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Feasibility and strategic potential of thermal desalination systems in Turkey

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Abstract

The efficient use of water resources is under great pressure due to population growth, industrialization, and climate change. Although Turkey is surrounded by seas, its limited freshwater resources place it in the category of water-stressed countries. In this context, alternative solutions such as desalination have strategic importance. This study provides a comprehensive evaluation of the technical, economic, and environmental feasibility of thermal desalination systems for Turkey. Unlike previous studies that focus mainly on general desalination trends, this paper specifically analyzes Turkey's geographical, climatic, and energy infrastructure conditions. It highlights the potential of integrating renewable energy sources and industrial waste heat into desalination systems to reduce costs and carbon emissions. The study also discusses region-specific challenges such as brine management and ecological impacts in the Mediterranean and Aegean Seas. A comparative assessment of Multi-Stage Flash (MSF), Multi-Effect Distillation (MED), and Vapor Compression (VC) technologies is provided, together with an economic analysis based on solar- and natural gas–assisted systems. The findings underline that renewable energy–assisted MED systems offer the most promising solution for Turkey. Strategically, the paper emphasizes the need for government incentives, pilot projects, and stronger integration of energy–water policies. By combining technical evaluation with strategic recommendations, the study contributes a novel framework for decision-makers seeking to ensure long-term water security in Turkey.

1. Introduction

Water, one of the most fundamental components of life, is of vital importance for the sustainability of the ecosystem. Although two-thirds of the Earth's surface is covered with water, only 2.5% of it is freshwater, and merely 0.10% of this amount is usable. However, factors such as global population growth, urbanization, and climate change increasingly hinder access to freshwater resources. In particular, the insufficiency of water resources in some regions is a significant problem that leads to economic and environmental crises. For example, limited access to clean water may lead to the spread of infectious diseases due to inadequate hygiene conditions and reduce product yield in the food sector. It can also diminish overall food production and threaten the livelihoods of communities' dependent on agriculture and livestock farming. This situation increases unemployment rates and lowers people's living standards.

According to the United Nations World Water Council (UNCWW), access to usable water was comparatively less critical in the 1950s; however, by the 1990s, water scarcity had become a significant issue in countries encompassing a total population of 300 million. As of 2023, approximately 40% of the world's population faces the risk of water scarcity, and by 2050, two-thirds of the global population is expected to experience severe water shortages [1].

Although Turkey is surrounded by seas on three sides, it is not classified as a water-rich country. The combination of its semi-arid climate, significant regional variability in precipitation, and projections by the Turkish Water Institute—which estimate that per capita water availability will decline from 1,313 m^3 in 2023 to 1,120 m^3 in 2050 due to a projected population of 100 million—places Turkey among the countries facing water stress. Water stress refers to a situation where a country's available water resources are insufficient relative to its population. Water availability of 1,000–1,700 m^3 per person indicates a state of water stress, while levels falling below 1,000 m^3 per person denote water scarcity. Data in Table 1 on Turkey's annual per capita water availability shows that the country has been experiencing water stress for the past 25 years. Due to increasing population, climate change, unregulated agricultural use, unplanned water consumption, and limited water resources, the annual per capita water amount continuously decreases [2].

Table 1. Annual Per Capita Water Availability in Turkey.

Year	Annual Per Capita Water Availability (m^3/person)	Population (Million)
2000	~1650	~63
2020	~1350	~83
2024	~1308	~86
2025	<1120	~100

The distribution of water resources in Turkey is regionally imbalanced; the Southeastern Anatolia and Central Anatolia regions face a higher risk of water scarcity. In addition, in the Marmara and Aegean regions, population growth and industrialization place increasing pressure on freshwater resources [3–4]. In recent years, the problem of water scarcity has become more pronounced in certain parts of Turkey. For example, the Konya Closed Basin is the largest endorheic basin in the country. Despite its agricultural significance, and the absence of any natural inflow or outflow, groundwater levels in the basin have dropped to alarming depths. In 2000, the groundwater level in the Konya Plain was approximately 10 meters, but by the 2020s it had declined to 45–60 meters. Factors contributing to this decline include uncontrolled irrigation, a decrease in precipitation (precipitation levels in Konya have fallen by approximately 20% since 2000), and increased evaporation due to rising temperatures [5]. Another example is the Salt Lake (Tuz Gölü) Basin, which spans the provinces of Konya, Ankara, Aksaray, and Niğde. Satellite imagery shows that the surface area of the lake decreased by approximately 50% between 2002 and 2022. Since 2000, the drilling of nearly 10,000 unlicensed groundwater wells has disrupted the inflows feeding the lake, while uncontrolled agricultural irrigation has further intensified drought in the region [6]. In the Mediterranean and Aegean regions, agricultural demand, high evaporation rates, and tourism activities have increased water demand, further highlighting the potential of desalination technologies to offer region-specific solutions.

Water management in Turkey primarily relies on dams, reservoirs, and groundwater extraction. However, population growth, urbanization, drought, and climate change have rendered conventional water resources insufficient. The imbalance between water supply and demand necessitates the exploration of alternative sources. Desalination is a technology that produces potable and utility water from seawater or brackish water sources. This technology not only utilizes a renewable water source but also enables sustainable water supply. Approximately 97.5% of the Earth's water is seawater. Harnessing seawater can provide both economic and environmental benefits on a global scale. Therefore, desalination technologies represent a strategic solution not only for regions experiencing water scarcity but also for many countries worldwide.

In Turkey, the decline of freshwater resources, particularly along coastal regions, has increased the significance attributed to desalination technologies. According to the 2023 Water Report of the Ministry of Agriculture and Forestry and the 11th Development Plan, desalination systems are recognized as key strategies for improving water supply security [7].

Among the two primary desalination methods—membrane-based and thermal—the adoption of thermal desalination has remained limited, primarily due to its high energy requirements. Nevertheless, its low maintenance requirements and long-term durability in large-scale applications have led many countries to adopt it. In particular, in regions where energy costs are low or where renewable energy can be integrated, the potential for thermal desalination is considerably high [4–6].

This study aims to evaluate the technical and economic feasibility of thermal desalination systems within the geographical, climatic, and energy infrastructure context of Turkey. The analysis covers the suitability of Turkey's seawater characteristics for such systems, the impact of varying climatic conditions in the Mediterranean, Aegean, and Black Sea regions on system performance, and the compatibility of existing energy resources. In addition, the study examines the environmental implications of brine management and assesses whether adequate incentives are in place to support thermal desalination projects in Turkey. Furthermore, it seeks to identify the barriers and opportunities for the broader adoption of these systems, thereby providing a strategic basis for policymakers and researchers.

2. Conceptual Framework of Thermal Desalination

2.1. Concepts of Thermal Desalination

Thermal desalination is a process in which seawater evaporates and subsequently condenses to obtain fresh water. As an effective method for seawater with high salinity, thermal desalination is widely employed in large-scale facilities. The main methods used in thermal desalination systems are as follows:

Multi-Stage Flash Distillation (MSF): In this method, as illustrated in Figure 1, seawater is heated to its boiling point via a heat exchanger. The heated water is then pumped into multiple chambers operating at different pressures, where the pressure in each chamber is reduced to induce partial vaporization (flash evaporation). The resulting vapor is condensed on cold surfaces, producing liquid fresh water. The remaining brine, seawater with a high salt concentration, is discharged from the system.

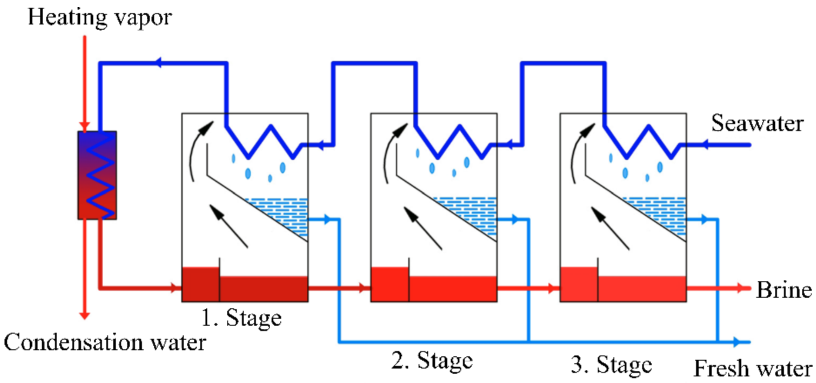

Figure 1. Schematic Diagram of the Multi-Stage Flash Desalination System [18].

Advantages [8–13]:

- Suitable for large-capacity facilities capable of producing thousands of cubic meters of fresh water per day.
- High efficiency in treating seawater with elevated salinity levels.
- Easy maintenance allows continuous operation for many years.
- The heat released during condensation can be recovered and reused, thereby reducing overall energy consumption.
- Can be integrated with renewable energy sources or industrial waste heat systems.

Disadvantages [8–13]:

- High installation costs make it a significant investment for large-scale facilities.
- Energy consumption is higher compared to other desalination methods.
- The separated brine has a high salinity level; its discharge back into the sea can disrupt marine ecological balance.

MSF plants are particularly common in water-scarce regions such as the Middle East. For instance, one of the main facilities that meet Dubai's water demand is the Jebel Ali Desalination Plant, was constructed with MSF technology in 1980s. According to Dubai Electricity and Water Authority (DEWA) reports, this plant produces 250,000 m^3/day of potable water at a unit cost of 1.50–1.80 USD/m^3. The brine is transported offshore via long pipelines and, due to its high density, settles at the seabed. However, environmental reports suggest that the measures implemented for brine management remain inadequate. [14–15].

Another example is the Yanbu Desalination Plant, located on the Red Sea coast of Saudi Arabia. As one of the world's largest thermal desalination plants, it stands out for achieving relatively low production costs due to low energy prices. According to the Saline Water Conversion Corporation (SWCC), Saudi Arabia's state-owned desalination authority, the natural gas-powered plant produces 880,000 m^3/day of potable water at a unit cost of 0.90–1.30 USD/m^3. Similarly, environmental assessments in the Red Sea region highlight that brine management practices remain inadequate, a concern also acknowledged by the Saline Water Conversion Corporation (SWCC) [15–17].

Both facilities demonstrate the feasibility of large-scale thermal desalination. However, given the high energy requirements and potential environmental impacts, the technology may not be suitable in all contexts. Integrating such systems with solar energy is projected to mitigate these disadvantages, particularly in countries like Turkey with high solar energy potential.

Multi-Effect Distillation (MED): As illustrated in Figure 2 and Figure 3, seawater is heated to its boiling point using a heat source such as steam, hot water, or waste heat. In the first effect, the heated water undergoes evaporation, and the resulting vapor serves as the heat source for the subsequent stage, thereby enhancing overall energy efficiency. The vapor formed in each stage condenses on cold surfaces to produce fresh water. Each subsequent effect operates at a lower pressure and temperature than the previous one.

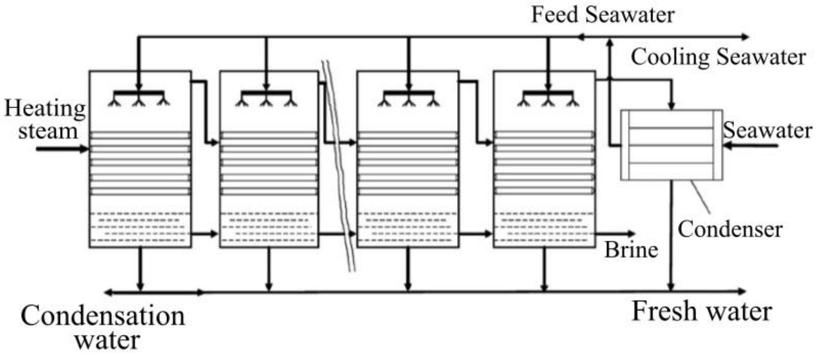

Figure 2. The Schematic Representation of the Multi-Effect Distillation (MED) System [15].

Advantages:

- The heat released in each effect is utilized as the heat source for the subsequent effect, thereby significantly reducing overall energy consumption.
- Energy recovery lowers operational costs.
- High efficiency in treating seawater with elevated salinity levels.
- Lower energy consumption and reduced environmental impact make it advantageous compared to other desalination methods.

Disadvantages:

- High installation costs require substantial investment for large-scale facilities.
- The design process is complex.

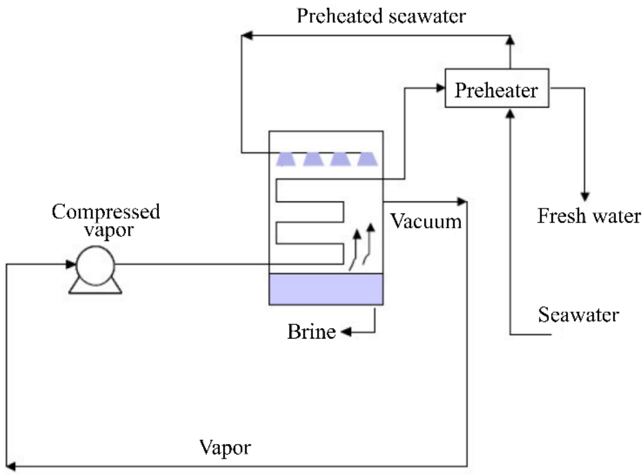

Figure 3. The Schematic Representation of the Vapor Compression (VC) Desalination System [21].

Advantages:

- Compression of the vapor using a compressor result in lower energy consumption, offering greater energy efficiency compared to other desalination methods.
- Highly suitable for small- and medium-scale facilities.
- Energy recovery contributes to reduced operational costs.

Disadvantages:

- Maintenance of the compressor, which is the most expensive component of the system, is costly.
- Not suitable for large-scale facilities.

Vapor Compression Distillation is distinguished by its advantages in energy savings and operational flexibility. However, its limited capacity and high technological requirements restrict its application in large-scale projects [8–13].

One successful example of a vapor compression desalination system is the Ashkelon Desalination Plant in Israel, with a daily capacity of 320,000 m^3. Due to their potential to improve energy efficiency, vapor compression desalination systems are often preferred as part of hybrid configurations [17]. In Turkey, the VC system is suitable for small- and medium-scale applications; however, its high electricity consumption may limit widespread adoption.

Table 2. Comparison of Thermal Desalination Systems in Terms of Applicability [22-27].

Evaluation Criteria / Technology	**MED**	**MSF**	**VC**
Specific Energy Consumption	1.5 – 2.5 kWh/m^3 (thermal) + low electricity	3.5 – 5.5 kWh/m^3 (thermal) + low electricity	7 – 12 kWh/m^3 (electric – compressor-based)
Operating Temperature	60 – 70 °C	90 – 120 °C	70 – 90 °C
Water Recovery Ratio	40% – 60%	25% – 40%	30% – 50%
Brine Discharge	Medium	High	Low – Medium
System Complexity	Medium	High	Low – Medium
Maintenance and Operational Difficulty	Medium	High	Low
Application Scale	Medium – Large scale	Very large scale (e.g., municipal supply)	Small – Medium scale (e.g., ships, hotels)
Energy Source Compatibility	Waste heat, solar thermal, steam	Waste heat, fossil fuels	Electricity (compatible with renewables)
Capital / Operating Cost	Medium	High	Low – Medium
Modularity / Flexibility	Medium	Low	High

A comparative evaluation of MSF (Multi-Stage Flash Distillation), MED (Multi-Effect Distillation), and VC (Vapor Compression Distillation) technologies is provided in Table 2. The water recovery ratio represents the proportion of feed seawater converted into potable water. MED exhibits the highest recovery efficiency among the evaluated technologies, due to its ability to function at lower temperatures and superior energy performance, though brine management improvements are still necessary. The initial capital expenditure for MED is moderate. MSF is characterized by its suitability for large-scale installations and long operational lifespan; nevertheless, its high energy demand, substantial capital investment requirements, and inherent system complexity constitute significant limitations. VC, as an electricity-driven technology, is well-suited for small-scale applications and offers high modularity and flexibility. Despite these advantages, its considerable electricity requirements and relatively higher operational costs constrain its broader deployment.

Table 3. Capacities of Commercially Established Desalination Plants [14, 15, 16, 19, 20].

Plant	Location	Daily Freshwater Production (m³/day)	Daily Brine Discharge (m³/day)	Brine Recovery system	Source
Jebel Ali	Dubai, UAE	250,000	100,000	Discharge only	DEWA Reports (2022), IDA
Yanbu	Saudi Arabia	880,000	352,000	Pilot projects	SWCC Reports (2022), IDA
Shuaiba North	Kuwait	486,000	194,400	Discharge-oriented operation	MEW Reports (2023), IDA
Ras Abu Fontas A3	Qatar	146,000	58,400	None	Kahramaa Reports (2023)
Al Taweelah	UAE	950,000	380,000	Pilot projects initiated	TAQA Reports (2023), IDA
Ashkelon	Israel	330,000	132,000	No existing infrastructure	IDE Technologies (2006), IDA

As presented in Table 3, the analyzed desalination plants generally discharge diluted brine into the sea through long-distance pipelines directed towards areas influenced by deep-water currents. Environmental reports indicate that current brine management practices remain insufficient; however, various mitigation and improvement initiatives are ongoing. In the case of Turkey, several measures are recommended: (i) developing solar-assisted technologies in regions such as Antalya and Mersin, (ii) directing R&D investments toward brine recovery projects, and (iii) establishing university–industry collaborations for pilot projects focused on mineral extraction (e.g., magnesium, lithium).

2.2. Comparison with Other Desalination Thechnologies

Thermal desalination methods are particularly effective and reliable for seawater with high salinity concentrations. When integrated with renewable energy sources or industrial power plants, the energy consumption costs can be significantly reduced. Moreover, their suitability for large-scale installations constitutes a notable advantage [28–30].

Alternatively, reverse osmosis (RO) represents another major desalination method for converting saline water into potable water. In the RO process, seawater undergoes preliminary treatment followed by pressurization to pass through a semi-permeable membrane, thereby removing dissolved salts. This technique can achieve up to 99% salt removal; however, the high operating pressure results in elevated energy costs. Furthermore, membrane fouling and degradation occur over time. In Turkey, the biological and physical characteristics of seawater—particularly during summer months—pose operational challenges for RO systems. High concentrations of phytoplankton, suspended solids, microbiological contaminants, and organic pollutants (e.g., oil, detergents) contribute to membrane fouling and raise pretreatment costs. Fouling also increases transmembrane pressure, water and chemical consumption during cleaning, and raises annual maintenance costs by 10–20% [28–30].

Moreover, the integration of thermal desalination systems with Reverse Osmosis (RO) offers notable benefits in terms of energy efficiency, water quality, and environmental performance. An illustrative example is the Fujairah 1 Desalination Plant in the United Arab Emirates, which operates as a hybrid facility combining Multi-Stage Flash Distillation (MSF) and RO technologies. The plant operates alongside an integrated power station that generates both electricity and steam, thereby utilizing waste heat from the thermal process to lower the energy demand of RO. The facility's daily capacity of 1,000,000 m^3 highlightes the practical significance of hybrid desalination technologies for large-scale implementation [17].

Thermal desalination systems involve higher initial costs than membrane-based systems; however, suitable choices of energy source and site can deliver long-term advantages. A regional analysis of Turkey shows that:

- **Mediterranean Region:** Tourism and agricultural demand place considerable pressure on available fresh water resources. Given the high salinity of Mediterranean seawater and the region's long sunshine duration, solar-assisted thermal desalination systems are the most suitable option.
- **Aegean Region:** Irrigation requirements and drinking water demand in tourism areas dominate water usage. Accordingly, hybrid configurations integrating thermal desalination with small-scale RO systems may represent a suitable option for this region.
- **Marmara Region:** High levels of industrial activity and population density increase water demand. Due to lower salinity levels compared to the Mediterranean and Aegean seas, and the feasibility of small-scale installations close to demand centres, RO systems are more appropriate.
- **Black Sea Region:** The low salinity of seawater in this region provides a distinct advantage for RO applications.

2.3. Energy Recovery Methods in Thermal Desalination

Energy recovery plays a critical role in improving the efficiency and sustainability of thermal desalination systems. In particular, optimization of heat exchangers reduces scaling and fouling while enhancing heat transfer, thereby lowering specific energy consumption. Multi-Effect Distillation (MED) systems inherently reuse latent heat between successive stages, and advanced configurations further increase recovery efficiency. Vapor compression technology also contributes by recycling part of the thermal energy, thus decreasing operational costs and reducing dependence on external energy sources.

Hybrid approaches that integrate thermal desalination with membrane-based processes, such as reverse osmosis (RO), can provide additional advantages. For instance, waste heat from thermal processes can be used to preheat RO feedwater, lowering the pressure requirement and improving overall energy efficiency. Furthermore, coupling with renewable energy—particularly solar and geothermal sources—enhances the applicability of these methods in regions like Turkey, where such resources are abundant. In this way, energy recovery strategies significantly improve the technical feasibility and long-term economic viability of thermal desalination projects.

3. Conceptual Framework of Thermal Desalination

3.1. Existing Technological Infrastructure and Applications

Although Turkey is bordered by seas on three sides and possesses substantial renewable energy potential, the deployment of desalination technologies has remained limited. Existing applications are generally small-scale, where energy costs are comparatively lower. For instance, small-scale reverse osmosis (RO) systems are employed in boutique hotels in tourist destinations such as Bodrum and Çeşme, as well as in Aliağa to supply process water for power plants and petrochemical facilities. Thermal desalination systems, however, are not widely deployed.

From a wider energy and resource perspective, Turkey's geographic position—characterized by abundant solar, wind, and geothermal potential, together with the relatively high salinity of its surrounding seas—offers distinct advantages for the application of thermal desalination systems. The fact that Turkey is bordered by seas on three sides facilitates the direct use of seawater as feedwater in desalination plants. Furthermore, the integration of rich renewable energy resources with desalination facilities can provide the required thermal energy at a lower cost. An additional advantage of thermal desalination is the limited requirement for chemical usage, thereby supporting environmental sustainability [8–13].

Salinity levels in the seas surrounding Turkey range from 16–22‰ in the Black Sea and 22–25‰ in the Sea of Marmara to 38–40‰ in the Aegean Sea and 39–41‰ in the Mediterranean Sea. The high salinity, particularly in the Aegean and Mediterranean, underscores the effectiveness and reliability of thermal desalination systems for treating seawater with elevated salt concentrations [29].

3.2. Cost Analysis of Thermal Desalination

Cost analysis of thermal desalination systems involves consideration of parameters such as capital investment, operational expenses, maintenance requirements, and energy consumption. These factors are central to evaluating both the feasibility and the long-term sustainability of the technology.

Due to the saline nature of seawater, maintenance costs constitute a significant portion of the total expenditure in desalination systems. The main contributors to maintenance expenses include heat exchangers, evaporators, and condensers, which require regular cleaning and servicing to prevent scaling, clogging, and other operational problems caused by seawater [12–31].

In thermal desalination systems, energy-related expenditures account for the largest share of total costs. As the integration of renewable energy sources is not yet common practice, current applications generally rely on natural gas or industrial waste heat. The incorporation of renewable energy sources into these systems can significantly improve environmental sustainability and reduce long-term costs. Relying on renewable resources eliminates fuel expenditures, thereby lowering operational costs throughout the plant's lifetime. Furthermore, lower carbon emissions and reduced dependence on imported fossil fuels constitute critical factors for strengthening national energy and water security.

Multi-Effect Distillation (MED) systems operate at lower temperatures than Multi-Stage Flash (MSF) systems, resulting in lower corrosion risks and reduced wear on components. The integration of MED systems with geothermal or solar energy can lead to significant reductions in energy costs [14]. Low- to medium-temperature geothermal resources can meet the thermal energy requirements of such systems, and their year-round availability ensures a continuous energy supply. In Turkey, the Kızıldere region in Denizli hosts geothermal resources with temperatures exceeding 200 °C, whereas the Germencik region in Aydın exhibits geothermal fluids ranging between 180–230 °C. Both sites are suitable for combined electricity generation and thermal applications. Geothermal sources in Manisa and İzmir regions, with temperatures between 90–150 °C, also provide favourable operating conditions for thermal desalination systems.

Solar energy is another viable option for supporting thermal desalination processes. The annual average sunshine duration is approximately 3,000 hours in Antalya and 2,900 hours in Mersin, making these provinces highly suitable for both electricity generation and thermal applications. For example, Ege University has implemented a research-oriented solar desalination system, operating a small-scale MED unit powered by vacuum-tube collectors. An illustrative cost comparison can be made for a 10,000 m^3/day thermal desalination system using either natural gas or solar energy as the primary energy source:

Table 4. Capital Expenditures (CAPEX) [19, 22, 32-38].

Component	Natural Gas–Assisted System (TRY)	Solar Energy–Based System (TRY)
Main Equipment	17,600,000	17,600,000
Heat Source	500,000 (Natural gas boiler)	4,000,000 (Solar collectors + storage tank)
Electrical/Automation	1,500,000	2,000,000 (Batteries, inverter, etc.)
Installation and Assembly	2,000,000	2,500,000
Site Preparation	1,000,000	1,000,000
Total Gross Capital Cost	22,600,000	27,100,000

As observed in the Table 4 and Table 5, although the capital investment for the solar energy–based system is higher due to the inclusion of solar collectors, storage tanks, and electrical infrastructure, it provides substantial long-term savings in energy expenditures.

Table 5. Energy Costs (OPEX) [19, 22, 32-38].

System	Energy Consumption	Unit Price (TRY / kWh)	Unit Cost (TRY / m³)
Natural Gas–Assisted	80 kWh/ton	2.20	2.70
Solar Energy–Assisted	60% solar, 40% natural gas	-	1.30

In the case of the solar energy–assisted system, it is assumed that partial natural gas support is required, considering that full-capacity energy supply cannot be achieved during the winter months. Table 6 and Table 7 provides that the solar energy-supported system has approximately 45% lower annual production costs.

Table 6. Annual Water Production Cost Comparison [19, 22, 32-38].

System	Production Cost (TRY / m³)	Annual Total Cost (10.000 m³/day x 365 days)
Natural Gas–Assisted	3.12	11,388,000 TRY
Solar Energy–Assisted	1.72	6,278,000 TRY

Table 7. Depreciation and Payback Period [19, 22, 32-38].

Parameter	Natural Gas System	Solar Energy System
Initial Investment Cost	3.12 TRY / m³	11,388,000 TRY
Annual Operating Cost	1.72 TRY / m³	6,278,000 TRY

According to the annual operational cost data presented in Table 7, the solar energy–assisted system achieves payback within approximately 5–6 years, performing more favourably than the natural gas–assisted alternative. In addition, it demonstrates lower environmental impact and stronger alignment with climate change mitigation objectives.

In conclusion, although the natural gas–assisted system involves lower capital investment, its high operating costs, limited sustainability, and elevated CO_2 emissions undermine its long-term viability. The solar energy–assisted alternative, with moderate investment, low operating expenses, rapid payback, and strong environmental performance, emerges as the more suitable option, especially for large-scale facilities [22, 32–36].

3.3. Cost Analysis of Thermal Desalination

In the desalination process, the discharge of concentrated brine back into the sea can have detrimental effects on marine ecosystems due to its elevated salinity. Additionally, changes in seawater temperature may impose stress on biological diversity. Therefore, methods for the environmentally safe disposal or reuse of brine must be developed.

At the global scale, the average daily production of brine is approximately 50% greater than the volume of freshwater generated, with total brine output estimated at 141.5 million m^3/day. In desalination facilities, the brine volume is determined by the recovery ratio, which refers to the proportion of feedwater converted into freshwater. Lower recovery ratios result in higher brine volumes, as is the case with thermal desalination technologies, which typically exhibit lower recovery rates and therefore produce greater quantities of brine [22].

Brine from desalination plants is enriched in salts and minerals. Its direct discharge into the environment can negatively impact ecosystems. However, brine can also serve as a valuable resource, offering a sustainable alternative in several sectors. In the chemical industry, it provides raw materials such as sodium chloride, magnesium, and other salts used in various industrial processes. In battery manufacturing, brine is an important source of lithium, a critical element for lithium-ion batteries. Additionally, in agriculture, it can be utilized for irrigating salt-tolerant crops and for the cultivation of marine algae. In Israel, some plants process brine for salt production, while in Australia facilities recover magnesium for construction and agriculture. Brine can also be integrated into aquaculture and agriculture. For instance, salt-tolerant algae such as Spirulina or halophyte crops irrigated with diluted brine have increased fish biomass by up to 300% [22].

The seawater intake process can also entrain marine organisms and plankton, contributing to a decline in biodiversity. To mitigate these effects, multi-stage pre-filtration systems, including sand or biological filters, can be implemented [29–32]. Additional measures, such as locating intake structures below the seabed and maintaining low intake velocities, can further reduce the entrainment of living organisms [22].

The potential impacts of brine discharge from planned thermal desalination systems in Turkey must be carefully evaluated, particularly in ecologically sensitive seas. For instance, in the Mediterranean Sea—a semi-enclosed basin characterized by limited water exchange and high evaporation rates—localized increases in salinity may become critical, with the potential to cause severe ecological degradation. Through crystallization technologies, salts and valuable minerals can be recovered from brine, simultaneously reducing waste and enhancing economic utility. Differences in salinity across Turkey's marine regions require the adoption of suitable technologies and region-specific brine discharge policies, particularly for the Mediterranean, Black Sea, and Aegean Sea, to reduce environmental risks.

While the deployment of such systems in Turkey remains limited, notable research efforts have been initiated. A TÜBİTAK-funded project in 2020, Recovery of Valuable Chemicals from Seawater Desalination Brine, demonstrated the successful recovery of NaCl, $Mg(OH)_2$, and $CaCO_3$, though commercialization has not yet been achieved [36]. In parallel, studies by the Department of Field Crops at Ege University examined the use of diluted brine for irrigating Salicornia; however, translation of these findings into large-scale practice remains pending [18]. Furthermore, studies conducted by the Agricultural Research Directorate of Middle East Technical University observed yield reductions and soil degradation in areas irrigated with brine. Consequently, the use of a dilution–rotation–monitoring model has been recommended to mitigate the adverse effects of brine irrigation, namely yield reduction and soil degradation [35].

4. Conceptual Framework of Thermal Desalination

4.1. Legal Regulations on Desalination Technologies in Turkey

In Turkey, regulatory frameworks specifically addressing desalination technologies remain limited; however, existing legislative provisions on the efficient utilization and management of water resources are applicable to this domain. Such provisions hold particular importance for projects implemented in coastal areas. Notably, the Environmental Law, the Water Pollution Control Regulation, and the Environmental Impact Assessment (EIA) Regulation define the requirements, environmental impact considerations, and mitigation measures to be observed during the construction and operation of desalination plants.

The planning of desalination facilities requires careful assessment of seawater protection and the sustainability of marine ecosystems. For instance, desalination projects proposed in the Datça and Bozburun regions encountered legal challenges, as the planned sites were situated within or adjacent to environmentally sensitive areas protected under national and international frameworks, including the Law on the Conservation of Cultural and Natural Assets (Law No. 2863), the Environmental Law, and the Barcelona Convention. These areas are recognized as UNESCO Biosphere Reserve sites with high biodiversity value. Although the EIA reports for these facilities stated that brine discharge would be diluted and released offshore through pipelines placed on the seabed, environmental groups and local fishermen argued that the risk assessment was incomplete. Consequently, the project was cancelled, and a new EIA study was mandated. This case underscores the critical role of regulatory compliance and environmental assessment in the establishment of desalination plants.

Within the broader context of efficient and sustainable water management, brine discharge management is increasingly emphasized in national policy, alongside legal arrangements that encourage water reuse. It has been proposed that eligible industrial sectors for brine discharge should be identified, and that incentives—such as those supported by TÜBİTAK and KOSGEB—should be introduced to promote brine recovery, with brine management made mandatory for desalination plants.

The Draft Water Law, prepared by the Ministry of Agriculture and Forestry and currently subject to public consultation, has not yet been enacted. Nevertheless, its provisions suggest that desalination will assume greater prominence in Turkey's future water management and sustainability strategies [39–40]. The draft law outlines strategic planning measures to address water scarcity under intensifying climate pressures, alignment with international standards on brine management, the promotion of new entrepreneurial opportunities in recovery technologies, and the establishment of a framework for public–private–academic partnerships in R&D activities.

In this context, the development of a dedicated legislative framework for desalination emerges as a necessity. Such a framework should establish minimum standards for brine management; prohibit brine discharge in ecologically sensitive coastal areas or mandate alternative disposal methods; integrate scientific advisory mechanisms into the Environmental Impact Assessment (EIA) process; and promote the creation of specialized academic centers focused on desalination and brine management.

4.2. Strategic Planning and Investment Policies

Strategic planning and investment policies in thermal desalination have been formulated to ensure the sustainable management of water resources and to address the challenges of water scarcity in Turkey. The country is classified among water-stressed nations, with per capita annual water availability at or below the 1,700 m^3/year threshold. This vulnerability is further aggravated by global drivers such as climate change and population growth, which threaten food production, constrain access to clean water with attendant public health implications, reduce agricultural and industrial productivity, and contribute to demographic imbalances [40].

In response, recent national strategies have emphasized sustainable water management, the adoption of efficient irrigation practices, and the development of alternative solutions, including desalination technologies. Within this framework, the integration of renewable energy into desalination systems is promoted as a means of enhancing sustainability while simultaneously reducing operational costs.

Furthermore, investment in desalination projects is encouraged through fiscal incentives such as tax reductions and low-interest loans, complemented by financial and technological support from international institutions, including the European Investment Bank and the World Bank [39–40].

5. Conceptual Framework of Thermal Desalination

In the current context of limited water resources in Turkey, compounded by the escalating effects of climate change, the deployment of thermal desalination systems has gained increasing significance. To ensure their effective and sustainable utilization in the future, the following recommendations are proposed:

- The adoption of low-energy thermal desalination systems, such as Multi-Effect Distillation (MED), is critical for enhancing energy efficiency. In particular, the integration of these systems with renewable energy sources and the implementation of advanced heat recovery technologies can substantially reduce energy consumption.

- Turkey's geographical location offers considerable potential for renewable energy exploitation. For example, supporting thermal desalination systems with photovoltaic solar panels or integrating them with the country's abundant geothermal resources is expected to improve system efficiency.
- Combining thermal desalination with membrane-based technologies such as reverse osmosis (RO) can further enhance energy efficiency in potable water production.
- Due to the saline nature of seawater, durable and corrosion-resistant materials should be employed. The use of high-performance heat transfer materials can also improve thermal efficiency.
- Desalination plants typically have high energy demands, often met by fossil fuels, which increases their carbon footprint. Prioritizing low-carbon technologies, particularly those powered by renewable energy, can mitigate environmental impacts.
- Investment in research and development (R&D) is necessary to advance thermal desalination technologies and improve efficiency. Awareness-raising programs should also be implemented to promote understanding of the benefits and applications of these systems.
- Modern technological solutions should be employed, such as sensor-based monitoring for data collection, predictive maintenance scheduling using model-based approaches, optimization of heat transfer rates and vapor pressure, and the development of control systems capable of switching between hybrid energy sources. Integration of artificial intelligence into these systems can minimize energy consumption and significantly reduce maintenance costs.
- Pilot projects should be conducted across different regions of Turkey to evaluate the applicability and effectiveness of thermal desalination systems. The development of system designs adapted to regional climate conditions and available energy resources is essential for achieving optimal performance. Such initiatives would facilitate the identification of the most efficient configurations, develop solutions adapted to specific water quality and energy supply conditions, and strengthen collaboration among public institutions, the private sector, and academia. For example, Antalya—one of Turkey's provinces with the highest annual sunshine duration and high Mediterranean salinity—may host a solar-assisted MED system through cooperation among the State Hydraulic Works (DSİ), Antalya Metropolitan Municipality, Akdeniz University, and local solar energy companies.

These technological advancements can provide effective solutions to Turkey's water scarcity challenges while supporting sustainable water management. Furthermore, making thermal desalination more economically viable through innovative approaches could promote its widespread adoption.

6. Conceptual Framework of Thermal Desalination

Turkey's geographical position and increasing water demand underscore the necessity of developing alternative water resources. The implementation of desalination systems, however, is constrained by high capital costs, limited domestic technological capacity, potential impacts on marine ecosystems, and geographical as well as geopolitical challenges. These barriers can be addressed through targeted R&D investments, region-specific pilot projects, and appropriate policy reforms.

Research on brine management and recovery, coupled with community engagement, will be central to advancing thermal desalination technologies. When combined with technological innovation and the integration of renewable energy, these efforts could position desalination as a viable component of Turkey's long-term water management strategies. Overcoming key barriers—namely high energy demand, environmental impacts, and elevated installation costs—will require continuous research initiatives and sustained financial commitment.

Relevant support may include project coordination and infrastructure facilitation by the State Hydraulic Works (DSİ); R&D funding and technological assistance from TÜBİTAK; and renewable energy incentives introduced by the Energy Market Regulatory Authority (EPDK). Through these mechanisms, Turkey can foster innovation in desalination technologies, ensuring potable water supply security while contributing to broader economic development. In the longer term, more extensive and efficient deployment of these systems will reinforce national efforts to preserve water resources and guarantee reliable access to freshwater.

Future research should focus on hybrid desalination systems that combine thermal and membrane-based processes to improve both energy efficiency and water quality. Advanced brine management strategies—such as mineral recovery and integration with aquaculture—merit further investigation for their environmental and economic benefits. Pilot projects integrating renewable energy into thermal desalination across Turkey's coastal regions will be crucial for testing real-world applicability. Finally, simulation-based techno-economic analyses and optimization studies are recommended to provide policymakers and investors with robust data for scaling up sustainable desalination solutions.

Author contributions
Beyza Nur Yavuzer: Conceptualization, Methodology, Software, Writing-Reviewing and Editing.
Gulcan Ozel Erol: Data curation, Management, Writing-Reviewing and Editing.

Conflicts of interest
The authors declare no conflicts of interest.

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