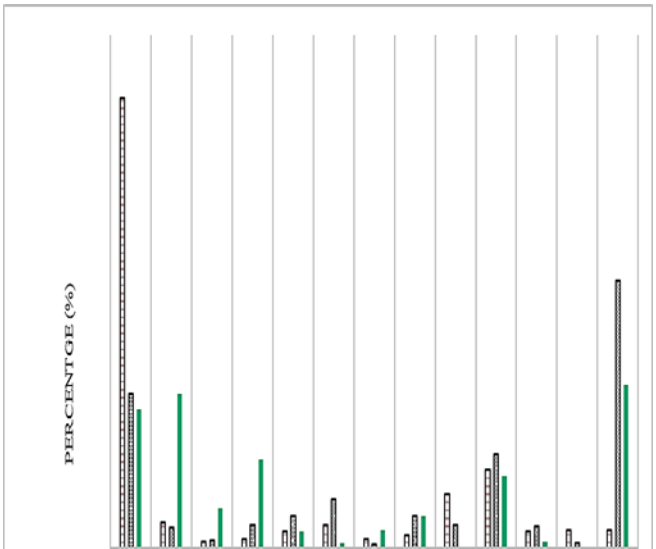
©Tanta University, Faculty of Engineering
ISSN: 2356-9441 https://erjeng.journals.ekb.eg/ e ISSN: 2735-4873

Indeed, the choice of desalination technology, be it membrane-based or thermal, comes with a distinct array of pros and cons. The selection of a specific desalination process should be guided by a comprehensive evaluation of numerous factors, contingent upon the intended purpose and objectives, as exemplified in reference [3].

II. SELECTION OF DESALINATION-PROCESS

When selecting a desalination method for a specific application, several factors necessitate careful examination. These encompass the quantity of freshwater needed for the application and the versatility of the available desalination techniques. Additionally, the assessment should encompass the process's energy efficiency, its compatibility with solar energy integration, the prerequisites for saltwater treatment, and the initial capital costs associated with procuring equipment and imported materials. The consideration of land area required for equipment installation, the potential availability of such land, and the robustness and user-friendliness criteria are all pivotal. Additionally, attributes like low maintenance requirements, compact size, and ease of transportation to the worksite carry significant weight. Furthermore, garnering acceptance and support from the local community while minimizing social disruptions is essential, as is having a local organization that demands minimal training [6].

Desalinated water on a global scale can be categorized into three primary types: seawater, brackish water, and wastewater. Notably, a substantial concentration of high-capacity desalination facilities is situated in the Middle East region.



	Gulf countries	East Asia	Australia	Japan,Korea,Taiwan	West Aisa	Middle East	Africia	Northern Europe	North Africia	Southern Europe	South America	Carinnean	North America
Sea Water	61.4	3.4	0.8	1.2	2.2	3.1	1.2	1.7	7.3	10.6	2.2	2.4	2.5
Brackish water	21.1	2.8	1.1	3.2	4.4	6.7	0.4	4.4	3.1	12.8	3	0.6	36.4
Waste Water	19	21	5.4	12.1	2.3	0.7	2.4	4.3	0	9.7	0.9	0	22.2

Figure 3. Global distribution of desalination capacities (million m3/day) as of 2013 [9].

The Persian Gulf, Gulf of Oman, and Red Sea, areas grappling with acute shortages of potable water, collectively contribute to a remarkable 65% share of the worldwide water desalination capacity [7], [8]. The geographical distribution of desalination capacities worldwide is visually depicted in Figure 3.

III. HYBRID DESALINATION SYSTEM

The hybrid desalination method involves the integration of multiple technologies to achieve superior solutions and reduce costs compared to individual processes. Desalination commonly employs distillation and membrane-based techniques, which can be amalgamated to create a more economically efficient procedure when employed in a hybrid context. In a hybrid configuration, two or more desalination processes can be seamlessly incorporated or connected with a power plant, enabling the cost-effective production of water. Table (I) describe the most important Hybrid system

Table I. Major findings of most important Hybrid system

Hybrid System	Major Findings
RO-MSF	• Emphasize hybridization [10], [11]. • Hybrid desalination configurations [10]. • Water reduction cost by 23–26% [12]. • Small scale hybrid solar-wind MSF-RO water cost (1.35–1.84 $/m3) [13]. • Reduce product water operation / maintenance expenses and increasing recovery and lowering energy consumption [14]. • Increase usable life of the RO membrane 3- 5 years, decrease yearly membrane replacement cost 40% [15] • Optimization methodology - fully integrated tri-hybrid power-MSF-RO plants [15]. • A hybrid MSF/RO, MSF fed by brine reject of the RO [16]. • The blow downstream leaving the MSF plant used as a feed to the RO plant [16]. • Economic impact [17] • Minimum water cost of 7 different designs of RO/MSF [18], [19]. • Pretreatment of seawater using nano-filtration (NF) membranes [20], [21].
RO-MD	• Overall system recovery could be improved from 30 to 35% for standalone RO to more than 76% [22] • Using AGM (a water recovery of RO-MD that more than 80%) [23]. • Cost of the thermal energy source [24]. • Mitigating strategies of integration [25], [26]. • Various configurations of MD-RO hybridization [27].

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©Tanta University, Faculty of Engineering
ISSN: 2356-9441 https://erjeng.journals.ekb.eg/ e ISSN: 2735-4873

RO-HDH	• Using RO brine as feed water of HDH unit [28]. • Improved GOR of 20 / equivalent electricity consumption of 9.5 kWh/m3 [29] • Exergy analysis (50% largest exergy destruction by the TVC) [30]. • Improving the hybridization by introducing a Pelton turbine or pressure exchanger [31].
MED/ MSF-MD	• Integrating multi-effect VMD and AGMD with a commercial-scale MSF [32]. • Optimized the thermal coupling network of MED and MD combined production of 3850 tons/day [33]. • Several configurations of hybridizations processes unit cost of MED-MD 4.93 MM$/y, 10% less than that of MSF-MD [34]. • A geothermal-based MED-DCMD hybrid system for multi- generation of cooling-power-desalination [35]. • MED-MD hybrid desalination system with different configurations of MD [36]. • a parallel feed 3-stage MED with spray nozzle header and silica gel AD bed, using potable water as feed water [37]. • dual-purpose power and desalination plant operation, the life-cycle unit water cost of MED-AD [38]. • Optimization of solar-powered MED-AD using high salinity Gulf seawater [39]. • Integrated MED-AD hybrid system with a nominal production capacity of 10 m3 /day with real saline water from Red Sea [40].
MED/ MSF-AD	• AD to bring the last stage temperature of MED to below ambient through the addition of AD cycle [41]. • AD as the downstream to take up vapor extracted from the last effect of MED [42].
MED/ MSF-VC	• Increase energy efficiency, distillate production and minimize operational costs [43]. • MED-VC configuration, part of the steam generated in the previous effect is taken, compressed, and fed to the first effect [44]. • One of the largest MED-TVC desalination plants is Yanbu II [45]. • MED-MVC up to 5000 m3 /day/unit [46]. • Zero-liquid discharge (ZLD) system to treat desalination brine with total dissolved solids of more than 70,000 mg/L [47]. • MED-TVC plants design [48] thermodynamic analysis [49], [50] ejector, improve the performances of TVC [51], [52]. • A pressure regulated method optimize [53]. • The addition of an auxiliary entrainment [54]. • flow patterns effect of ejector [55]. • Ejector efficiency Improvement by 14% [56]. • non equilibrium condensation phenomena [57]. • The dynamic behaviors of MED-MVC and MED-TVC [58]. • MED-TVC system with a parallel/cross flow configuration [59]. • Optimization MSF with brine circulation and TVC [60].
HDH	• Humidification-dehumidification - water flashing evaporation [61]. • HDH-SS integrated with solar air-water heater [62]. • HDH hybrid with solar distiller [63]–[65] with different configurations [66]

IV. Desalination Technologies and Energy

Water, energy, and desalination are intricately interconnected, and this interrelation will become even more pronounced with the global population's growth and evolving consumption patterns, leading to heightened demands for water resources. Presently, a significant portion of desalination facilities is situated in areas where conventional energy sources are readily accessible and cost-effective. Table (II) illustrate the energy requirements of the main desalination techniques. Assessing the quantity of conventional energy necessitated by desalination processes, is crucial for understanding the imperative need to transition towards renewable and sustainable energy sources.

Desalinating both saltwater and brackish water holds the promise of addressing the escalating global demand for freshwater resources. However, this approach faces sustainability challenges due to its substantial energy requirements, largely sourced from fossil fuels. Accessing these energy sources can be particularly challenging in remote regions, and their costs are notoriously volatile. Notably, certain Middle Eastern nations, like Qatar and Kuwait, are heavily reliant on desalinated water for both domestic and commercial purposes. [67].

Table II. **Energy requirements of the main desalination techniques [68].**

	Typical unit size (m3 /d)	Electrical Energy Consumption (kWh/ m3)	Thermal Energy Consumption (kJ/ kg)	Total Equivalent Energy Consumption (kWh /m3)
MSF	50,000 - 70,000	4 – 6	190 - 390	13.5 - 25.5
(TVC)	10,000 - 35,000	1.5 – 2.5	145– 390	11 – 28
MED	5,000 - 15,000	1.5 – 2.5	230– 390	6.5 - 11
MVC	100 - 2500	7 - 12	None	7_ 12
RO	24,000	3 – 7	None	3 – 7
ED	24,000 - 145,000	2.6 – 5.5	None	2.6 – 5.5

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©Tanta University, Faculty of Engineering
https://erjeng.journals.ekb.eg/
ISSN: 2356-9441 e ISSN: 2735-4873

Renewable energy desalination (RED) systems are experiencing a surge in popularity on a global scale, with the inauguration of over 130 RED plants in recent years [69]. Figure 4 illustrates the worldwide distribution of contributions from various renewable energy sources to desalination technology. There are two primary approaches for integrating a desalination plant with renewable energy: a direct connection or feeding the generated power into the electrical grid to offset the intermittent nature of renewable energy sources [70].

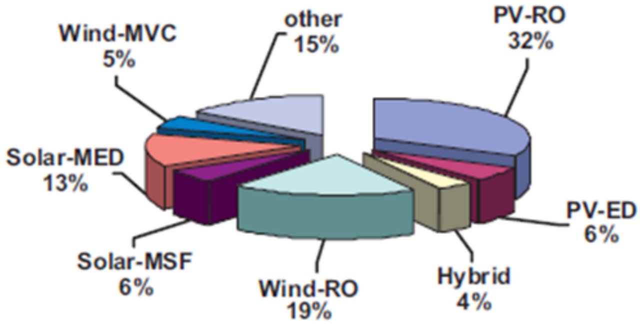

Figure 4. Distribution of renewable energy powered desalination technologies [71].

Multiple technical pairings can be established between desalination systems and renewable energy sources. Table (III) provides an overview of these potential combinations. Nevertheless, it's essential to note that not all of these combinations have been subjected to real-world testing and validation.

***Table III.* Possible combinations of renewable energy with desalination technologies [72].**

	Solar				Wind		Geothermal		Ocean Power		
	Thermal -collectors	CSP Thermal	CSP Electrical	PV	Mechanical	Electrical	Thermal	Electrical	Electrical	Mechanical	Thermal
SD	■										
MED	■	■					■				■
MD	■	■					■				■
TVC		■					■				■
MSF		■					■				
MED	■	■					■				■
ED			■	■	■			■	■		
MVC			■	■	■	■		■	■	■	
RO			■	■	■	■		■	■	■	

V. Commercially -Operational Hybrid Desalination Plants

There are roughly 16,000 operational desalination plants dispersed across 177 countries, collectively producing an estimated 95 million cubic meters per day of freshwater.

Table (IV) presents a comprehensive overview of the most significant desalination plants located in various countries worldwide. It includes details such as the water production capacity and the specific desalination technology employed. Notably, the table highlights the substantial and noteworthy disparity in production capacity between single-technology plants and hybrid plants. The keen interest of countries in hybridization processes can be attributed to their heavy reliance on desalination techniques as the primary source of water supply.

Table (V), which consolidates data on the most crucial operational hybrid plants, vividly underscores that Middle Eastern nations have emerged as leaders in the realm of hybrid desalination. Notably, the three largest countries in the region—Saudi Arabia, the United Arab Emirates, and Kuwait—rely entirely on water desalination for their freshwater supply. It's important to note that the integration of renewable energies into desalination plants or their direct utilization has not been widely implemented on the ground, despite the fact that certain countries in the region have established facilities for generating electricity from renewable energy sources.

***Table IV.* The most important operational Desalination plant [71].**

Location		Capacity (m^3/day)	Process type	Plant Type
Algeria	Arzew [73]	90,000	RO/ NF	Power dual purpose
	Cap Djinet [74]	100,000	RO	Energy Recovery, Inc. (ERI)
Aruba	Aruba [75]	44,000 (RO) 3,000 (IE)	RO / ION EXCHA NGE	Power dual purpose
Bahrain	Al Hidd [76]	272,760	MFD	Independe nt Water & Power Plant (IWPP)
	Durrat Al Bahrain [77]	36,000	RO	Power dual purpose
China	Tianjin [78]	200,000	RO	combinatio n desalinatio n and coal-fired

doi: 10.21608/erjeng.2023.235480.1238

Journal of Engineering Research (ERJ)
Vol. 7 – No. 5, 2023
©Tanta University, Faculty of Engineering
ISSN: 2356-9441 https://erjeng.journals.ekb.eg/ e ISSN: 2735-4873

				power plant
	Hong Kong [79]	137,000	RO	
Egypt	Dahab [80]	15,000	RO	
India	Minjur [81]	10,000	RO	
	Nemmeli, Chennai [82]	100,000	RO	
Iran	Chabahar-Kenarak [83]	35,000	RO/MSF	
Israel	Ashkelon [84]	330,000	RO	
	Palmachim [85]	124,000	RO	
	Hadera [86]	348,000	RO	
	Sorek [87]	625,000	RO	
	Sorek 2 [88]	570,000	RO	
	Ashdod [89]	274,000	RO	
Malta	Ghar Lapsi [90]	50,000	RO	energy recovery devices (ERDs)
Mexico Morocco	Rosarito [91]	380,160	RO	
	Chtouka [92]	753,425	RO	
	Casablanca [92]	684,930	RO	
	Jorf Lasfar [93]	109,589	RO	
Oman	Dakhla [94]	82,190	RO	
	Sur [95]	80,000	RO	
	Qarn Alam [95]	45,000	RO	Power dual purpose
	Al Najdah [96]	200	FO	
	Al Khaluf [97]		FO	
Qatar	Ras Abu Fontas [98]	160,000	(MSF)	
Pakistan	Gwadar [99]	254,000 gallons/day	RO	
Saudi Arabia	Jubail [100]	1,400,000	MED/RO	Power dual purpose
	Jeddah [100]	12.5 million gallon/day	MSF/RO	Power dual purpose
	Ras Al-Khair [88]	1,036,000	MSF/RO	Power dual purpose
	Yanbu [101]	146,160	9 MSF units and one RO plant	
	Shuaiba 3 [88]	880,000		
Singapore	TuasSpring [102]	318,500	UF / RO	Power dual purpose
	Jurong Island [103]	130,000	RO	Power dual purpose
South Africa	Mossel Bay [104]	15,000	RO	
	Transnet Saldanha [105]	2,400	RO	Energy recovery system
	Knysna [106]	2,000	RO	
	Plettenberg Bay [107]	2,000	RO	
	Bushman's River Mouth [108]	1,800	RO	
	Lambert's Bay [109]	1,700	RO / dual media pressure filters	
	Cannon Rocks [110]	1800	RO	
United Kingdom	Thames 0 [111]	150,000	RO	
	Jersey [112]	6,000	MSF / RO	
United States	El Paso, Texas [113]	27,500,000 gallons/day	RO	
	Carlsbad (California) [114]	50 million gallons/day	RO	
	Concord (California) [115]	20 million gallons/day	RO	
	Santa Barbara (California) [116]	3 million gallons/day	RO	
	Tampa Bay (Florida) [117]	95,000	RO	
Gibraltar	Gibraltar [118]	6,300	MSF/RO	Power dual purpose

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©Tanta University, Faculty of Engineering
ISSN: 2356-9441 https://erjeng.journals.ekb.eg/ e ISSN: 2735-4873

Kuwait	Kuwait [119]	1.65 million	MSF/RO	Power dual purpose
United Arab Emirates	Kalba [120]	15,000	RO	
	Taweelah [88]	909,200	RO	
	Fujairah F2 [121]	591,000	MED-RO	Power dual purpose
	Umm Al Quwain [88]	682,900	RO	
	DEWA Station M, Dubai [88]	636,000	MSF	Power dual purpose
Saudi Arabia	Jubail [100]	1,400,000	MSF/RO	Steam Power plant
	Jeddah [100]	12.5 million gallon/day	MSF/RO	Steam Power plant
	Ras Al-Khair [88]	1,036,000	MSF/RO	Steam Power plant
	Yanbu [101]	550,000	9 MSF units and one RO plant	Steam Power plant
Iran	Chabahar-Kenarak [83]	35,000	RO/MSF	nuclear

VI. HYBRID DESALINATION PROCESS OBSTACLES AND CHALLENGES

The most important challenges can be summarized in main factors:

- Unique circumstances, such as the need for plant remediation or upgrades, regional disparities in energy expenses, and location-specific considerations regarding raw material costs [122].
- Dealing with tube scaling issues in Multi-Stage Flash (MSF) and addressing membrane fouling problems in Reverse Osmosis (RO) [123].
- The complexity in effectively integrating hybrid renewable energy systems lies in determining the optimal design by adopting a system-oriented approach [124].
- While solar energy is abundant and freely available, the hardware required for economically harnessing, efficiently collecting, converting it into usable forms, and storing it poses significant challenges [125].

Table V. **Operational Hybrid Desalination plant**

Location		**Capacity (m^3/day)**	**Hybrid System**	**Powered by**
United Arab Emirates	Fujairah F2 [121]	591,000	MED-RO	Steam Power plant
Kuwait	Kuwait [119]	1.65 million	MSF/RO	electrical power
Gibraltar	Gibraltar [118]	6,300	MSF/RO	electrical power
United Kingdom	Jersey [112]	6,000	MSF / RO	electrical power

VII. CONCLUSION

Several critical observations come to light. Firstly, there is an evident scarcity of freshwater resources, and the prevalence of saltwater covers the majority of the Earth's surface. Secondly, Reverse Osmosis (RO) stands out as the dominant and most efficient desalination process. The Middle East and Arab Gulf nations have taken the lead in global desalination operations, surpassing the 70% mark. A noteworthy development in desalination practices is the emergence of hybridization techniques and the integration of renewable energy sources. This shift is essential because desalination processes are notoriously energy-intensive, consuming approximately 5 tons of crude oil to produce 1000 cubic meters of freshwater.

Of particular significance is the substantial disparity in production capacities, which becomes evident when employing hybrid systems in real-world applications. The Middle East boasts the majority of operational hybrid desalination plants globally, collectively capable of producing over 17 million cubic meters per day. Among these operational hybrid plants, the RO-MSF hybrid system stands out as the most effective and widely adopted, underscoring its remarkable reliability compared to other hybridization systems.

Nomenclature

CSP concentrating solar power
ED electro dialysis
EDR Electro dialysis Reversed
MD membrane distillation
MED multiple effect desalination
MEH multiple effect humidification
MSF multi stage flash
MVC mechanical vapor compression
PV Photovoltaic
RO reverse osmosis
SD solar distillation
TVC thermal vapor compression
RED Renewable energy desalination

doi: 10.21608/erjeng.2023.235480.1238

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Vol. 7 – No. 5, 2023
©Tanta University, Faculty of Engineering
ISSN: 2356-9441 https://erjeng.journals.ekb.eg/ e ISSN: 2735-4873

Statements & Declarations

Funding: The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Conflicts of Interest: The authors have no relevant financial or non-financial interests to disclose.

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Journal of Engineering Research (ERJ)
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