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ENERGY AND CARBON FOOTPRINT OF MODERN DESALINATION TECHNOLOGIES

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Abstract. Membrane-based desalination technologies demonstrate substantially lower energy consumption than thermal technologies, with seawater reverse osmosis requiring 2–6 kWh/m³ compared to 7.7–24 kWh/m³ for multi-effect distillation and multi-stage flash. RO achieves the highest exergy efficiency at 30.1%, nearly four times that of MSF (7.73%). However, energy source exerts a dominant influence on carbon footprint that often exceeds technology choice effects. Coal-powered RO produces 1.8–11.7 kg CO_2/m³, while renewable-powered RO achieves 0.1–0.3 kg CO_2/m³, representing a 90–95% emission reduction. Grid electricity carbon intensity creates 20–60-fold variation in emissions for the same technology, and thermal technologies utilizing low-carbon heat sources can achieve carbon footprints comparable to membrane systems. Emerging technologies show promise, with adsorption desorption desalination consuming <1.38 kWh/m³ and achieving 70% carbon emission reductions when coupled with renewable energy, though scalability barriers including high capital costs, renewable energy intermittency, and technological immaturity currently limit widespread deployment. For maximum climate impact, transitioning existing desalination capacity to renewable energy sources should be prioritized over incremental technology efficiency improvements.

Keywords: Desalination; energy consumption; carbon footprint; reverse osmosis; thermal desalination; renewable energy integration.

Introduction

Growing pressure on freshwater resources has intensified the global reliance on desalination technologies as a strategic solution for water supply, particularly in arid and coastal regions. However, this technological pathway remains intrinsically energy-intensive, raising concerns about its environmental sustainability in the context of climate change. The relationship between energy consumption and carbon emissions in desalination systems is not straightforward, as it depends not only on process design but also on the carbon intensity of the energy source. Consequently, evaluating desalination technologies requires an integrated perspective that considers both thermodynamic performance and environmental impact [1-3]. As shown in Figure 1, globa lGHG emissions in 2016 were described by the source.

Over the past decade, significant advances have been achieved in both membrane-based and thermal desalination processes. Reverse osmosis has emerged as the dominant technology due to its comparatively low specific energy consumption, while thermal methods such as multi-stage flash and multi-effect distillation remain widely deployed, particularly in regions with access to low-cost thermal energy. At the same time, emerging technologies and hybrid systems are being explored to further reduce energy demand and emissions. Despite these developments, reported performance metrics vary widely across studies, reflecting differences in operational conditions, system boundaries, and methodological approaches [5].

An additional layer of complexity arises from the increasing integration of renewable energy into desalination systems. While such integration offers substantial potential for emission reduction, it introduces new challenges related to intermittency, system design, and economic feasibility. As a result, the relative importance of technology choice versus energy source remains an open question requiring careful examination [8-9].

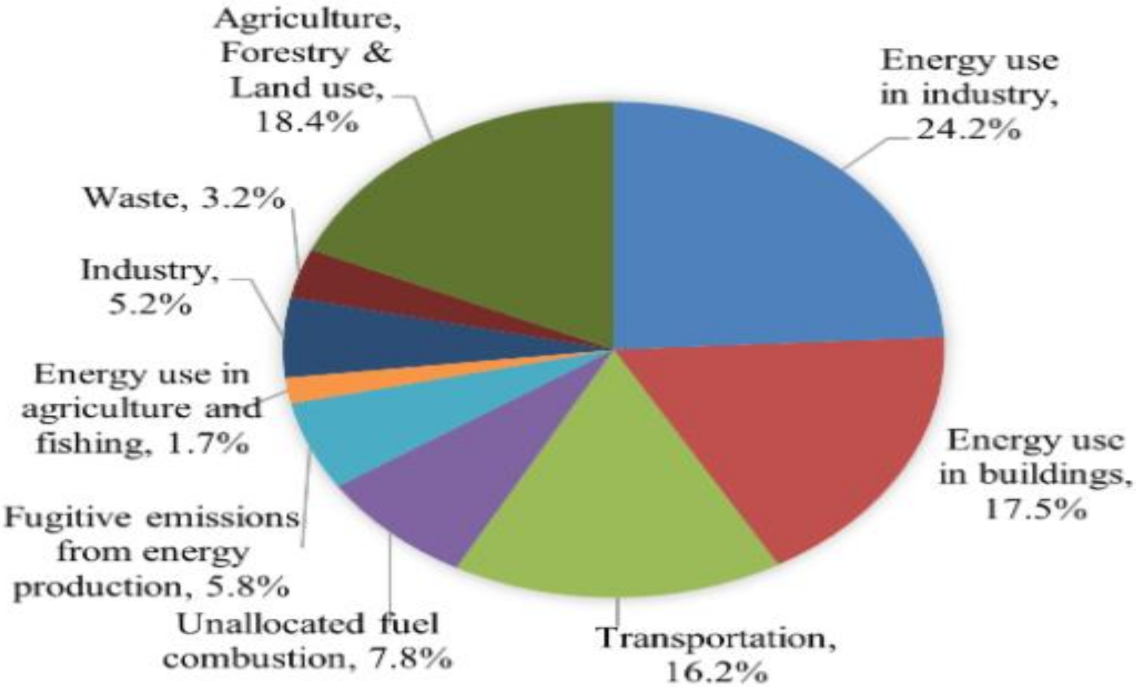

Figure 1 - Global greenhouse gas emissions by sector in 2016 [11]

This study synthesizes recent literature on the energy consumption and carbon footprint of modern desalination technologies, with a focus on identifying consistent patterns, sources of variability, and key drivers of environmental performance. Particular attention is given to the interplay between process efficiency and energy sourcing, as well as to the implications for future development of low-carbon desalination systems.

2. Materials and methods. The literature search was conducted using the query "Energy and Carbon Footprint of Modern Desalination Technologies," which yielded fifty records. All retrieved studies were subjected to an initial relevance assessment based on their abstracts. Selection decisions were not made through rigid filtering steps but rather through an integrated evaluation of each study's contribution to the research question, with particular attention to whether the work provided quantitative evidence on energy consumption or carbon emissions associated with desalination processes. Preference was given to studies addressing technologies developed or implemented in the contemporary period, broadly interpreted as post-2010, and focusing on widely deployed or emerging desalination approaches such as reverse osmosis, thermal distillation variants, electrodialysis, and hybrid or novel systems. Only full research articles presenting empirical, modeled, or systematically synthesized evidence were retained, while works lacking explicit energy or carbon metrics, or focusing primarily on unrelated operational aspects, were excluded.

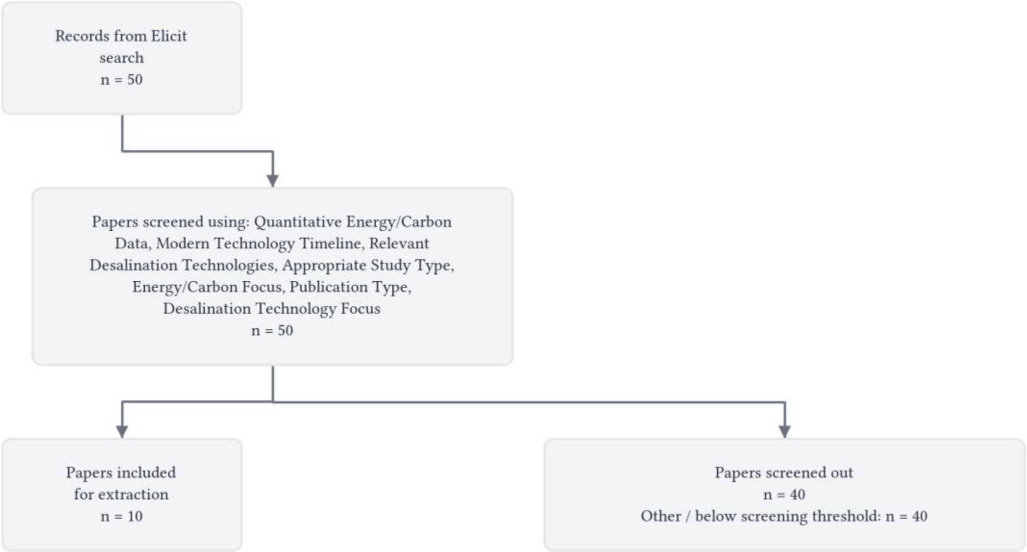

Figure 2 - Paper search and Screening methods

Following this stage, forty studies were deemed insufficiently aligned with the scope and were excluded, leaving a core set of publications for detailed analysis. Rather than treating exclusion criteria as discrete categories, decisions reflected the extent to which each study meaningfully contributed to understanding the energy and carbon implications of desalination technologies.

The analytical phase focused on extracting and synthesizing information across several interrelated dimensions. Technologies were characterized not only by their primary classification but also by specific configurations, hybridizations, and operational scales where such distinctions influenced performance. Reported energy consumption was examined in terms of specific energy demand, variability across operating conditions, and the form of energy input, with attention to both electrical and thermal requirements. Where available, efficiency indicators grounded in thermodynamic or exergy-based frameworks were considered to enable more nuanced comparisons.

Carbon footprint data were interpreted with similar care, taking into account differences in system boundaries, emission scopes, and methodological approaches. Reported values were contextualized within their respective assessment frameworks, distinguishing between direct operational emissions and broader lifecycle impacts where possible. Comparative insights were derived cautiously, recognizing that differences in assumptions, regional energy mixes, and plant configurations can significantly influence reported outcomes.

Operational context emerged as a critical factor shaping both energy use and emissions. Variations in feedwater salinity, plant capacity, geographic setting, and energy sourcing were consistently found to influence performance metrics. In particular, the carbon intensity of the energy supply proved to be a dominant determinant of overall environmental impact, often outweighing differences attributable to technology choice alone.

The integration of renewable energy into desalination systems was examined as a distinct but closely related dimension. Studies addressing solar, wind, or other renewable-driven configurations were evaluated in terms of their potential to reduce both energy intensity and carbon emissions, as well as the practical constraints associated with intermittency, system design, and economic feasibility. While such integrations generally demonstrated clear emission reduction potential, their performance remained highly context-dependent.

Methodological heterogeneity across the literature required careful interpretation. Data sources ranged from full-scale operational plants to pilot studies and simulation-based analyses, each with inherent limitations. Differences in calculation methods, functional units, and system boundaries were explicitly considered when comparing results, and conclusions were drawn with an awareness of these underlying uncertainties.

Across the selected studies, a consistent pattern emerges: membrane-based desalination, particularly reverse osmosis, tends to exhibit lower specific energy consumption and associated carbon emissions compared to thermal processes under comparable conditions, although this advantage can be moderated by factors such as feedwater characteristics and energy source. Thermal technologies, while generally more energy-intensive, may offer advantages in specific contexts, especially when coupled with waste heat or integrated energy systems. Emerging and hybrid technologies show potential for performance improvements, but their large-scale applicability remains less well established.

Overall, the literature indicates that reducing the environmental footprint of desalination is less a question of a single optimal technology and more a function of system integration, energy sourcing, and operational context. Future progress is likely to depend on advances in energy efficiency, broader deployment of low-carbon energy, and improved standardization in the assessment of energy and carbon metrics, which would enable more robust cross-study comparisons.

3. Results. The included studies span from 2010 to 2025, with six providing full-text data and four limited to abstract-only information. Studies evaluated a diverse range of desalination technologies across multiple geographic contexts, with primary focuses on energy consumption, carbon emissions, and renewable energy integration. The most commonly evaluated technologies were reverse osmosis (RO), multi-stage flash (MSF), and multi-effect distillation (MED), appearing in seven, six, and six studies respectively [1–6, 9]. Emerging technologies such as forward osmosis (FO), membrane distillation (MD), and adsorption desorption desalination (ADD) were evaluated in three to four studies each [1, 4, 5, 9].

Table 1- Characteristics of Included Studies

Study	Technologies evaluated	Primary focus	Geographic context
Argyris Panagopoulos, 2025	RO, FO, OE, BCr, MD, OARO, CDI, MCDI [1]	Energy and carbon footprint of thermal and membrane technologies with RES integration [1]	Europe (Spain, Greece) [1]
Yongqing Wang et al., 2024	RO, MSF, MED, ED, MVC, MD, HDH [6]	Carbon footprint review of seawater desalination [6]	Not specified
Na Xue et al., 2023	ED [7]	Carbon footprint and carbon neutrality potential of ED [7]	China [7]
Othman Alnajdi et al., 2020	RO, MSF, MED, ADD, HDH, FO, MD [4]	Decentralized desalination with renewable energy [4]	Saudi Arabia [4]
M. Antonyan, 2019	RO, MSF, MED [2]	Energy footprint comparison of desalination methods [2]	Saudi Arabia (case study) [2]

Study	**Technologies evaluated**	**Primary focus**	**Geographic context**
P. Cornejo et al., 2014	RO (seawater and brackish water) [8]	Carbon footprint of water reuse and desalination [8]	Florida, USA [8]
Huyen Trang Do Thi & A. Tóth, 2023	RO, MSF, MED [3]	Life cycle carbon footprint with fossil and renewable energy [3]	Global [3]
Guoyu Zhang & Xiaodong Wang, 2024	RO, FO, ED, MD, CDI, MSF, HDH, MED, FD, AD [9]	Sustainable energy-driven desalination systems [9]	Middle East, North Africa, East Asia, North America, Western Europe [9]
R. Kempton et al., 2010	MSF, RO, MD [5]	Thermodynamic efficiency and GHG emissions [5]	Not specified
Yuanyuan Li et al., 2021	Thermal-based desalination (technologies not specified) [10]	Renewable energy and waste heat utilization [10]	Not specified

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Table 2 - Energy Consumption by Technology Type

Technology	**Energy consumption range (kWh/m³)**	**Energy type**	**Study sources**
Brackish water RO	1.9 [2]	Electrical	Antonyan, 2019
Seawater RO	2–6 [1], 3.29 [5], 4.3–4.4 [2], 4.5 [4], 5–9 [3]	Electrical	Multiple studies
Forward osmosis (FO)	0.8–13 [1]	Electrical	Panagopoulos, 2025
Osmotically assisted RO (OARO)	6–19 [1]	Electrical	Panagopoulos, 2025
Capacitive deionization (CDI)	1–8 [1]	Electrical	Panagopoulos, 2025
Membrane distillation (MD)	5.9 [5]	Electrical/thermal	Kempton et al., 2010
Multi-effect distillation (MED)	7.7–21 [1], 8.6 [4], 11.9 [2]	Thermal	Multiple studies

Technology	**Energy consumption range (kWh/m³)**	**Energy type**	**Study sources**
Multi-stage flash (MSF)	12.5–24 [1], 14 [4], 16.7 [5], 17.1 [2]	Thermal	Multiple studies
Osmotic evaporation (OE)	80–100 [1]	Thermal	Panagopoulos, 2025
Brine crystallizers (BCr)	52–70 [1]	Thermal	Panagopoulos, 2025
Adsorption desorption desalination (ADD)	<1.38 [4]	Thermal (low-grade/renewable)	Alnajdi et al., 2020

Membrane-based technologies demonstrated substantially lower energy consumption compared to thermal technologies shown in table 2. Seawater RO consistently emerged as the most energy-efficient commercially deployed technology, with energy consumption ranging from 2–6 kWh/m³ [1–3, 5]. Brackish water RO showed even lower consumption at 1.9 kWh/m³ [2], reflecting the reduced energy required to overcome lower osmotic pressures. Among thermal technologies, MED demonstrated better energy performance (7.7–21 kWh/m³) [1, 2, 4] than MSF (12.5–24 kWh/m³) [1, 2, 4, 5]. The highest energy consumption was observed in zero liquid discharge (ZLD) technologies: osmotic evaporation required 80–100 kWh/m³ [1] and brine crystallizers consumed 52–70 kWh/m³ [1], reflecting the intensive energy demands of complete water recovery.

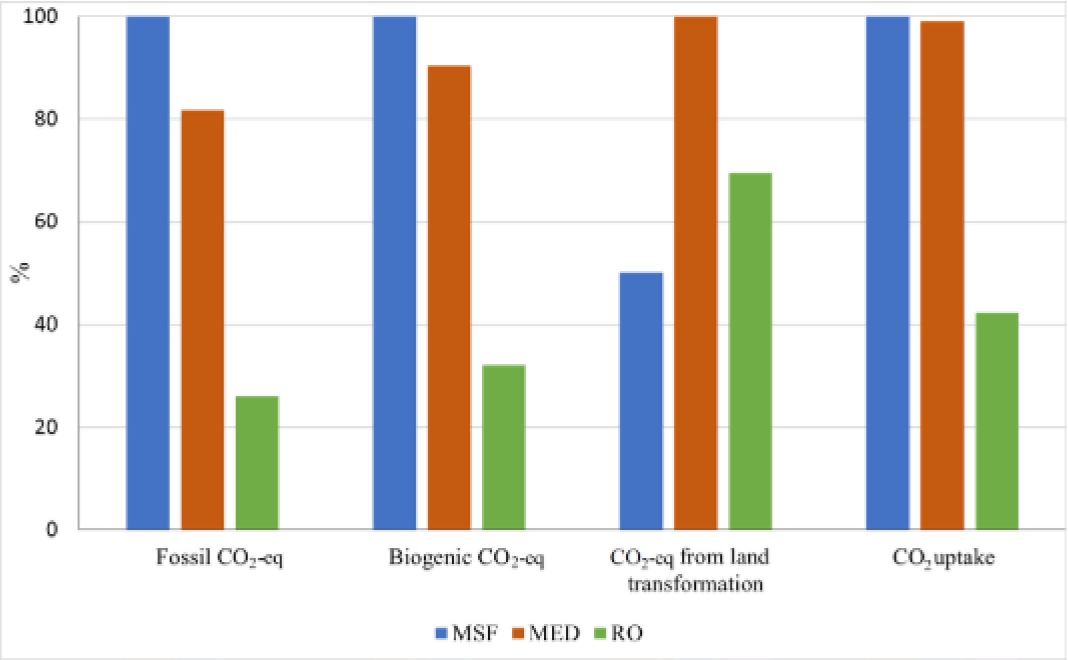

Figure 3 - The percentage of carbon emissions between three desalination technologies [3]

Emerging technologies showed variable performance. Adsorption desorption desalination (ADD) demonstrated remarkably low energy consumption (<1.38 kWh/m³) [4] when coupled with renewable or waste heat sources, representing a 69% reduction compared to conventional SWRO (4.5 kWh/m³) [4]. Forward osmosis exhibited a wide consumption range (0.8–13 kWh/m³) [1], likely reflecting variations in draw solution regeneration requirements. Membrane distillation consumed 5.9 kWh/m³ [5], positioning it between RO and thermal technologies. A detailed breakdownof each type of carbon emission is divided into percentages in Fig. 3

Table 3. Thermodynamic Efficiency

Technology	**Exergy efficiency**	**Power consumption (kWh/m³)**	**Study**
Reverse osmosis	30.1% [5]	3.29 [5]	Kempton et al., 2010
Membrane distillation	14.27% [5]	5.9 [5]	Kempton et al., 2010
Multi-stage flash	7.73% [5]	16.7 [5]	Kempton et al., 2010

RO demonstrated the highest exergy efficiency at 30.1% [5], nearly four times that of MSF (7.73%) [5] and more than double that of MD (14.27%) [5]. This efficiency advantage directly translated to power consumption differences, with RO requiring 3.29 kWh/m³ [5] compared to MD's 5.9 kWh/m³ [5] and MSF's 16.7 kWh/m³ [5]. The low exergy efficiency of MSF indicates substantial energy losses in the thermal distillation process, primarily through heat transfer inefficiencies and the need to maintain temperature gradients across multiple stages shown in table 3.

Table 4. Carbon Emissions by Technology and Energy Source

Technology	**Carbon footprint (kg CO_2/m^3)**	**Energy source**	**Study sources**
Coal-powered systems			
Seawater RO	1.8–11.7 [1]	Coal	Panagopoulos, 2025
Forward osmosis	1.8–11.7 [1]	Coal	Panagopoulos, 2025
Osmotic evaporation	72–100 [1]	Coal	Panagopoulos, 2025
Brine crystallizers	46.8–70 [1]	Coal	Panagopoulos, 2025
Grid electricity			
Seawater RO	0.4–6.7 [8], 2.562 [3]	Grid	Cornejo et al., 2014; Do Thi & Tóth, 2023
Brackish water RO	0.4–2.5 [8]	Grid	Cornejo et al., 2014
Multi-stage flash	2.988 [3]	Grid	Do Thi & Tóth, 2023
Multi-effect distillation	1.280 [3]	Grid	Do Thi & Tóth, 2023
Membrane distillation	5.22 [5]	Grid	Kempton et al., 2010
Electrodialysis	59.74 kg CO_2-eq/metric ton salt removed [7]	Grid	Xue et al., 2023
Renewable energy			
Seawater RO	0.1–0.3 [1]	Renewable	Panagopoulos, 2025
Water reuse systems	0.1–2.4 [8]	Mixed	Cornejo et al., 2014

As shown in table 4 the carbon footprint of desalination technologies varied dramatically based on both the technology type and energy source. For fossil fuel-powered systems, thermal ZLD technologies exhibited the highest emissions, with osmotic evaporation generating 72–100 kg CO_2/m^3 [1] and brine crystallizers producing 46.8–70 kg CO_2/m^3 [1] under coal power. In contrast, membrane-based technologies powered by coal showed substantially lower emissions, with RO and FO both producing 1.8–11.7 kg CO_2/m^3 [1].

Among grid-powered systems, RO consistently demonstrated lower carbon footprints. Seawater RO emissions ranged from 0.4–6.7 kg CO_2/m^3 [8], with brackish water RO showing even lower values (0.4–2.5 kg CO_2/m^3) [8] due to reduced energy requirements. Thermal technologies showed variable performance: MED produced 1.280 kg CO_2/m^3 [3], which was lower than both MSF (2.988 kg CO_2/m^3) [3] and RO (2.562 kg CO_2/m^3) [3] in one study, though this likely reflected differences in grid carbon intensity. RO emitted CO_2 approximately 3–4 times lower than MED and MSF in comparative analyses [3].

The most dramatic emissions reductions occurred with renewable energy integration. Renewable-powered RO achieved carbon footprints of just 0.1–0.3 kg CO_2/m^3 [1], representing a 90–95% reduction compared to coal-powered systems [1, 1]. Water reuse systems achieved comparable low emissions (0.1–2.4 kg CO_2/m^3) [8]. For electrodialysis, power grid decarbonization and improved waste recycling in China were projected to reduce the carbon footprint by up to 92% [7], with power consumption identified as the main hotspot of GHG emissions [7].

Lifecycle Emission Analysis

The scope of carbon footprint assessments varied across studies. Some focused primarily on operational emissions from energy consumption [6, 7], while others incorporated broader lifecycle stages including construction and material production [3]. Direct and indirect emissions were considered in lifecycle assessments [3, 8], with operational energy consumption identified as the dominant contributor to total carbon footprint [6]. For electrodialysis, power consumption during operation accounted for 95.83% of total emissions for organic solvent desalination, though this contribution was projected to decrease to 77.84% with grid decarbonization [7].

Table 5. Emission Reductions from Renewable Sources

Energy source	**Technology**	**Emission reduction**	**Study**
Renewable energy (general)	RO, thermal	90–95% [1]	Panagopoulos, 2025
Power grid decarbonization	Electrodialysis	Up to 92% [7]	Xue et al., 2023
Decentralized ADD + renewables	ADD	~70% savings [4]	Alnajdi et al., 2020
Wind + MSF	MSF	Emissions reduced from 18.19 to 0.04 times tap water [3]	Do Thi & Tóth, 2023

As shown in table 5 renewable energy integration achieved substantial carbon emission reductions across all desalination technologies. The transition from conventional to renewable energy sources reduced emissions by 90–95% [1], with renewable-powered RO achieving carbon footprints as low as 0.1–0.3 kg CO_2/m^3 [1] compared to 1.8–11.7 kg CO_2/m^3 [1] for coal-powered systems. Power grid decarbonization showed similar potential, with projections of up to 92% carbon footprint reduction for electrodialysis in China [7]. Decentralized ADD technology coupled with renewable energy reduced specific energy consumption from 4 kWh/m³ to less than 1.38 kWh/m³ [4], achieving approximately 70% carbon emission savings [4].

Wind energy integration demonstrated particularly strong performance with thermal technologies. MSF combined with wind energy reduced emissions from 18.19 to 0.04 times that of tap water production [3], representing a nearly 450-fold improvement. Solar energy emerged as the most cost-effective and widely used sustainable technology for desalination [9], while geothermal and tidal energy were also evaluated as potential renewable sources [9].

4. Discussion

4.1 Challenges and Barriers

Despite demonstrated emission reductions, renewable energy integration faced several significant barriers. High capital costs for renewable energy infrastructure represented a primary obstacle [1, 3], with investment requirements substantially exceeding those for conventional systems. Intermittency of renewable sources (solar, wind) created operational challenges requiring energy storage solutions [1], though specific storage technologies and costs were not detailed in most studies. Technological immaturity affected energy-demanding processes [1], particularly for emerging desalination technologies.

Renewable-powered desalination plants exhibited lower efficiency and higher costs than traditional fossil fuel-based systems [9], though they offered superior environmental protection and long-term sustainability. Small capacity limitations made renewable-powered plants non-competitive with conventionally powered facilities [2], with energy consumption ranging widely from 1.5 to 21.1 kWh/m³ [2]. Seasonal availability of renewable energy sources created additional operational constraints [3], requiring either hybrid configurations or oversized renewable installations to ensure continuous operation.

4.2 Hybrid and Integrated Systems

Hybrid renewable energy configurations emerged as a strategy to address intermittency and cost challenges. Combining renewable energy sources (RES) with conventional power sources helped mitigate intermittency issues [1], while hybrid systems combining solar and wind energy showed potential for improved efficiency and reduced costs [9]. Multi-sustainable energy sources demonstrated better performance than single renewable sources, though efficiency remained lower and costs higher than fossil fuel-based systems [9, 9]. Integrated energy utilization systems and energy internet systems represented recent developments in using multiple energy resources for desalination [10].

4.3 Operational and Contextual Factors

Water Type and Salinity

Water source significantly influenced both energy consumption and carbon footprint. Brackish water RO consumed substantially less energy (1.9 kWh/m³) [2] than seawater RO (4.3–4.4 kWh/m³) [2], reflecting the lower osmotic pressure of brackish water. This energy difference translated directly to carbon emissions, with brackish water RO producing 0.4–2.5 kg CO_2/m³ [8] compared to seawater RO's 0.4–6.7 kg CO_2/m³ [8]. Higher total dissolved solids (TDS) levels necessitated more extensive pretreatment and higher operating pressures, increasing both energy consumption and carbon footprint [8].

For electrodialysis, seawater desalination exhibited a carbon footprint one order of magnitude lower than high-salinity wastewater treatment and organic solvent desalination [7], at 59.74 kg CO_2-eq per metric ton of salt removed [7]. This counterintuitive finding suggested that the specific application context and salt concentration significantly affected ED performance metrics.

4.4 Geographic and Scale Variations

Studies examined desalination across diverse geographic contexts, including Saudi Arabia [2, 4], China [7], the Middle East and North Africa [9], and North America [8, 9]. Geographic location influenced carbon footprint through differences in electricity grid carbon intensity, availability of renewable resources (solar irradiance, wind speeds), and local water quality parameters.

Scale effects on energy and carbon performance received limited attention in most studies, though industrial-scale ED processes were specifically evaluated [7]. Small-scale desalination (SSD) systems were noted to have lower cost and energy consumption compared to larger-scale systems [9], though this finding appeared to focus on capital costs rather than specific energy consumption per unit volume. Large-scale operational facilities for MSF and RO were contrasted with experimental-scale MD processes [5], suggesting maturity differences influenced reported performance metrics.

4.5 Energy Performance Patterns

The consistent superiority of membrane-based technologies in energy efficiency emerges clearly across studies, but the magnitude of advantage varies substantially by operational context. RO demonstrates energy consumption of 2–6 kWh/m^3 for seawater [1–3] across multiple studies, while thermal technologies consume 7.7–24 kWh/m^3 [1, 2, 4, 5]. However, this 3–10-fold difference reflects optimal conditions for RO with modern energy recovery systems. Studies noting higher RO consumption (5–9 kWh/m^3) [3] likely examined older facilities or systems without advanced energy recovery, while lower values (2–6 kWh/m^3) [1] represent state-of-the-art installations.

The wide range reported for forward osmosis (0.8–13 kWh/m^3) [1] illustrates technology maturity effects. The lower bound approaches theoretical minimum energy requirements, suggesting laboratory optimization, while the upper bound reflects draw solution regeneration inefficiencies in less-developed configurations. Similarly, renewable-powered desalination's broad consumption range (1.5–21.1 kWh/m^3) [2] spans efficient solar-RO systems at the low end and less-optimized thermal systems at the high end, compounded by intermittency-related inefficiencies.

Thermal technologies show consistent performance across studies (MSF: 12.5–24 kWh/m^3; MED: 7.7–21 kWh/m^3) [1, 2, 4], with the ranges primarily reflecting variations in heat source quality and system design rather than fundamental measurement disagreements. The lower thermal consumption values likely represent waste heat utilization or cogeneration scenarios, while higher values indicate standalone facilities requiring dedicated heat generation.

4.6 Carbon Footprint Heterogeneity

Grid electricity carbon intensity emerges as the dominant driver of carbon footprint variation across studies. The same RO technology produces 0.4–6.7 kg CO_2/m^3 [8] depending on electricity source, with coal grids yielding 1.8–11.7 kg CO_2/m^3 [1] and renewable sources achieving 0.1–0.3 kg CO_2/m^3 [1]. This 20–60-fold range dwarfs technology choice effects within the same energy context [11].

Apparent contradictions in thermal versus membrane carbon performance resolve when accounting for energy source. MED showing lower emissions (1.280 kg CO_2/m^3) [3] than RO (2.562 kg CO_2/m^3) [3] in one study likely reflects waste heat utilization or low-carbon thermal energy, while other studies showing MSF at 2.988 kg CO_2/m^3 [3] represent grid-heated or fossil fuel systems. The "low-carbon heat driven MSF, MED and MD" [6] referenced by Wang et al. specifically denote systems using renewable thermal energy or waste heat, explaining their carbon advantage over grid-electric RO in high-carbon grids.

Lifecycle boundary definitions create additional heterogeneity. Studies including construction, materials, and disposal phases [3] necessarily report higher absolute values than those focusing solely on operational emissions [6, 7], but this methodological difference doesn't invalidate either approach. For electrodialysis, operational power consumption comprised 95.83% of total lifecycle emissions [7], indicating that operational-only assessments capture the dominant emission source while understating total impact by approximately 5% [12].

4.7 Technology Selection Implications

For coastal regions with access to renewable electricity (solar, wind), membrane-based RO emerges as the optimal choice, combining low energy consumption (2–6 kWh/m^3) [1] with minimal carbon emissions (0.1–0.3 kg CO$_2$/m^3) [1] when renewable-powered. This recommendation holds across multiple studies [1, 3, 5] and represents the most robust finding in the literature [13].

For regions with abundant low-grade waste heat or concentrated solar thermal resources, thermal technologies (MED or MSF) become competitive. Their higher theoretical energy consumption (7.7–24 kWh/m^3) [1, 4] matters less when utilizing otherwise-wasted thermal energy, and their carbon footprint drops to levels comparable with RO when heat sources are low-carbon [3]. This context-dependent advantage explains why thermal technologies maintain 40% global market share despite inherent thermodynamic inefficiencies [14].

Emerging decentralized ADD technology shows exceptional promise for small-scale, renewable-powered applications, achieving <1.38 kWh/m^3 [4] with 70% carbon emission reductions [4]. However, scalability challenges and technological immaturity [1] currently limit deployment to pilot scale [4]. Forward osmosis similarly demonstrates theoretical advantages (0.8–13 kWh/m^3) [1] but faces draw solution regeneration challenges that must be resolved before commercial viability.

4.8 Research and Development Priorities

The 90–95% emission reduction achievable through renewable energy integration [1] indicates that energy source decarbonization should be prioritized over incremental technology efficiency improvements for maximum climate impact. A coal-powered RO plant (1.8–11.7 kg CO$_2$/m^3) [1] produces more emissions than a renewable-powered thermal plant, reversing the technology-based hierarchy.

Energy storage solutions represent the critical bottleneck for renewable desalination scaling [1, 3]. Current renewable systems suffer from intermittency-related inefficiencies reflected in the wide consumption range (1.5–21.1 kWh/m^3) [2], and high capital costs [1, 3] prevent competitive deployment at scale. Advances in low-cost thermal or electrochemical storage could eliminate these barriers [15].

For membrane technologies, continued focus on energy recovery system optimization offers diminishing returns given already high exergy efficiencies (30.1% for RO) [5]. Greater impact would come from membrane materials enabling operation at lower pressures or improving fouling resistance to reduce pretreatment energy. For thermal technologies, integration with industrial waste heat sources or concentrated solar thermal systems addresses their fundamental energy intensity without requiring technological breakthroughs.

Process optimization tailored to specific applications shows significant potential. The non-linear relationship between process variables and carbon footprint identified for electrodialysis [7] suggests that context-specific optimization could reduce emissions beyond source-switching alone. Similarly, the order-of-magnitude variation in ED carbon footprint across applications (seawater versus high-salinity wastewater) [7] indicates that technology-application matching deserves greater research attention than generic performance improvements [16].

Conclusion.

The analysis indicates that membrane-based desalination, particularly reverse osmosis, consistently demonstrates lower specific energy consumption compared to thermal processes under comparable operating conditions. This advantage is reflected in higher exergy efficiency and reduced operational energy demand. However, the findings also show that technology choice alone does not determine environmental performance. The carbon footprint of desalination is strongly governed by the energy source, with variations in electricity carbon intensity producing order-of-magnitude differences in emissions for the same process.

The integration of renewable energy emerges as the most effective pathway for reducing the environmental impact of desalination. Transitioning from fossil-based to low-carbon energy sources can achieve emission reductions on the order of 90% or more, often outweighing gains from incremental improvements in process efficiency. At the same time, renewable-powered systems remain constrained by economic and technical challenges, including high capital costs and variability in energy supply.

Thermal desalination technologies, despite their higher intrinsic energy demand, can achieve competitive carbon performance when coupled with low-carbon or waste heat sources, highlighting the importance of system-level optimization. Emerging technologies such as adsorption-based desalination demonstrate promising energy performance but remain limited by scalability and technological maturity.

Overall, the evidence suggests that the future of sustainable desalination will depend less on identifying a single superior technology and more on optimizing the interaction between process design, energy sourcing, and operational context. Advancing toward low-carbon desalination systems will require coordinated progress in renewable energy deployment, energy storage solutions, and standardized methodologies for assessing energy and carbon performance across technologies.

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ЭНЕРГЕТИЧЕСКИЙ И УГЛЕРОДНЫЙ СЛЕД СОВРЕМЕННЫХ ТЕХНОЛОГИЙ ОПРЕСНЕНИЯ ВОДЫ

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Аннотация. Мембранные технологии опреснения демонстрируют существенно более низкое энергопотребление по сравнению с термическими технологиями: для опреснения морской воды методом обратного осмоса требуется 2–6 кВт·ч/м^3, тогда как для многоэффектной дистилляции и многоступенчатого мгновенного испарения - 7,7–24 кВт·ч/м^3. Обратный осмос характеризуется наивысшей эксергетической эффективностью - 30,1%, что почти в четыре раза выше, чем у MSF (7,73%). Однако источник энергии оказывает доминирующее влияние на углеродный след, часто превосходя по значимости различия между технологиями. При использовании угля обратный осмос приводит к выбросам 1,8–11,7 кг CO_2/м^3, тогда как при использовании возобновляемых источников энергии - всего 0,1–0,3 кг CO_2/м^3, что соответствует снижению выбросов на 90–95%. Углеродоёмкость электроэнергии в сети приводит к вариациям выбросов в 20–60 раз для одной и той же технологии, при этом термические технологии, использующие низкоуглеродные источники тепла, могут достигать углеродного следа, сопоставимого с мембранными системами. Перспективные технологии демонстрируют значительный потенциал: адсорбционно-десорбционное опреснение характеризуется энергопотреблением менее 1,38 кВт·ч/м^3 и обеспечивает снижение выбросов углерода на 70% при интеграции с возобновляемыми источниками энергии, однако масштабирование таких решений в настоящее время ограничено высокими капитальными затратами, прерывистостью возобновляемой генерации и технологической незрелостью. Для достижения максимального климатического эффекта приоритет следует отдавать переходу существующих мощностей опреснения на возобновляемые источники энергии, а не постепенному повышению энергоэффективности технологий.

Ключевые слова: опреснение воды; энергопотребление; углеродный след; обратный осмос; термическое опреснение; интеграция возобновляемых источников энергии.

ЗАМАНАУИ ТҰЩЫЛАНДЫРУ ТЕХНОЛОГИЯЛАРЫНЫҢ ЭНЕРГИЯ ТИІМДІЛІГІ ЖӘНЕ КӨМІРТЕК ІЗІ

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Аннотация. Мембраналық тұщыландыру технологиялары термиялық әдістермен салыстырғанда энергияны едәуір аз тұтынады: теңіз суын кері осмос арқылы тұщыландыруға 2–6 кВт·сағ/м³ қажет, ал көп әсерлі буландыру мен көпсатылы лезде булану процестерінде бұл көрсеткіш 7,7–24 кВт·сағ/м³ аралығында болады. Кері осмос ең жоғары эксергиялық тиімділікке ие — 30,1%, бұл MSF технологиясымен салыстырғанда (7,73%) шамамен төрт есе жоғары. Алайда көміртек ізіне негізгі әсер ететін фактор — энергия көзі, және оның ықпалы көбінесе технология түрінен де басым түседі. Көмірге негізделген энергияны пайдаланғанда кері осмос 1,8–11,7 кг CO_2/м³ шығарындыларын тудырады, ал жаңартылатын энергия көздерін қолданғанда бұл көрсеткіш 0,1–0,3 кг CO_2/м³-ке дейін төмендейді, яғни шығарындылар 90–95% азаяды. Электр желісінің көміртек сыйымдылығы бір технология үшін шығарындылардың 20–60 есе айырмашылығына әкелуі мүмкін, ал төмен көміртекті жылу көздерін пайдаланатын термиялық технологиялар мембраналық жүйелермен салыстырмалы деңгейдегі көміртек ізіне қол жеткізе алады. Болашағы бар жаңа технологиялар да айтарлықтай әлеует көрсетеді: адсорбция-десорбция негізіндегі тұщыландыруда энергия тұтыну 1,38 кВт·сағ/м³-тен төмен болуы мүмкін және жаңартылатын энергиямен біріктірілген жағдайда көміртек шығарындылары шамамен 70% қысқарады. Дегенмен, мұндай технологияларды кең ауқымда енгізу қазіргі уақытта жоғары бастапқы инвестициялық шығындармен, жаңартылатын энергия көздерінің тұрақсыздығымен және технологиялық жетілмегендігімен шектеліп отыр. Климатқа әсерді барынша азайту үшін тұщыландырудың қолданыстағы қуаттарын жаңартылатын энергия көздеріне көшіруді бірінші кезекте қарастырған жөн, ал технологиялардың энергия тиімділігін біртіндеп арттыру екінші кезекте қалуы тиіс.

Түйін сөздер: тұщыландыру; энергия тиімділігі; көміртек ізі; кері осмос; термиялық тұщыландыру; жаңартылатын энергияны интеграциялау.