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Renewable energy integration in seawater desalination: A life cycle costing perspective for sustainable water supply

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ABSTRACT

Freshwater scarcity is intensifying in Mediterranean regions due to population growth, tourism, intensive agriculture, and climate-driven hydrological stress. In parallel, countries highly dependent on energy imports and lacking resilient water infrastructure face structural disruptions in water supply. While seawater desalination has emerged as a viable solution worldwide, its deployment remains limited in several regions due to cost and energy constraints.

This study assesses the techno-economic feasibility of integrating renewable energy into seawater desalination to support an affordable and sustainable water supply. A Life Cycle Costing approach is applied to a 12,500 m^3/day seawater reverse osmosis plant operating under six alternative energy configurations. Energy modeling is conducted using HOMER Pro, based on updated regional economic and environmental data. The analysis provides the first comprehensive techno-economic assessment of hybrid solar-wind-grid solutions for Mediterranean desalination, demonstrating that optimized renewable oversizing can significantly reduce water costs without relying on energy storage.

Results indicate that renewable-powered scenarios can reduce the Levelized Cost of Water by up to 20% compared to grid-only systems, while improving resilience to fossil fuel price volatility. The most cost-effective scenario performs competitively with conventional municipal water tariffs and remains significantly more economical than emergency alternatives.

Using a Mediterranean case study (Gela, Italy) as a reference, this work demonstrates the potential for renewable-powered desalination to support secure, low-carbon, and climate-resilient water supply in energy-constrained and water-stressed regions worldwide.

1. Introduction

The growing global demand for freshwater, combined with the effects of anthropogenic climate change, is placing unprecedented pressure on water resources worldwide. The world's population, currently exceeding 8 billion, is projected to surpass 9.7 billion by 2050 (United Nations Department of Economic and Social Affairs PDivision, 2022), with urbanization, industrial development, and agricultural expansion driving a continuous rise in water consumption (Food and Agriculture Organization FAO, 2017; United Nations Educational S and CO (UNESCO), 2024). At the same time, climate change significantly alters the global hydrological cycle, worsening the frequency, intensity, and duration of extreme weather events, including both droughts and floods (Douville et al., 2021; Caretta et al., 2023). There is a significant regional disparity in the impacts of climate change. Between 1970 and 2019, low- and lower-middle-income countries experienced 41% of all natural disasters but accounted for 82% of the resulting deaths. Droughts, despite comprising only 6% of all the events, led to 34% of all disaster-related fatalities, the majority of which occurred in sub-Saharan Africa (World Meteorological Organization, 2021).

The severity of these climate-related impacts is not equally distributed worldwide. Regions already experiencing water stress are expected to see a further decline in freshwater availability, with southern and eastern Mediterranean areas among the most vulnerable. Specifically, the Mediterranean basin, situated at the intersection of temperate European and arid North African climates, is recognized as a climate

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change hotspot (Lionello and Scarascia, 2018). In this region, temperature increases and precipitation anomalies are more pronounced than global averages, contributing to hydrological and agricultural droughts. Several areas will be affected by more severe agricultural and ecological droughts even if global warming is stabilized at 2 °C. At 4 °C of global warming, about 50% of all inhabited regions would be affected by increases in agricultural and ecological droughts (Intergovernmental Panel for Climate Change (IPCC), 2023). These trends are already manifesting with more frequent and prolonged dry periods, degraded water quality, and pressure on food and energy systems. Moreover, tourism growth, intensive agriculture, and seasonal population surges further exacerbate water demand in Mediterranean countries (European Environment Agency (EEA), 2023).

In this context, the European Green Deal identifies water scarcity and droughts as priority policy issues (European Commission (EC), 2024a), further emphasized in several major EU strategies, including the 2021 EU Strategy on Adaptation to Climate Change (European Commission (EC), 2021), the 2020 Circular Economy Action Plan (European Commission (EC), 2025a), and the EU Biodiversity Strategy for 2030 (European Commission (EC), 2023a). These frameworks highlight the need to move towards a water-efficient and climate-resilient economy, promoting long-term, diversified, and resilient water supply options (United Nations Educational S and CO (UNESCO), 2024; Lebu et al., 2024; European Environment Agency (EEA), 2021). Among these, alternative water sources such as desalination are increasingly considered for coastal and drought-prone areas.

Technological progress and the use of renewable energy have greatly enhanced the environmental and economic performance of desalination plants (Ghaffour et al., 2013; Caldera et al., 2016), making them competitive with traditional water supply methods. However, deploying desalination systems must be tailored to specific circumstances, particularly in regions where water infrastructure is vulnerable, grid reliability is limited, energy costs are high, or socio-economic factors pose additional challenges.

Integrating best practices and maximizing onsite renewable energy use offers a dual benefit. On the one hand, it reduces both the economic and carbon cost of desalination, facilitating its broader adoption as a primary source of potable water, particularly in water-stressed regions (Guo et al., 2024). On the other hand, increasing the share of desalinated water in the supply mix can alleviate pressure on fragile surface and groundwater resources. These combined effects, enhancing supply resilience while mitigating environmental and climate impacts, underscore the strategic importance of making desalination more cost-effective. In parallel, several EU initiatives are actively supporting the deployment of sustainable desalination technologies; among them, the BlueInvest platform is accelerating innovation and investment in the sustainable blue economy, reinforcing the strategic relevance of integrating desalination with onsite renewable generation (European Commission (EC), 2025b).

This study aims to enrich the scientific literature by examining the structural integration of seawater desalination into Italy's water supply system, a country where, unlike Spain, North Africa, or the Middle East, desalination has historically been employed only as an emergency or marginal solution.

By focusing on the coastal city of Gela, located in a region particularly impacted by critical water infrastructure, supply interruptions, and increasing water stress, this research investigates the feasibility of transitioning from emergency-driven interventions to a more resilient and decentralized water supply model, which is possible thanks to the presence of updated data on the cost faced by citizens to purchase water privately during water emergencies. A key innovation of this work is the coupling of desalination with renewable energy sources to lower both operational costs and environmental impacts, an aspect increasingly recognized as essential for the long-term sustainability of energy-intensive water supply systems.

Beyond its technical and economic insights, the Gela case study provides strategic guidance for other Mediterranean regions seeking to improve water resilience amid climate change, infrastructure challenges, and rising demand.

In addition to techno-economic performance, this study provides a preliminary estimation of operational carbon emissions across scenarios, assessing alignment with EU sustainable finance thresholds (European Investment Bank (EIB), 2022).

The remainder of the article is structured as follows. Section 1 presents the theoretical background. Section 2 details the methodological framework, including case selection, RO plant design, Life Cycle Costing (LCC) approach, characterization of energy scenarios, and emergency supply data. Section 3 reports the techno-economic results across the six configurations. Finally, Section 4 provides the main conclusions and policy implications.

2. Theoretical background: Desalination as a potential solution

The increasing pressure on water resources, exacerbated by climate change, has driven the European Union to consider desalination as a strategic solution to ensure water security, especially in the Southern European regions most exposed to drought risk (European Parliamentary Research Service (EPRS), 2025). In fact, desalination can significantly alleviate pressure on freshwater resources, particularly in chronically water-stressed areas such as Southern Italy, Greece, and Southern Spain.

RO technology is currently the most efficient and competitive solution due to ongoing reductions in energy consumption and water production costs (Jan et al., 2021). Over the past two decades, energy consumption for Seawater Reverse Osmosis (SWRO) desalination has drastically decreased due to advancements in membrane technologies and energy recovery devices. From 8 kWh/m^3 in the 1980s, modern state-of-the-art RO plants operate at 2.5–2.8 kWh/m^3, while the industry average is approximately 3.1 kWh/m^3 (Voutchkov, 2018), achieving water costs below 1 USD/m^3. These improvements have established RO as the preferred technological and economic option compared to thermal processes such as multi-stage flash (MSF) and multi-effect distillation (MED), which require 9–16 kWh/m^3.

Technological advancements in SWRO desalination have driven its global diffusion, reaching 100 million m^3/d in 2023, particularly in Middle Eastern countries characterized by rapid economic growth and severe water scarcity (GWI, 2024). Currently, MSF and RO technologies dominate the global desalination market. In Europe, RO is the most widespread technology, accounting for 88.5% of installed capacity, whereas thermal processes (MSF: 31%, MED: 9%) are still widely used in the MENA (Middle East and North Africa) region due to low-cost fuels and co-location with large power plants.

Desalination plants are classified by operational capacity as small (<1000 m^3/day), medium (1000–10,000 m^3/day), large (10,000–50,000 m^3/day), and extra-large (>50,000 m^3/day). Economies of scale and rising demand are driving the construction of increasingly large desalination plants in the GCC (Gulf Cooperation Council) region. Over the past five years, the average capacity of large-scale plants awarded in the GCC reached 390,000 m^3/day, a 132% increase from the 168,000 m^3/day average in the preceding five-year period. A notable example is the Hassyan RO desalination plant in Dubai, powered by renewable energy, with a production capacity of 800,000 m^3/day and a water cost as low as 0.37 USD/m^3 (GWI, 2024).

Integrating RO desalination with renewable energy sources, such as photovoltaic (PV) and wind power, is increasingly seen as a sustainable solution to mitigate operational and environmental costs associated with fossil-fuel-powered desalination plants. Furthermore, renewable energy integration counteracts the volatility of fossil fuel markets and makes desalination viable for regions with limited conventional energy resources (García et al., 2015). Recent Life Cycle Assessment (LCA) studies have shown that integrating wind and solar power significantly reduces the environmental impacts associated with desalination processes (Najjar et al., 2022; Nurjanah et al., 2024; Pistocchi et al., 2020; Raluy et al., 2005). Forecasts suggest that in solar-rich areas such as the Mediterranean region, large-scale adoption of PV-powered RO systems could lead to water production costs falling below 1 USD/m^3 by 2030 (Pistocchi et al., 2020).

Desalination has become a key technology in addressing water scarcity, yet its high energy consumption remains a central concern. The energy source used in desalination significantly affects both its environmental footprint and economic viability. Currently, most desalination plants rely on fossil fuels, leading to a high carbon footprint (Pistocchi et al., 2020). To align with the ongoing energy transition and global climate goals, we need to phase out fossil fuels (International Energy Agency (IEA), 2021). Therefore, several studies have explored desalination powered exclusively by renewable sources. An international research (Caldera et al., 2016) evaluated the feasibility of meeting global desalination demand by 2030 using only PV, wind energy, batteries, and Power-to-Gas (PtG), eliminating the need for grid electricity. Another study (Ganora et al., 2019) analyzed large-scale PV-powered RO desalination in the Mediterranean region, demonstrating that such systems could supply water to 200 million people, with energy storage significantly reducing dependence on the grid. However, these studies also highlight that without grid support, Capital Expenditure (CAPEX) increases, underscoring the importance of energy storage for financial viability. In fact, it was found that if the CAPEX under continuous operation (i.e., with grid exchanges) is 0.33 USD/m^3, the CAPEX of a plant with battery and reservoir storage would be 1.9 times higher (0.62 USD/m^3). In contrast, a plant without energy storage and without a grid would incur CAPEX about 2.5 times higher (0.83 USD/m^3). Generally, the intermittency of renewable energy sources poses operational challenges for maintaining system stability, requiring energy storage solutions and hybrid power supply systems that integrate grid electricity (Nurjanah et al., 2024; Karavas et al., 2019; Calise et al., 2019).

The integration of renewable energy sources and the grid into desalination systems has been examined in several regional studies. A study based in Lebanon (Najjar et al., 2022) evaluated the environmental and economic impacts of desalination, integrating various energy sources, including grid electricity, PV, wind, and Anaerobic Digestion (AD). It has been discovered that the grid-wind configuration had the lowest carbon footprint (60% lower than grid-only). At the same time, grid-AD was the most economically viable at 0.94 USD/m^3, by reducing the already low prices of Lebanon's grid electricity. However, the article did not investigate the integration of multiple renewable energy sources along with the grid, such as solar-wind-grid layouts.

The operational efficiency of desalination plants significantly influences their cost-effectiveness. In fact, Ayou et al. (2022) reported a PV-RO system in Madura Island, Indonesia, where 84% of the energy demand is met by PV, with grid electricity as partial backup. Such a high percentage of renewable energy utilization without energy storage systems is only possible by reducing the plant's operating time. Indeed, the plant operates only 8–9 h per day, aligning with peak solar availability. This results in lower capital amortization over time but still achieves a water cost of 9 USD/m^3, which remains competitive with local water supply alternatives. Moreover, Aljuwaisseri et al. (2023) analyzed high-salinity SWRO plants in Kuwait and found that, despite low electricity costs, the unit water cost is 1.36 USD/m^3, higher than the regional average. This is explained by the low plant utilization rate (30% of capacity), which increases the share of capital costs to 62–77% of the total water cost. The study emphasizes the importance of maximizing plant operation time to optimize costs.

A review by Nurjanah et al. (2024) examined the integration of RO desalination and renewable energy sources, including solar, wind, wave energy, and Pressure Retarded Osmosis (PRO). The reported levelized water costs for PV-, wind- and hybrid PV-wind-powered RO systems generally range from 1.3 to 1.8 USD/m^3, depending on scale and configuration. Consistent with these findings, Ghaithan et al. (2022) showed that hybrid PV-wind-grid systems can achieve lower water costs and emissions than grid-dominated configurations, even without battery storage.

Beyond plant design and planning, desalination costs can be reduced by integrating operations with the energy system. Salomons et al. (2023) examined the water-energy nexus in Israel, where desalination provides 80% of municipal water and accounts for 3% of national electricity consumption. The study highlights the role of electricity load-shedding programs (ELSPs), which offer financial incentives for desalination plants to reduce energy use during peak demand. Given the low grid electricity costs (0.102 USD/kWh), Israel has not incorporated renewables into desalination, making water production entirely dependent on the grid and vulnerable to supply disruptions during extreme weather events. Compensation for ELSPs participation can reach 2 USD/kWh for reductions within 30 min, creating strong economic incentives but potentially compromising the stability of water supply and emphasizing the need for better coordination between the energy and water sector. Due to high electricity costs, this case is poorly applicable to Europe, where a plant generally needs to uptake as lower electricity as possible from the grid.

Recent regional studies emphasize that Brackish Water Reverse Osmosis (BWRO) coupled with renewable energy is increasingly adopted to reduce energy costs and enhance water security, particularly in water-stressed inland regions. In Jordan, techno-economic assessments demonstrated the effectiveness of combining PV power with BWRO. One study (Bdour et al., 2022) reported that grid-dependent BWRO entails moderate water costs (0.60–1.18 USD/m^3), while PV integration reduced energy expenditure by 69–74%, resulting in Levelized Cost of Water (LCOW) values of 0.18–0.60 USD/m^3. Another Jordanian analysis (Zhang et al., 2025) similarly found that PV-BWRO can achieve costs as low as 0.36 USD/m^3. In the United States, large-scale modeling of hybrid PV-BWRO systems estimated LCOW values ranging from 0.80 to 1.62 USD/m^3 (Zhang et al., 2025). A distinctive feature of both the US and Jordan studies is the relatively high specific energy consumption of BWRO, 2.69–3.63 kWh/m^3 in the US and 2.7–5.6 kWh/m^3 in Jordan, despite the lower salinity of brackish groundwater. This is primarily due to the substantial pumping energy needed to extract water from deep aquifers (up to 900 m). Collectively, these works show that renewable-powered BWRO can become cost-competitive in regions with strong solar resources and accessible brackish groundwater. Although informative, these studies remain poorly comparable to Mediterranean coastal SWRO contexts. Their focus on brackish groundwater and generally lower electricity prices (especially in the US) limit direct translation to seawater desalination in Italy. Nevertheless, they reinforce a key insight relevant to this study: renewable integration consistently reduces unit water costs and enhances resilience in regions facing water scarcity and climate-induced supply deficits.

This study aims to conduct a technical and economic analysis of drinking water supply systems in areas subjected to water shortages and high energy costs. Recent literature has made significant advances in modeling the techno-economic feasibility of renewable-powered desalination; however, several critical gaps remain. First, few studies to date have investigated hybrid configurations that simultaneously integrate solar, wind, and grid electricity, despite the potential of such combinations to improve reliability and reduce the overall energy cost of desalination. Second, although several models acknowledge the role of the electricity grid in stabilizing power supply, they rarely quantify the economic constraints associated with high grid dependence. This aspect becomes particularly critical in countries such as Italy, where electricity prices are among the highest in Europe. Third, the combined influence of plant scale and operational efficiency is frequently overlooked. Larger plants benefit from economies of scale, but excessive oversizing can lead to intermittent operation, underutilization, and ultimately higher LCOW.

Addressing these gaps, the present study aims to:

(i) design a seawater reverse osmosis desalination plant capable of ensuring a stable and independent freshwater supply for the city of Gela, regardless of local climatic variability;
(ii) evaluate a set of hybrid energy mixes, solar, wind, and grid, to minimize both the economic and environmental burdens of desalination within the constraints of the Italian electricity system;
(iii) compare the resulting water costs with those currently borne by residents and businesses for emergency water supply measures, such as tanker ships and water trucks.

3. Methodology

3.1. Research design and methodological overview

This study employs a case study research design to evaluate the economic performance of seawater desalination under different energy supply configurations, to make a comprehensive comparison with emergency water supply costs. As displayed in Fig. 1, the primary objective is to calculate the LCOW for a SWRO desalination plant located in Gela, a water-stressed city in southern Italy. By simulating multiple energy scenarios, this research aims to assess the cost-effectiveness and economic sustainability of integrating desalination into a local water supply system that currently lacks structural use of this technology. This methodological choice is based on established frameworks for empirical case study research, particularly suitable for context-specific techno-economic investigations (Eisenhardt, 1989; Yin, 1994). A LCC approach is utilized to capture both capital and operational expenditures associated with the proposed desalination infrastructure. The analysis includes detailed estimations of energy consumption and cost, enabling comparisons across different electricity sourcing strategies (e.g., renewable-based, grid-connected, or hybrid). The technical modeling of the RO system is based on a standard single-stage Mediterranean configuration, adapted to local climatic and salinity conditions, using equations developed by Ganora et al. (2019) and Najjar et al. (2022). These models enable realistic estimations of feed pressure, recovery efficiency, and specific energy demand. To simulate and optimize the energy supply configurations, HOMER Pro (UL Solutions, 2024), a widely used platform for techno-economic optimization of distributed energy systems, is employed. This platform facilitates techno-economic analysis of hybrid power systems by incorporating site-specific solar and wind resource data, grid prices, and cost parameters. The scenarios modeled include both baseline and sensitivity configurations, aiming at identifying energy layouts that minimize LCOW while enhancing energy independence and environmental performance. The work integrates with the preliminary estimation of operational carbon emissions for each scenario.

3.2. Case selection

Italy, like much of Southern Europe, is facing increasing water stress caused by climate change. Analyses from 1951 to 2015 show that droughts have become more frequent and severe, especially during the summer and in Mediterranean areas (Poljanšek and MFMDGTCI, 2017). National water availability can be measured using the “internal flow” indicator, defined by the OECD and Eurostat as the volume of surface and groundwater produced solely from precipitation under natural conditions (Eurostat, 2024). The areas affected by extreme droughts have grown significantly across Italy (FAO; ISPRA; ISTAT, 2023; Braca et al., 2022), while the average national water availability has decreased by about 20% between 1991 and 2020 compared to the baseline period 1921–1950. Climate change projections suggest this trend will worsen. A reduction of up to 10% in water availability is expected under an aggressive mitigation scenario, with losses reaching 40%, and peaks close to 90% in Southern Italy, under a high-emission scenario (Braca et al., 2019).

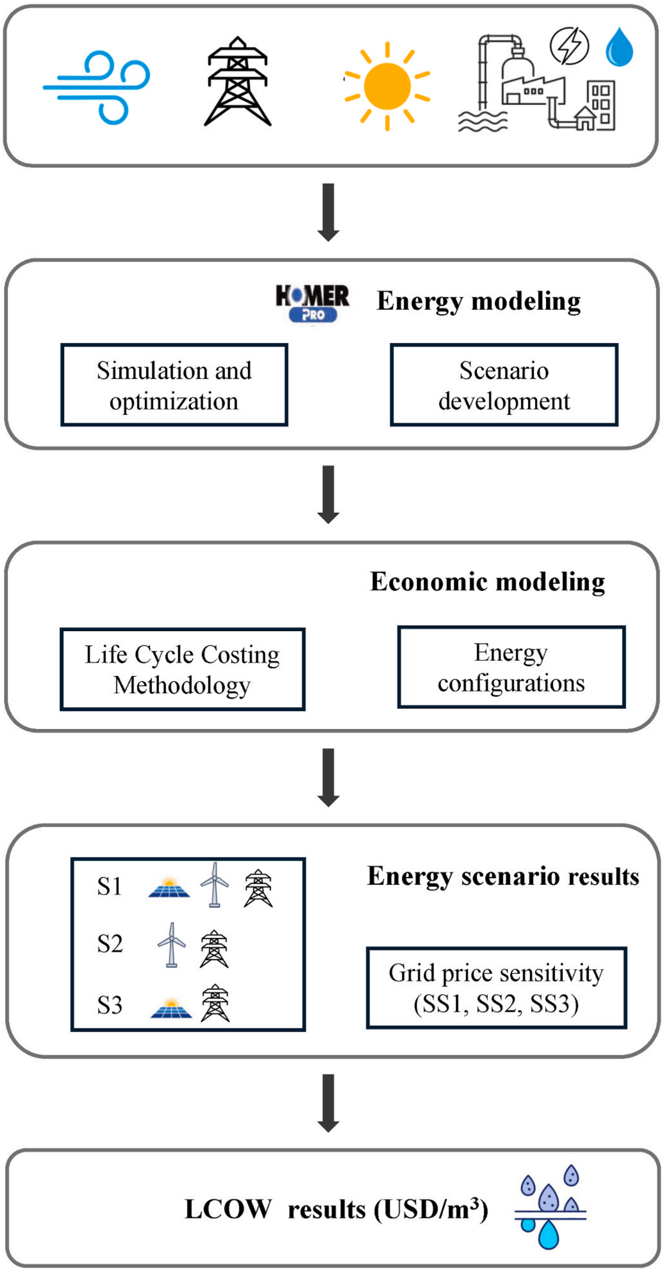

Fig. 1. Modeling framework. Input data (wind, solar, grid electricity, and RO plant demand) are processed in HOMER Pro to generate energy scenarios (S1–S3). These scenarios feed the Life Cycle Costing model, along with grid price scenarios (SS1–SS3), to compute the LCOW and its corresponding sensitivity analysis.

At the same time, inefficiencies in distribution networks worsen water insecurity. In 2023, about 43% of water entering the national system was lost, with leakage rates exceeding 53% in some southern and central regions, including Sicily (Istituto nazionale di statistica ISTAT, 2024). Sicily, the largest Italian region and the biggest Mediterranean island, is among the most affected by prolonged droughts. This vulnerability results from a combination of climate stress and aging, and inefficient water infrastructure. Reservoir inflows have decreased sharply, with a 30% reduction in total storage reported across Sicily and Sardinia, indicating a significant hydrological deficit. These changes have further reduced water resources in the area. Groundwater, which accounts for roughly 42% of the regional water supply, is also under stress. According to ARPA Sicilia (Vacante et al., 2023; Gao et al., 2017)% of monitored wells showed poor chemical quality, mainly due to elevated levels of nitrates, pesticides, and inorganic contaminants.

To address frequent water emergencies, municipalities in Sicily often rely on short-term measures, such as tanker truck deliveries. These services frequently operate in an unregulated market, leading to inconsistent and inflated costs for residents and farmers. This illustrates a reactive and fragmented water management system that lacks regional coordination. Recently, most provinces in Sicily have adopted rationing measures. In 2023, restrictions affected nearly 800,000 people. The situation worsened in 2024, with more municipalities affected and longer, more intense emergency measures (Istituto nazionale di statistica ISTAT, 2024). A recent example is in July 2024, when the Italian Navy's Nave Ticino was sent to deliver 900 m^3 of drinking water to the Port of Licata for USD 23,106.42 (Dipartimento della protezione civile RS, 2024). While this temporary relief was helpful, it also highlighted the economic and practical unsustainability of such emergency measures.

Despite clear evidence of structural water vulnerability, Italy has historically underinvested in desalination infrastructure. One key barrier is the high cost of electricity, which undermines the financial sustainability of seawater desalination. The country is highly dependent on natural gas, which accounted for approximately 50% of total electricity generation between 2021 and 2023, the second-highest share within the IEA countries after Mexico. Moreover, with 94% of gas being imported, the Italian energy system remains particularly vulnerable to supply chain disruptions and price volatility (International Energy Agency (IEA), 2023). In contrast, countries like Spain, where energy costs are comparatively lower and renewable integration is more advanced, have developed extensive desalination networks that are structurally embedded into national water supply strategies.

Spain accounts for over 60% of the EU's total desalination capacity (more than 4.2 million m^3/day), which is 5.7% of the world's total

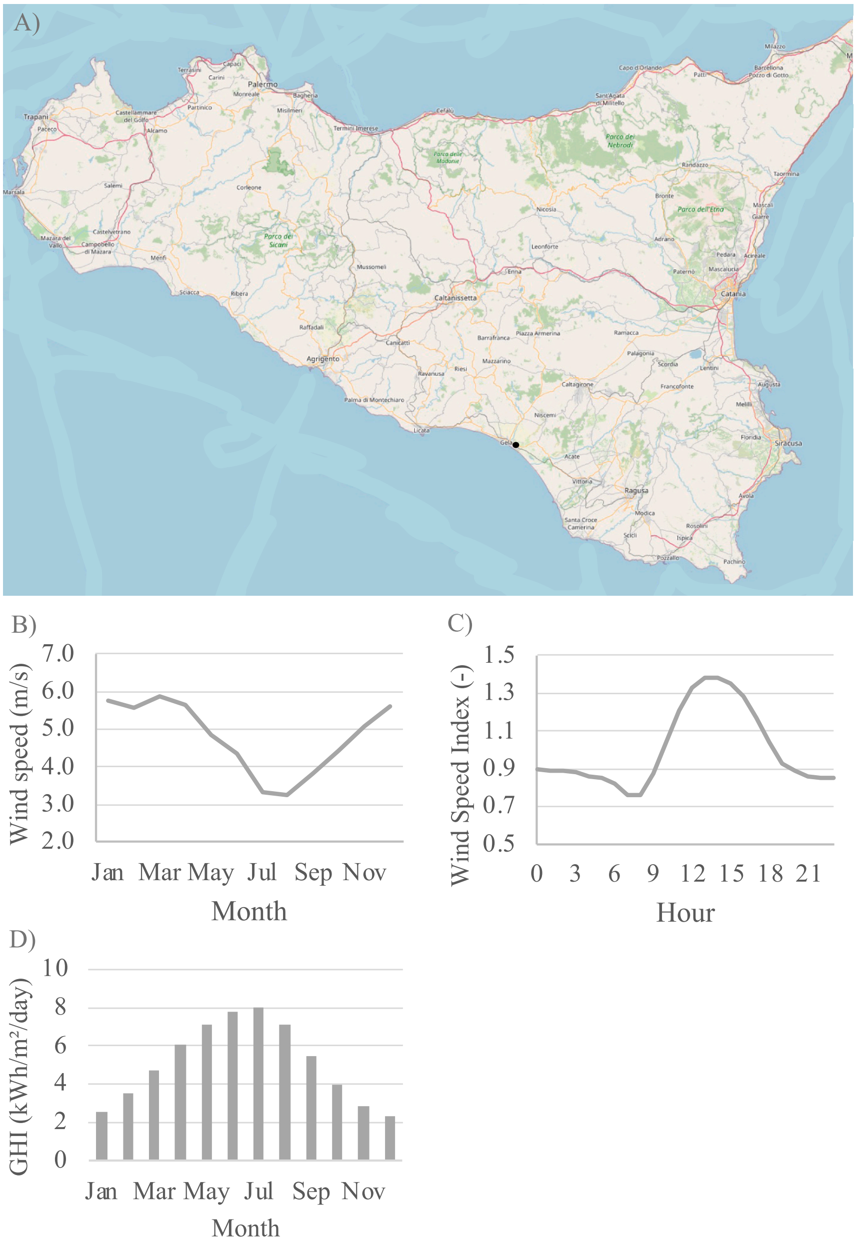

Fig. 2. (A) Location of the Gela site (Sicily, Italy). (B) Monthly mean wind speed at 100 m height (m/s). (C) Diurnal wind speed profile (–). (D) Monthly mean daily GHI (kWh/m^2/day). These renewable resource data are used as climatic inputs for the HOMER Pro simulations.

installed capacity (Jan et al., 2021). Italy, by comparison, has only a small share of the European total. Only lately has Italy begun, via the Drought Law (Parlamento Italiano, 2023), to officially recognize desalination as both an emergency and longer-term solution, easing regulations for small- and medium-scale plants (<17,500 m^3/day).

Within this context, the city of Gela has been chosen as the study site for this paper. Gela is an industrial coastal city in southern Sicily, with about 103,700 residents and a per capita water use of 0.270 m^3/day. Its water supply depends on three main reservoirs, Disueri (3.7 million m^3/year), Comunelli (0.7 million m^3/year), and Cimia (4.5 million m^3/year), with the utility Caltaqua managing variable water sources. The distribution network includes two tanks at different heights (T1: 86 m a.s.l.; T2: 59 m a.s.l.) with a combined capacity of 25,000 m^3, serving about 73,000 people. In 2023, the overall water loss rate in Gela's network was 42%, with a leakage rate of 17.6 m^3/day/km over a 350 km pipeline, including 150 km of secondary lines. A thermal desalination plant operated in Gela but ceased operations in 2016. A 2014 study examined its integration into the water system under acceptable conditions at the time (Puleo et al., 2014), but those conditions no longer apply. Still, the existing infrastructure is partly intact and will be reused in this study's proposed design for a modern RO plant, helping to cut costs and ensure easier integration.

Beyond its severe water-supply constraints, Gela also offers a distinctive renewable-energy profile, making it an appropriate site for evaluating the coupling between SWRO and local renewable resources. Southern Sicily exhibits one of the highest solar irradiation levels in Europe, with Global Horizontal Irradiance (GHI) commonly exceeding 1900–2000 kWh/m^2/year. Wind speeds along the southern coast are more moderate than in western Sicily. Yet, they follow a diurnal and seasonal pattern that provides partial balancing to PV variability and enables hybrid RE-grid operation. The local solar and wind conditions around Gela, which constitute the renewable energy inputs used for the hybrid configurations analyzed in Section 2.5, are shown in Fig. 2.

3.3. RO plant description

Based on consultations with local water authorities, the desalination plant was dimensioned to supply up to 12,500 m^3/day of freshwater, reaching 50% of the municipal tanks' daily maximum storage capacity. Mixing desalinated water with conventional sources ensures a continuous, resilient freshwater supply and enhances overall water quality during normal conditions.

The technical design adopts a single-stage SWRO configuration, with a design lifetime of 25 years (Papapetrou et al., 2017), and energy performance parameters derived from Mediterranean case studies (Ganora et al., 2019). The plant operates at a constant feed flow rate of 1085 m^3/h (26,041 m^3/day), producing freshwater at a recovery rate of 48%, as recommended for optimized cost-performance balance (Voutchkov, 2018).

Plant availability was fixed at 95%, reflecting expected scheduled and unscheduled downtime (Papapetrou et al., 2017), resulting in a 5% annual decrease in nominal water output.

The system's energy requirements were estimated using equations based on established literature (Arenas et al., 2019; Shemer and Semiat, 2017). Local seawater salinity (37.85 g/L) was used as a site-specific input (Sammartino et al., 2022). Energy consumption includes high-pressure pumping and additional treatment needs. An energy recovery device with 90% efficiency and a high-pressure pump with 85% efficiency were included in the model (Voutchkov, 2018).

Following the site-specific calculations, the pressure required by the RO process was found to be 60.05 bar, while the power required by the desalination plant is 1.76 MW, resulting in a unit power production of 3.39 kWh/m^3.

The key technical parameters of the desalination plant are summarized in Table 1.

Table 1
Main technical parameters of the SWRO plant.

Parameter	Value	Unit	Source
RO configuration	Single-stage	–	–
lifetime	25	year	Papapetrou et al. (2017)
plant availability	95	%	Papapetrou et al. (2017)
Feed salinity	37.85	g/l	Sammartino et al. (2022)
feed pressure	60	bar	Ganora et al. (2019)
Specific energy consumption	3.39	kWh/m^3	Ganora et al. (2019)
ERD efficiency	90	%	Voutchkov (2018)
pump efficiency	85	%	Voutchkov (2018)

3.4. Life cycle costing methodology

To evaluate the economic feasibility of the proposed desalination infrastructure, a LCC approach has been adopted. According to ISO 15686–5:2017 (International Standard Organization (ISO). ISO 15686–5:2017, 2017), LCC is defined as a technique for assessing the total economic costs of an asset, considering all costs associated with its acquisition, use, maintenance, and disposal over time.

In alignment with international guidelines (International Standard Organization (ISO). ISO 15686–5:2017, 2017; Woodward, 1997), the LCC applied in this study comprises the following components:

- Capital Expenditures: including all upfront investments, such as engineering, procurement, construction, installation, membrane units, and auxiliary systems.
- Operational Expenditures (OPEX): including annual energy consumption, membrane replacement, chemical usage, maintenance, and labor costs.
- Time-Adjusted Economic Evaluation: the entire cost stream is discounted to its net present value using a constant discount rate, enabling a robust comparison between alternative energy supply scenarios.

To ensure comparability across different technological configurations, the LCOW has been used as the key indicator. LCOW represents the average cost of producing 1 cubic meter of water over the plant's lifetime, including both fixed and variable costs. The metric is expressed in USD/m^3 and calculated as follows:

$$LCOW = \frac{I_0 + \sum_{t=1}^{n} \frac{C_{O,t}}{(1+r)^t}}{\sum_{t=1}^{n} \frac{M_{w,t}}{(1+r)^t}}$$

- I_0: Initial capital investment (USD)
- $C_{O,t}$: Operational and maintenance costs in year t (USD/year)
- $M_{w,t}$: Water produced in year t (m^3/year)
- r: Discount rate (%)
- n: Plant lifetime (years)

This formulation allows the estimation of the discounted total cost per cubic meter of water and facilitates comparison among different energy supply configurations, including grid-only and hybrid options.

All economic assumptions adopted for the LCC analysis, including specific OPEX components, discount rate, and capital cost formulation, are summarized in Table 2.

All costs were converted into United States dollars (USD) using the average USD/EUR exchange rate over the period from April 2015 to April 2025, equal to 1 EUR = 1.1173 USD. This long-term average was selected to smooth out the significant volatility observed in recent years (extremes: minimum of 0.9565 USD/EUR in September 2022; maximum of 1.2493 USD/EUR in February 2018). No inflation adjustment was

Table 2
Economic assumptions and cost parameters used in the LCC analysis.

Parameter	Value	Unit	Source
Membrane replacement cost	0.004	USD/m^3	Bhojwani et al. (2019)
Labor cost	0.1	USD/m^3	Gao et al. (2017)
Chemicals cost	0.032	USD/m^3	Najjar et al. (2022)
Maintenance cost	0.004	USD/m^3	Najjar et al. (2022)
Capital cost calculation	Parametric CAPEX equation	–	(Najjar et al., 2022) (Loutatidou et al., 2014)
Discount rate	3	%	(European Investment Bank (EIB))

applied, as the analysis is based on nominal values (European Central Bank (ECB), 2024).

3.5. Energy scenario characterization

Following the estimation of the specific energy demand of the SWRO desalination plant, this section evaluates a set of energy supply strategies tailored to the local energy context. The primary objective is to identify energy configurations that minimize grid reliance while maintaining operational and economic sustainability.

The three baseline scenarios were generated in HOMER Pro to explore hybrid configurations combining renewable and grid electricity. These include:

- S1: PV-Wind-Grid
- S2: PV-Grid
- S3: Wind-Grid

These configurations aim to maximize onsite electricity production, thereby reducing dependence on external energy markets and lowering both carbon emissions and operational expenditures.

Electricity production in Italy, mainly due to its heavy reliance on imported natural gas, is structurally more expensive than in other major European economies (Autorità di Regolazione per Energia Reti e Ambiente (ARERA), 2022).

The dynamics of electricity prices are tracked using the Prezzo Unico Nazionale (PUN), Italy's wholesale electricity price index, published by the Gestore dei Mercati Energetici (GME) (Gestore Mercati Energetici (GME), 2025), the institution that manages the Italian energy market. However, the PUN excludes several key cost components, including dispatching services, network losses, balancing costs, grid services, commercialization, and taxation, which the final consumer ultimately incurs.

As illustrated in Fig. 3, electricity prices in Italy have exhibited high volatility over the past two decades, with sharp increases coinciding with natural gas market shocks, such as the 2022 energy crisis linked to the war in Ukraine.

To complement the baseline analysis and better understand the cost sensitivity to electricity price fluctuations, three additional grid-only sensitivity scenarios were introduced:

- SS1: Grid-only baseline average (2023–2025)
- SS2: Grid-only lower price (pre-pandemic average, 2015–2019)
- SS3: Grid-only higher price (Ukraine crisis peak, 2022)

These sensitivity scenarios are designed to reflect the potential volatility and risks associated with exclusive dependence on the grid. This distinction is particularly relevant in fossil fuel-dependent electricity markets, such as Italy's, where long-term price uncertainty poses challenges for desalination plant operators.

A more accurate estimate of the electricity cost faced by large consumers, such as medium-voltage users exceeding 5 GWh/year, was derived from ARERA's detailed tariffs (Autorità di Regolazione per Energia Reti e Ambiente (ARERA), 2025). The six configurations modeled, not excluding surplus electricity, are summarized in Table 3.

All simulations were performed using HOMER Pro, a software platform that supports the design and evaluation of hybrid microgrids by

Table 3
Summary of baseline (S1–S3) and sensitivity (SS1, SS2, SS3) energy scenarios modeled using HOMER Pro software, including excess electricity production.

Scenario	PV Share (%)	Wind Share (%)	Grid Share (%)	Grid Electricity Cost (USD/kWh)
S1	33.9	12.6	53.6	0.25
S2	42.6	0.0	57.4	0.25
S3	0.0	36.0	64.0	0.25
SS1	0.0	0.0	100.0	0.25
SS2	0.0	0.0	100.0	0.16
SS3	0.0	0.0	100.0	0.32

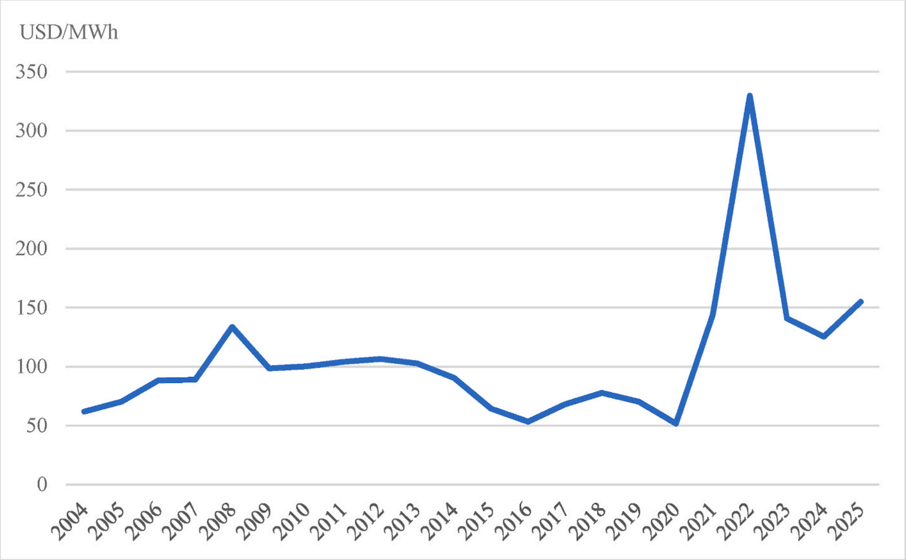

Fig. 3. Annual average variation in electricity prices (PUN) in Sicily, Italy, from 2004 to 2025 (Gestore Mercati Energetici (GME), 2025).

integrating various power generation sources, storage technologies, and grid connections.

Although the platform provides default datasets, this study used manually entered site-specific environmental, technical, and economic parameters to enhance accuracy and replicability.

In off-grid systems, studies indicate that keeping surplus electricity under 10% is optimal to avoid economic inefficiencies and oversizing. In Europe, where most regions have access to the synchronous electrical grid, surplus electricity is not an issue (Vaziri Rad et al., 2023). Nonetheless, there remains a strong interest in maximizing onsite electricity consumption to reduce transmission losses and better match local peak demand. Therefore, a moderate surplus threshold of 13% was adopted as a balanced compromise between renewable oversizing and system integration feasibility.

Table 4 summarizes all energy-related input parameters and modelling assumptions adopted in the HOMER Pro simulations, including resource characterization, techno-economic inputs, financial assumptions, and temporal resolution.

This framework enables a robust comparison between hybrid and fully grid-connected configurations, supporting a comprehensive evaluation of their implications on the LCOW and long-term sustainability.

3.6. Emergency supply data

As outlined in the Study Area Description section, during the summer of 2024, an extreme drought event forced the Sicilian region to rely on emergency water supply measures, including a water tanker ship (for a limited period) and water tankers, which significantly increased costs for citizens. This is not the first time such emergency measures have been implemented, and similar challenges have driven other water-stressed regions, such as Spain, to develop extensive desalination infrastructures (Martínez-Medina et al., 2024).

Table 4
Input parameters and assumptions used in HOMER Pro energy modelling.

Parameter	Value	Unit	Source
Solar irradiance and yield	Fig. 2 C	Monthly GHI + daily profiles	(Urraca et al., 2017, 2018)
Wind resource data	Fig. 2 A-B	Monthly averages + hourly variability	Davis et al. (2023)
PV installation cost	821	USD/kW	(International Renewable Energy Agency (IRENA), 2024)
Onshore wind installation cost	1369	USD/kW	(International Renewable Energy Agency (IRENA), 2024)
PV-Wind turbines lifetimes	25	years	(International Renewable Energy Agency (IRENA), 2017; International Energy Agency (IEA), 2022)
PV maintenance costs	10.0	USD/kW/year	(International Renewable Energy Agency (IRENA), 2024)
Wind turbines maintenance costs	45.4	USD/kW/year	(International Renewable Energy Agency (IRENA), 2024)
Financial assumptions	5	%	(International Renewable Energy Agency (IRENA), 2023) (European Central Bank (ECB), 2024)
inflation	2	%	(European Central Bank (ECB), 2024)
Grid electricity cost	0.246	USD/kWh	(Autorità di Regolazione per Energia Reti e Ambiente (ARERA), 2025)
Exclusion of energy storage systems	–	–	–
HOMER pro simulation timestep	Hourly	–	–

Quantifying the exact volume of water purchased from water tankers by Sicilian households and businesses remains challenging due to the lack of centralized reporting. However, based on statements from local authorities, households equipped with private water storage tanks purchased an estimated 3–6 m^3 per week, with prices exceeding 8.33 USD/m^3 (Azienda Idrica Comuni Agrigentini (AICA), 2024). However, actual water tanker prices might be higher. Regarding the water purchased by the region from the army water tanker ship, the cost amounted to 25.59 USD/m^3 (Dipartimento della protezione civile RS, 2024). These emergency costs are approximately 8–25 times higher than the normal cost of freshwater in Sicily, where the potable water supply component ("acquedotto") averages around 1.01 USD/m^3 (Autorità di Regolazione per Energia Reti e Ambiente (ARERA), 2021). This component represents only about 39.5% of the final tariff paid by citizens, once taxes, sewerage, wastewater treatment, and fixed charges are included.

One objective of this study is to compare the cost of desalinated water with the costs of emergency water supply measures. The regional data collected provide a basis for the comparative analysis presented in Section 3.3.

4. Results and discussion

4.1. RO plant design and LCC results

The capital and operational costs derived from section 2.4 and summarized in Table 5 are consistent with values reported in the literature for large-scale SWRO facilities. Assuming a plant lifetime of 25 years and a high operational availability (95%), the resulting capital cost contribution amounts to 0.21 USD/m^3 of produced water. This value falls within the typical range reported for modern utility-scale RO plants and reflects the benefits of long asset lifetimes and stable operation.

It should be noted that further reductions in the capital cost contribution are potentially achievable. Recent studies report operational SWRO plants lifetimes of up to 30 years; this aspect is explicitly investigated through the parametric analysis presented in Section 3.4.

Excluding electricity costs, the operational expenditures (OPEX) amount to 0.176 USD/m^3, a value comparable to the CAPEX contribution on a unit water basis. This result highlights that, even before accounting for energy consumption, non-energy operational costs represent a substantial share of the overall water cost. Given the inherently energy-intensive nature of reverse osmosis desalination, electricity costs are therefore expected to dominate the total LCOW, as further discussed in Sections 3.2 and 3.3.

4.2. Energy scenario results

Fig. 4 presents the Levelized Cost of Electricity (LCOE) results for the six scenarios, excluding surplus electricity. The outcomes clearly show the benefits of integrating onsite renewable energy, even in locations with modest wind availability. Because electricity purchases from the grid dominate operational expenditures, the LCOE is driven mainly by the amount of energy supplied by renewables versus the grid.

Scenario S1 (PV-Wind-Grid) achieves the lowest LCOE (0.17 USD/kWh), representing a 30% reduction compared with its grid-only analogue SS1 (0.25 USD/kWh). This performance is driven by the

Table 5
Capital and operational costs (excluding electricity) for the RO plant, expressed in USD per cubic meter of produced water.

Parameter	Cost (USD/m^3)
CAPEX	0.210
OPEX (excluding electricity)	0.176

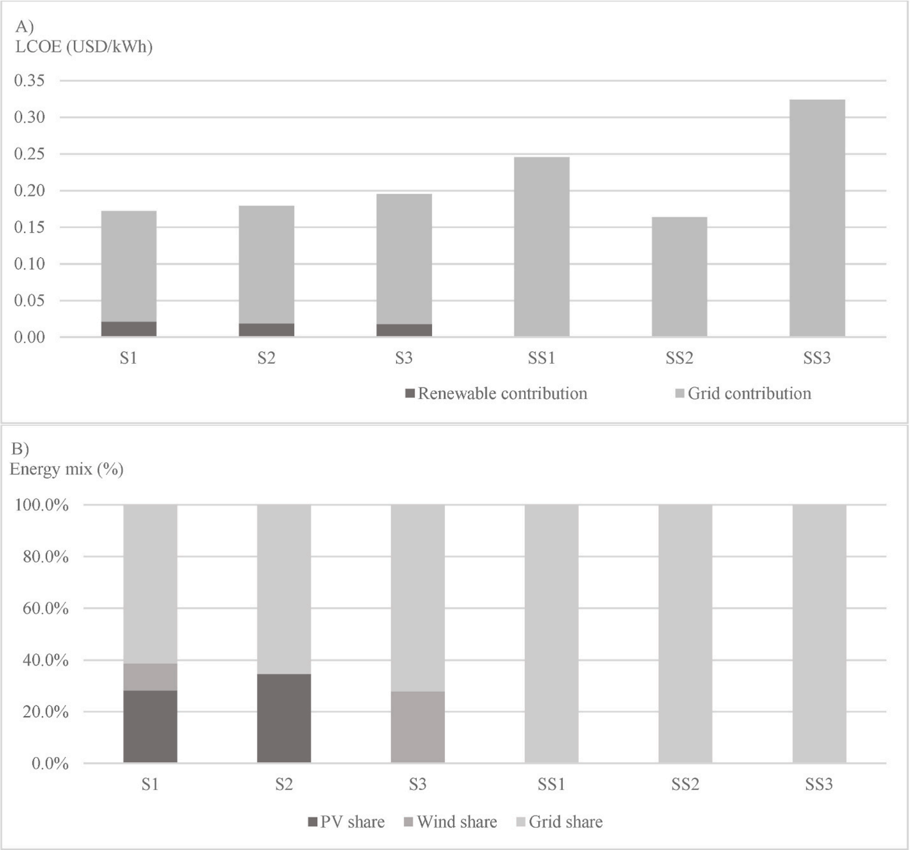

Fig. 4. (A) LCOE (USD/kWh) and (B) energy mix (%) for all six scenarios. Hybrid configurations (S1–S3) show lower LCOE due to the contribution of onsite renewable energy, whereas grid-only scenarios (SS1-SS3) rely entirely on grid electricity. Surplus renewable generation is excluded.

complementary behavior of solar and wind resources in southern Sicily (Fig. 2). The region benefits from one of Europe's highest levels of solar irradiation, enabling PV to supply a large share of onsite electricity. Although wind speeds in Gela are moderate, they provide two forms of complementarity that meaningfully enhance the hybrid system. First, wind speeds do not drop to zero at night, supplying a renewable baseline during non-solar hours. Second, the seasonal wind profile follows the opposite trend of solar availability, with stronger winds during autumn and winter. This dual complementarity, nocturnal continuity and seasonal anti-correlation, increases overall renewable penetration without requiring storage and explains why S1 outperforms both PV-only (S2) and wind-only (S3) scenarios.

Scenarios S2 (PV-Grid) and S3 (Wind-Grid) exhibit slightly higher LCOEs (0.18 and 0.20 USD/kWh, respectively). The lower performance of S3 reflects both the moderate wind resource in Gela and the limited nighttime wind intensities compared with wind-rich regions of Sicily. Conversely, S2 benefits from the high solar resource but lacks the balancing effect that wind provides in S1. These findings reinforce that hybrid layouts are typically more cost-effective than single-source renewable systems in Mediterranean settings, where solar energy is abundant but continuous renewable coverage requires at least some contribution from wind.

Although not monetized within the system boundaries, the renewable scenarios produced approximately 12% surplus electricity. Given the negligible marginal cost of PV and wind generation, oversizing renewable capacity, even at the expense of producing surplus, remains an economically favorable strategy. In real deployment, selling excess electricity through net metering or market participation could further reduce the LCOE, improving both economic performance and renewable integration.

The grid-only scenarios (SS1-SS3) reveal the sensitivity of energy costs to market volatility. SS2, modeled with pre-pandemic tariffs (0.16 USD/kWh), is competitive with renewable-enhanced systems with higher grid costs (S1–S3). However, LCOE rises sharply to 0.32 USD/kWh in SS3 under 2022 peak prices, reflecting the strong dependence of Italian electricity costs on international natural gas markets. These results emphasize the importance of reducing exposure to grid volatility in energy-intensive applications such as desalination.

4.3. LCOW results

The LCOW obtained for the six energy scenarios shows significant variability, mainly driven by electricity supply setups and grid price fluctuations (Fig. 5). Since CAPEX accounts for a relatively small portion of total costs, usually less than 15% across all scenarios, the LCOW largely reflects the behavior of the LCOE. Configurations with higher renewable penetration result in lower water costs, while grid-only scenarios are highly sensitive to electricity market conditions.

Among the hybrid layouts, Scenario S1 (PV-Wind-Grid) has the lowest LCOW, at 0.97 USD/m^3, about 20% less than its grid-only counterpart SS1. This reduction reflects the dominance of energy-related OPEX in SWRO systems and shows that even moderate renewable shares can provide economic benefits. As discussed in Section 3.2, wind availability in Gela is modest but offers beneficial nocturnal and seasonal complementarity to PV, boosting the renewable share without requiring storage and enhancing hybrid scenario performance. In regions with stronger and more consistent wind, such as western Sicily, Sardinia, or coastal Greece, the LCOW for hybrid systems would likely be even lower.

The fully grid-powered scenarios demonstrate the vulnerability of desalination economics to electricity price volatility. LCOW decreases from 1.22 USD/m^3 in SS1 to 0.94 USD/m^3 in SS2 when using pre-

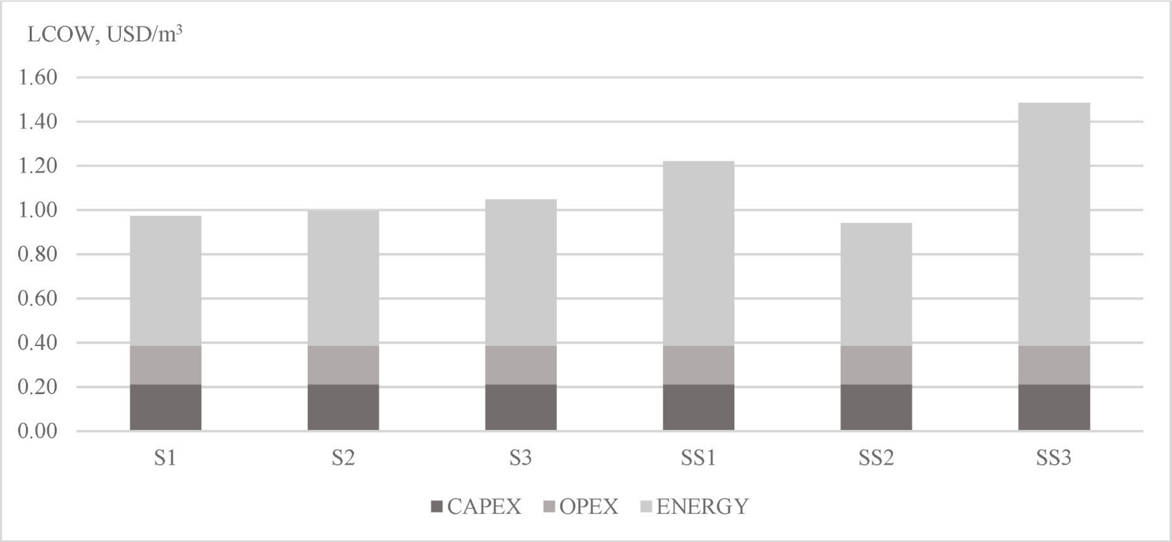

Fig. 5. Stacked bar chart showing the contribution of CAPEX, OPEX, and energy costs to the LCOW for each scenario.

pandemic tariffs, then sharply increases to 1.49 USD/m^3 in SS3.

Overall, these results indicate that renewable electricity can substantially improve the cost competitiveness and economic stability of desalination. The LCOW values for Gela fall within the typical range documented for utility-scale renewable-powered desalination systems (0.94–1.80 USD/m^3 for utility-scale systems), demonstrating that hybrid renewable-grid SWRO is a viable option for drought-prone regions like southern Sicily. Additionally, these low values are comparable to those of traditional water supply strategies. For context, the LCOW values for Gela are close to the potable water supply tariff ('acquedotto') currently charged in Sicily, which averages 1.01 USD/m^3. The LCOW achieved remains significantly lower than the cost of emergency water supply, which is usually 4 to 10 times higher, highlighting the economic advantage of renewable-powered desalination in drought-prone areas.

To assess the robustness of the LCOW results and quantify the influence of key techno-economic parameters, a parametric analysis was conducted. The results are presented in Section 3.4.

4.4. *Parametric analysis*

A parametric sensitivity analysis, shown in Fig. 6, was conducted to assess the LCOW's robustness to variations in key techno-economic parameters. Scenario S1 (PV-Wind-Grid), which yielded the lowest LCOW in the primary analysis, was used as the baseline (0.97 USD/m^3). Each parameter was varied individually while all others were held constant, allowing the relative influence of each factor to be isolated. The parameters tested, renewable electricity costs, discount rate, plant availability, and plant lifetime, were selected based on recent literature and financing guidelines relevant to large-scale desalination projects.

The discount rate was varied between 5% and 7%, reflecting the financing conditions reported by the European Investment Bank (EIB) for public and mixed public-private utility infrastructures. Meanwhile, higher discount rates increased the LCOW to 1.02 USD/m^3 (5%) and 1.08 USD/m^3 (7%). This effect highlights the strong influence of financing conditions on desalination economics, given the

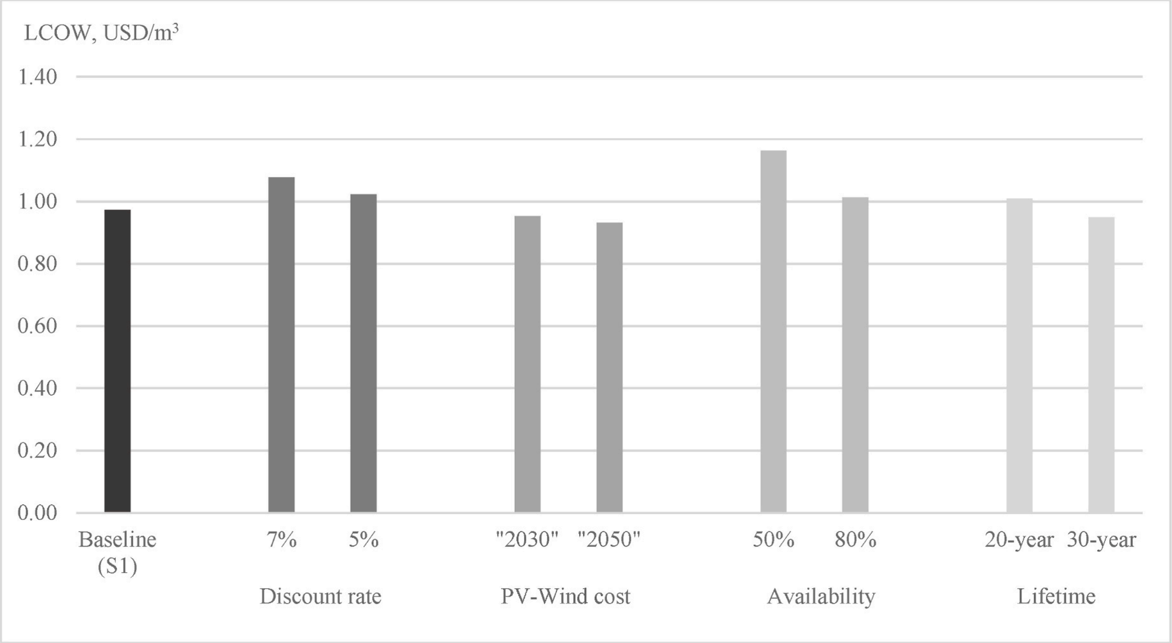

Fig. 6. Sensitivity of LCOW (USD/m^3) to variations in discount rate, projected PV-wind electricity costs (2030–2050), plant availability, and plant lifetime.

capital-intensive nature of SWRO systems.

Future renewable electricity costs were varied according to projected cost reductions by 2030 and 2050 (Vatankhah et al., 2025). Applying these projected decreases to PV (−22.6% by 2030; −50.9% by 2050) and wind energy (−36.3% by 2030; −44.1% by 2050) resulted in LCOW values of 0.95 and 0.93 USD/m^3, respectively. These results confirm that continued cost declines in renewable energy technologies would further enhance the competitiveness of hybrid RE-powered desalination.

Plant availability was varied between 50% and 80%, consistent with lower operational variability that can occur during extraordinary hydrological fluctuations in annual water demand. Reducing availability to 50% and 80% increased LCOW to 1.16 USD/m^3 and 1.01 USD/m^3, respectively. These results reflect the effect of spreading fixed capital and O&M costs over a variable volume of produced water, demonstrating the economic importance of maintaining high utilization rates.

Plant lifetime was varied from 20 to 30 years, reflecting growing evidence that modern SWRO plants can exceed conventional design horizons with proper maintenance. Extending the lifetime to 30 years reduced LCOW to 0.95 USD/m^3, whereas lowering it to 20 years increased LCOW to 1.01 USD/m^3. Although its influence is smaller than that of the discount rate or plant availability, lifetime still contributes meaningfully to the long-term economics of desalination assets.

4.5. Carbon intensity and avoided emissions

The carbon footprint of each scenario was estimated by focusing on operational energy consumption, as shown in Table 6. Based on average Italian grid emissions, which amounted to 287 g CO_2/kWh in 2025 (EMBER, 2025), and life-cycle emission factors of photovoltaic and wind energy, equal to 37 and 12.4 g CO_2/kWh (UNITED NATIONS ECONOMIC COMMISSION FOR EUROPE (UNECE), 2022), respectively, the fully grid-powered scenarios (SS1-SS3) result in a carbon intensity of approximately 970 g CO_2eq/m^3 of desalinated water. Conversely, the hybrid renewable scenarios achieve values that are 35% lower, namely 640 (S1), 670 (S2), and 690 g CO_2eq/m^3 (S3). Under the best-performing configuration (S1), this corresponds to an annual reduction of over 1457 tonnes of CO_2 equivalent compared to grid-only operation.

All scenarios stay well below the European Union Taxonomy's “Do No Significant Harm” threshold of 1080 g CO_2eq/m^3 for seawater desalination, including treatment, pumping, brine disposal, and related energy use, established by the European Commission (European Commission (EC), 2023b).

This compliance confirms that renewable-powered desalination meets the eligibility criteria of the EU sustainable finance mechanisms (Lebu et al., 2024). As noted by the European Commission's Blue Economy Observatory, desalination projects that maximize renewable energy use can access green financing and, in some cases, national or EU subsidies. Notably, Recovery and Resilience Facility (RRF) funds and other EU financing tools have already been used by Member States to support climate-resilient water infrastructure, including desalination (European Commission (EC), 2024b). This study also emphasizes that integrating renewables into desalination not only boosts energy independence and reduces costs but also improves environmental and financial sustainability.

Table 6
Energy source contribution and resulting carbon intensity per cubic meter of desalinated water for the six modeled scenarios.

Scenario	PV share (kWh/m^3)	Wind share (kWh/m^3)	GRID share (kWh/m^3)	Total Carbon Intensity (kg CO2eq./m^3)
S1	0.95	0.35	2.08	0.64
S2	1.20	0.00	2.19	0.68
S3	0.00	1.01	2.38	0.71
SS1	0.00	0.00	3.39	0.97
SS2	0.00	0.00	3.39	0.97
SS3	0.00	0.00	3.39	0.97

4.6. Limitations

This study assesses the techno-economic performance of a site-specific desalination plant powered by a hybrid PV-wind-grid system. Consequently, the analysis assumes a stable and fully reliable electrical grid. Constraints related to grid stability at high renewable penetration, such as voltage regulation, fault-ride-through, curtailment policies, and local hosting capacity, are not explicitly modeled, as they depend on regional grid codes and utility-specific requirements. Lastly, the results are specific to the site and depend on local resource availability, renewable capacity factors, and electricity prices. Therefore, the quantitative values cannot be directly applied to other regions, although the methodology remains applicable.

5. Conclusions

This study evaluated the economic performance of a 12,500 m^3/day SWRO desalination plant in Gela, Italy, across six different energy configurations. Using HOMER Pro simulations, a life-cycle cost analysis, and current national cost data, it examined how various energy sourcing strategies affect desalination economics in a Mediterranean environment increasingly affected by water scarcity. The results show that incorporating renewable energy, especially hybrid solar and wind, can substantially lower desalination costs, even without energy storage.

The most cost-effective hybrid scenario (S1) achieved a LCOW of 0.97 USD/m^3, approximately 20% less than its grid-only counterpart (SS1). This is significant given that excess renewable electricity was not monetized, highlighting the economic potential of oversized renewable systems when marginal generation costs are low.

Sensitivity scenarios further highlighted desalination's vulnerability to grid electricity price volatility. In fact, in grid-only setups, LCOW ranged from 0.98 USD/m^3 (SS2, pre-pandemic prices) to 1.52 USD/m^3 (SS3, 2022 crisis prices), showing how macroeconomic shocks can undermine the viability of energy-intensive infrastructures. Hybrid renewable-grid scenarios, on the other hand, demonstrated greater stability, confirming that renewable integration can serve as a hedge against external energy shocks. These findings are particularly relevant for Italy, where electricity markets remain heavily reliant on fossil fuels and are subject to global fluctuations in natural gas prices.

Significantly, all modeled LCOW values fell within economically acceptable ranges for large-scale SWRO. The lowest-cost scenario not only competes with regional potable water tariffs but is also up to twenty-five times cheaper than emergency water supply methods commonly used in Sicily, such as tanker trucks and naval deliveries. These results demonstrate that renewable-powered desalination can provide water at predictable and competitive costs even under adverse market conditions (Section 2.6).

Beyond immediate economic advantages, renewable-integrated desalination offers broader strategic benefits. In regions like Sicily, where water resources are increasingly limited by climate variability, infrastructure decay, and groundwater contamination, cost-effective desalination could help ease pressure on overused aquifers and improve long-term water security.

These findings also align with broader European policy trends. Recent EU strategies under the European Green Deal highlight drought resilience and sustainable water management as key challenges for the coming decades. In this context, renewable-powered desalination systems that reduce reliance on the grid align with European goals for climate adaptation, energy transition, and regional water security. Therefore, the results of this study offer not only technical and economic insights but also policy-relevant support to inform future national and regional planning efforts in the Mediterranean and drought-prone areas.

CRediT authorship contribution statement

Edoardo Teresi: Writing – review & editing, Writing – original draft, Software, Resources, Methodology, Investigation, Formal analysis. **Cristian Chiavetta:** Writing – review & editing, Supervision, Project administration. **Gabriele Freni:** Writing – review & editing, Supervision, Resources. **Letizia Caroscio:** Writing – review & editing. **Alessandra Bonoli:** Writing – review & editing, Supervision.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT-4 in order to improve language and readability. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

Aljuwaisseri, A., Aleisa, E., Alshayji, K., 2023. Environmental and economic analysis for desalinating seawater of high salinity using reverse osmosis: a life cycle assessment approach. Environ. Dev. Sustain. 25, 4539–4574. https://doi.org/10.1007/s10668-022-02214-9.

Arenas, Urrea S., Díaz Reyes, F., Peñate Suárez, B., de la Fuente Bencomo, J.A., 2019. Technical review, evaluation and efficiency of energy recovery devices installed in the Canary Islands desalination plants. Desalination 54–63. https://doi.org/10.1016/j.desal.2018.07.013.

Autorità di Regolazione per Energia Reti e Ambiente (ARERA), 2021. Spesa Media Annua per Il Servizio Idrico Integrato.

Autorità di Regolazione per Energia Reti e Ambiente (ARERA), 2022. Elaborazione Su Dati Eurostat Relazione Annuale 2022.

Autorità di Regolazione per Energia Reti e Ambiente (ARERA), 2025. Relazione Annuale Sullo Stato Dei Servizi, 2015–2025.

Ayou, D.S., Ega, H.M., Coronas, A., 2022. A feasibility study of a small-scale photovoltaic-powered reverse osmosis desalination plant for potable water and salt production in madura island: a techno-economic evaluation. Therm. Sci. Eng. Prog. 35. https://doi.org/10.1016/j.tsep.2022.101450.

Azienda Idrica Comuni Agrigentini (AICA), 2024. Richiesta servizio approvvigionamento idrico mediante autobotte. https://www.aicaonline.it/richiesta-servizio-approvvigionamento-idrico-mediante-autobotte/. (Accessed 3 June 2025).

Bdour, A.N., Al-Sadeq, N., Gharaibeh, M., Mendoza-Sammet, A., Kennedy, M.D., Salinas-Rodriguez, S.G., 2022. Techno-economic analysis of selected PV-BWRO desalination plants in the context of the water–energy nexus for Low–medium-income countries. Energies 15. https://doi.org/10.3390/en15228657.

Bhojwani, S., Topolski, K., Mukherjee, R., Sengupta, D., El-Halwagi, M.M., 2019. Technology review and data analysis for cost assessment of water treatment systems. Sci. Total Environ. 651, 2749–2761. https://doi.org/10.1016/j.scitotenv.2018.09.363.

Braca, G., Bussettini, M., Ducci, D., Lastoria, B., Mariani, S., 2019. Evaluation of national and regional groundwater resources under climate change scenarios using a GIS-based water budget procedure. Rendiconti Lincei. Sci. Fis. Nat. 30, 109–123. https://doi.org/10.1007/s12210-018-00757-6.

Braca, G., Mariani, S., Lastoria, B., Piva, F., Archi, F., Botto, A., et al., 2022. Bilancio Idrologico Nazionale: Focus Su Siccità E Disponibilità Naturale Della Risorsa Idrica Rinnovabile. Aggiornamento al.

Caldera, U., Bogdanov, D., Breyer, C., 2016. Local cost of seawater RO desalination based on solar PV and wind energy: a global estimate. Desalination 385, 207–216. https://doi.org/10.1016/j.desal.2016.02.004.

Calise, F., Cappiello, F.L., Vanoli, R., Vicidomini, M., 2019. Economic assessment of renewable energy systems integrating photovoltaic panels, seawater desalination and water storage. Appl. Energy 253. https://doi.org/10.1016/j.apenergy.2019.113575.

Caretta, M.A., Mukherji, A., Arfanuzzaman, M., Betts, R.A., Gelfan, A., Hirabayashi, Y., et al., 2023. Water. Climate Change 2022 – Impacts, Adaptation and Vulnerability. Cambridge University Press, pp. 551–712. https://doi.org/10.1017/9781009325844.006.

Davis, N.N., Badger, J., Hahmann, A.N., Hansen, B.O., Mortensen, N.G., Kelly, M., et al., 2023. The global wind atlas: a high-resolution dataset of climatologies and associated web-based application. Bull. Am. Meteorol. Soc. 104, E1507–E1525. https://doi.org/10.1175/BAMS-D-21-0075.1.

Dipartimento della protezione civile RS, 2024. Decreto D.D.G. N. 1183 Del 05.12.2024 – Impegno E Liquidazione "Oneri Finanziari Sostenuti Dal Ministero Della Difesa – Marina Militare COVI Stato Maggiore" per L'Intervento Nave Ticino "Servizio Di Rifornimento Idrico a Favore Della Regione Sicilia". € 20.680,59 a valere sul capitolo 117318 (Codice U.1.10.99.99.999).

Douville, H., Raghavan, K., Allan, R.P., Arias, P.A., Barlow, M., Cerezo-Mota, R., et al., 2021. Climate Change 2021. Climate Change 2021 – the Physical Science Basis. Cambridge University Press, pp. 1055–1210. https://doi.org/10.1017/9781009157896.010.

Eisenhardt, K.M., 1989. Building theories from case study research. Acad. Manag. Rev. 14, 532. https://doi.org/10.2307/258557.

EMBER, 2025. Yearly Electricity Data Europe.

European Commission (EC), 2021. EU adaptation strategy - climate action. https://climate.ec.europa.eu/eu-action/adaptation-and-resilience-climate-change/eu-adaptation-strategy_en.

European Commission (EC), 2023a. Biodiversity strategy for 2030 - environment. https://environment.ec.europa.eu/strategy/biodiversity-strategy-2030_en.

European Central Bank (ECB), 2024. Harmonised index of consumer prices (HICP) – italy – all-items, annual rate. Dataset ICP.M.IT.N.000000.4.ANR. https://DataEcbEuropaEu/Data/Datasets/ICP/ICPMITN0000004ANR.

European Commission (EC), 2023b. Commission Delegated Regulation (EU) 2023/2486 of 27 June 2023 Amending Delegated Regulation (EU) 2021/2139. Official journal of the European Union.

European Commission (EC), 2024a. Water scarcity and droughts - environment. https://environment.ec.europa.eu/topics/water/water-scarcity-and-droughts_en.

European Commission (EC), 2024b. Desalination - EU blue economy observatory. https://blue-economy-observatory.ec.europa.eu/eu-blue-economy-sectors/desalination_en.

European Commission (EC), 2025a. Circular economy - environment. https://environment.ec.europa.eu/strategy/circular-economy_en.

European Commission (EC), 2025b. The blue economy report. https://doi.org/10.2771/2333701.

European Environment Agency (EEA), 2021. Water resources across Europe-confronting water stress: an updated assessment. https://doi.org/10.2800/320975.

European Environment Agency (EEA), 2023. Waterbase - Water Quantity.

European Investment Bank (EIB). The Economic Appraisal of Investment Projects at the EIB.

European Investment Bank (EIB), 2022. EIB Water Sector Lending Orientation: Strengthening Water Security EIB Water Sector Lending Orientation: Strengthening Water Security.

European Parliamentary Research Service (EPRS), 2025. The future of water availability and use in the EU. https://doi.org/10.2861/6213761.

Eurostat, 2024. Water Statistics.

FAO; ISPRA; ISTAT, 2023. A Disaggregation of Indicator 6.4.2 "Level of Water Stress: Freshwater Withdrawal as a Proportion of Available Freshwater Resources" at River Basin District Level in Italy. FAO. https://doi.org/10.4060/cc5037en.

Food and Agriculture Organization (FAO), 2017. Water for sustainable food and agriculture: a report produced for the G20 presidency of Germany, p. 1. Rome, Isbn: 978-92-5-109977-3.

Ganora, D., Dorati, C., Huld, T.A., Udias, A., Pistocchi, A., 2019. An assessment of energy storage options for large-scale PV-RO desalination in the extended mediterranean region. Sci. Rep. 9. https://doi.org/10.1038/s41598-019-52582-y.

Gao, L., Yoshikawa, S., Iseri, Y., Fujimori, S., Kanae, S., 2017. An economic assessment of the global potential for seawater desalination to 2050. Water (Switzerland) 9. https://doi.org/10.3390/w9100763.

García, Latorre FJ., Pérez Báez, S.O., Gómez Gotor, A., 2015. Energy performance of a reverse osmosis desalination plant operating with variable pressure and flow. Desalination 366, 146–153. https://doi.org/10.1016/j.desal.2015.02.039.

Gestore Mercati Energetici (GME), 2025. Electricity – PUN index. https://gme.mercatoelettrico.org/en-us/Home/Results/Electricity/MGP/Results/PUN.

Ghaffour, N., Missimer, T.M., Amy, G.L., 2013. Technical review and evaluation of the economics of water desalination: current and future challenges for better water supply sustainability. Desalination 309, 197–207. https://doi.org/10.1016/j.desal.2012.10.015.

Ghaithan, A.M., Mohammed, A., Al-Hanbali, A., Attia, A.M., Saleh, H., 2022. Multi-objective optimization of a photovoltaic-wind- grid connected system to power reverse osmosis desalination plant. Energy 251. https://doi.org/10.1016/j.energy.2022.123888.

Guo, P., Liu, Z., Huang, S., Liu, S., Han, M., 2024. Minimizing energy footprint of seawater desalination system via wind power generation in coastal areas. J. Environ. Manag. 369. https://doi.org/10.1016/j.jenvman.2024.122244.

GWI, 2024. IDRA Desalination and Reuse Handbook 2023-2024.

Intergovernmental Panel for Climate Change (IPCC), 2023. Weather and climate extreme events in a changing climate. In: Climate Change 2021 – the Physical Science Basis. Cambridge University Press, pp. 1513–1766. https://doi.org/10.1017/9781009157896.013.

International Energy Agency (IEA), 2021. Net zero by 2050. https://www.iea.org/reports/net-zero-by-2050,Licence:CCBY4.0.

International Energy Agency (IEA), 2022. Solar PV Global Supply Chains. Paris.

International Energy Agency (IEA), 2023. Energy Policy Review Italy 2023.

International Renewable Energy Agency (IRENA), 2017. Renewable Energy Benefits: Leveraging Local Capacity for Onshore Wind. International Renewable Energy Agency, Abu Dhabi.

International Renewable Energy Agency (IRENA), 2023. The Cost of Financing for Renewable Power. Abu Dhabi.

International Renewable Energy Agency (IRENA), 2024. Renewable Power Generation Costs in 2023. Abu Dhabi.

International Standard Organization (ISO). ISO 15686-5:2017, 2017. Buildings and Constructed Assets – Service Life Planning – Part 5: Life-Cycle Costing.

Istituto nazionale di statistica (ISTAT), 2024. Le statistiche sull'acqua. Anni 2020-2023, p. 5.

Jan, Post, Jong, P de, Matthew, Mallory, Mathieu, Doussineau, Ales, Gnamus, 2021. Smart Specialisation in the Context of Blue Economy : Analysis of Desalination Sector. Publications Office of the European Union.

Karavas, C.S., Arvanitis, K.G., Papadakis, G., 2019. Optimal technical and economic configuration of photovoltaic powered reverse osmosis desalination systems operating in autonomous mode. Desalination 466, 97–106. https://doi.org/10.1016/j.desal.2019.05.007.

Lebu, S., Lee, A., Salzberg, A., Bauza, V., 2024. Adaptive strategies to enhance water security and resilience in low- and middle-income countries: a critical review. Sci. Total Environ. 925, 171520. https://doi.org/10.1016/j.scitotenv.2024.171520.

Lionello, P., Scarascia, L., 2018. The relation between climate change in the mediterranean region and global warming. Reg. Environ. Change 18, 1481–1493. https://doi.org/10.1007/s10113-018-1290-1.

Loutatidou, S., Chalermthai, B., Marpu, P.R., Arafat, H.A., 2014. Capital cost estimation of RO plants: GCC countries versus southern Europe. Desalination 347, 103–111. https://doi.org/10.1016/j.desal.2014.05.033.

Martínez-Medina, M.À., Pérez-Martín, M.Á., Estrela, T., 2024. Desalination in Spain and the role of solar photovoltaic energy. J. Mar. Sci. Eng. 12. https://doi.org/10.3390/jmse12060859.

Najjar, E., Al-Hindi, M., Massoud, M., Saad, W., 2022. Life cycle assessment and cost of a seawater reverse osmosis plant operated with different energy sources. Energy Convers. Manag. 268. https://doi.org/10.1016/j.enconman.2022.115964.

Nurjanah, I., Chang, T.T., You, S.J., Huang, C.Y., Sean, W.Y., 2024. Reverse osmosis integrated with renewable energy as sustainable technology: a review. Desalination 581. https://doi.org/10.1016/j.desal.2024.117590.

Papapetrou, M., Cipollina, A., La Commare, U., Micale, G., Zaragoza, G., Kosmadakis, G., 2017. Assessment of methodologies and data used to calculate desalination costs. Desalination 419, 8–19. https://doi.org/10.1016/j.desal.2017.05.038.

Parlamento Italiano, 2023. Legge 13 Giugno 2023, N. 68. Decreto Siccità.

Pistocchi, A., Bleninger, T., Breyer, C., Caldera, U., Dorati, C., Ganora, D., et al., 2020. Can seawater desalination be a win-win fix to our water cycle? Water Res. 182. https://doi.org/10.1016/j.watres.2020.115906.

Poljanšek, K., Mfm, Dgt, Ci, 2017. Science for disaster risk management. https://doi.org/10.2788/842809.

Puleo, V., Fontanazza, C.M., Notaro, V., Freni, G., 2014. Multi sources water supply system optimal control: a case study. In: Procedia Eng, vol. 89. Elsevier Ltd, pp. 247–254. https://doi.org/10.1016/j.proeng.2014.11.184.

Raluy, R.G., Serra, L., Uche, J., 2005. Life cycle assessment of desalination technologies integrated with renewable energies. Desalination 183, 81–93. https://doi.org/10.1016/j.desal.2005.04.023.

Salomons, E., Housh, M., Katz, D., Sela, L., 2023. Water-energy nexus in a desalination-based water sector: the impact of electricity load shedding programs. npj Clean Water 6. https://doi.org/10.1038/s41545-023-00281-7.

Sammartino, M., Aronica, S., Santoleri, R., Buongiorno Nardelli, B., 2022. Retrieving Mediterranean Sea surface salinity distribution and interannual trends from multi-sensor satellite and in situ data. Remote Sens (Basel) 14, 2502. https://doi.org/10.3390/rs14102502.

Shemer, H., Semiat, R., 2017. Sustainable RO desalination – energy demand and environmental impact. Desalination 424, 10–16. https://doi.org/10.1016/j.desal.2017.09.021.

UL Solutions, 2024. HOMER Pro.

United Nations Department of Economic and Social Affairs PDivision, 2022. World Population Prospects: Summary of Results. UNDESA/POP/2024/TR/NO.9.

UNITED NATIONS ECONOMIC COMMISSION FOR EUROPE (UNECE), 2022. Carbon Neutrality in the UNECE Region: Integrated life-cycle Assessment of Electricity Sources.

United Nations Educational S and CO (UNESCO), 2024. The United Nations World Water Development Report 2024: Water for Prosperity and Peace Water for Prosperity and Peace. Perugia.

Urraca, R., Gracia-Amillo, A.M., Koubli, E., Huld, T., Trentmann, J., Riihelä, A., et al., 2017. Extensive validation of CM SAF surface radiation products over Europe. Remote Sens. Environ. 199, 171–186. https://doi.org/10.1016/j.rse.2017.07.013.

Urraca, R., Huld, T., Gracia-Amillo, A., Martinez-de-Pison, F.J., Kaspar, F., Sanz-Garcia, A., 2018. Evaluation of global horizontal irradiance estimates from ERA5 and COSMO-REA6 reanalyses using ground and satellite-based data. Sol. Energy 164, 339–354. https://doi.org/10.1016/j.solener.2018.02.059.

Vacante, G., Zappia, V., Palumbo, V., 2023. Documento Di Sintesi Sullo Stato Qualitativo Delle Acque Sotterranee Della Sicilia. JHW Publishing.

Vatankhah, Ghadim H., Haas, J., Breyer, C., Gils, H.C., Read, E.G., Xiao, M., et al., 2025. Are we too pessimistic? Cost projections for solar photovoltaics, wind power, and batteries are over-estimating actual costs globally. Appl. Energy 390. https://doi.org/10.1016/j.apenergy.2025.125856.

Vaziri Rad, M.A., Kasaeian, A., Niu, X., Zhang, K., Mahian, O., 2023. Excess electricity problem in off-grid hybrid renewable energy systems: a comprehensive review from challenges to prevalent solutions. Renew. Energy 212, 538–560. https://doi.org/10.1016/j.renene.2023.05.073.

Voutchkov, N., 2018. Energy use for membrane seawater desalination – current status and trends. Desalination 431, 2–14. https://doi.org/10.1016/j.desal.2017.10.033.

Woodward, D.G., 1997. Life cycle costing—Theory, information acquisition and application. Int. J. Proj. Manag. 15, 335–344. https://doi.org/10.1016/S0263-7863(96)00089-0.

World Meteorological Organization, 2021. Atlas of Mortality and Economic Losses from Weather Climate and Water Extremes 1970-2019.

Yin, R.K., 1994. Discovering the future of the case study. Method in evaluation research. Eval. Pract. 15, 283–290. https://doi.org/10.1177/109821409401500309.

Zhang, Z., Atia, A.A., Xu, P., Yetman, G., Fthenakis, V., 2025. Water production by renewable energy powered desalination for meeting climate change induced water supply-demand deficits in the United States. Progr. Energy 7. https://doi.org/10.1088/2516-1083/adf795.