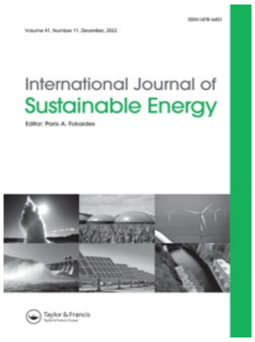

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REVIEW ARTICLE

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Wind-turbine waste heat for desalination: a scoping review and research agenda

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ABSTRACT

Using wind-turbine waste heat for seawater desalination could boost efficiency and water security, but evidence is scarce. A scoping review (2018–2024) found 28 studies; only four quantified integration with thermal desalination. Available heat is low–mid grade (≈100–150 °C) with recoverable power of hundreds of kilowatts. Modeling a 7.58 MW turbine (~231 kW at 140 °C) driving multi-effect distillation yields ≈45 m^3/day (~0.52 L/s), serving ~900 people at 50 $L{\cdot}cap^{-1}{\cdot}day^{-1}$. Simulated nanofluid enhancements show up to 30% gains, without experimental validation. No levelized cost of water estimates or field demonstrations were found. We conclude the concept is technically plausible but remains at the simulation stage. Key barriers include temperature mismatch, moving heat from nacelles, thermal storage, corrosion, and economics. Priorities include robust heat-recovery hardware, TES/heat-pump integration, corrosion control, techno-economic modeling, and pilot trials in wind-rich coasts such as La Guajira.

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KEYWORDS
Wind turbine; waste heat; seawater desalination; MED; HDH; scoping review

1. Introduction

La Guajira, a department in northern Colombia, faces severe water scarcity, contributing to high infant mortality rates (54 deaths per 1,000 live births) (consultorsalud.com 2024). Limited access to potable water, particularly among the Wayuu communities, underscores the urgent need for sustainable solutions. Globally, seawater desalination (SWD) has emerged as a viable option to address freshwater shortages (Ghazi et al. 2022), yet conventional desalination processes are energy-intensive and can have significant environmental impacts if not properly managed (Vicuña 2022).

Wind turbines (WTs) are a key source of renewable energy, reducing greenhouse gas emissions and supporting the transition to a low-carbon economy. Beyond electricity generation, WTs produce waste heat (WH) as a byproduct, which could be harnessed to improve the efficiency and sustainability of SWD systems (Cai et al. 2023). Integrating WH recovery from WTs into desalination processes aligns with multiple Sustainable Development Goals (SDGs): SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation, and Infrastructure), and SDG 13 (Climate Action) (Shatat, Worall, and Riffat 2013; UNESCO, 2020).

Unlike prior works that broadly discuss renewable desalination, this review specifically addresses WT-WH utilization for thermal desalination, synthesizing what is known and identifying research gaps. To clarify the state of the art, Table 1 summarizes the few studies that directly model or analyze WT-WH integration, highlighting desalination type, WH conditions, modeled output, and economic reporting. For example, Khalilzadeh and Hossein Nezhad (2018) modeled MED using ~231 kW of WH at ~140 °C from a 7.58 MW turbine, producing ~45 m^3/day of water under ideal conditions. Rostamzadeh and Rostami (2020) explored nanofluid-based heat recovery, reporting up to 30% efficiency gains in HDH simulations. Other studies propose modular DCMD (Rostamzadeh and Rostami) and hybrid MED–MVC–HDH flowsheets (Rostami et al. 2023), but no field-scale implementations or LCOW estimates exist.

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Table 1. Summary of studies directly addressing WT-WH integration with desalination.

Study	Desalination Process	WH Source & Conditions	Modeled Output	Economic Data	Key Notes
Khalilzadeh and Hossein Nezhad (2018)	MED	~231 kW WH at ~140 °C from 7.58 MW WT	~45 m^3/day	Thermo-economic indicators only	Requires continuous WH; idealized conditions
bbva.com (2024)	HDH	Generator WH; nanofluids (Al_2O_3, Cu/water)	Up to 30% heat-transfer improvement	Not reported	Focus on heat-transfer enhancement
Memon et al. (2022)	DCMD	WT-grade WH (low-mid temperature)	Flux sensitivity to ΔT and module design	Not reported	Modular scalability explored
Rostami et al. (2023)	Hybrid MED–MVC–HDH	WH integration with brine recirculation	Higher recovery; minimal liquid discharge	Not reported	Complex hybrid flowsheet

In La Guajira, the coexistence of a structural water crisis and the accelerated development of wind energy projects creates a unique scenario for integrated energy-water solutions. Eight wind projects under construction add up to more than 1,000 MW of capacity, while Wayuu communities face severe drinking water shortages. This socio-technical convergence justifies exploring technologies that utilize byproducts of wind power generation, such as waste heat, to power desalination processes. Such integration not only optimizes the use of energy resources but also contributes to water resilience and to achieving the Sustainable Development Goals (SDGs) in vulnerable territories.

This review focuses on the potential of using WH from wind turbines—not from desalination systems—to drive seawater desalination. Given the limited literature on this topic, the study adopts a scoping approach to map existing evidence, identify technical and economic barriers, and outline future research needs. The motivation stems from ongoing wind farm projects in La Guajira, which offer an opportunity to integrate renewable energy and water solutions in one of Colombia's most vulnerable regions (Moher 2009; projects.roldanlogistics 2024).

Key challenges include optimizing energy recovery, reducing capital and operational costs, ensuring environmentally responsible brine management, and adapting technologies to local conditions. Addressing these issues is essential to advance research and enable practical implementation of innovative desalination solutions that contribute to sustainable development globally.

This work does not propose a paradigm shift in large-scale desalination, but rather a decentralized, niche application geared toward isolated communities where integrating waste heat from wind turbines can improve water resilience.

2. Scoping review methods

This study adopts a scoping review approach following the methodological framework proposed by Arksey and O'Malley (2005), complemented by the PRISMA-ScR guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews) to ensure transparency and rigor.

The objective of this review is to map the existing evidence on the integration of wind turbine waste heat (WT-WH) into seawater desalination (SWD) processes, identify technical and economic gaps, and outline a research agenda.

2.1. Databases and search strategy

We conducted structured searches in ScienceDirect (Elsevier) and Scopus, for the period 2018–2024, considering only peer-reviewed articles in English. Search strings combined keywords such as shown in Table 2.

The search equations used were the following:

Scopus

TITLE-ABS-KEY ('waste heat' AND 'wind turbine' AND desalination OR 'thermal desalination' OR 'MED' OR 'HDH' OR 'membrane distillation') AND PUBYEAR > 2018 AND PUBYEAR < 2024 AND (LIMIT-TO (LANGUAGE, 'English')) AND (LIMIT-TO (DOCTYPE, 'ar')).

Table 2. Key Boundaries of the Literature Review.

Items to Consider	Description
Database:	Science Direct (Elsevier)—Scopus
Research Topics:	Waste heat; Heat recovery; Desalination; Thermal desalination processes; Wind turbines.
Keywords:	Waste heat, Wind turbine, Desalination, Renewable energy.
Year:	From 2018 to 2024.
Language:	For the analysis, scientific articles published in English were considered.
Type of Articles:	Scientific articles.

ScienceDirect

'waste heat' AND 'wind turbine' AND (desalination OR 'thermal desalination' OR MED OR HDH OR 'membrane distillation') AND YEAR > 2018 AND YEAR < 2024.

Inclusion Criteria

- Studies addressing **waste heat recovery from wind turbines** for desalination or closely related thermal desalination processes.
- Articles providing **quantitative or qualitative analysis** of integration feasibility, performance, or economics.
- Peer-reviewed journal articles.

Exclusion Criteria

- Studies focused solely on electrical coupling (e.g. wind-to-RO without WH integration).
- Non-scholarly sources unless they provide unique technical data.
- Publications outside the defined time frame.

Screening and Selection

From 3,045 initial records, duplicates and irrelevant titles were removed. After abstract and full-text screening, 28 articles were retained for qualitative synthesis. Of these, 4 studies directly analyzed WT-WH integration with thermal desalination processes (e.g. MED, HDH, DCMD). The selection process is illustrated in Figure 2, now captioned as 'Scoping search and selection process'.

Data Extraction and Charting

For each included study, we extracted:

- Desalination process type (MED, MSF, HDH, MD, etc.).
- WH source characteristics (temperature, power level).
- Modeled or experimental water output.
- Reported efficiency gains or economic indicators.
- Identified technical and operational constraints.

Limitations

This review does not perform meta-analysis due to the scarcity and heterogeneity of data. Instead, it synthesizes available evidence and highlights gaps for future research. Further details are provided in Figure 1.

Table 3 summarizes the risk-of-bias and quality indicators for the four studies that directly address WT-WH integration with desalination. It uses a traffic-light style to assess key dimensions: study type (experimental vs. simulation), WH data quality (measured vs. assumed), presence of economic analysis (LCOW or TEA), and temporal resolution (steady-state vs. time-series). All studies scored high concern for economic and temporal aspects because none reported LCOW or used high-resolution time-series modeling. This table highlights that current evidence is based on simulation with assumed WH data, reinforcing the need for empirical measurements and comprehensive techno-economic evaluations in future research.

We applied a traffic-light appraisal with explicit criteria:

Study type: Green = experimental data; Yellow = validated simulation; Red = conceptual or unvalidated model.

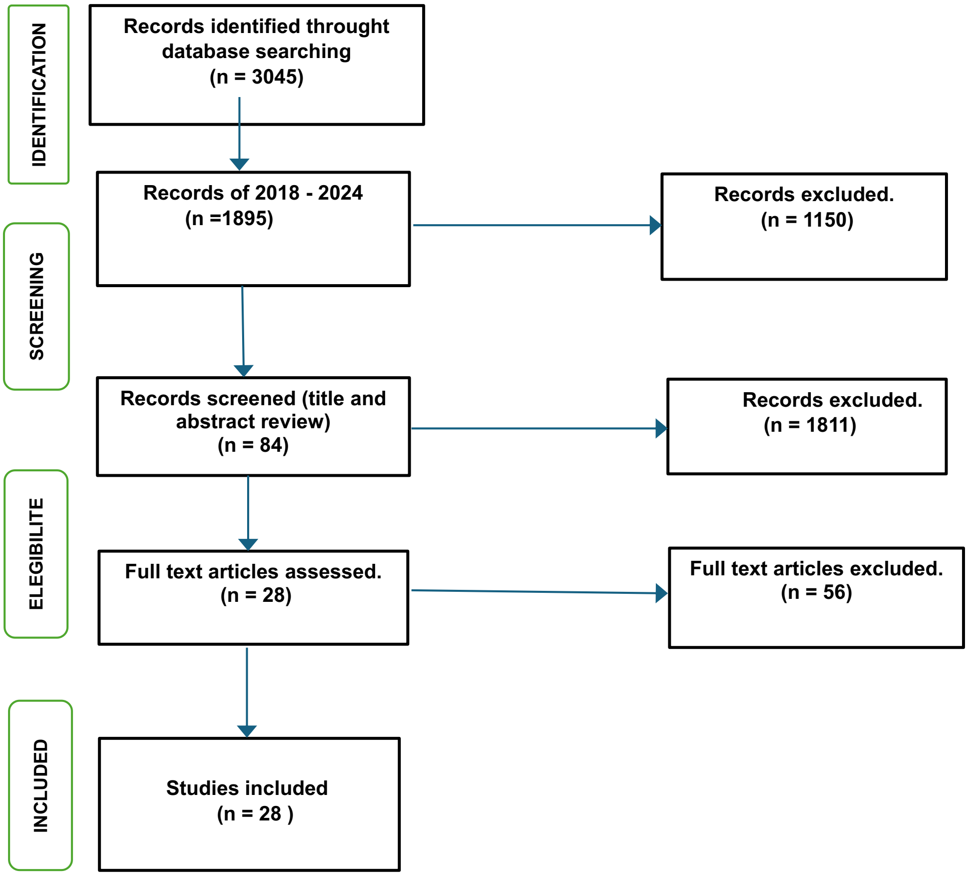

Figure 1. Scoping search and selection process.

Table 3. Risk-of-bias/Quality Indicators.

Study	Type (Exp/Sim)	WH data quality	Economics (LCOW/TEA)	Temporal resolution	Overall
Khalilzadeh and Hossein Nezhad (2018)	Sim	Assumed (Moderate)	Absent (High concern)	Steady-state (High concern)	High concern
Rostamzadeh and Rostami	Sim	Assumed (Moderate)	Absent (High concern)	Parametric steady (High concern)	High concern
Memon et al. (2022)	Sim	Assumed (Moderate)	Absent (High concern)	Parametric steady (High concern)	High concern
Rostami et al. (2023)	Sim	Assumed (Moderate)	Absent (High concern)	Parametric steady (High concern)	High concern

WH data quality: Green = measured values; Yellow = partially assumed or estimated; Red = fully assumed without validation.

Economic analysis: Green = includes LCOW or TEA; Yellow = partial cost indicators; Red = absent.

Temporal resolution: Green = dynamic/time-series; Yellow = parametric steady-state; Red = single-point steady-state.

Complementary bibliometric analysis

In addition to the qualitative analysis, a bibliometric analysis was incorporated to map the field structure and visualize term co-occurrences and co-authorship networks from the study's reference set. Forty-five records with title/author pairs retrieved from the manuscript's reference list were processed (see CSV files of nodes/links, compatible with VOSviewer). Complete counting and basic term normalization (lowercase, removal of punctuation, and stopwords) were applied. For the keyword network, a co-occurrence matrix was constructed for each document; for the co-authorship network, authors appearing together in the

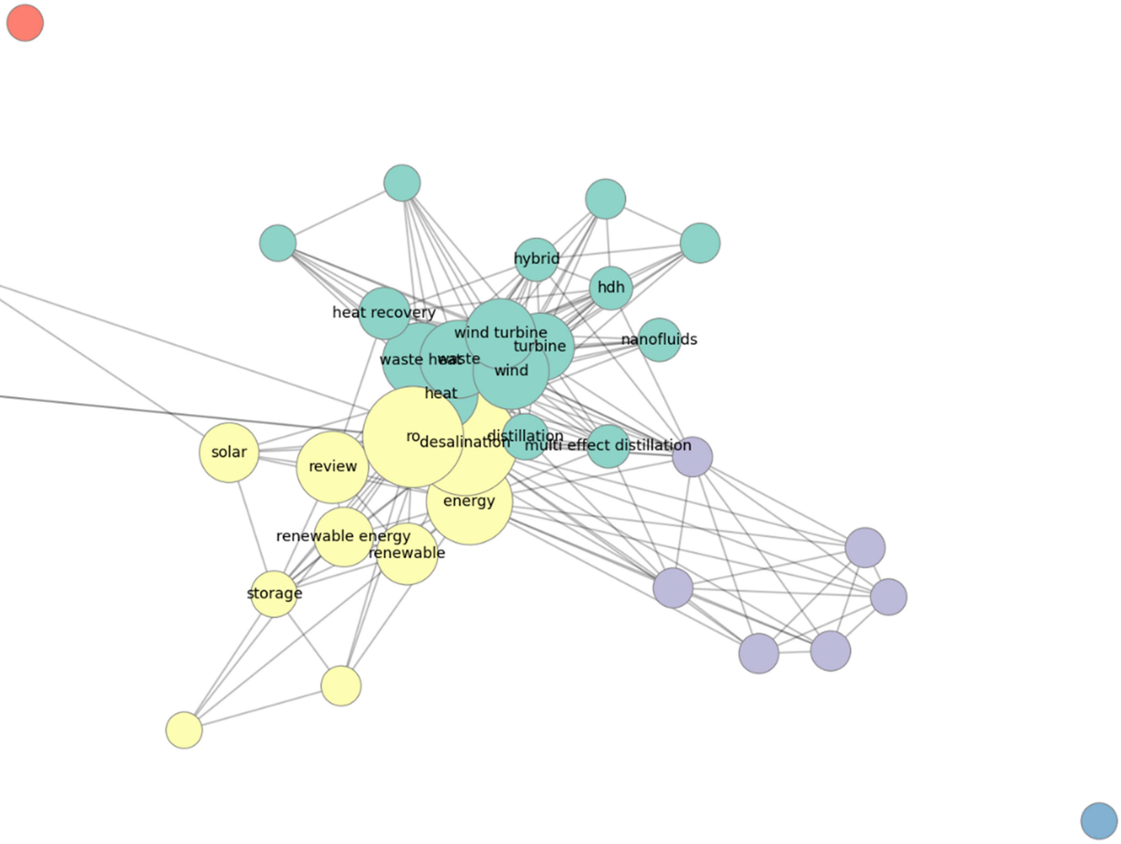

Figure 2. Keyword co-occurrence map.

same reference were linked. Thematic cluster detection was performed using modularity communitarization (a technique analogous to VOSviewer's approaches), and the visualization was exported in a nodes/links format suitable for VOSviewer. Figure 2 shows the keyword co-occurrence map.

The analyzed bibliography comprises 45 references with identifiable titles and/or authors from the manuscript corpus. The resulting maps show the thematic structure and existing collaborations in the literature on desalination powered by renewable energy and the utilization of waste heat (WH) from wind turbines, the central topic of the article.

3. Technical context

3.1. *Definition of wind turbines*

WT are devices used to convert the kinetic energy of the wind into electrical energy (Manwell, Mcgowan, and Rogers 2009). These devices consist of a structure with blades or rotors that capture the energy of the wind and convert it into mechanical energy through a rotor (Sathiya Moorthy et al. 2016). This mechanical energy is transmitted to a generator, which converts it into electricity (Olabi et al. 2020).

In other words, wind turbines represent a significant advancement in the pursuit of renewable and sustainable energy sources, but they face critical challenges due to their dependence on wind availability (Abdelkareem et al. 2024), and the risks associated with their installation and maintenance.

Consequently, this dependence on wind to generate energy, along with the variability in its speed and direction, can unpredictably affect production. Depending on their installation, wind turbines may also have visual and environmental impacts, including disturbances to the landscape and local wildlife (Dhar et al. 2020). Although technological advances have been made, concerns persist regarding their efficiency and reliability, especially under extreme weather conditions, and the management of waste at the end of their life cycle, which requires attention and innovative solutions to maximize their contribution to sustainable energy (Nagle et al. 2020).

3.2. Waste heat

Waste heat (WH) refers to thermal energy lost during mechanical or industrial processes. In wind turbines (WTs), WH originates mainly from generator cooling loops and power electronics, typically at 100–150 °C, with recoverable power in the order of hundreds of kilowatts for large turbines. For example, a 7.58 MW WT can provide approximately 231 kW of WH at 140 °C, which could produce up to 45 m^3/day of potable water via Multi-Effect Distillation (MED) under ideal conditions (Khalilzadeh and Hossein Nezhad 2018; Rostamzadeh and Rostami 2020). This corresponds to nearly 6 L/day per kW of WH.

The feasibility of using WT-WH for desalination depends on factors such as heat quantity, temperature stability, and continuous availability (www.rmit.edu.au 2019). Integrating WH recovery into desalination systems improves energy efficiency, reduces fossil fuel dependence, and lowers greenhouse gas emissions (Rostamzadeh and Rostami 2020; Olabi et al. 2020; Memon et al. 2022). Studies highlight MED and Humidification–Dehumidification (HDH) as the most compatible processes, while membrane distillation (MD/DCMD) offers potential for low-grade WH (Melissa Díaz González and Alejandra Rojas Gutierrez 2019; Rostamzadeh et al. 2021; Memon et al. 2022).

Challenges include technical and economic viability, corrosion under saline conditions, and variability in WH output due to wind fluctuations (Zhou et al. 2023). Estimates vary by turbine design and operating conditions, and detailed performance data remain scarce (Xydis, Pechlivanoglou, and Nayeri 2015; Subiela, Peñate, and García-Rodríguez 2019; engineeringhulk.com 2021). Addressing these gaps requires robust recovery systems, techno-economic analysis, and pilot-scale validation.

Waste heat is commonly classified into low-, medium-, and high-grade categories, with WT-WH falling in the medium range (100–150 °C) (Forman et al. 2016). Most WH sources globally are low-grade, reinforcing the need for technologies that can utilize moderate temperatures efficiently. While industrial sectors such as steel and aluminum have explored WH recovery to improve energy efficiency (Energy.com; NOWICKI and GOSSELIN 2012; Saha, Chakraborty, and Dutta 2020; Nwosu et al. 2023), the application in wind turbines remains limited and requires tailored solutions due to spatial constraints and variability.

The amount of WH generated by a wind turbine varies according to design, cooling system, and operating conditions. No consistent evidence indicates systematic differences between HAWT and VAWT in terms of WH output.

3.3. Waste heat recovery

The amount of waste heat (WH) depends on the mass flow rate and enthalpy of the stream; higher temperatures and flow rates yield greater recovery potential (Christodoulides et al. 2022). The physical state and composition of the stream are critical, especially when corrosive materials are present, as they influence material selection for heat exchangers. Additionally, the availability of the heat sourcecontinuous or intermittentaffects system design and integration feasibility. These factors must be considered when adapting WH recovery for wind turbines, where variability and spatial constraints require compact, corrosion-resistant solutions.

3.3.1. Heat recovery systems

Heat recovery systems transfer WH between streams to preheat or heat process fluids, reducing energy demand (mundohvacr.com 2024). Heat exchangers are the core components, with designs such as recuperators and passive air preheaters for low- and medium-grade WH (thermal-engineering.org 2024). In industrial settings, WH boilers use exhaust gases to generate steam, sometimes supplemented by auxiliary burners when WH is insufficient.

For low-temperature sources, heat pumps offer a promising solution by upgrading thermal quality, enabling conversion of low-pressure steam into medium- or high-pressure steam for specific applications (Sánta, Garbai, and Fürstner 2015; Valancius et al. 2019; Suárez Sarmiento Tutor and Javier Pino Lucena n.d.). These principles are relevant for WT-WH integration, where compact exchangers and heat pumps can overcome temperature limitations and improve desalination efficiency.

3.3.2. Heat recovery systems

The efficiency of heat capture and storage depends on technology, materials, operating temperature, and design (cicenergigune.com, 2024). Common options include phase change materials (PCMs) with efficiencies above 90%, molten salts (70–95%) for high-temperature applications (Ong 2024), and thermal batteries for versatile storage across wide temperature ranges. Other alternatives, such as hot rocks, offer long-term storage but depend on geological conditions.

These systems are particularly relevant for WT-WH integration, as they enable buffering of intermittent heat and reuse in thermal desalination processes like MED or MSF, improving overall efficiency and stability. Studies highlight that performance can be enhanced through advanced materials and intelligent control systems, though adoption depends on resource availability and economic factors (Al-Mudhafar, Nowakowski, and Nicolleau 2020; Carrión-Chamba, Murillo-Torres, and Montero-Izquierdo 2022; Szajding et al. 2023; iadb.org 2024).

3.4. Desalination concept

Integrating wind turbines (WTs) with desalination systems offers a promising solution for water scarcity in remote coastal areas by leveraging renewable energy to produce potable water (Greco, Heijman, and Jarquin-Laguna 2021). Estimating water output requires considering both turbine power capacity and desalination process efficiency.

Despite its potential, key challenges remain: optimizing heat capture and storage systems, adapting desalination technologies to effectively utilize waste heat (WH), and addressing technical and regulatory barriers for large-scale adoption (Melissa Díaz González and Alejandra Rojas Gutierrez 2019; Al-Obaidi et al. 2024). These factors are critical for transforming WT-WH integration into a viable and sustainable approach.

3.4.1. Desalination processes

The efficiency of desalination when using waste heat (WH) depends on the process and integration method (Gorjian and Ghobadian 2015). Thermal distillation technologies such as Multi-Stage Flash (MSF) (Al-Mutaz 2020) and Multi-Effect Distillation (MED) (Al-Hotmani et al. 2020) can significantly reduce energy demand by preheating seawater with WH (Namboodiri and Rajagopalan 2014; Feria-Díaz et al. 2021). Membrane-based processes like reverse osmosis (RO) and electrodialysis (ED) remain widely used, and WH can improve RO efficiency by preheating feedwater (Dhakal et al. 2015; Curto, Franzitta, and Guercio 2021).

Renewable energy–driven desalination systems, including solar and wind-powered configurations, are increasingly applied in remote areas where grid access is limited (Tzen and Morris 2003; Elsaid et al. 2020). Effective WH integration improves the energy-to-water (E/W) ratio, reducing operational costs and enhancing sustainability (Ahmadvand et al. 2019). Despite this potential, only 1% of desalination technologies currently use renewable energy (Ahmadvand et al. 2019), highlighting the need for hybrid solutions combining wind energy and WH recovery (Mezher et al. 2011; Grueso-Dominguez et al. 2019; Elewa 2024). The most common desalination processes and how WH can enhance their efficiency are summarized in Table 4. And various renewable energy–driven desalination technologies include solar desalination, wind-powered desalination, and hybrid renewable energy desalination technologies as shown in Figure 3.

Desalination technologies integrated with solar and wind energy are being explored (www.iagua.es 2023), highlighting the effectiveness and feasibility of solar energy in desalination. Solar energy can be applied directly or indirectly (Ahmed and Alkassem 2020), using photovoltaic (PV) technology or solar thermal systems to generate electricity or heat (Gorjian and Ghobadian 2015) PV panels power desalination technologies such as RO, while solar thermal energy is used in technologies like MSF, MED, and TVC (Mathioulakis, Belessiotis, and Delyannis 2007). Solar desalination stands out for its affordability and simplicity compared to conventional desalination technologies. Additionally, membrane distillation is mentioned as an emerging technology well suited for solar energy (pv-magazine.com 2018; Fthenakis et al. 2024).

Table 4. WH integration in desalination processes: specific pathways and expected impacts.

Process	WH Integration Pathway	Expected Impact	Integration Notes/References
MSF (Multi-Stage Flash)	Use WH to preheat feedwater and brine blowdown before flashing stages	↓ Specific thermal energy consumption (SEC); ↑ stage efficiency	Requires WH ≥90 °C; corrosion and scaling management critical Olabi et al. (2020); Sayed et al. (2023)
MED (Multi-Effect Distillation)	WH replaces or supplements top-brine heater duty; cascades across effects	↑ Gain Output Ratio (GOR); ↓ steam demand; improved energy recovery	Optimal with WH at 70–140 °C; may need heat pump for temperature lift Khalilzadeh and Hossein Nezhad (2018); Rostami et al. (2023)
MVC/TVC (Mechanical/Thermal Vapor Compression)	WH preheats feed and/or drives ejector steam	↓ Electrical or auxiliary steam consumption	Integration depends on ejector/compressor efficiency; WH stability matters, Dhakal et al. (2015); Rostami et al. (2023)
HDH (Humidification–Dehumidification)	WH heats air or water in humidifier section	↑ Water production rate; improved thermal utilization	Compatible with low-grade WH; nanofluids can enhance heat transfer Rostamzadeh and Rostami (2020)
MD/DCMD (Membrane Distillation)	WH provides hot-side feed temperature for transmembrane vapor flux	↑ Flux and recovery; better thermal efficiency	Sensitive to ΔT; module design and fouling control required Memon et al. (2022)

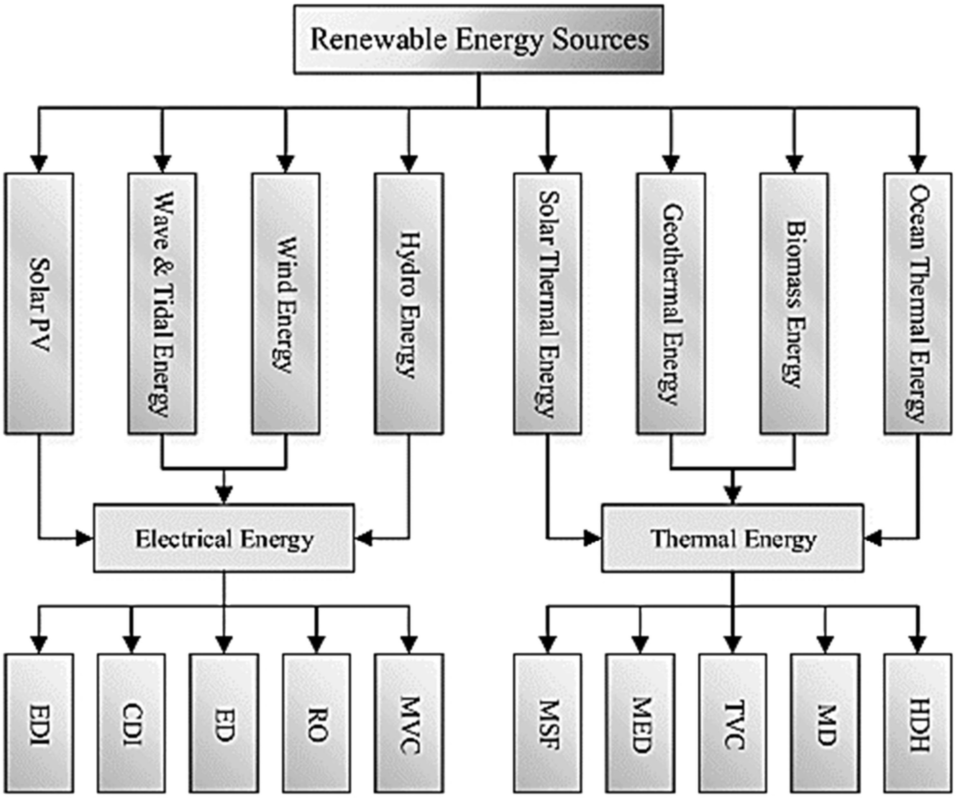

Figure 3. Desalination technologies powered by renewable energy (Alawad et al. 2023).

The integration of wind energy into desalination is still at an early stage in Latin America, with pilot and research projects under development (Barliza, Barliza, and Martha 2019). A project in Chile is mentioned that combines wind energy and desalination, highlighting its ability to generate electricity and its contribution to the strategy of hybridizing renewable power plants (Rebolledo Smitmans Secretario Ejecutivo, Castillo Fabio García Luis Mosquera Targelia Rivadeneira Katherine Segura Marco Yujato Colaboradores, and Guerra Fabricio Ramos 2023) While the integration of solar and wind energy into desalination technologies represents a promising step toward sustainability and energy autonomy, there are critical challenges that must be addressed (Bretas 2020). On the one hand, although solar desalination stands out for its affordability and simplicity compared to conventional technologies, there are still limitations in terms of efficiency and scalability. Climate variability and

Table 5. Main product cost in US$/m^3 (Mexico).

Cost (USD/m^3)	
Total capital investment	1.63-0.815
Membrane replacement	0.2–0.1
Annual O&M cost	0.32–0.16
Unit product cost	2.15–1.075

dependence on sunlight availability can affect the production of desalinated water inconsistently (Al-Addous et al. 2024).

Additionally, the integration of wind energy into desalination requires further technological development and comprehensive evaluations of economic and environmental feasibility. It is crucial to address these challenges to maximize the potential of renewable energies in desalination and to ensure their effective and sustainable long-term application.

Similarly, in Mexico, studies have also been conducted on the technical and economic feasibility of this integration (Canales, Wehncke, and Gudino-Elizondo 2020). However, despite these advances, there are still challenges that limit the widespread adoption of this technology in the region. These include the availability of financial resources for implementing large-scale projects, the lack of specific policies and regulatory frameworks, and the need to develop technical and research capacities in the areas of desalination and wind energy (Podestá et al. n.d.).

Among the studies on the value of desalination in Mexico, Carlos (2018), developed an RO–PV prototype system capable of producing between 0,5 and 1 m^3/day. This performance is considered good, with a unit cost of permeate water ranging from 1,075 to 2,15 US$/m^3, taking into account construction and operation costs—making it a competitive cost for this type of system.

The unit cost of permeate water was calculated as the sum of total capital cost, membrane replacement, and O&M costs, divided by the total amount of permeate water produced (7.300 m^3) over the lifespan of the solar desalination system. Table 5 presents the main product cost in US$/m^3.

Despite significant advances in research on the technical and economic feasibility of integrating desalination and renewable energy in Mexico, challenges still hinder its widespread adoption. The main obstacles include the limited availability of financial resources for large-scale projects, the lack of specific policies and regulatory frameworks that promote investment in this area, and the need to develop technical and research capacities in desalination and renewable energy. Although prototype systems, such as the RO–PV developed by the authors, show promising performance with competitive costs, it is crucial to address these challenges to achieve broader and more effective implementation of this technology in the region.

It is worth noting that Latin America has great potential to harness wind energy and address freshwater scarcity through desalination (offshorewind.biz 2014; Vicuña 2022) The development and promotion of research projects, collaboration between the public and private sectors, and the implementation of supportive policies and regulatory frameworks could help advance the use of waste heat (WH) from wind turbines (WT) in seawater desalination in the region (Bretas 2020). Although it is encouraging to highlight Latin America's potential to leverage WT and address freshwater scarcity through desalination, it is also important to acknowledge that implementing such projects still faces significant challenges in the region.

Although it is encouraging to highlight Latin America's potential to harness wind turbines (WT) and address freshwater scarcity through desalination, it is essential to acknowledge that implementing such projects presents significant challenges in the region. These challenges may include the need for substantial financial investments in infrastructure and technology, as well as overcoming regulatory and policy barriers that could hinder effective collaboration between the public and private sectors. Additionally, an integrated approach is required—one that considers environmental and social sustainability, as well as the involvement of local communities. Therefore, while the potential certainly exists, realizing it effectively will demand significant commitment and a coordinated strategy among multiple stakeholders.

4. Results

This section presents the findings from the systematic literature review, focusing on the analysis of the potential to utilize WH from WT in SWD processes. It also highlights global advances, the current state in

Colombia (with special attention to the La Guajira region), and the main technical, economic, and environmental challenges identified in the selected studies.

4.1. VOSviewer analysis

The co-occurrence map identifies dominant terms and their connectivity. The most frequent terms include ‘desalination,’ ‘wind,’ ‘waste heat/heat,’ ‘wind turbine,’ and ‘RO/reverse osmosis,’ as well as thermal process labels (MED, HDH) and renewable integration concepts (solar/photovoltaic). In the processed set, the most frequent keywords are: desalination (9), wind (7), waste heat (6), wind turbine (5), and RO (5) (frequencies per document with ≥1 occurrences). These nodes exhibit strong co-occurrence, reflecting three main thematic clusters:
Cluster A: (Renewable Integration–Desalination): desalination, renewable, solar, photovoltaic, RO.
Cluster B: (WH Utilization and Thermal Processes): waste heat, wind turbine, MED, HDH, nanofluids.
Cluster C: (Design/scale and economic gaps): Terms linked to techno-economic and LCOW appear with low centrality, suggesting a gap in economic evidence in the field.

4.1.1. Author collaboration network

The co-authorship network suggests moderate, fragmented collaboration, with the highest connectivity concentrated among authors publishing on WH desalination and renewable energy integration (e.g. review articles and wind/solar integration studies). The main component of the network comprises authors who appear in articles in Desalination, Energy, S Afr J Chem Eng, Processes, etc. At the same time, institutional documents and non-academic sources (reports/organizations) generate isolated nodes or are not added to the graph due to a lack of conventional authorship. This is consistent with the fact that the field, although emerging, still lacks large consortia and large-scale experimental case series.

4.1.2. Implications for La Guajira and the research agenda

The thematic pattern shows that the use of wind energy and thermal processes (MED/HDH/MD/DCMD) is well represented in the literature. At the same time, comprehensive economic-techno-environmental analyses (LCOW/TEA/LCA) are scarce, underscoring the need for an agenda that includes LCOW models, integration of TES/heat pumps, and pilot projects in coastal wind contexts like La Guajira.

4.2. Utilization of waste heat

Evidence on the direct utilization of wind turbine (WT) waste heat (WH) for seawater desalination (SWD) is extremely limited and primarily confined to simulation and conceptual studies. The few available analyses provide quantitative insights into potential performance:

- Multi-Effect Distillation (MED) modeling: Khalilzadeh and Hossein Nezhad (2018) evaluated an integrated system where WH from a high-capacity WT (≈7.58 MW) is recovered at ~140 °C, delivering ~231 kW of thermal energy to an MED unit. Under ideal conditions, this configuration could produce approximately 45 m^3/day of potable water, equivalent to ~0.52 L/s—enough for about 900 people at 50 $L{\cdot}cap^{-1}{\cdot}day^{-1}$.
- Heat-transfer enhancement using nanofluids: Rostamzadeh and Rostami (2020) simulated WH extraction from WT generators employing nanofluids (e.g. Al_2O_3, Cu/water), achieving up to 30% improvement in heat-transfer efficiency compared to water alone. This enhancement increased modeled freshwater output in humidification–dehumidification (HDH) systems.
- Membrane-based configurations: Memon et al. (2022) explored modular direct contact membrane distillation (DCMD) powered by WT-grade WH, identifying operating parameters that influence flux and scalability.
- Hybrid thermal systems: Rostami et al. (2023) proposed a combined MED–MVC–HDH scheme with brine recirculation to improve recovery and approach minimal liquid discharge (MLD).

Despite these conceptual advances, no field-scale implementations or techno-economic assessments (e.g. levelized cost of water) have been reported. All studies emphasize technical feasibility but highlight critical barriers, including temperature mismatch, heat transport from nacelles, thermal storage requirements, and integration complexity.

In Colombia, and specifically in La Guajira, the potential for WT-WH utilization is significant due to strong wind resources and acute water scarcity. However, there are no ongoing projects applying this concept. Current efforts remain focused on wind power generation and conventional desalination technologies, underscoring the need for targeted research and pilot demonstrations to validate performance and economic viability under local conditions.

4.2.1. Vision for waste heat utilization in la guajira

In the region of La Guajira, located on Colombia's northern coast, there is significant wind energy potential (Hoyos 2019) yet it simultaneously faces serious challenges regarding access to drinking water. Consequently, given these conditions, there is an opportunity to harness the waste heat (WH) from wind turbines (WT) to enhance the efficiency of desalination systems in the region (Barliza, Barliza, and Martha 2019).

Although there are still no large-scale implementations of this integration in La Guajira, several studies and research projects have been conducted to assess its technical and economic feasibility (Lechuga 2023), These efforts aim to leverage the region's abundant wind resources and reduce the energy costs associated with seawater desalination (Barliza, Barliza, and Martha 2019), It is important to emphasize that the successful implementation of WH utilization from WT in La Guajira will require coordinated collaboration among various stakeholders, including the energy sector, the water and sanitation sector, and local communities. This will involve addressing critical aspects such as the necessary infrastructure, the adaptation of suitable technologies, and ensuring long-term economic and environmental sustainability (de D. R. 2021).

Eight wind power generation projects in La Guajira together represent approximately 1.000 MW of capacity. To date, the National Environmental Licensing Authority (ANLA) has granted key licenses for transmission infrastructure in the region, including the Colectora transmission line (1.050 MW) and the connection of the Alpha and Beta wind farms (492 MW), enabling the evacuation of over 1.000 MW of wind energy to the national grid (Global Energy Monitor). However, although these transmission lines mark an important step in infrastructure development, the construction of the wind farms still faces significant challenges. These include regulatory delays, opposition from local communities, and the withdrawal of investors such as EDP Renewables (Zapata). In response, in 2.025 the Colombian government launched a plan comprising 19 measures aimed at streamlining permits and promoting the development of these projects.

Additionally, in Alta Guajira, specifically in the community of Nazaret, a hybrid system was implemented in 2.010 that includes two wind turbines of 100 kW each, alongside other energy resources. In the villages of Puerto Estrella and Nazareth, located in the municipality of Uribia in La Guajira department, eight dual-axis solar trackers were installed, each with a capacity of 12,5 kW. These systems generate electricity at a three-phase voltage of 120/208 volts, connected to an isolated microgrid. They are integrated with other generation sources, including the two 100 kW wind turbines and generators running on liquefied petroleum gas (LPG) and diesel (ACPM) (CORPOGUAJIRA 2018).

Similarly, in the villages of Puerto Estrella and Nazareth in the municipality of Uribia, located in the Department of La Guajira, the installation and assembly of two wind turbines—each with a capacity of 200 kW—was carried out. These wind turbines are part of a hybrid system that also incorporates solar energy, liquefied petroleum gas (LPG), and diesel (ACPM).

This research project focuses on evaluating the performance of the two single-blade wind turbines from social, economic, and environmental perspectives. At present, the possibility of replicating this project in other locations within the Non-Interconnected Zone is being assessed (CORPOGUAJIRA 2018).

Independently, a list of small-scale water supply systems (micro aqueducts) was identified in the Department of La Guajira that use RO plants. This list shows the production capacity, the energy source, the method of water collection, and the communities served, including the number of inhabitants who benefit from these systems.

The reviewed studies provide a comprehensive overview of the integration of wind turbines into seawater desalination (SWD), highlighting both the benefits and challenges associated with this application. Bundschuh et al. (2021) conduct an in-depth review of the current state of research in this field, analyzing technological advancements, methodologies, and results achieved to date. Ghaffour et al. (2015), identify technologies and the economic and environmental challenges linked to the integration of wind turbines in desalination systems. Alhaj and Al-Ghamdi (2019) assess the economic and environmental benefits and challenges, offering recommendations to maximize the advantages of this application.

The importance of considering factors such as economic viability, wind resource availability, and environmental implications is emphasized when evaluating the implementation of this technology. There is a strong need for comprehensive studies that address economic, technical, and environmental analyses, as well as continued research and development of more efficient and sustainable technologies. Collectively, these studies provide a detailed perspective on the integration of wind turbines in seawater desalination processes and their contribution to environmental sustainability and access to potable water.

4.2.2. Wind power projects in Colombia

Colombia’s current energy matrix is considered the sixth cleanest in the world (Alcogen), as 69% of its installed capacity comes from renewable sources—nearly all of which is generated through hydropower (see Figure 4).

However, this heavy dependence on water resources has had significant consequences. For instance, at the end of the 20th century (in 1992) (canalinstitucional.tv 2022) the country experienced a severe energy shortage due to the El Niño phenomenon. This led to a prolonged electricity rationing period that lasted nearly a year. Measures taken at the time included changes to the national time zone—commonly referred to as ‘Gaviria Time’—as well as daily power outages ranging from 9 to 18 hours. Among the solutions implemented were the completion of several hydropower projects and a reinforcement of thermal energy generation.

More recently, in late 2023 and early 2024, another El Niño event significantly reduced reservoir levels, once again forcing thermal power plants to operate at increased capacity (Redacción Economía, 2024).

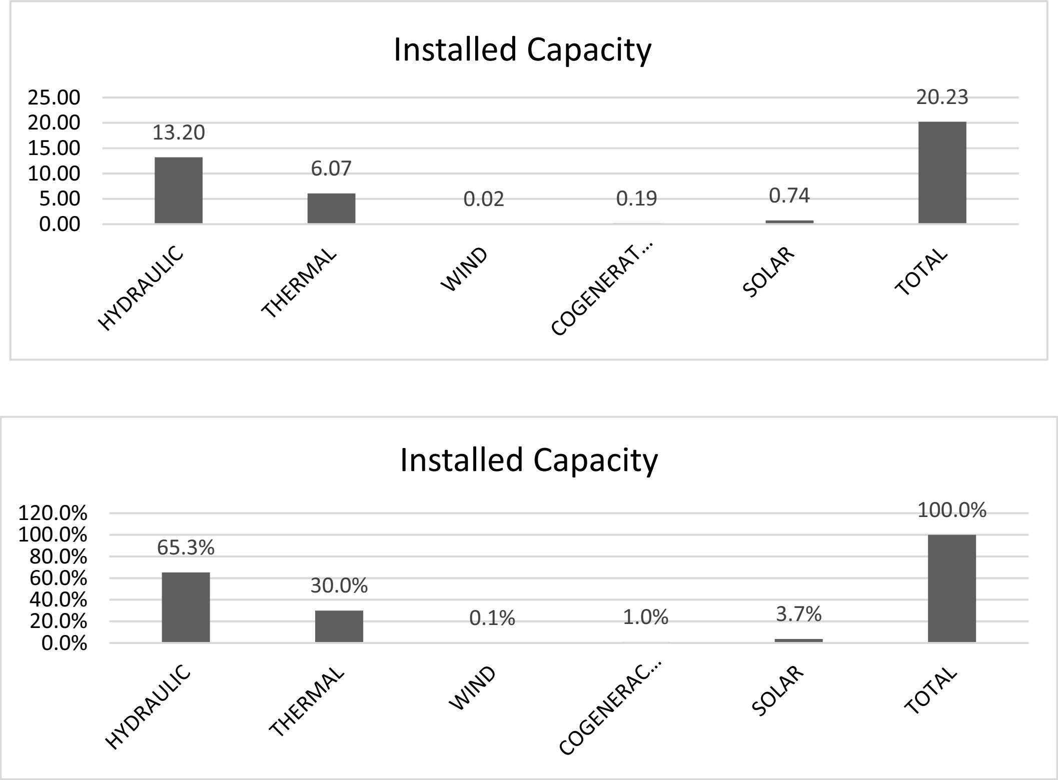

Figure 4. Installed energy capacity in Colombia (GW).

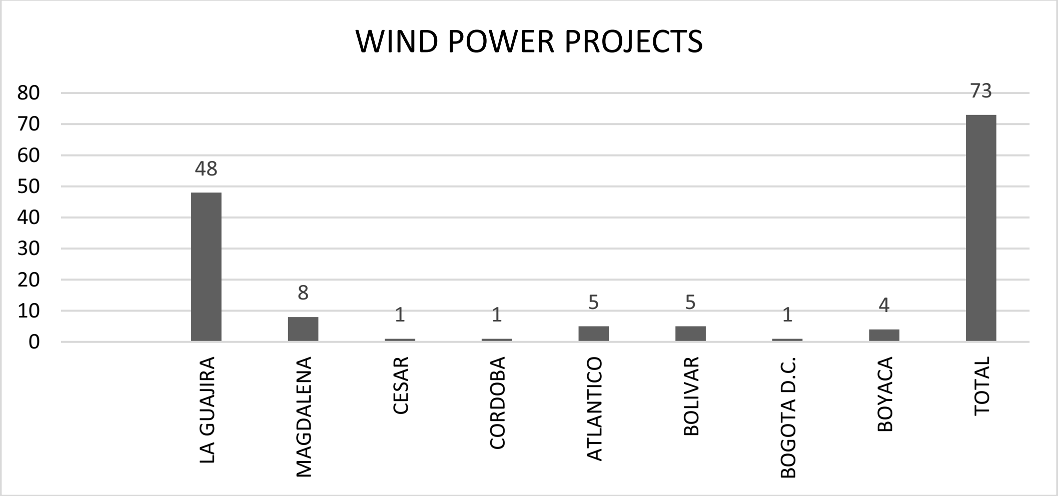

Figure 5. Wind farm projects under construction in Colombia.

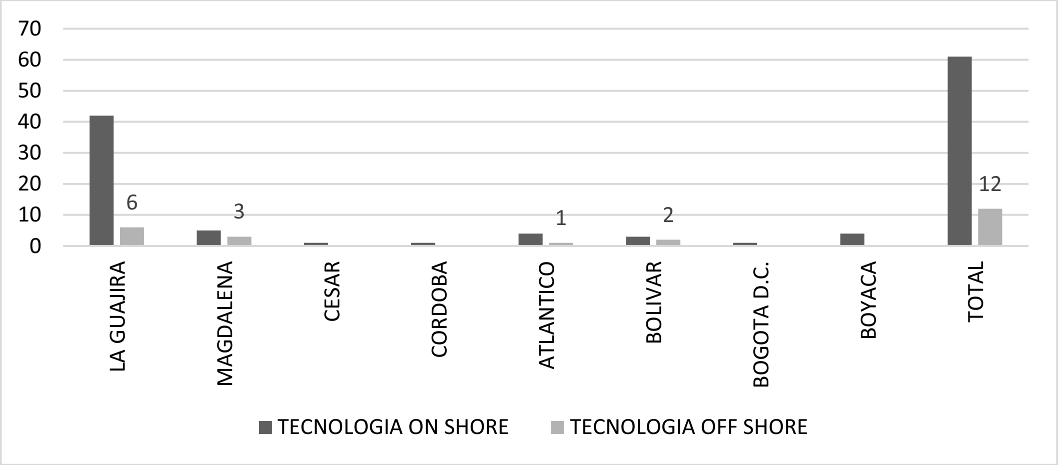

Figure 6. Wind farm projects in Colombia by technology.

The Colombian government is strongly committed to renewable energy to expand its energy infrastructure. In this ambitious plan, the department of La Guajira plays a key role due to its favorable natural conditions (Sathiya Moorthy et al. 2016; Rostami, Rostamzadeh, and Fatehi 2021). The comprehensive project includes building 73 wind farms across Colombia, with 48 located in La Guajira (powerbi). As shown in Figure 5, La Guajira will host the majority (66%) of the wind farms planned by the Colombian government. Notably, these farms will use different technologies: onshore wind farms will have a generation capacity of 3.2 GW, while offshore farms—which, although fewer in number as shown in Figure 6 (powerbi), will produce a higher energy output of 5.1 GW—are expected to contribute more energy. This projection is for the year 2040 (La Republica, 2024).

Given these developments, there will be significant potential for residual heat generated by the wind farms under construction in La Guajira resource which can be harnessed effectively.

4.2.3. Waste heat recovery from wind turbines

Regarding the utilization of waste heat (WH) from these systems, the literature reveals very limited information, except for the work by Khalilzadeh and Hossein Nezhad (2018), who propose an integrated system in which seawater desalination is carried out through the Multi-Effect Distillation (MED) process, with the required steam generated from the heat released by a wind turbine (WT). Reported challenges

Table 6. Study metadata matrix (WT-WH to Desalination).

Authors	Turbine (rated MW)	WH Conditions (°C; kW)	Desalination Process	Scale (type)	Main outcomes (incl. LCOW if any)	Study type
(Khalilzadeh and Hossein Nezhad 2018)	~7.58	~140°C; ~231 kW	MED	Simulation	~45 m^3/day modeled; no LCOW	Energy/exergy + thermoeconomic
Rostamzadeh and Rostami 2020; Rostami, Rostamzadeh, and Fatehi (2021)	–	Generator WH; nanofluids	HDH	Simulation	Up to ~30% heat-transfer enhancement; higher modeled yield; no LCOW	Parametric
Memon et al. (2022)	–	Low–mid grade WH	DCMD	Simulation	Flux sensitivity to ΔT/module; no LCOW	Parametric
Rostami et al. (2023)	–	Thermal hybridization	Hybrid MED–MVC–HDH	Simulation	Higher recovery; MLD approach; no LCOW	Parametric

include wind speed intermittency and variations in ambient temperature. In the case of La Guajira, these limitations are minimized, as both ambient temperature and wind speed remain relatively constant throughout the year.

Olabi et al. (2020), in an insightful study, analyze various thermally driven desalination processes that WH can power. Their research focuses on seawater (SW) desalination and compares several processes Multi-Stage Flash (MSF), MED, Humidification–Dehumidification (HDH), Membrane Distillation (MD), and Adsorption Desalination (AD) using different WH sources. Some of these sources include exhaust from natural gas compressor stations, flue gases from industrial furnaces, and exhaust gases from marine diesel engines, among others. In conclusion, they state that despite the technical, economic, and environmental potential of using WH in seawater desalination (SWD) processes, most of these systems are still in the development stage, often limited to pilot projects. It is worth noting that in the perspective provided by Olabi et al., the potential use of WH generated by a WT is neither addressed nor mentioned.

Rostamzadeh and Rostami (2020) In their study, they found that using Al_2O_3 nanoparticles increases cooling efficiency by up to 30%. Based on this finding, they carried out a simulation integrating a WT with an HDH unit and also examined the system's performance with other types of nanoparticles. For this study, they drew upon the work of Khalilzadeh and Hossein Nezhad (2018) among other authors. While (Khalilzadeh and Hossein Nezhad 2018) employed the WH from a WT in an MED unit using water as the coolant, (Rostamzadeh and Rostami 2020) used an HDH unit and incorporated nanoparticles into the water to enhance heat transfer efficiency, thereby increasing the system's freshwater production capacity. Among the conclusions of Rostamzadeh and Rostami (2020), a key point is the use of WH from a WT for water production instead of releasing it into the environment, with Cu/water nanoparticles providing the highest performance and increasing the overall energy efficiency of the WT/HDH system.

The most recent publication (2023) proposes a hybrid system that combines MED, MVC, and HDH thermal processes for SWD. Rostami et al. (2023) address brine management by reintegrating the brine discharged from the MED unit into the HDH system, thereby optimizing the overall process. This work integrates the systems studied in (Khalilzadeh and Hossein Nezhad 2018; Rostamzadeh and Rostami). Although the studies by Rostami, Rostamzadeh, and Khalilzadeh present interesting simulations for utilizing WT WH in SWD processes, it is important to note that the existing literature in this field remains limited (Khalilzadeh and Hossein Nezhad 2018; Rostamzadeh and Rostami 2020; Rostami et al. 2023).

These studies represent significant progress in research on the integration of renewable technologies into desalination; however, it remains to be seen how these proposals will translate into large-scale practical applications. Furthermore, additional research and experimental studies are needed to assess the technical, economic, and environmental feasibility of these hybrid systems under different contexts and operational conditions. Table 6 shows the study metadata matrix.

The next challenge is to determine whether these technologies can be adapted and enhanced to take advantage of the environmental conditions and the wind farms currently under construction in La Guajira, Colombia.

Table 7. Thermal matching: WH temperature bands vs. desalination options.

WH band	Typical WH source on WT	Candidate desal process	Minimum useful hot-side T/ΔT (indicative)	Notes on feasibility
Low (<100 °C)	Nacelle ventilation; low-temp loops	HDH; MD/DCMD (low-ΔT); RO preheating	HDH ≥ 60–80 °C; MD flux rises with ΔT ≥ 10–20 K	Lower flux; good for preheating and HDH; limited MED/MSF utility Olabi et al. (2020); Memon et al. (2022)
Medium (100–180 °C)	Generator/converter cooling; gearbox oil	MED, HDH, MD/DCMD	MED top-brine heater typically 70–140 °C; higher T improves GOR	Best match for MED (with pinch constraints); may still need heat pump Khalilzadeh and Hossein Nezhad (2018); Rostami et al. (2023); Sayed et al. (2023)
High (>180 °C)	Rare for WT-WH	MSF, high-T MED, TVC	MSF stages benefit from high T; TVC needs motive steam	Usually not available from WT-WH without additional lift (Olabi et al. (2020); Sayed et al. (2023)

Reported WT-WH is typically low- to mid-grade (100–150 °C) with tens to a few hundred kW available per large turbine, depending on generator/converter design, cooling loops, and operating point (Xydis, Pechlivanoglou, and Nayeri 2015; Khalilzadeh and Hossein Nezhad 2018; Memon et al. 2022; Zhou et al. 2023; Rostamzadeh and Rostami 2020) as shown in Table 7.

5. Discussion

Wind turbines (WTs) are pivotal in the global energy transition, converting wind's kinetic energy into electricity. However, as highlighted by Sathiya Moorthy et al. (2016) and Olabi et al. (2020), their inherent dependence on wind variability introduces uncertainties in supply stability. Environmental concerns—such as landscape alteration and wildlife disruption (Elsaid et al. 2020; Rostami et al. 2023)—and technical challenges associated with extreme operating conditions and end-of-life waste management (Manwell, Mcgowan, and Rogers 2009; Olabi et al. 2020) further complicate large-scale deployment. These limitations open opportunities to explore complementary uses of waste heat (WH), an underutilized by-product that could enhance overall system efficiency.

Recent simulation studies by Khalilzadeh and Hossein Nezhad (Khalilzadeh and Hossein Nezhad 2018), Rostamzadeh et al. (2021), Memon et al. (2022), and Rostami et al. (2023) demonstrate the theoretical potential of integrating WT-WH into seawater desalination (SWD) processes. For instance, recovering 231 kW of WH at 140 °C from a 7.58 MW turbine could yield about 45 m^3/day of potable water via multi-effect distillation (MED) (Khalilzadeh and Hossein Nezhad 2018). While technically feasible, this corresponds to only ~0.52 L/s sufficient for roughly 900 people at 50 $L\cdot cap^{-1}\cdot day^{-1}$—thus negligible compared with municipal or industrial demands of thousands of cubic meters per day. This emphasizes a key limitation: scale. Even when aggregated across several turbines, WH-driven desalination remains a niche solution unless supported by thermal storage or hybrid configurations.

Beyond scale, several technical barriers constrain implementation. The relatively low- to mid-grade temperature of WT waste heat (100–150 °C), the complexity of transferring heat from nacelles to ground-level systems, and the need for thermal energy storage (TES) or heat pumps to buffer wind intermittency all increase capital and operational expenditures. Yet, no studies to date report the levelized cost of water (LCOW) or conduct full techno-economic analyses. Moreover, corrosion and fouling under saline conditions, together with mechanical constraints in rotary heat-transfer systems, raise additional concerns regarding long-term reliability.

Despite these limitations, WH utilization could offer context-specific value in isolated coastal regions, where small-scale desalination (tens of cubic meters per day) can meaningfully improve water access. In La Guajira, for instance, strong and consistent winds, high solar irradiation, and severe water scarcity create favorable conditions for pilot-scale projects. However, realizing this potential demands coordinated research across three fronts:

(1) Technical feasibility—quantifying WH potential across turbine designs and developing robust recovery systems;
(2) Economic viability—establishing transparent LCOW models accounting for TES, piping, and maintenance; and

(3) Environmental sustainability—assessing brine management and material durability under harsh coastal conditions.

The absence of WT-WH-specific LCOW data represents a major evidence gap. For comparison, large-scale RO plants typically achieve 0.5–1.5 US$/m³, while MED systems powered by low-cost steam or WH range from 1–3 US$/m³ depending on scale and site (Mezher et al. 2011; Alhaj and Al-Ghamdi 2019; Sayed et al. 2023) Small off-grid units often exceed these values due to high specific CAPEX. Comprehensive cost models must therefore integrate plant investment, WH recovery, O&M, tariffs, and discount rates (commonly 6–12%).

From an environmental and social perspective, desalination projects in regions like La Guajira must address brine disposal and community acceptance. Effective brine management—via hybrid high-recovery schemes or controlled discharge is essential to protect marine ecosystems. Additionally, wind developments intersect with indigenous territories and fragile environments, requiring participatory planning, transparent benefit-sharing, and local capacity-building. Prior studies stress that energy-water projects succeed only when embedded in territorial development plans and supported by inclusive governance frameworks. Hence, social and institutional feasibility must be assessed alongside technical and economic criteria to ensure sustainable outcomes.

In terms of thermal potential, most studies report WT-WH as low- to mid-grade (100–150 °C), with recoverable power between tens and several hundred kilowatts per turbine. Khalilzadeh et al. (2018) Khalilzadeh and Hossein Nezhad (2018), for example, modeled 231 kW of WH at 140 °C from a 7.58 MW turbine—approximately 3% of its rated power. Extrapolating yields an average of ~30 kW of WH per MW installed, though subject to ± 30–50% uncertainty due to wind speed variability, cooling efficiency, and ambient temperature. Such quantification is crucial for identifying which desalination technologies—particularly MED or HDH—can operate effectively under site-specific WH conditions.

The assumption of 231 kW of waste heat at 140 °C for a 7.58 MW wind turbine is based on the thermodynamic modeling by Khalilzadeh and Hossein Nezhad (2018). This scenario considers high-capacity turbines equipped with liquid-cooled generators operating under near-rated conditions. Actual WH availability varies significantly with turbine design, cooling system, and ambient conditions, and most commercial units produce lower values. Therefore, this estimate should be interpreted as an upper-bound case for feasibility analysis rather than a typical operational figure.

The modeled output of 45 m³/day from a 7.58 MW turbine highlights a fundamental limitation: even under ideal conditions, WT-WH desalination cannot compete with large-scale plants producing thousands of cubic meters per day. Scaling up would require aggregating heat from multiple turbines, adding complexity and cost for heat transport and storage. Therefore, this approach is inherently suited for niche applications, such as decentralized microsystems in remote coastal communities where conventional desalination is impractical. These systems can complement renewable energy projects by improving water resilience without aiming to replace utility-scale solutions.

Thermal compatibility analysis further refines this selection. WH temperatures of 100–150 °C align well with thermal desalination methods such as MED or Multi-Stage Flash (MSF), operating between 70–120 °C. Lower-temperature options like Humidification–Dehumidification (HDH) and Membrane Distillation (MD/DCMD) exploit 50–90 °C sources, whereas Reverse Osmosis (RO) benefits indirectly through seawater preheating. As shown in the temperature–process matrix, feasibility depends not only on thermal range but also on heat flow stability, exchanger efficiency, and storage strategy. Consequently, integration design should prioritize technologies that maximize WH recovery while minimizing losses from thermal mismatch.

Potential capture points include generator stator cooling loops, gearbox oil coolers (for geared WTs), power-electronics heat sinks, and nacelle ventilation exhaust. Integration requires compact, corrosion-resistant heat exchangers (plate/frame, microchannel), rotary joints, or secondary loops that respect turbine movement constraints. While co-locating small desalination units near turbine bases can reduce transport losses, it entails decentralized system layouts and higher per-unit cost.

Thermal storage adds further complexity. Insulated tanks, pumps, and control systems impose additional cost, and round-trip efficiencies (70–95%) vary by storage medium (sensible, PCM, molten salts) (Szajding et al. 2023; cicenergigune.com, 2024; Ong 2024). Where temperature lift is necessary, high-temperature heat pumps can supplement, though with added CAPEX and O&M (Suárez Sarmiento Tutor and Javier Pino Lucena n.d.). These components must be incorporated into techno-economic and LCOW analyses to yield realistic cost projections.

Environmental impacts also extend to embodied emissions from additional heat exchangers, piping, tanks, and maintenance logistics. Previous life-cycle assessments (LCA) of wind systems highlight materials and end-of-life burdens (Dhar et al. 2020; Nagle et al. 2020), while desalination LCAs emphasize brine disposal and energy source selection. Hence, cradle-to-grave LCAs of WT-WH desalination are needed—covering materials, installation, operation, and decommissioning—to benchmark performance against conventional wind-powered RO.

Because wind and WH availability fluctuate, dynamic modeling at hourly or sub-hourly resolution is essential. Yet, existing WT-WH studies rely mostly on steady-state or parametric simulations. Future research should thus adopt co-simulation frameworks coupling WT thermal losses and desalination duty under real wind datasets, enabling of control strategies, hybrid operation, and TES requirements.

La Guajira presents a unique socio-technical context where two realities converge: a structural water crisis and the accelerated development of wind energy projects. Eight wind farms under construction have a combined capacity of over 1,000 MW, while Wayuu communities face severe drinking water shortages. This coexistence justifies exploring integrated energy-water solutions that leverage byproducts of wind power generation, such as waste heat, to drive desalination. Such integration not only optimizes the use of energy resources but also contributes to water resilience and the achievement of the Sustainable Development Goals (SDGs) in vulnerable territories.

International experiences reinforce this relevance. In northern Chile, hybrid wind-solar projects have been evaluated to supply isolated communities, highlighting the importance of decentralized schemes and brine management. In Mexico, RO-PV systems have achieved competitive costs (US\$1,075–2,15/m^3), demonstrating that integrating renewable sources can reduce costs and improve water resilience (Carlos 2018). Similarly, studies in the MENA region underscore that combining solar and wind energy with thermal and membrane technologies is key to addressing water scarcity (Sayed et al. 2023). These experiences demonstrate that integrating renewable energy into desalination is viable in arid environments with abundant renewable resources, reinforcing the relevance of harnessing waste heat from wind turbines in La Guajira.

However, the specific literature on waste heat and wind power (WT-WH) remains limited and focused on simulations. To move toward real-world applications, interdisciplinary research is needed that addresses three fronts: (i) quantifying the thermal potential of wind turbines and developing robust recovery systems; (ii) conducting a comprehensive economic analysis that includes levelized cost of water (LCOW) and thermal storage costs; and (iii) environmental and social assessment, considering brine management and community acceptance. International evidence indicates that successful projects are based on participatory schemes and inclusive governance, critical aspects for implementation in indigenous territories such as La Guajira.

Although simulations report up to 30% heat-transfer improvement using nanofluids, practical implementation faces significant challenges. First, thermal stability and long-term dispersion of nanoparticles in closed loops remain uncertain, as agglomeration can reduce performance and increase maintenance needs. Second, cost implications are non-negligible: high-purity nanoparticles and specialized handling increase CAPEX and O&M compared to conventional fluids. Third, environmental and health concerns arise from potential nanoparticle leakage into saline environments, requiring strict containment and disposal protocols. Finally, scalability for large wind farms is unclear, as most evidence comes from laboratory-scale or simulation studies. Future research should include experimental validation, life-cycle assessment (LCA), and techno-economic analysis to determine whether nanofluid-based WH recovery is viable beyond conceptual models.

La Guajira presents a unique convergence: a structural water crisis and the expansion of wind power projects that generate waste heat (WH) usable in thermal desalination processes. This integration does not seek to replace global paradigms, but rather to offer decentralized, niche solutions for isolated communities, where the estimated production can meet the basic needs of ~900 people. Linkage with SDG Indicators are:

SDG 6: The estimated production capacity directly contributes to increasing the proportion of Wayuu communities with access to safe water, where coverage is critical.

SDG 7: The use of waste heat increases the efficiency of renewable energy use, although its impact on national consumption is marginal; its relevance is high in microgrids and isolated systems.

SDG 13: The pilot implementation must be aligned with territorial plans and adaptation strategies, incorporating social and environmental safeguards.

Although integrating waste heat reduces external energy demand and emissions (positive for SDGs 7 and 13), it introduces additional CAPEX and operational complexity. This could strain affordability (SDG 6) if costs are not optimized using LCOW models. Furthermore, the use of TES and materials entails environmental impacts that must be assessed through life-cycle assessment (LCA). It is recommended to incorporate exergy analysis (Second Law) to quantify the quality of the waste heat (100–150 °C) and minimize irreversibilities in MED, HDH, and MD processes.

Although no studies report LCOW for WT-WH desalination, a preliminary analytical framework can be outlined. Assuming a 7.58 MW turbine provides 231 kW of WH and produces 45 m^3/day via MED, annual output is 16,425 m^3. If additional CAPEX for heat recovery and TES is estimated at \$150,000–\$250,000 and O&M at \$10,000/year, the levelized cost of water (LCOW) over 20 years at 8% discount rate falls in the range of \$1.8–\$3.5/m^3, excluding brine management and contingencies. This is higher than large-scale RO (\$0.5–\$1.5/m^3) but comparable to small off-grid thermal systems. These figures highlight that WT-WH desalination is economically viable only for decentralized, niche applications, where avoided fuel costs and social benefits justify the investment. Future work should refine these estimates through detailed techno-economic modeling and sensitivity analysis.

Finally, governance and institutional factors can be decisive. In La Guajira, challenges related to permitting, grid interconnection, and water rights have deterred investment. To advance WT-WH desalination, projects must align with regional development agendas and employ FPIC-based (Free, Prior, and Informed Consent) engagement with Wayuu communities, ensuring benefit-sharing and transparent monitoring. Embedding pilot projects within territorial planning can foster local ownership and long-term sustainability.

Overall, the literature converges on a clear conclusion: WT-WH desalination is not a large-scale solution in the near term, but it holds promise as a complementary pathway for decentralized water supply in resource-constrained regions. Advancing this field requires interdisciplinary collaboration, pilot-scale validation, and integrated assessments across technical, economic, environmental, and social dimensions. If successfully developed, such systems could meaningfully contribute to achieving SDG 6 (Clean Water and Sanitation) and SDG 7 (Affordable and Clean Energy), leveraging Colombia's emerging wind energy potential.

6. Conclusions

This scoping review identifies a significant knowledge gap in the integration of wind turbine waste heat (WT-WH) into seawater desalination (SWD). Current evidence is limited to conceptual and simulation studies, with no experimental validation or techno-economic assessments.

Key findings:

- WT-WH is typically low- to mid-grade (100–150 °C), aligning with thermal desalination processes such as MED and HDH.
- Modeled outputs (≈45 m^3/day per 7.58 MW turbine) confirm technical feasibility but highlight inherent scale limitations, restricting applications to decentralized microsystems.
- Nanofluid-based heat recovery shows up to 30% efficiency gains in simulations, but practical viability, cost, and environmental implications remain unresolved.

Novelty: This work provides the first structured scoping review on WT-WH desalination, mapping thermal compatibility and identifying research gaps across technical, economic, and environmental dimensions.

Research agenda:

1. Experimental measurement of WT-WH under real operating conditions.
2. Development of compact heat recovery systems and TES integration.
3. Comprehensive techno-economic modeling, including LCOW and sensitivity analysis.

4. Environmental and social impact assessments (nanoparticle containment, brine management).
5. Pilot-scale demonstrations in wind-rich, water-scarce regions such as La Guajira.

WT-WH desalination should be considered a niche solution for off-grid communities rather than a large-scale alternative, but it can contribute meaningfully to SDG 6 and SDG 7 if implemented within integrated energy-water strategies.

6.1. Strategic roadmap for advancing WT-WH desalination

To transform this proposal into viable solution, a five-phase roadmap is proposed:

Phase 1 (Basic Research): experimental measurement of waste heat in wind turbines and exergy analysis to determine its thermal quality and compatibility with MED/HDH/MD processes.

Phase 2 (Technological Development): design of compact heat recovery systems and their integration with thermal energy storage (TES) and heat pumps to overcome temperature limitations.

Phase 3 (Economic and Environmental Assessment): development of LCOW models and life cycle assessment (LCA), including brine management and material durability in saline environments.

Phase 4 (Pilot Implementation): deployment of decentralized units (10–50 m^3/day) in isolated communities in La Guajira, with community participation and inclusive governance. Phase 5 (Selective Scaling Up): Replication in other coastal wind energy zones with high water vulnerability, prioritizing social and environmental sustainability.

Each phase must include measurable milestones (e.g. experimental validation within 12 months and <10% error in thermal estimation) and strategic partnerships among academia, the energy sector, and local communities. This roadmap transforms the proposal into a concrete action plan, geared towards decentralized and niche applications, consistent with the SDGs and the socio-technical conditions of La Guajira.

Future studies should include exergy analysis to optimize the use of waste heat and reduce energy-quality losses, complementing the First-Law-based assessment.

Author contributions

CRediT: **Javier Mejía Pinedo:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Visualization, Writing – original draft; **Juan Fajardo:** Conceptualization, Investigation, Methodology, Project administration, Supervision, Validation, Writing – original draft, Writing – review & editing; **Dario Serrano-Florez:** Conceptualization, Formal analysis, Investigation, Methodology, Resources, Writing – original draft; **Ana Buelvas:** Conceptualization, Data curation, Investigation, Methodology, Resources, Writing – review & editing.

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Data availability statement

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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