



Techno-economic assessment of a novel wind-powered RO system with a compressed air energy storage for water desalination

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ABSTRACT

The convergence of renewable energy and water desalination offers a promising solution to water scarcity and climate change. Utilizing wind power to operate reverse osmosis (RO) systems promises a sustainable future with ample freshwater and reduced carbon emissions. This paper introduces a novel wind-powered RO desalination system, employing a pneumatic approach with wind-driven compressors, energy storage, and air-operated pumps. Additionally, an energy recovery pressure exchanger enhances efficiency by capturing energy from the brine. A detailed mathematical model using MATLAB/Simulink evaluates system performance across various Egyptian coastal locations, optimizing wind turbine numbers to minimize desalination costs. The findings reveal that compressed air energy storage is essential for consistent operation despite wind variability, ensuring reliability during low or fluctuating wind conditions. The techno-economic assessment highlights the importance of site-specific adaptations for maximizing performance and cost-effectiveness. Hurghada emerged as the optimal location with the lowest desalination cost (\$0.65/m³) and highest annual water production (19,500 m³), while Suez had the highest cost at \$1.35/m³. Seasonal variations impact performance, with mid-winter showing more system on-off cycles compared to mid-summer. Sensitivity analysis highlights the importance of optimizing capital and operational costs, as a 20 % variation in these costs shifts the levelized cost of water by 10 %.

1. Introduction

The burgeoning global population and intensifying climate change pose significant threats to water security worldwide. This escalating challenge is compounded by the intricate relationship between water and energy, known as the "water-energy nexus." This concept underlines the interdependence of these resources, influenced by geographical disparities and technological infrastructure. Particularly, the nexus highlights two primary domains: the energy required for water production (treatment and desalination) and the water needed for power generation [1]. Water scarcity presents a critical challenge to billions worldwide, especially in arid and semi-arid regions where water availability is severely constrained [2]. Population growth further intensifies

the strain on water resources, and geographical factors amplify these pressures [3]. Coastal nations without significant river systems, for instance, rely heavily on rainfall and groundwater. Fig. 1a reveals significant regional disparities in total renewable internal freshwater resources (bcm) relative to the population in 2020, with the Middle East and North Africa (MENA) possessing the least, while Latin America and the Caribbean (LAC) have substantially more, according to World Bank data [4]. Egypt is considered to have arid climatic conditions, presenting a very high risk of water scarcity [5]. Fig. 1b shows the historical and projected trends in per capita water share and population from 1800 to 2050, highlighting a sharp decline in water availability per person, falling below the water poverty threshold by the mid-20th century, while the population has increased significantly, exacerbating the imbalance between water resources and population growth [6]. This is

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Nomenclature:		Abbreviations	
A	Area, m ²	bcm	Billion cubic meters
C	Cost, \$	BGWD	Brackish groundwater desalination
CapEx	Total capital cost, \$	CAES	Compressed air energy storage
CRF	Capital recovery factor, -	COW	Cost of water
FF	Fouling factor, %	DOD	Depth of discharge
k	Permeability, LMH	ED	Electrodialysis
i	Time step	EDR	Electrodialysis reversal
LCOW	Levelized cost of water, \$/m ³	EES	Engineering equation solver
$\dot{m}$	Mass flowrate, Kg/s	FC	Conventional fixed capacity
n	System lifetime, years	FDP	Floating desalination plant
N	Number of turbines	FO	Forward osmosis
O&M	Operating and maintenance cost, \$	GC	Gradual capacity
OpEx	Total operating and maintenance cost, \$	GHG	Greenhouse gas
P	Power, kW	HAWTs	Horizontal axis wind turbines
p	Pressure, Pa	HPP	High pressure pump
r	Interest rate, %	HVAWT	Hybrid vertical-axis wind turbine
RR	Recovery ratio, %	IPHRO	Integrating pumped hydro energy storage with reverse osmosis
S	System status	KW	Keyword
SPC	Specific power consumption, kWh/m ³	LAC	Latin America and the Caribbean
SR	Salt rejection, %	LCC	Lowered lifecycle costs
t	Time, second	MBFOA	Multiresolution brute force optimization algorithm
T	Temperature, K	MED	Multi-effect distillation
TCF	Temperature correction factor, °C	MENA	Middle East and North Africa
V	Volume, m ³	MILP	Mixed integer linear programming
$\dot{V}$	Volume flowrate, m ³ /hr	MSF	Multi-stage flash
X	Salt concentration, ppm	ORC	Organic Rankine cycle
ω	Rotational speed, rpm	POWER	Prediction of worldwide energy resources
Subscripts		PV	Photovoltaic
a	Air	PVT	Photovoltaic thermal
ave	Average	PX	Pressure exchanger
b	Brine	RE	Renewable energy
Comp	Compressor	RESs	Renewable energy sources
Flow	Flow	RO	Reverse osmosis
in	Inlet	SDGs	Sustainable development goals
LB	Lower bound	SWD	Seawater desalination
out	Outlet	UW-CAES	Underwater compressed air energy storage
p	Product/permeate	VAWTs	Vertical axis wind turbines
sw	Feed seawater	WE	Wind energy
UB	Upper bound	WE-SWRO	Wind energy-based seawater reverse osmosis
vent	Ventilation	WHO	World health organization
w	Water	WoS	Web of science
		WT	Wind turbine

considered an alarming indicator, underscoring the urgent need for sustainable water management practices to address these gaps and ensure global water security. Climate change exacerbates this issue by disrupting established hydrological cycles, leading to prolonged droughts and erratic precipitation patterns [7]. Both natural phenomena and human activities significantly contribute to the problem of water scarcity [8]. Greenhouse gas (GHG) emissions from the combustion of fossil fuels play a critical role in driving climate change by trapping heat in the atmosphere leading to a global rise in temperatures [9]. This increase in temperature has profound consequences, including more frequent and intense heatwaves, accelerated polar ice melt, and altered weather patterns, all of which significantly impact ecosystems and human communities worldwide. Fig. 2a illustrates trends in GHG emissions from 1990 to 2020, highlighting a steep rise in emissions worldwide [10]. In addressing these dual challenges of water scarcity and GHG emissions, renewable energy (RE) plays a pivotal role [11]. Transitioning to renewable energy sources (RESs) is essential to reduce the carbon footprint associated with water and energy production.

Fig. 2b highlights the total installed electricity capacity of different RE technologies from 2013 to 2023 [12]. Wind energy offers a promising solution. As a clean and inexhaustible resource, it can significantly cut down energy supply for various applications, including water treatment and desalination processes. The integration of wind energy into water infrastructure can enhance the resilience and sustainability of water systems.

Seawater desalination (SWD) is the process of removing salts and impurities from seawater to produce fresh water suitable for human consumption, irrigation, and industrial use. Ongoing research and development in the desalination sector have led to a rise in the number of plants to nearly 16,000, with a total capacity of 96 million m³/day. However, only approximately 130 of these plants use RESs, representing less than 1 % of the total desalination capacity [13], with the majority still dependent on fossil fuels [14]. SWD technologies vary in mechanisms, energy consumption, and operational efficiencies. Multi-stage flash (MSF) distillation heats seawater to create steam in multiple stages at progressively lower pressures, making it robust for large-scale

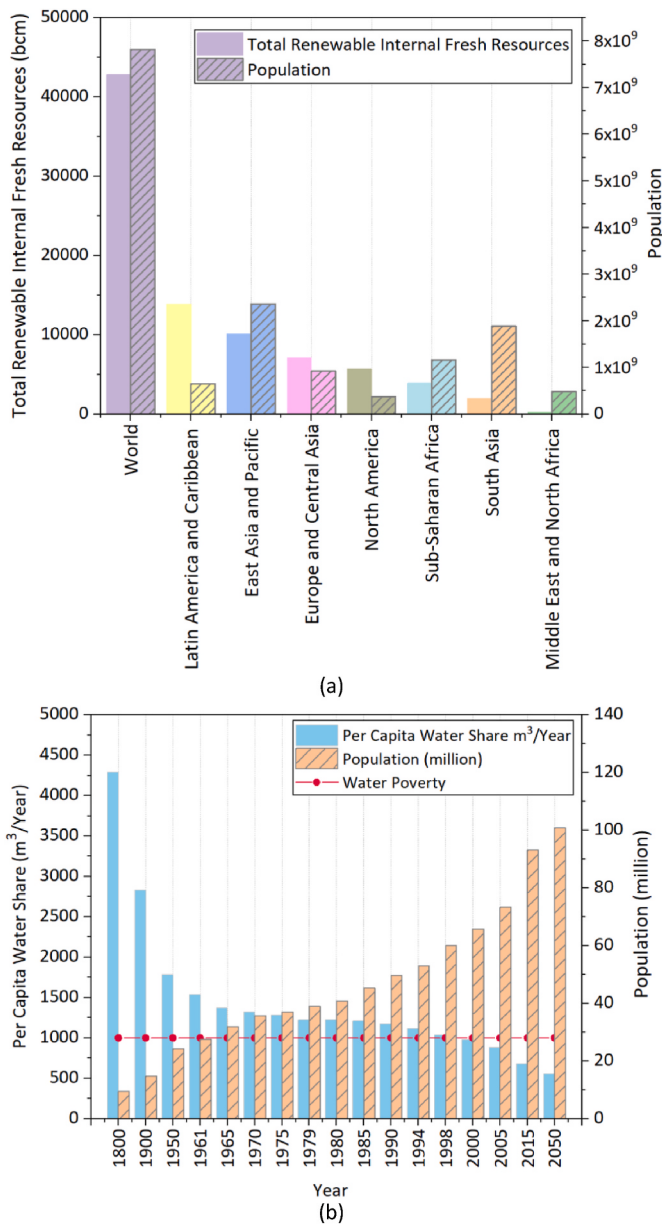


Fig. 1. (a) Regional total renewable internal fresh resources (bcm) based on World Bank data for the year of 2020 [4] and (b) Historical and projected trends of per capita water share and population growth of Egypt [6].

operations but also energy-demanding due to its thermal requirements. Multi-effect distillation (MED) improves efficiency by using a series of evaporators at decreasing pressures, reducing energy consumption compared to MSF [15]. Emerging technologies like forward osmosis (FO), which uses a natural osmotic process driven by concentration gradients, offer potential energy savings but face challenges in drawing solution recovery [16]. Electrodialysis (ED) and electrodialysis reversal (EDR) use electrical potential to move salt ions through selective membranes. The suitability of each technology depends on factors like energy availability, operation scale, feedwater quality, and economic considerations [17]. On the other hand, reverse osmosis (RO) uses high pressure to force seawater through a semi-permeable membrane to effectively remove salts and impurities [18,19]. The salinity difference across the semi-permeable membrane generates an osmotic pressure that drives water from the low salinity side to the high salinity side. RO can be employed in various applications, including seawater desalination and wastewater treatment.

Wind turbines transform kinetic energy from wind into mechanical work by utilizing turbine blades. The energy available from the wind depends on various factors, including the Earth's rotation, temperature differences between locations, and the site's geography [20,21]. This kinetic energy is converted into mechanical work by rotating the turbine's shaft, which drives a generator to produce electrical energy. There are two primary types of wind turbines: vertical axis wind turbines (VAWTs) and horizontal axis wind turbines (HAWTs). VAWTs can capture wind energy from any direction but generally have lower efficiency, [22]. However, they can generate substantial torque even at low wind speeds, making them a promising candidate for investigation as an alternative energy source [23]. On the other hand, HAWTs have more efficiency, however they capture wind from only one direction at a time [24,25]. SWD powered by RESs emerges as a critical strategy in mitigating water scarcity, especially for coastal regions. Desalination processes are energy-intensive but coupling them with RESs such as wind power can make them more sustainable and environmentally friendly [26,27]. This approach not only addresses the immediate need for fresh water but also aligns with global efforts to reduce GHG emissions.

1.1. Literature review

Several research studies have investigated the feasibility of employing hybrid RESs to power RO desalination, focusing on off-grid areas [28–35]. Fig. 3 displays the annual number of published articles from 2004 to 2025 in the field of wind energy-based seawater reverse osmosis (WE-SWRO), indexed by Scopus [36] and Clarivate Web of Science (WoS) [37], using the keywords KW1 "Wind Energy RO" and KW2 "Wind Powered RO." The figure reveals an increase in publications over time, peaking around 2021, with KW1 consistently showing a higher number of articles than KW2 across both databases. In a recent analysis conducted by Sayed et al. [38], it was found that WE-SWRO systems constitute approximately 19 % of the global RE-based desalination landscape. Karaca et al. [39] investigated a solar and WE system integrating compressed air energy storage (CAES), organic Rankine cycle (ORC), and multistage SWRO units, designed for potential deployment in Antigua and Barbuda using Engineering Equation Solver (EES) software. Their study demonstrates the system's capability to annually generate 365 GWh of electricity and produce 376.4 tons of fresh water daily, highlighting its potential to replace imported heavy fuel oil. Zhao et al. [40] examined a RESs system utilizing underwater compressed air energy storage (UW-CAES) for SWRO plants, highlighting the unsustainability of using a diesel engine in the off-grid configuration. It was found that the grid-connected setup, which included 511 photovoltaic panels (PV), 12 WTs, and a 900 m³ UW-CAES unit, was both economically viable and effective in lowering carbon emissions. Conversely, the off-grid configuration, despite further reducing carbon emissions with 705 PV panels, 8 wind turbines, and the same UW-CAES capacity, faced higher overall project costs and lacked revenue. Mohamed and Papadakis [41] proposed a stand-alone hybrid wind-PV system to power an SWRO unit. Their study demonstrated that with the inclusion of a pressure-exchanger-type energy recovery unit, the water production cost was reduced to €5.2/m³, and energy savings of up to 48 % were achieved. Gökçek [42] investigated off-grid power systems for a small-scale RO unit on Bozcaada Island, Turkey. The studied system comprised a 10 kW WT, a 20 kW PV solar panel, and an 8.90 kW-rated diesel generator. For a water production rate of 1 m³/h, the system achieved an electricity cost of \$0.308/kWh and a water cost of \$2.20/m³. The study concluded that this hybrid system significantly reduced fossil fuel consumption and CO₂ emissions compared to standalone diesel systems.

Amin et al. [43] conducted a numerical study to assess the viability of a floating desalination plant (FDP)-based RO system utilizing PV and WE for Egypt. The study focused on the stability and hydrodynamic performance, showing that it is a viable and efficient design for Egypt's environmental conditions. These findings suggest that the FDP concept

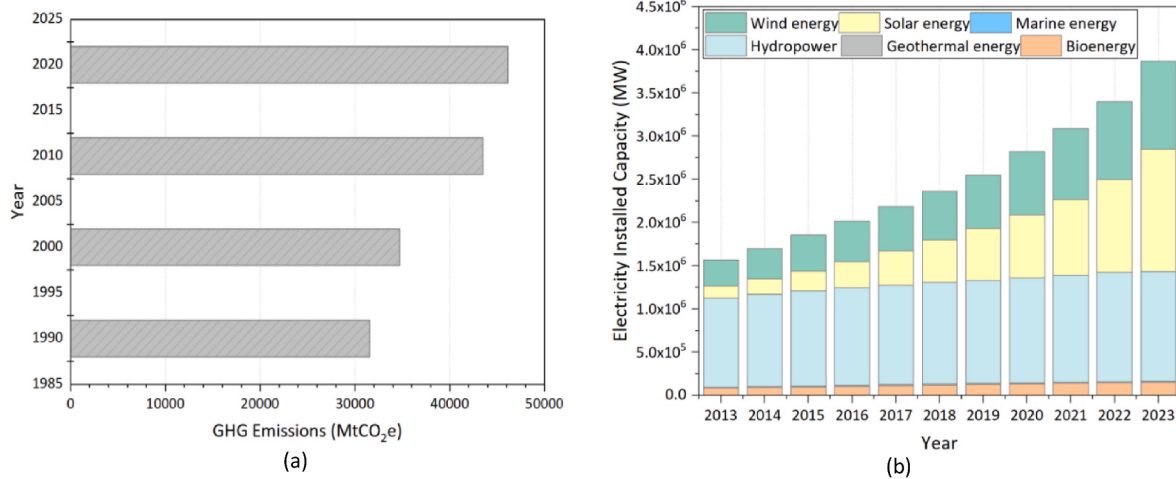


Fig. 2. (a) Historical GHG emissions according to Climate Watch [10] and Global Renewable Electricity Installed Capacity for the last 10 years [12].

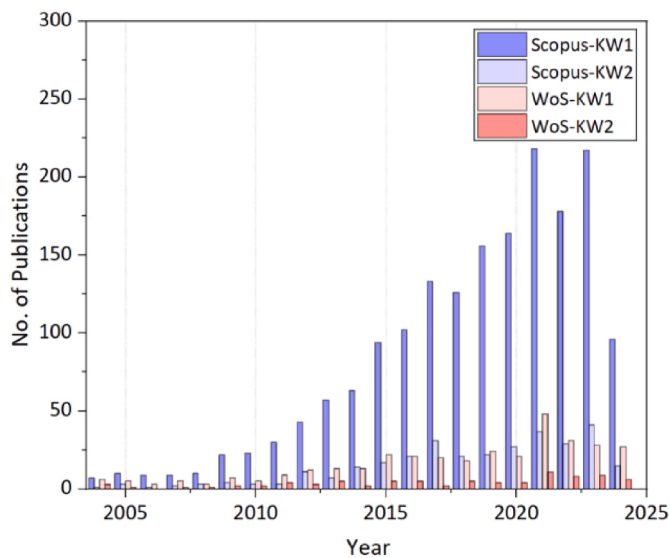


Fig. 3. Number of published articles in the field of WE-SWRO for the last 20 years.

can significantly contribute to the socio-economic development of remote areas. Ahmed et al. [44] performed a feasibility study examining various potable water supply options, including SWRO and the pumping of Nile water. Their research concluded that SWRO is the most economical choice for providing potable water to northwestern communities in Egypt. Moreover, SWRO's ability to produce water with varying salinities, depending on operating conditions and system design, makes it versatile for diverse applications such as potable water provision and treated water for drip irrigation. Atallah et al. [45] studied the use of hybrid RESs to meet freshwater demands in remote areas such as Nakhl, Egypt, which lack grid connectivity. Their analysis of PV, wind, diesel, and battery configurations identified an optimal setup featuring 160 kW of PV panels, a 50 kW diesel generator, and 19 strings of lead-acid batteries. This configuration achieved cost savings, with an energy cost of \$0.107/kWh and a net present cost of \$502,661.50. Ibrahim et al. [46] investigated off-grid hybrid RESs for SWD in Ras El Bar, Egypt. They compared two setups: one with a 10 kW wind turbine, 4.90 kW diesel generator, and 20 kW PV panel, which achieved costs of \$0.2252/kWh for electricity and \$1.10/m³ for water; the other with a 5 kW hydrokinetic turbine, 4.90 kW diesel generator, and 2.82 kW PV panel, which had lower costs of \$0.1216/kWh for electricity and

\$0.56/m³ for water. However, both setups still rely on diesel generators, contributing to GHG emissions and reducing sustainability.

Ben-Mansour et al. [47] conducted a numerical investigation assessing the performance of both WE-SWRO and PV-SWRO in Dhahran, Saudi Arabia. The results indicated that WE-SWRO produced desalinated water at a lower cost (\$1.366/m³ for a 1000 m³ daily demand) compared to PV-SWRO systems (\$2.119/m³), highlighting the economic and environmental benefits of using wind energy over solar energy for desalination. The feasibility of using WE-SWRO at a concrete factory in Al-Taweel, Kuwait was presented by Alsairafi and Al-Shehaima [48]. The findings revealed that WE could generate sufficient electricity to produce 15.75 m³/hr of fresh water with an RO system operating at 78 m, requiring 58.5 kW of power. This represents about 20 % of the potential WE available, highlighting the viability of integrating RE for water production in Kuwait. Dahoui and Loudiyi [49] performed a simulation of an WE-SWRO system. The study revealed that variable WE can cause significant fluctuations in feed water pressure, often surpassing the operational limits of RO membranes; however, solutions such as WT de-rating and pressure stabilizers can effectively mitigate these fluctuations. Economic assessments showed that in regions with strong wind resources, like the southern Saharan coast of Morocco, WE-SWRO can produce water at highly competitive costs (7.35 MAD/m³), significantly lower than in other areas, such as certain Greek islands where costs can rise to 30 MAD/m³.

Novosel et al. [50] examined integrating SWRO with brine-operated pump storage units and WE-PV plants to tackle Jordan's energy and water issues. This system was projected to boost RE use to 76 % by 2050, reducing CO₂ emissions by 2.24 times and lowering total system costs by 1.3 times. The findings demonstrated the economic and environmental viability of flexible desalination systems in enhancing RE integration and providing essential water resources. Another research conducted by Dehmas et al. [51] in Ténès, Algeria focusing on the use of WE-SWRO. Results showed that a wind farm with five 2 MW Bonus turbines could meet the energy needs of the plant, offering a viable alternative to diesel for irrigation and electricity generation. The analysis indicated that WE is a cost-effective and environmentally friendly option for desalination in wind-rich regions like northern Algeria, with electricity costs at 7c \$/kWh. Mallek et al. [52] performed an optimization of a hybrid PV-WE system integrated with the National Grid for a SWRO plant located in Sfax, Tunisia. Their results showed a substantial 50.2 % reduction in energy costs required to produce 1 m³ of water, highlighting the economic and environmental benefits over conventional methods. This integration of RESs with traditional grids not only enhances operational efficiency but also mitigates environmental impact in desalination operations, offering a promising solution to challenges posed by freshwater

scarcity and energy sustainability. Other RO systems considered the use of different RESs as a sustainable power option. Shams and Ahmadi [53] presented a water and power system design tailored for Iran's Sistan and Baluchestan province, featuring PV and Photovoltaic Thermal (PVT) panels, a battery bank, SWRO, and thermal storage. Their study, employing techno-economic optimization, revealed that deploying both PV and PVT panels concurrently reduced system costs by up to 19.2 %. Optimizing variables such as battery depth of discharge (DOD) and water tank capacity significantly lowered lifecycle costs (LCC).

Gökçek, M. and Gökçek, O [54]. reported a techno-economic analysis of a small-scale WE-SWRO on Gökçeada Island, Turkey, showed that water production costs ranged from \$2.962 to \$6.457/m³ for off-grid systems and \$0.866 to \$2.846/m³ for grid-connected systems, with significant reductions in CO₂ emissions. Carta and Cabrera [55] investigated the optimal design of standalone WE-SWRO plant of medium scale. Their work focused on eliminating the requirement for large-scale energy storage by prioritizing flywheels for dynamic system regulation. The study revealed that configurations employing flywheels achieved lower specific costs (€1.93/m³) compared to a reference system that relied on massive energy storage solutions. Slocum et al. [56] proposed integrating pumped hydro energy storage with reverse osmosis desalination (IPHRO) to address energy storage and freshwater needs in coastal regions with nearby mountains in Southern California. Co-locating these systems reduced capital costs and facilitated efficient brine disposal, proving economically and environmentally beneficial. Clayton et al. [57] examined combining WE with brackish groundwater desalination (BGWD) to balance RE availability with desalination processes. Their study found that, although integrated systems require significant capital investment, the higher value of treated water can result in greater profitability than selling intermittent electricity. Case studies in West Texas, particularly in Lubbock, Midland, and Abilene, showed this approach to be economically viable. A case study of a small size WE-SWRO without batteries was considered in Trinidad and Tobago by Ramkissoon et al. [58]. The calculations indicated that the system, equipped with a 1 kW VAWT, could produce 57.6 gallons of fresh water per day at an energy consumption rate of 26.7 KWh/kgal. These findings suggest that this configuration holds promise as an alternative for SWRO, with prototype testing necessary to validate performance under variable wind conditions and to improve efficiency using a Clark pump for energy recovery.

Another study was conducted by Penate et al. [59], comparing a 1000 m³/d Gradual Capacity (GC) design with a conventional Fixed Capacity (FC) SWRO plant powered by off-grid WE systems. The GC design, which adjusted its capacity based on available WE, achieved higher annual operational efficiency despite producing slightly less water annually compared to the FC design. A model for RE-RO was presented by Brendel et al. [51], incorporating hourly energy availability and economic factors. RO and MSF systems driven by wind, solar PV, and solar thermal energy were compared to conventional grid and natural gas sources, using levelized cost of water and primary energy usage as key performance indicators. When applied to Aruba, the model demonstrated that wind and solar PV-driven desalination systems were highly cost-competitive, highlighting its effectiveness in economic and sensitivity analyses. Asensio et al. [60] proposed an alternative to conventional SWRO by integrating RESs, based on operational data from Soslaires Canarias S.L.'s WE plant. The study recommended improvements to reduce the cost of water (COW) with potential economic benefits including a net present value of 74,360.95 EUR and an internal rate of return of 224.49 %. Integrating 2.64 MW wind turbines with an additional 196,000 EUR investment was identified as a viable strategy to enhance system efficiency and cost-effectiveness. Pietrasanta et al. [61] investigated the optimal integration of WTs and PVs with SWRO units to meet freshwater demand efficiently. Using a mixed integer linear programming (MILP) model, the results showed that hybrid PV-WE systems in Rio Grande and Camarones, Argentina, such as PV/WE/SWRO and WE/SWRO, offer cost-effective freshwater production at \$0.60/m³ to

\$0.67/m³ annually. The study highlights the variability of solar resources in Rio Grande and suggests potential enhancements through integrating various energy storage technologies.

1.2. Scope and Contributions

This study proposes a novel wind-powered desalination system that integrates WE and RO technology with CAES for sustainable water production. The originality of this approach lies in its use of an oil-free wind-driven compressor coupled with air storage to power specialized air-operated pumps for optimal SWRO operation. Unlike traditional systems that rely on electricity generation from WTs to power the SWRO, this design directly utilizes the WT to drive the air compressor. The compressed air then energizes a high-pressure piston pump, eliminating the need for conventional electrical components like generators, motors, and battery storage (as shown in Fig. 4). This innovative approach significantly simplifies the system, enhancing both performance and reliability. Furthermore, this research focuses on the Egyptian context, where WE potential is high (as illustrated in Fig. 5), and water scarcity is a pressing concern. Given the rising costs of fossil fuels and GHG emissions, this study aims to pave the way for strategic investments in sustainable water resources to address the increasing water demand in arid regions like Egypt. Also, while the potential of WE-SWRO systems has been explored in literature, limited research exists on their optimization and evaluation within the Egyptian context. This study addresses this gap by conducting a comprehensive techno-economic analysis across twenty coastal locations and throughout a year. A simulation model is developed to optimize system performance and predict desalination costs under different geographical and seasonal conditions within Egypt. The model incorporates experimentally predicted correlations specific to different employed components for enhanced accuracy. Also, sensitivity analysis of the system has been conducted. The remainder of the manuscript is organized as follows: Section 2: Methodology provides a detailed explanation of the research methods employed. This section encompasses a description of the system components, the experimental approach undertaken, the meteorological data utilized, and the development of both simulation and economic models. Section 3: Results and Discussion analyses the system's performance through an optimization process aimed at achieving minimal desalination costs. Key findings are presented and critically discussed. Additionally, a sensitivity analysis is conducted to evaluate the impact of cost variations. Section 4: Conclusion summarizes the study's principal findings and emphasizes their significance for future advancements in the field of desalination technology.

2. Methodology

This section outlines the comprehensive methodology employed in the study, detailing the various components and processes critical to the research. The methodology is structured to provide a clear understanding of the system components, the experimental procedures, and the mathematical approaches utilized. Subsection 2.1, System Components Description, offers an in-depth explanation of the key components involved in the WE-SWRO system. Subsection 2.2, Experimental Approach, describes the experimental setup and procedures undertaken to understand the main components of the system. In subsection 2.3, Meteorological Data, details of the collection and processing of meteorological data essential for the system's operation are provided. Subsection 2.4, Mathematical Approach, presents the mathematical models and equations used to simulate the system's behaviour. Subsection 2.5, Economic Model, discusses the economic analysis performed to evaluate the system's cost-effectiveness. Finally, Subsection 2.6, Sizing Methodology, explains the optimization algorithms and methodologies employed to determine the optimal performance for various locations.

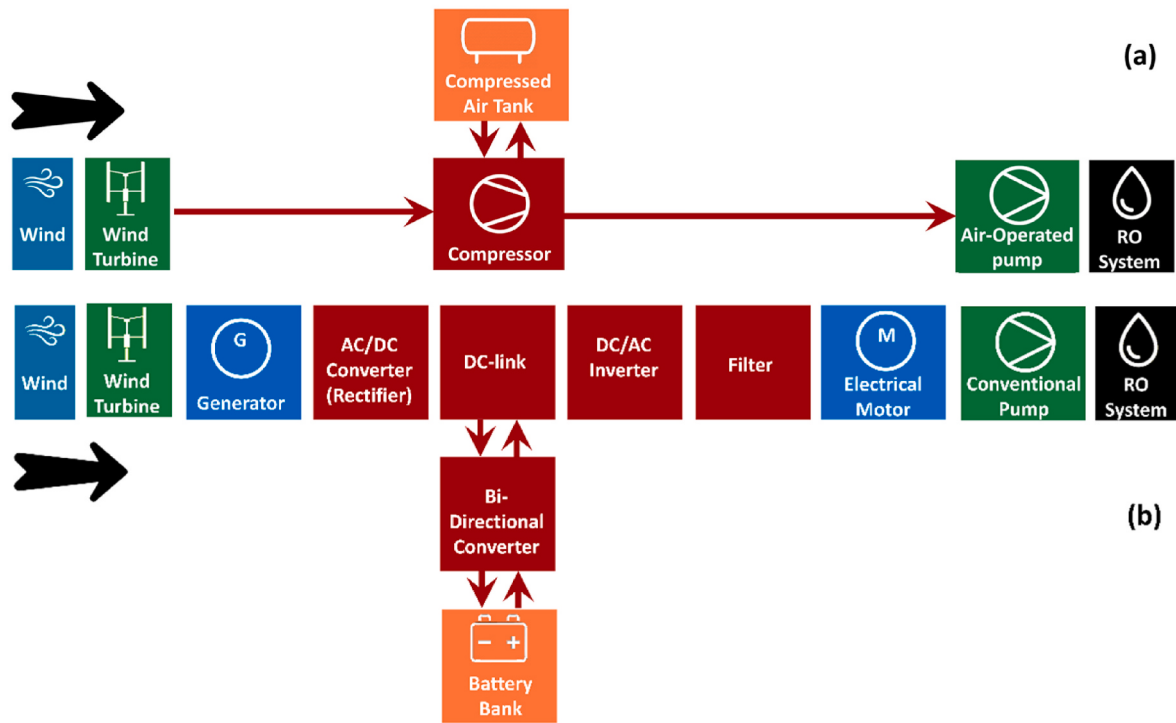


Fig. 4. Block diagram of: (a) The proposed concept for wind-powered compressed air-operated RO System (b) Conventional electrical motor-operated RO system.

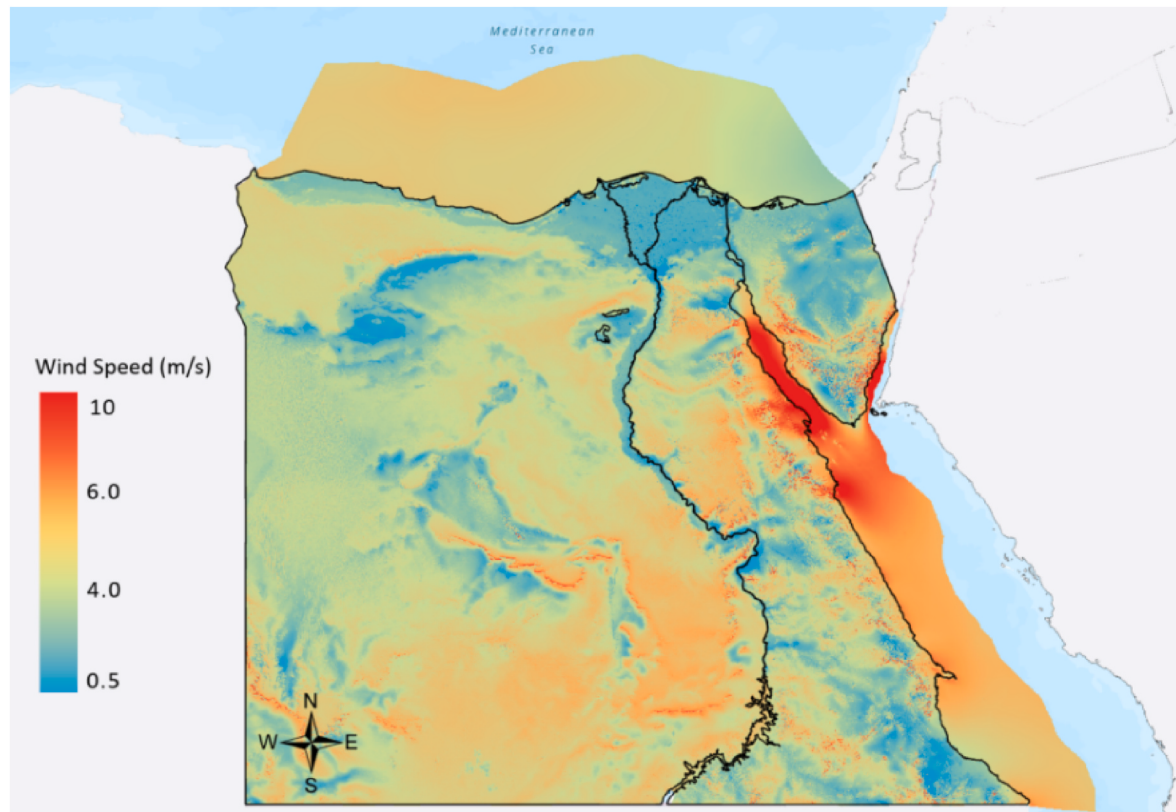


Fig. 5. A geographical map illustrating the wind energy potential across Egypt displaying average wind speeds at a height of 10 m (The data adapted from Refs. [62,63]).

2.1. System Components Description

The schematic flowsheet depicted in Fig. 6 illustrates the proposed WE-SWRO system, which utilizes wind energy to compress, store, and

power air-operated pumps, facilitating the required pressure for the desalination process. The red lines in the diagram denote compressed air hoses, while the blue lines represent water pipes. Initially, torque from Hybrid Vertical-Axis Wind Turbine (HVAWT) propels an oil-free

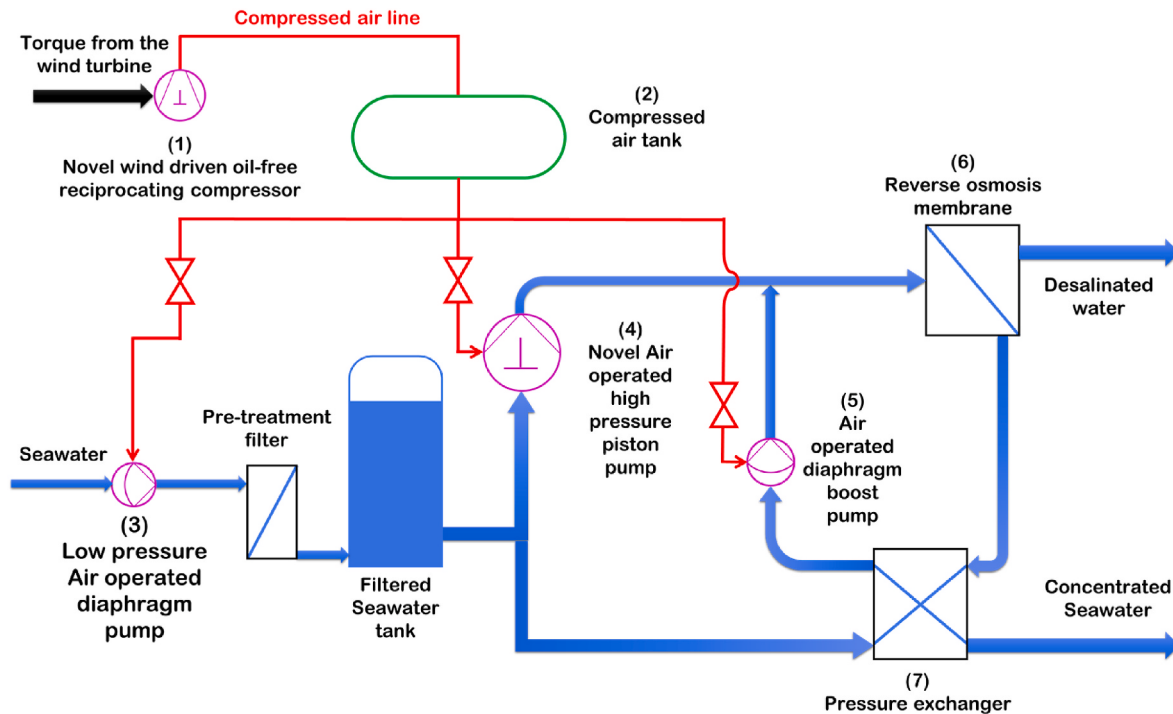


Fig. 6. Schematic diagram of the proposed WE-SWRO system flowsheet.

reciprocating compressor (No.1), which generates compressed air. This air is temporarily stored in a designated storage tank (No.2) for short-term energy storage, effectively balancing supply and demand fluctuations. The system employs air-operated pumps powered by this compressed air to provide the necessary pressure for the RO membrane. The process begins with the feed diaphragm pump (No.3) conveying seawater to the filtered seawater tank. Subsequently, a novel air-operated high-pressure piston pump (No.4) pressurizes the water, allowing it to flow through the RO membrane (No.6), where desalination occurs. Freshwater is then directed to a storage tank, while high-pressure brine is discharged to an energy recovery pressure exchanger (No.7). This device recuperates wasted energy from the brine, using it to elevate the pressure of the incoming seawater stream, thereby enhancing the system's energy efficiency. The energy is further boosted by an additional booster pump (No.5) before the seawater enters the membrane. Key components, including control valves and pressure gauges, are strategically integrated into the system to regulate airflow and monitor pressure levels, ensuring optimal operation. Through this integrated approach, the WE-SWRO system effectively leverages WE, drastically reducing dependence on non-renewable energy sources and mitigating environmental impact. This proposed system represents a sustainable solution to desalination, aligning with sustainable development goals (SDGs) of energy efficiency and environmental protection.

2.2. Experimental approach

This section outlines the experimental approach, which is divided into two distinct stages. The first stage encompasses the design, installation, and performance analysis of a HVAWT. The second stage involves an in-depth experimental investigation to understand the behaviour of the air compressor system. The initial step in the experimental testing involved selecting an innovative HVAWT design as the primary energy source. This design seamlessly integrates the lift-driven Darrieus turbine with the drag-oriented Savonius rotor on a unified shaft, thereby enhancing both start-up characteristics and power coefficient across a broad spectrum of wind speeds. The Darrieus component is derived from recent optimizations of low-speed VAWTs, featuring three straight

blades with a diameter of 1.8 m and an aspect ratio of 1.0 [64]. Utilizing the spars and ribs concept, the turbines are precisely crafted with the spars, ribs, and connecting arms precision-cut from steel plates using advanced laser cutting technology. These components are then enveloped in stainless steel sheets to form the aerofoil shape characteristic of the blades. The Savonius turbine, with a diameter of 0.6 m and a height of 0.3 m, employs a three-bucket configuration with curved endplates [65]. The buckets, which exhibit a semi-circular cross-section, are also accurately manufactured from stainless steel sheets utilizing precision laser cutting techniques. The HVAWT prototype, incorporating these optimized design features was subsequently installed atop the Faculty of Engineering building at Port Said University as shown in Fig. 7. To ensure accurate assessment of the HVAWT's performance, wind speed measurements were conducted using a Testo 435 vane anemometer (accuracy $\pm 1.5\%$) [66], while the rotational speed of the turbine was measured using a SHIMPO DT-205LR optical tachometer (accuracy $\pm 1\%$) [67]. To ensure repeatability and reliability, each measurement was repeated three times. The recorded data were systematically analysed, as illustrated in Fig. 9, to facilitate the development of a comprehensive mathematical model for the entire system. It can be seen from Fig. 9 that there is a positive correlation between wind speed and the rotational speed of the HVAWT. Even modest increases in wind speed led to significant increases in rotational speed, indicating the turbine's high efficiency in harnessing wind energy.

The second phase of experimental testing is pivotal for obtaining data crucial to subsequent mathematical calculations of the air compressor, aimed at understanding the relationship between volume flow rate and rotational speed. The experimental setup, illustrated in Fig. 8, for air compressor testing involved a multispeed rotary motor coupled to a gearbox, an Omega digital flow meter (accuracy $\pm 0.8\%$) [68], a pressure gauge (accuracy $\pm 2\%$), a control valve, and the compressor unit. To simulate operational conditions similar to WT speeds, a SHIMPO DT-205LR optical tachometer (accuracy $\pm 1\%$) [67] was installed upstream of the gearbox to accurately measure motor speed. The gearbox subsequently adjusted the rotational speed to an optimal level conducive to efficient compressor operation. A consistent back pressure was carefully maintained through precise adjustments of

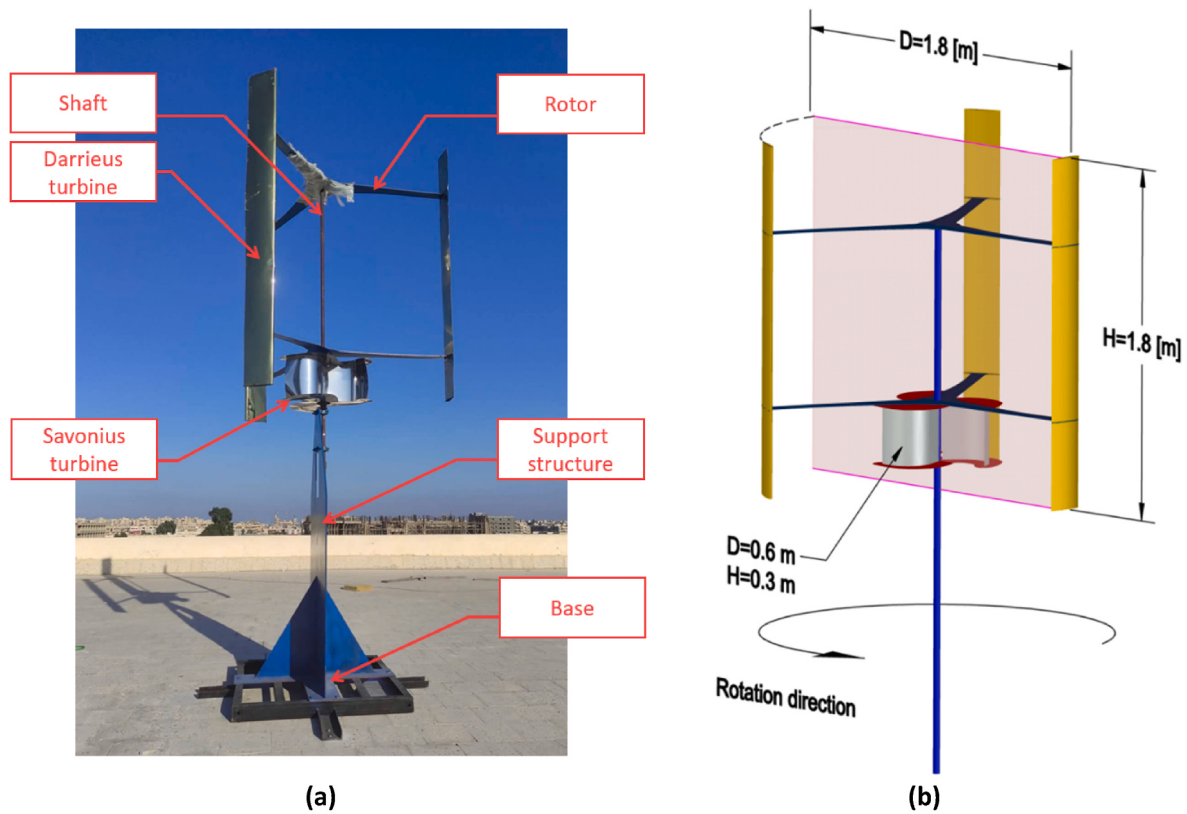


Fig. 7. The proposed HVAWT model for the SWRO system: (a) a photograph of the implemented design and (b) a graphical illustration.

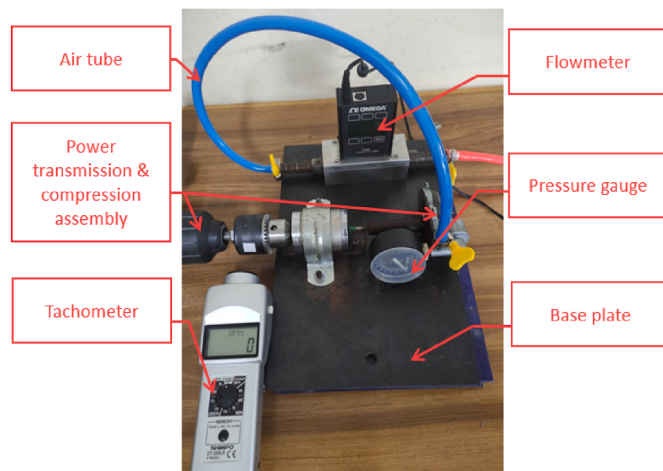


Fig. 8. Test rig for laboratory testing of the air compressor.

the control valve, ensuring standardized loading conditions for the compressor. Prior to initiating tests, rigorous calibration of the rotary motor speed settings was conducted using the tachometer to validate accuracy. Additionally, the digital flow meter and pressure gauge underwent calibration to ensure measurements precision. Throughout the testing phase, the flow meter provided continuous real-time data on airflow rates, while the pressure gauge monitored the system's internal pressure. The experiments were repeated three times to ensure accuracy and repeatability. Data collected included the relationship between rotational speed and airflow rate, which forms the basis for subsequent analysis. Fig. 9 illustrates that the relationship between the rotational speed and the flow rate of the compressor is linear, suggesting a direct proportionality between rotational speed and air flow rate. As the

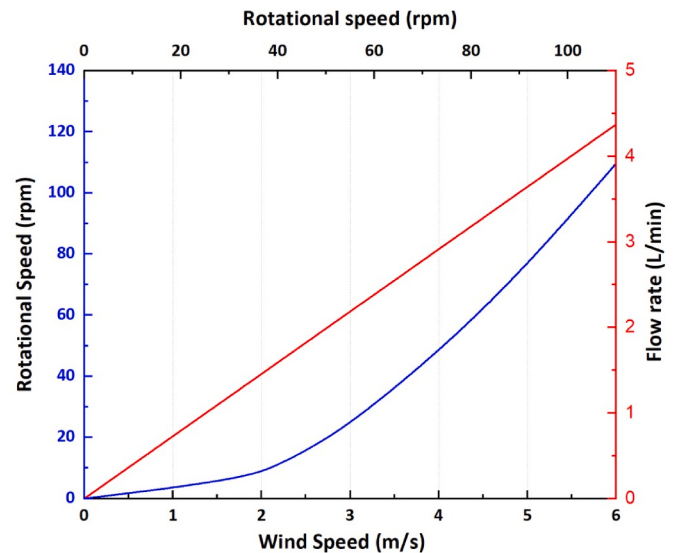


Fig. 9. Relationship between wind speed and the rotational speed of the HVAWT, and the corresponding variation in air flow rate with rotational speed.

rotational speed increases, the air flow rate correspondingly increases, demonstrating the compressor's efficiency in converting rotational energy into air flow.

2.3. Meteorological data

To comprehensively evaluate the proposed WE-SWRO system across Egypt's coastal environments, twenty coastal cities were selected. Site selection prioritized locations distant from the Nile and Delta, where

desalination is more economically viable due to reduced piping costs. Consequently, coastal areas adjacent to remote tourist hubs were emphasized to assess the system's performance in diverse geographic and socioeconomic contexts. The Red Sea coast was a primary focus, with additional sites considered on the Mediterranean Sea coast and Sinai Peninsula. In coastal environments at a low elevation of 10 m above ground, wind speeds can vary significantly depending on geographical location due to the influence of complex terrain. Consequently, the performance of wind turbines in these areas is highly sensitive to the specific latitude and longitude coordinates of the chosen locations, rather than merely the location names. To ensure consistency and accuracy, a tool has been employed to obtain precise geographical coordinates from the location names. This method facilitates more reliable data collection and analysis, leading to more accurate assessments of wind turbine performance. Fig. 10 illustrates the selected cities' locations, while Table 1 provides detailed geographic coordinates and categorizes the sites into three coastal regions: Red Sea, Sinai Peninsula, and Mediterranean Sea. Table 1 also presents year-averaged wind speeds at 10 m height, derived from the Prediction of Worldwide Energy Resources (POWER) database [69]. The Red Sea coast demonstrated substantial wind energy potential, with Hurghada (27.2579°N, 33.8116°E, 6.86 m/s), El Gouna (27.4025°N, 33.6511°E, 6.84 m/s), Ras Ghareb (28.3508°N, 33.07536°E, 6.12 m/s), and Ras Shukeir (28.1354°N, 33.2731°E, 6.4 m/s) exhibiting high wind speeds. The Sinai Peninsula coast, with Dahab (28.4956°N, 34.50043°E, 5.06 m/s) and Sharm El Sheikh (27.9158°N, 34.3299°E, 4.45 m/s), offered moderate wind resources suitable for localized initiatives. The Mediterranean Sea coast, including Marsa Matruh (31.3366°N, 27.25533°E, 5.63 m/s) and Gamasa (31.4412°N, 31.53645°E, 5.08 m/s), also presented viable opportunities for wind energy projects.

2.4. Mathematical approach

This section introduces a comprehensive mathematical model designed to simulate and optimize the proposed SWRO-based oil-free air compressor system driven by an HVAWT. The model is implemented within the MATLAB/Simulink environment [70] to evaluate the system's performance and productivity across various coastal Egyptian cities over a one-year period. As depicted in Fig. 11, the system utilizes compressed air generated by the HVAWT and air compressor to power multiple high-pressure pumps, which force seawater through an RO membrane. A booster pump elevates seawater pressure upstream of the RO, while a pressure exchanger recuperates energy from the high-pressure brine effluent. An advanced one-dimensional controller governs system operation. Specifically, the controller initiates a system shutdown when air storage drops below the minimum threshold and subsequently reactivates the system upon air storage refill to nominal capacity. Furthermore, the controller mitigates excessive WE by venting excess air when air storage approaches maximum capacity. Under optimal operating conditions, the RO system delivers a desalinated water output of 4 m³/h, sufficient to cater to a community of 1000 individuals based on the World Health Organization's (WHO) recommendation of 100 L/capita/day for basic needs and minimal health risks [71]. The installed RO membrane achieves a recovery ratio of 40 % [60], producing desalinated water while recycling the remaining 60 % as brine. This brine subsequently undergoes the pressure exchange process, which significantly augments the overall system efficiency and sustainability. The subsequent mathematical and economic analyses were conducted utilizing the parameters and assumptions outlined in Tables 3 and 4. Before that, a set of specific assumptions underlying the model are outlined as follows.

- A time series of wind speed data, sourced from the POWER database [69], is employed to dynamically update wind speed within the

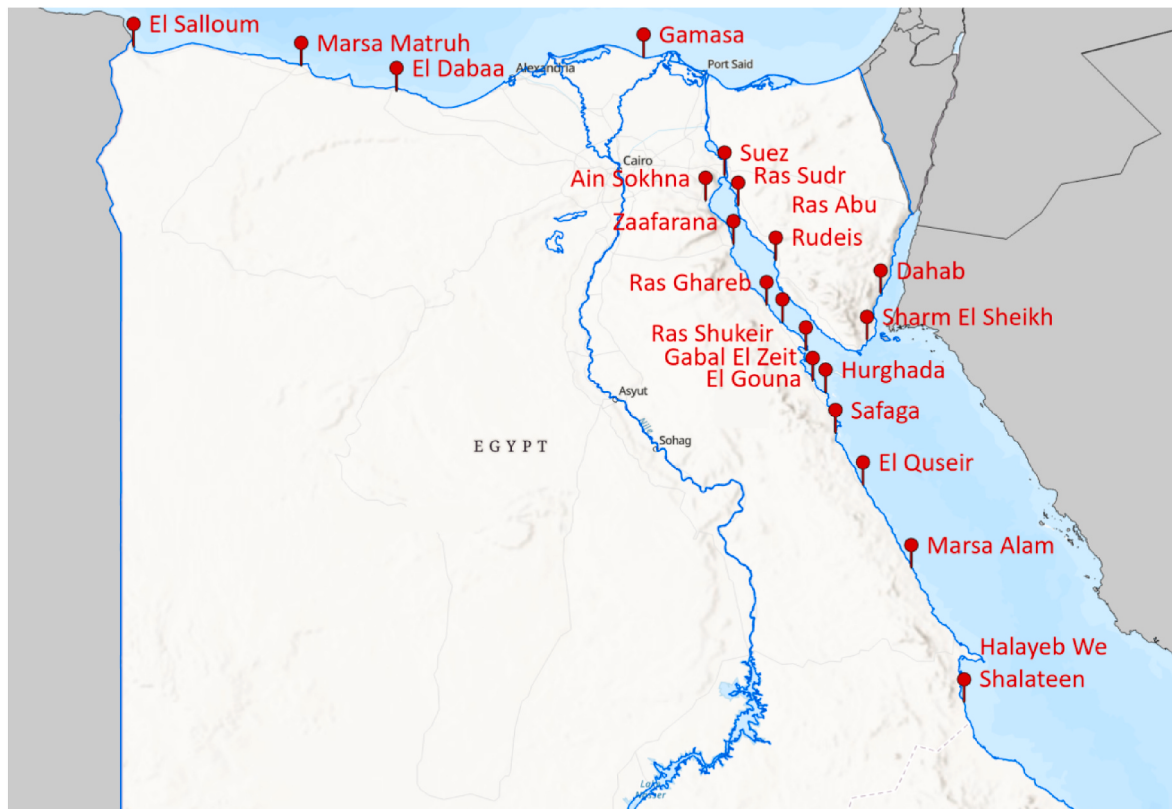


Fig. 10. An illustration of the twenty selected locations on the Egyptian map.

Table 1

The detailed locations of the selected coastal cities in Egypt and the corresponding average wind speed at 10 m above the ground [m/s].

No.	City	Latitude (Degree)	Longitude (Degree)	Average wind speed at 10 m above the ground in [m/s]	Region
1	Suez	29.9668	32.5498	4.05	Red Sea coast
2	Ain Sokhna	29.651	32.31112	4.53	
3	Zaafarana	29.1107	32.66038	4.94	
4	Ras Ghareb	28.3508	33.07536	6.12	
5	Ras Shukeir	28.1354	33.2731	6.4	
6	Gabal El Zeit	27.7833	33.5666	5.66	
7	El Gouna	27.4025	33.6511	6.84	
8	Hurghada	27.2579	33.8116	6.86	
9	Safaga	26.753	33.93559	5.69	
10	El Quseir	26.1014	34.2803	5.36	
11	Marsa Alam	25.0684	34.88419	5.48	
12	Halayeb We Shalateen	22.2860	35.10756	4.58	Sinai Peninsula coast
13	Dahab	28.4956	34.50043	5.06	
14	Sharm El Sheikh	27.9158	34.3299	4.45	
15	Ras Abu Rudeis	28.906	33.18981	4.98	Mediterranean Sea coast
16	Ras Sudr	29.591	32.71954	4.53	
17	Gamasa	31.4412	31.53645	5.08	
18	El Dabaa	31.0224	28.44776	4.92	
19	Marsa Matruh	31.3366	27.25533	5.63	
20	El Salloum	31.575	25.15932	4.67	

model at 1-h intervals. A cubic spline linear interpolation scheme is implemented to provide the instantaneous wind speed to the Simulink model allowing the system to operate under transient conditions, with variables fluctuating in response to wind speed variations.

- Heat exchange with the environment is considered negligible, treating the system as adiabatic.
- Air is modelled as an ideal gas.
- Water is treated as an incompressible fluid, maintaining constant density irrespective of pressure fluctuations.
- Isentropic processes are assumed for compression within the compressor and pumps.

- Pressure losses attributed to friction within pipes and minor components are neglected.
- Perfect mixing within the compressed air tank ensures uniform pressure distribution.
- The RO membrane permeability is assumed to remain constant over time.

The relationship between the rotational velocity, ω , of the HVAWT and the incoming wind speed, V , is modelled using a sixth-order polynomial function derived through curve fitting of experimental data, as follows:

$$\omega = -0.0001 V^6 + 0.0055 V^5 - 0.1013 V^4 + 0.585 V^3 + 2.5149 V^2 - 2.3307 V \quad (1)$$

The air discharge, $\dot{V}_a$, from the compressor can be characterized using the subsequent equation which is derived from the experimental results where ω denotes to the rotational speed and N represents the number of turbines.

$$\dot{V}_a = 0.03975 \omega N \quad (2)$$

The compressed air tank serves as a storage reservoir, ensuring a consistent supply of compressed air to various system components. The compressed air tank is nominally designed with a capacity of 150 cubic meters. However, its operational range is fine-tuned to fluctuate between a minimum pressurized air capacity of 100 cubic meters and a maximum capacity of 180 cubic meters. Assuming isothermal and isobaric tank conditions, the volume balance equation for the storage tank can be described as follows [72,73]:

$$\frac{dV}{dt} = \dot{V}_{a,in} - \dot{V}_{a,out} \quad (3)$$

In the proposed system, the considered air-operated high-pressure piston pump (HPP) is the Ingersoll Rand ARO Model AF0807M11RS48-1

Table 2

Validation of the RO system.

Parameter	Present Results	Nafey et al. [80]	Liu et al. [81]	Unit
SPC	7.67	7.76	7.81	kWh/m ³
P	1113	1130	1149	kW
$\dot{V}_{sw}$	485	486	485.3	m ³ /h
$\dot{V}_b$	340	340.23	340.8	m ³ /h
X_b	62000	66670	64180	ppm
X_p	239	200	250	ppm
SR	99.43	99.27	99.39	%

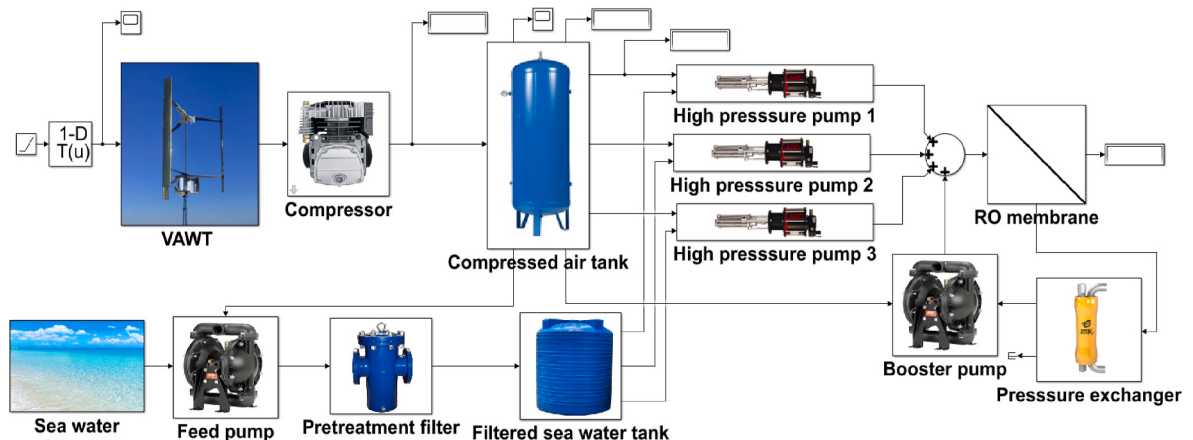


Fig. 11. The MATLAB/Simulink model for the proposed HVAWT-SWRO desalination system.

Table 3

Technical specifications of the WE-SWRO system [74,85–88].

Components	Parameters	Specifications
HVAWT with air compressor	Darrieus turbine diameter	1.8 m
	Darrieus turbine height	1.8 m
	Savonius turbine diameter	0.6 m
	Savonius turbine height	0.3 m
	Air compressor maximum discharge	12 L/min
	Compressor operating pressure	8.3 bar
	Compressor maximum pressure	10 bar
	Maximum noise level	62 dB
	Receiver sizes	200,000 L
	Capacity	Up to 170,000 at 10 bar
Compressed air tank	Maximum permissible gauge pressure	11 bar
	Coating	Internal and external galvanization
	Maximum air inlet pressure	8.3 bar
Air operated high-pressure piston pump	Maximum Outlet Pressure	70 bar
	Discharge	88.8 l/min
	Speed	70 rpm
	Noise Level	86.8 dB
	Centre section material	Polypropylene
Air operated boost diaphragm pump	Fluid cap & manifold material	Stainless steel
	Ball material	PTFE
	Diaphragm material	PTFE/Santoprene
	Maximum flow rate	12 gpm
	Noise level	75 dB
Pressure exchanger	Discharge	4.5–6.8 m ³ /h
	Efficiency	up to 96 %
	Noise Level	79 dB
Reverse osmosis membrane	Membrane type	Thin-Film Composite
	Permeate flow rate	7.4 m ³ /day
	Maximum operating temperature	45 °C
	pH Range	2–11
	Maximum feed flow Rate	3.6 m ³ /h
	Minimum salt rejection	99 %
	Fouling factor	85 %
	Minimal recovery rate	8 %

Table 4

Economic parameters of the system [74,85–91].

Parameter	Value
Cost of HVAWT & air compressor	200\$
Cost of compressed air tank and fittings	4411\$
Cost of air operated high-pressure piston pump	7370\$
Cost of air operated booster diaphragm pump	790\$
Cost of pressure exchanger	10969\$
Cost of RO membrane	444\$
O&M of HVAWT & air compressor	1 %
O&M of SWRO	0.32\$/m ³
O&M of air storage	2 %
Interest rates for small enterprises	5 %
Lifetime	25 years

[74]. This pump is characterized as a four-balls air-operated piston pump, featuring a pressure ratio of 7:1, capable of achieving pressures up to 70 bars. According to the manufacturer datasheet, the relation between the back pressure (p) and the water flowrate ($\dot{V}_{sw}$) is represented by equation (4), while the relation between the air consumption ($\dot{V}_a$) and water flowrate ($\dot{V}_{sw}$) is characterized by equation (5):

$$p = -0.0014 \dot{V}_{sw}^2 - 0.0579 \dot{V}_{sw} + 53.347 \quad (4)$$

$$\dot{V}_a = -0.0048 \dot{V}_{sw}^2 + 1.4801 \dot{V}_{sw} - 1.1344 \quad (5)$$

RO units employ membranes with minuscule openings to filter out non-ionic substances. As a result, only uncharged molecules can traverse the membrane, transforming seawater into freshwater. The permeate product of such systems can be determined by Refs. [75,76]:

$$\dot{V}_p = RR \dot{V}_{sw} \quad (6)$$

Where $\dot{V}_p$ is the freshwater product from the unit, RR is the recovery ratio, and $\dot{V}_{sw}$ is the seawater flow rate. The freshwater's salt concentration can be determined by using the following relation [77]:

$$X_p = X_{sw} (1 - SR) \quad (7)$$

Where SR is the salt rejection rate. Also, by applying the conservation of mass law on the RO unit, the relation between the seawater, freshwater, and brine can be written as follows:

$$\dot{V}_b = \dot{V}_{sw} - \dot{V}_p \quad (8)$$

In addition, the brine discharged from the RO process is characterized by its flow rate and salt content using the following relation:

$$X_b = \frac{\dot{V}_{sw} X_{sw} - \dot{V}_p X_p}{\dot{V}_b} \quad (9)$$

The differential pressure across the RO membrane can be expressed as [78]:

$$\Delta p = \frac{\dot{V}_p}{3600 TCF FF A_w k_w} + P_{ave} \quad (10)$$

In the abovementioned equation, P_{ave} denotes the mean osmotic pressure, while TCF and FF signify the temperature correction factor and fouling factor of the RO unit, respectively. Additionally, A_w represents the membrane area, and k_w symbolizes the membrane's water permeability. Considering that the average flux of most commercial membranes ranges from 11 to 17 LMH, the SW30-4040 membrane used in this study has an average flux of approximately 15 LMH [79]. The temperature correction factor and average osmotic pressure can be estimated using the following equations [77]:

$$TCF = \exp \left(2700 \times \left(\frac{1}{T} - \frac{1}{298} \right) \right) \quad (11)$$

$$P_{ave} = 37.92 (X_b + X_{sw}) \quad (12)$$

To validate the performance of the RO unit, a comparative analysis was conducted using the studies by Nafey et al. [80] and Liu et al. [81] as benchmarks. The findings of this comparative analysis are summarized in Table 2. The table demonstrates that the results obtained from the present study are consistent with those reported in the referenced works, thereby affirming the reliability of the achieved outcomes.

Within this investigation, the Energy Recovery Company's PX30 pressure exchanger is employed as an energy recovery device to harness energy from concentrated brine at high flow rates, necessitated by its operational range of 4.5–6.8 m³/h and a guaranteed efficiency of 93.4 % at a flow rate of 5.6 m³/h [82]. The high-pressure water discharged from the PX is directed into the RO membrane unit, facilitated by a circulating pump.

2.5. Economic model

The financial viability of the system is evaluated through the Levelized Cost of Water (LCOW) concept. This method provides a comprehensive analysis by accounting for all costs over the system's lifetime, including initial investment, operation and maintenance costs. Table 4 presents a comprehensive overview of the cost components associated

with the proposed system. Certain cost data is derived from information supplied by the manufacturer. The total capital cost (CapEx) can be calculated as follows [54]:

$$CapEx = \sum_{i=1}^n C_i \quad (13)$$

Where C_i is the capital cost of the i -th component and n is the total number of components in the WE-SWRO system. On the other hand, the operating cost (OpEx) of the system can be represented as the sum of all the recurring expenses required to operate and maintain the system over a period of time. These costs can include maintenance, labour, and consumables. Therefore, the OpEx can be expressed as [83]:

$$OpEx = \sum_{i=1}^n O\&M_i \quad (14)$$

Where $O\&M_i$ is the operating cost of the i -th component and n is the total number of components in the WE-SWRO system. Then, the capital recovery factor (CRF) can be calculated as follows [84]:

$$CRF = \frac{r(1+r)^n}{(1+r)^n - 1} \quad (15)$$

Where r and n are the interest rate and lifetime of the system in years, respectively. Therefore, the LCOW can be estimated using the following equation [54]:

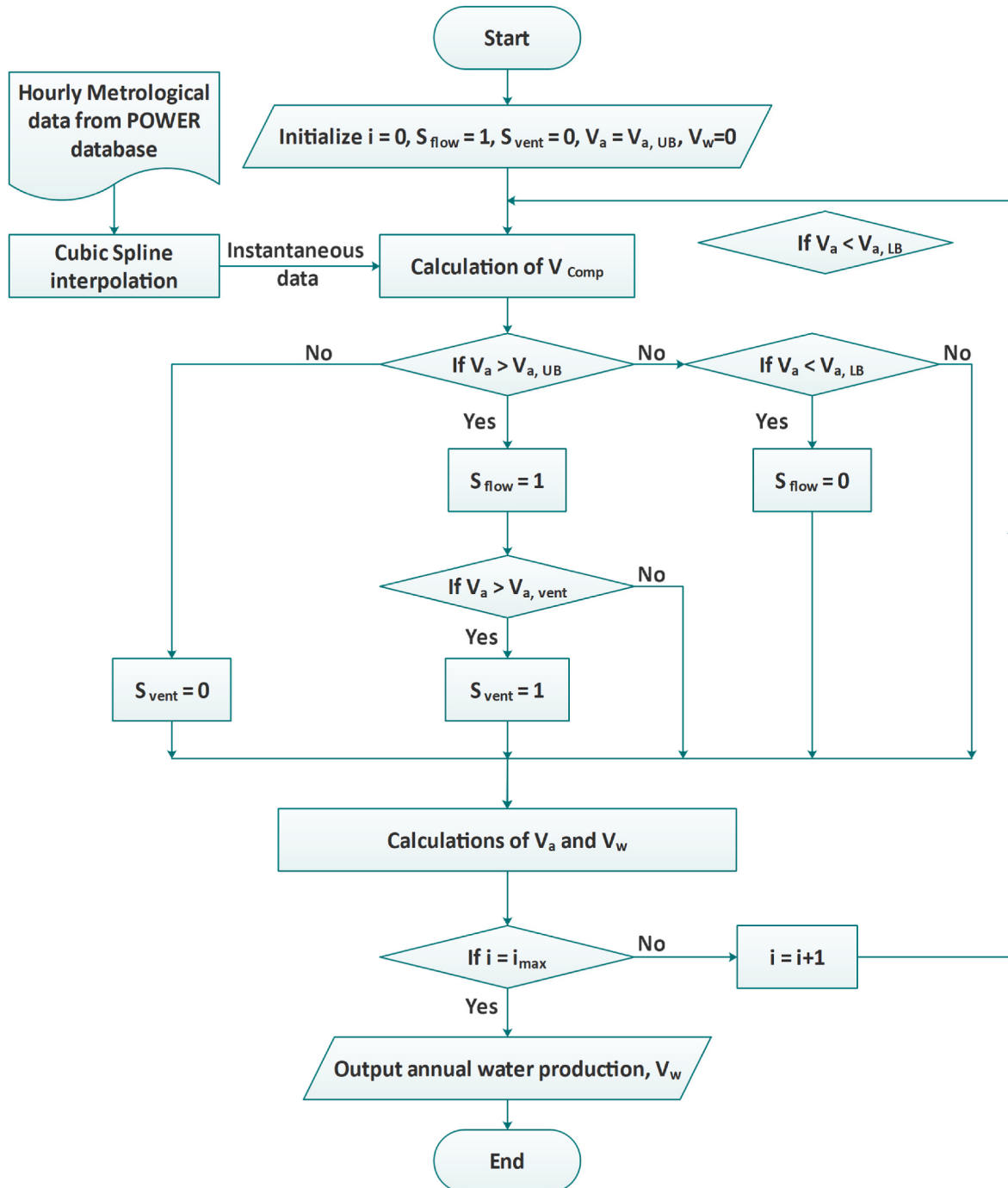


Fig. 12. Algorithmic process for estimating annual water output of the proposed WE-SWRO system.

$$LCOW = \frac{CRF \text{ CapEx} + \text{OpEx}}{\text{Annual freshwater production}} \quad (16)$$

2.6. Sizing Methodology

The previously discussed techno-economic models are utilized to determine the optimal size of the system. These models are integral in assessing various parameters to ensure the system operates efficiently and cost-effectively. Fig. 12 illustrates the systematic approach to calculating the annual water production from the WE-SWRO system. Initially, hourly meteorological data is sourced from the POWER database and subjected to cubic spline interpolation to derive instantaneous data. The process begins with the initialization of several parameters: the time step index (i) is set to 0, the flow system's status (S_{flow}) is set to 1, the vent system's status (S_{vent}) is set to 0, the initial air volume (V_a) is equated to the upper bound air volume ($V_{a,UB}$) and the initial water volume (V_w) is set to 0. Subsequently, the compressor volumetric flow rate (V_{comp}) is computed using the instantaneous data. The algorithm then evaluates whether the air volume (V_a) exceeds the upper bound ($V_{a,UB}$), adjusting (S_{flow}) to 1 if true. If (V_a) falls below the lower bound ($V_{a,LB}$), (S_{flow}) is set to 0. Additionally, the algorithm checks if (V_a) surpasses the ventilation threshold ($V_{a,vent}$), setting (S_{vent}) to 1 if this condition is met, or to 0 otherwise. Following these conditional checks, the air volume (V_a) and water volume (V_w) are recalculated based on the updated conditions and system's statuses. The time step index (i) is then incremented, and the process iterates until (i) reaches its maximum value (i_{max}). Upon completion of all iterations, the total annual water production (V_w) is outputted. This methodological framework ensures a detailed and accurate estimation of water production, leveraging meteorological data, system performance parameters, and dynamic system responses. In order to optimize the number of turbines for optimal system performance, the multiresolution brute force optimization algorithm (MBFOA) is utilized. This technique is an enhancement of the brute force method which ensures a comprehensive search for the optimal solution by gradually refining the search space. Initially, a broad search identifies promising regions, and subsequent iterations narrow down the range with increased resolution. The final stage involves a precise search with a resolution of 1 turbine, ensuring the exact optimal number of turbines is identified. This systematic approach enhances the efficiency and accuracy of the optimization, leveraging the multiscale nature of the algorithm to achieve a balance between computational effort and solution precision. The flowchart in Fig. 13 outlines the MBFOA used to determine the optimal number of wind turbines for minimizing the LCOW in the WE-SWRO desalination system. The process starts with initializing the number of turbines (N) at 50. The algorithm then calculates the LCOW for the current number of turbines. If N reaches 500, the algorithm identifies the lower bound (N_{LB}) and upper bound (N_{UB}) of the best range that minimizes the LCOW. Next, the number of turbines is set to $N_{LB} + 1$, and the LCOW is recalculated for each increment in N until it reaches $N_{UB} - 1$. At this stage, the algorithm identifies the optimal number of turbines that minimizes the LCOW, thereby concluding the optimization process.

3. Results and Discussion

This section presents the results obtained by simulating WE-SWRO system performance using the custom-developed MATLAB code. As detailed previously (Section 2), the code incorporated the specifications of each system component, historical meteorological data for various Egyptian coastal locations, and relevant economic parameters. The simulations aimed to achieve two key objectives: optimizing system performance and evaluating its economic feasibility. Firstly, the code was used to identify the optimal number of wind turbines required to meet the designated supply needs at minimal cost for each location. This analysis encompassed twenty distinct locations along the Egyptian

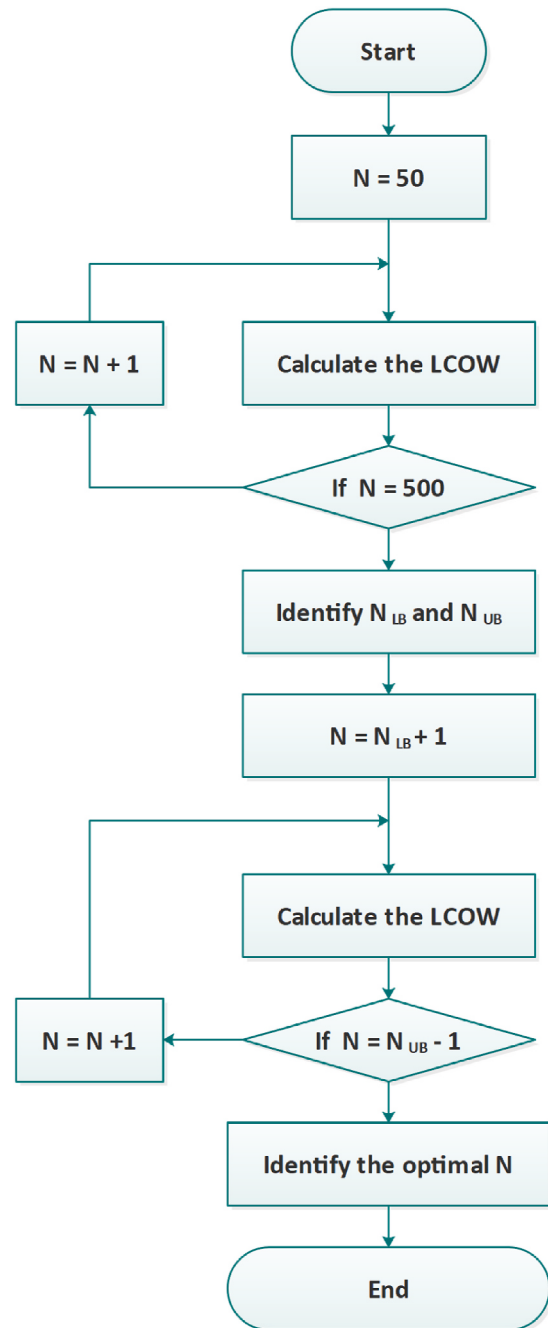


Fig. 13. Flow chart of the optimization procedure used for the WE-SWRO system.

coastline, as elaborated upon in Section 2. Following the selection of optimal turbine configurations, the code was further utilized to investigate various aspects of system behaviour. This analysis provided valuable insights into the system's characteristics under diverse seasonal conditions. Additionally, for each location, annual water production and associated costs were calculated. To comprehensively understand the system's response to economic factors, a sensitivity analysis is presented later. This analysis explores how various scenarios, such as fluctuations in different economic aspects, impact the overall system cost. This comprehensive approach ensures a thorough evaluation of the WE-SWRO system's potential for sustainable desalination across various coastal regions.

3.1. Optimization and system characteristics

Wind energy is inherently stochastic, characterized by continuous fluctuations in wind speeds across seasons and even within individual hours. The year-long data provide valuable insights into the temporal variability and consistency of wind resources, which are essential considerations for designing and optimizing wind energy systems. Fig. 14 illustrates this phenomenon by depicting the instantaneous and year-averaged wind speeds for Suez, Sharm El Sheikh, and Hurghada over a one-year period. The data reveal significant spatiotemporal variability, with all three locations exhibiting notable deviations from their respective annual averages. Suez experiences frequent fluctuations exceeding its average wind speed of approximately 4 m/s. Sharm El Sheikh demonstrates a slightly higher average wind speed of around 3.5 m/s but still undergoes considerable temporal variations. Hurghada emerges as the location with the highest wind energy potential, boasting a year-averaged wind speed close to 5 m/s and frequent peaks exceeding 12 m/s. While Hurghada stands out with its superior wind conditions, Suez and Sharm El Sheikh also present viable opportunities due to their

pronounced instantaneous wind speeds. These high wind events can be strategically exploited during peak periods to maximize energy capture. This inherent variability of wind speeds necessitates the integration of CAES into the WE-SWRO system design. While wind potential may exhibit seasonal variations with high levels during specific periods and lower levels during others, the system must be equipped to handle these fluctuations. During periods of elevated wind potential, excess compressed air can be produced that may surpass the storage capacity of the CAES tank. In such instances, a controlled venting procedure must be implemented to prevent over-pressurization of the storage system.

As depicted in Fig. 15, the relationship between the number of turbines and system performance in Hurghada has been analysed, given its highest wind speed among the 20 locations under consideration. The results demonstrate that an increase in the number of turbines leads to a corresponding increase in the percentage of system operation time, indicating improved utilization of wind energy resources. However, a critical threshold is observed when the number of turbines exceeds 200. Beyond this point, the compressed air tank accumulates excess compressed air, necessitating venting to prevent over-pressurization. This

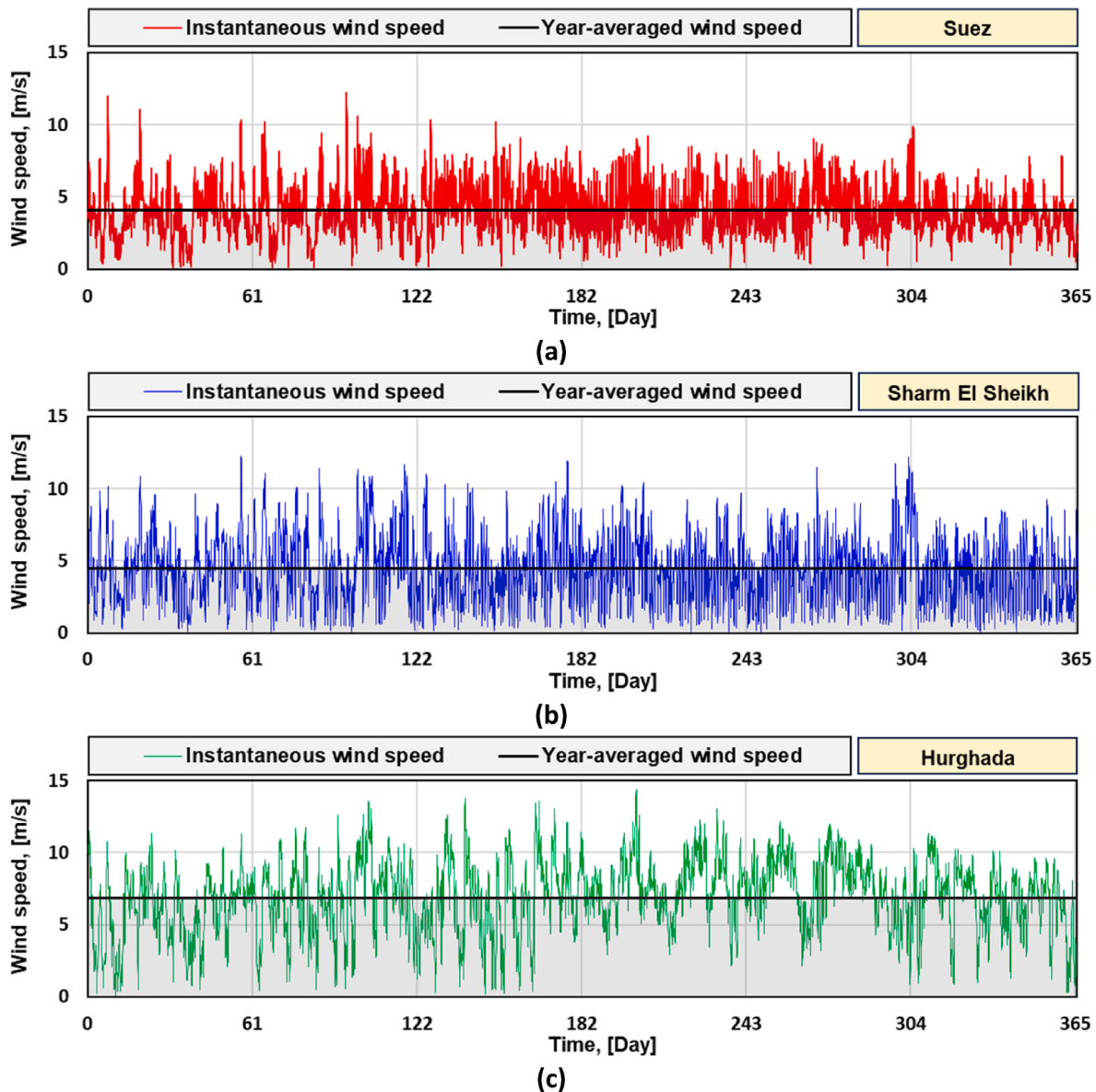


Fig. 14. The instantaneous wind speed and year-averaged wind speed at (a) Suez, (b) Sharm El Sheikh, and (c) Hurghada according to the data obtained from the POWER database [69].

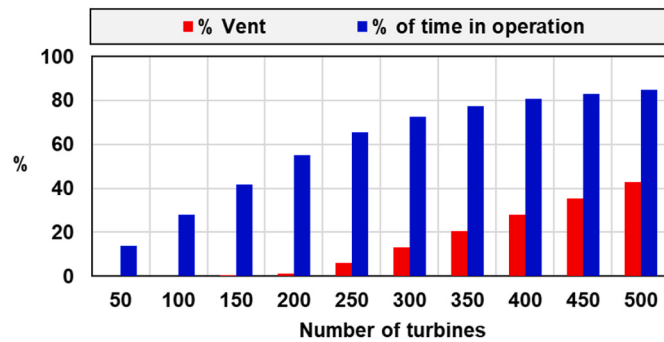


Fig. 15. Operation characteristics tracking in Hurghada.

venting represents an energy loss, which is depicted by the red bars in the figure. The blue bars indicate the percentage of time the system remains in operation, highlighting that with up to 200 turbines, the system operates efficiently without significant energy loss. However, as the number of turbines continues to increase, the percentage of time spent venting also rises sharply, reaching a notable proportion when the number of turbines approaches 500. This inefficiency necessitates an optimization study to determine the optimal turbine number for such a system.

The optimization process investigates the ideal number of turbines by incrementally increasing the number by one, aiming to minimize the LCOW. Table 5 illustrates how the number of turbines in Hurghada affects both the vent percentage and the LCOW. This detailed examination reveals the complex interplay between turbine quantity, system efficiency, and economic feasibility. The results indicate that with 50–100 turbines, there is no venting observed, and the LCOW decreases significantly from \$0.94/m³ to \$0.74/m³, showcasing substantial cost savings with increased turbine deployment. As the number of turbines increases to 150 and 200, minimal venting (0.01 % and 1.00 %, respectively) occurs, while the LCOW continues to decline, reaching \$0.66/m³ at 200 turbines. However, a pivotal point as shown in Fig. 16 is reached at 206 turbines, where the vent percentage increases to 1.36 %, and the LCOW slightly reduces to \$0.65/m³, suggesting a marginal benefit. Beyond this point, the venting percentage escalates sharply, with 250 turbines resulting in a vent percentage of 5.88 % and a slightly increased LCOW of \$0.66/m³. The trend continues with 300 and 350 turbines, where venting reaches 13.01 % and 20.50 %, respectively, and the LCOW rises to \$0.75/m³. This analysis underlines the importance of optimizing the number of turbines to balance operational efficiency and economic viability. While increasing the number of turbines initially reduces the cost of desalinated water, excessive turbine numbers lead to significant energy losses through venting, which in turn increases costs.

Fig. 17 provides a detailed comparative analysis of the operational metrics of the optimal system in Hurghada during one week of mid-winter and mid-summer. The figure presents four key parameters: wind speed, system operation status, vent status, and air storage, over a seven-day period for each season. In mid-winter, Fig. 17a, the wind speed fluctuates significantly, reaching peaks of up to 11 m/s. The

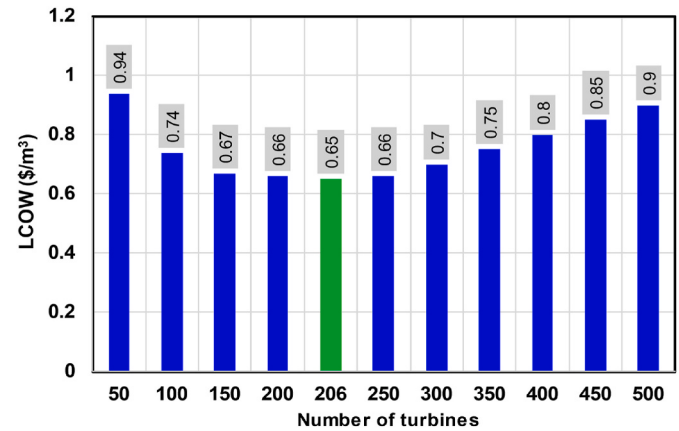


Fig. 16. Wind turbine number required for optimized operation in Hurghada.

system operation status indicates that the system is frequently turned on and off in response to these wind speed variations. Markedly, there is a brief period of venting on day 5, suggesting that the CAES system reached its maximum capacity due to high wind speeds, necessitating the release of excess air to prevent over-pressurization. The air storage graph corroborates this, showing that air storage consistently approaches maximum capacity, particularly around day 5, before dropping slightly after venting occurs. In mid-summer, Fig. 17b, the wind speed also shows variability but is generally lower. The system operation status graph reflects more consistent operation compared to mid-winter, with fewer on-off cycles. This is likely due to more stable wind conditions. Importantly, there is no venting observed in mid-summer, indicating that the air storage system effectively manages the compressed air without reaching maximum capacity. The air storage graph supports this observation, as the air storage levels fluctuate but do not approach the maximum capacity, thereby eliminating the need for venting.

To better understand the importance of selecting the optimal number of turbines for system performance, Fig. 18 presents data for Hurghada at mid-winter season. Specifically, Fig. 18a and b illustrate the impact of reducing and increasing the number of turbines by 50 % compared to the optimal number of turbines (Fig. 17a). The system operation status for the lower number of turbines' setup (Fig. 18a) exhibits a high frequency of on-off cycles, indicating a highly responsive yet potentially less stable operation due to its smaller capacity. Conversely, the higher number of turbines' setup (Fig. 18b) demonstrates fewer on-off cycles, reflecting a more stable and robust operation. Meanwhile, the optimal number of turbines' configuration (Fig. 17) strikes a balance between the two, with a moderate frequency of switching, suggesting an optimized response to wind fluctuations while maintaining stability. Furthermore, the vent status, indicating the activation of air management mechanisms, varies significantly among the three configurations. The lower number of turbines' system does not utilize venting, whereas the higher number of turbines' system activates venting on Days 1, 4, and 5 to handle the larger volume of air and prevent overcapacity. In contrast, the optimal number of turbines' setup engages venting only once, on Day 4, suggesting an efficient design that minimizes the need for active air management while maintaining optimal performance. Moreover, air storage capacity trends provide insights into the energy management of each system. The lower number of turbines' setup (Fig. 18a) maintains air storage levels below maximum capacity with minor fluctuations, indicating efficient energy management but limited storage capabilities. On the other hand, the higher number of turbines' system (Fig. 18b) shows more complex storage patterns, with levels approaching maximum capacity towards the end of the week, reflecting periods of surplus energy generation and the need for robust storage solutions. Similarly, the optimal number of turbines' configuration (Fig. 17) maintains air storage consistently below maximum capacity with fewer fluctuations,

Table 5

The effect of the number of turbines in Hurghada on the vent percentage and the leveled cost of desalinated water.

No. of turbines	Vent [%]	levelized cost of desalinated water [\$/m ³]
50	0.00	0.94
100	0.00	0.74
150	0.01	0.67
200	1.00	0.66
206	1.36	0.65
250	5.88	0.66
300	13.01	0.70
350	20.50	0.75

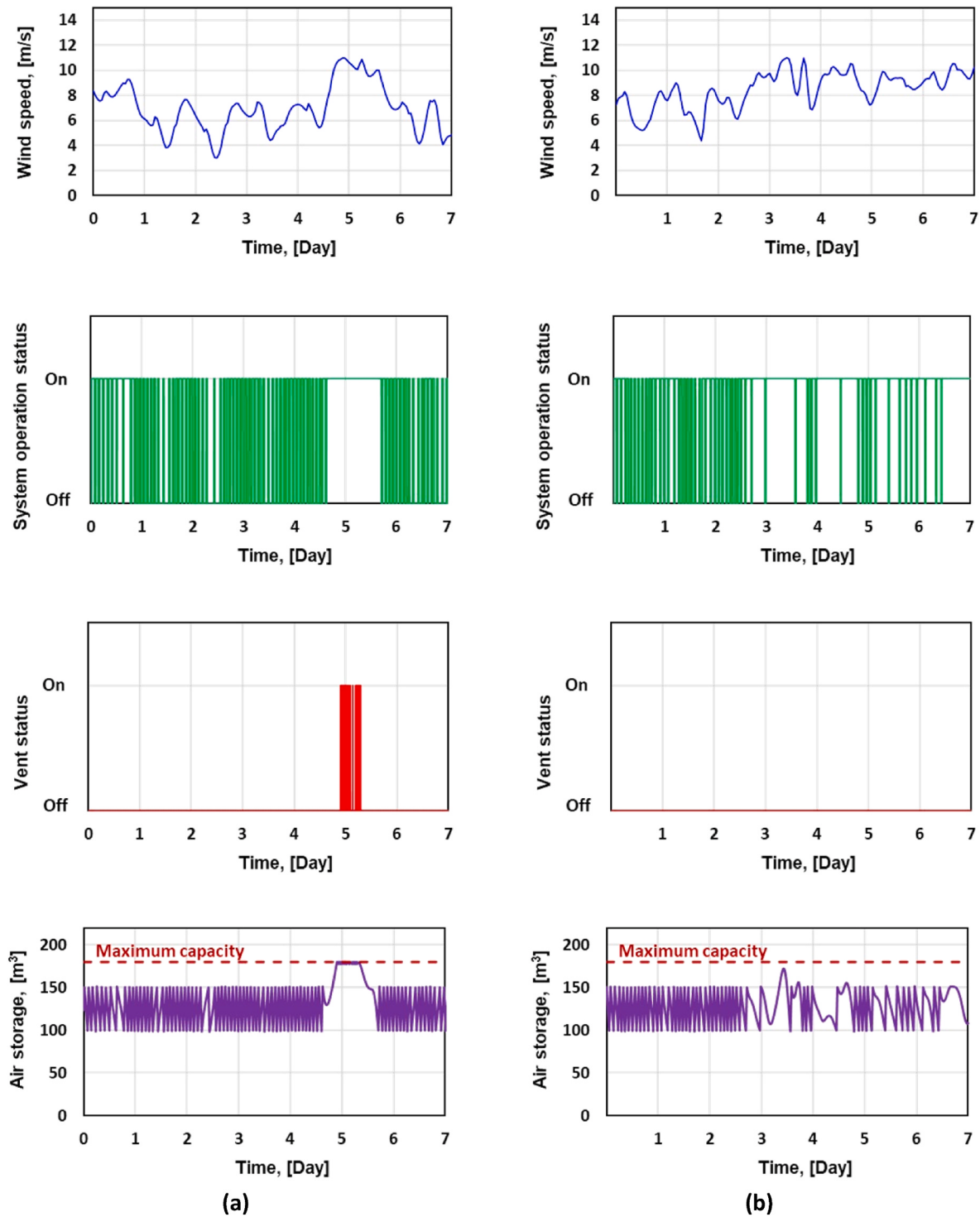


Fig. 17. Comparative operational metrics of the optimal Hurghada system at: (a) Mid-Winter and (b) Mid-Summer.

indicating a well-balanced energy management system that effectively handles energy generation and storage. Overall, this comparative analysis reveals that the system with a higher number of turbines, while offering greater capacity and potential energy output, requires more sophisticated control mechanisms to manage surplus energy and maintain stability. In contrast, the system with a lower number of turbines, though stable, has limited capacity and may not fully capitalize on the available wind energy. Although venting is considered an energy loss, eliminating it entirely is not always favourable. Analysing Figs. 15 and 16 reveals that neither minimizing venting nor maximizing operational

time alone would result in the most economic operation. Instead, an optimal compromise between these factors is necessary to determine the optimal number of turbines that minimizes the LCOW. This compromise ensures that the system remains economically viable by balancing the need to maximize capital utilization while mitigating energy losses.

Optimization is subsequently conducted for the rest of selected locations in Egypt. Fig. 19 presents the optimization results for the twenty selected locations along Egypt's Red Sea, Sinai Peninsula, and Mediterranean Sea coasts, detailing the optimal number of wind turbines required and the corresponding minimum cost per cubic meter of

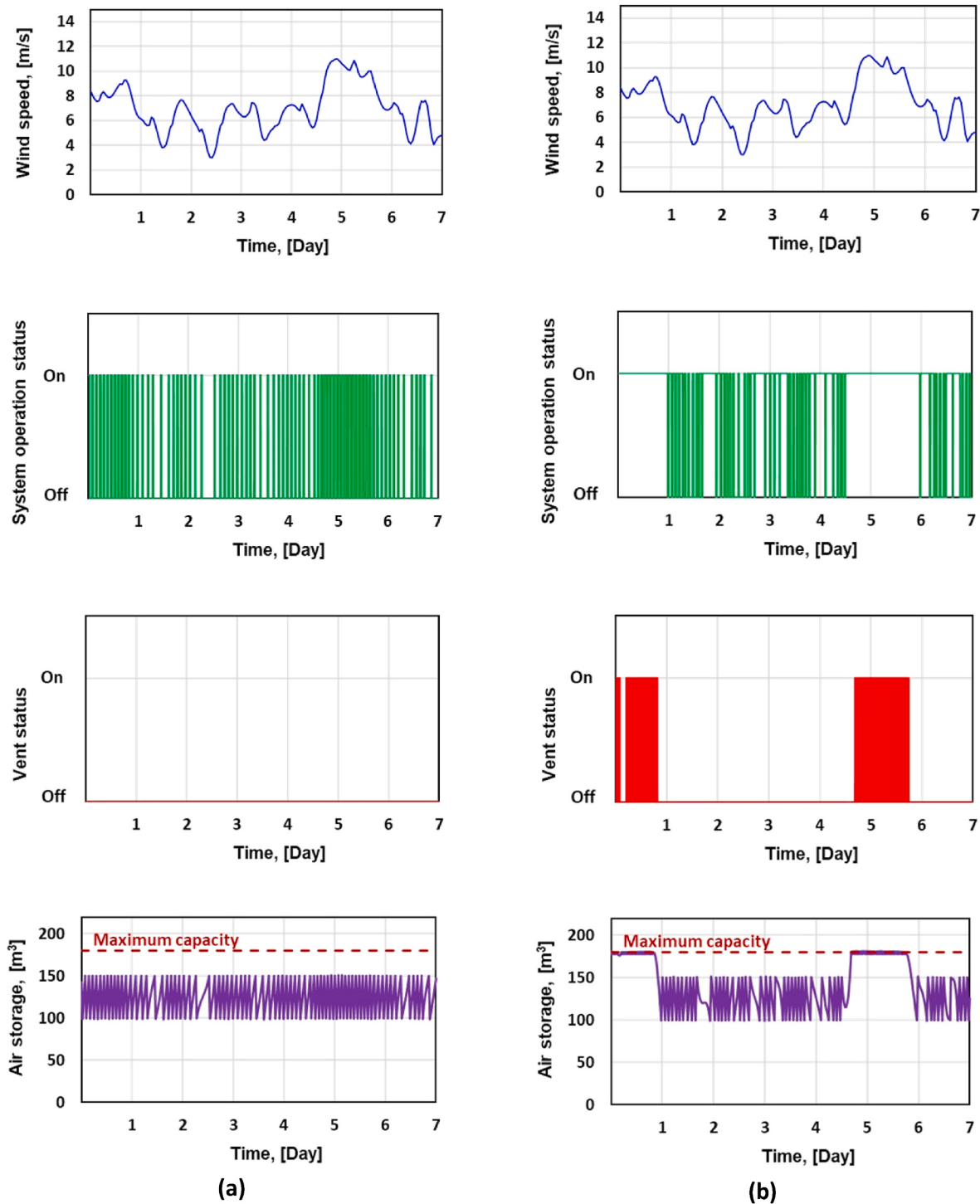


Fig. 18. System operational characteristics of Hurghada at (a) 103 turbines and (b) 309 turbines system at Mid-Winter.

desalinated water. Notably, Hurghada emerges as the most cost-efficient location, with a desalination cost of \$0.65 per cubic meter, emphasizing its potential as a prime site for sustainable water production. This low cost is facilitated by promising wind conditions, which reduce the number of turbines needed. Conversely, Suez exhibits the highest water cost at \$1.3 per cubic meter, necessitating the largest optimal number of turbines. This indicates that while Suez may possess significant wind resources, the economic efficiency of desalination is impacted by factors such as installation costs. The Red Sea coastal cities, including Hurghada, El Gouna, Ras Shukeir, Ras Ghareb, and Safaga, demonstrate relatively lower desalination costs. This trend is attributed to the

consistent and robust wind patterns along the Red Sea, enabling more efficient energy harnessing and reducing the required number of turbines. Specifically, El Gouna requires the fewest turbines, further highlighting the efficiency of this region. Locations along the Sinai Peninsula coast, such as Dahab and Ras Abu Rudeis, exhibit moderate costs, indicating a balance between wind resource availability and desalination efficiency. However, cost efficiency decreases moving towards the Mediterranean exhibiting moderate desalination costs. This can be ascribed to less favourable wind conditions in these areas.

Fig. 20 illustrates the annual water production for these locations. It can be seen that the Red Sea coast shows generally high-water

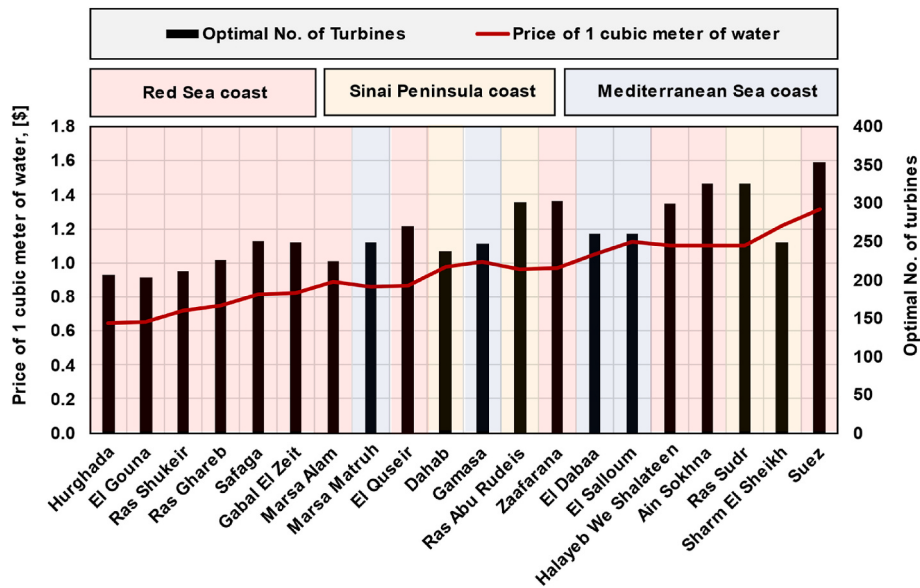


Fig. 19. The optimum number of wind turbines and the corresponding lowest cost per cubic meter of desalinated water for each one of the twenty chosen locations.

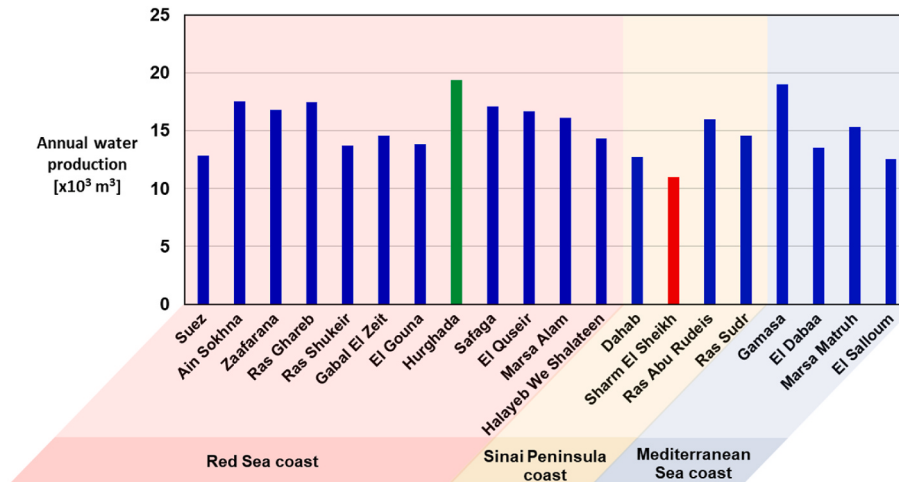


Fig. 20. An illustration of the annual water production from the proposed WE-SWRO desalination system at each specific location.

production capabilities, with Hurghada standing out due to its exceptional annual outputs of approximately 19,500 cubic meters, indicating favourable wind conditions and efficient utilization of wind energy. Locations such as Ras Ghareb, Zaafarana, and Ain Sokhna also demonstrate substantial water production, reinforcing the Red Sea coast's suitability for wind-powered desalination. Moreover, the Mediterranean Sea coast presents generally moderate water production capabilities compared to the Red Sea coast, though locations like Gamasa and El Dabaa exhibit relatively higher production levels, indicating localized advantageous conditions. In contrast, the Sinai Peninsula displays more varied water production capabilities, with Ras Abu Rudeis and Ras Sudr showing moderate levels, while Sharm El Sheikh has the lowest output among the Sinai locations. Fig. 21 shows the impact of seasonal variation on the system performance of Sharm El Sheikh as it represents the lowest water productivity among the selected locations. In mid-winter, wind speeds fluctuate significantly, peaking at 9 m/s and dropping below 1 m/s, leading to frequent system on-off switching and considerable air storage fluctuations. In contrast, mid-summer wind speeds are more consistent, with less pronounced peaks and troughs, resulting in a smoother operational profile with fewer adjustments. The vent status remains off throughout both periods, indicating that the system

maintains adequate internal conditions without additional ventilation due to the low wind speeds in comparison with Hurghada (Fig. 17). Overall, despite the seasonal differences, the system's robustness and adaptability are evident, maintaining functionality across varying conditions.

3.2. Sensitivity analysis

Upon optimizing the WE-SWRO system, it becomes imperative to examine the influence of parameters susceptible to variation over time due to dynamic policies and regulations [50,92]. These parameters include economic factors such as capital costs, operating and maintenance expenses, and project-specific factors such as system lifespan and interest rate. This section incorporates a sensitivity analysis that considers $\pm 25\%$ fluctuations in these parameters to evaluate their impact on the water cost. Conducting this analysis provides a comprehensive understanding of the system's robustness and resilience under varying economic and regulatory conditions. Fig. 22 illustrates the sensitivity analysis conducted to evaluate the impact of relative changes in various economic parameters on the LCOW. The results indicate that CapEx and OpEx have a nearly symmetrical and linear impact on the LCOW. An

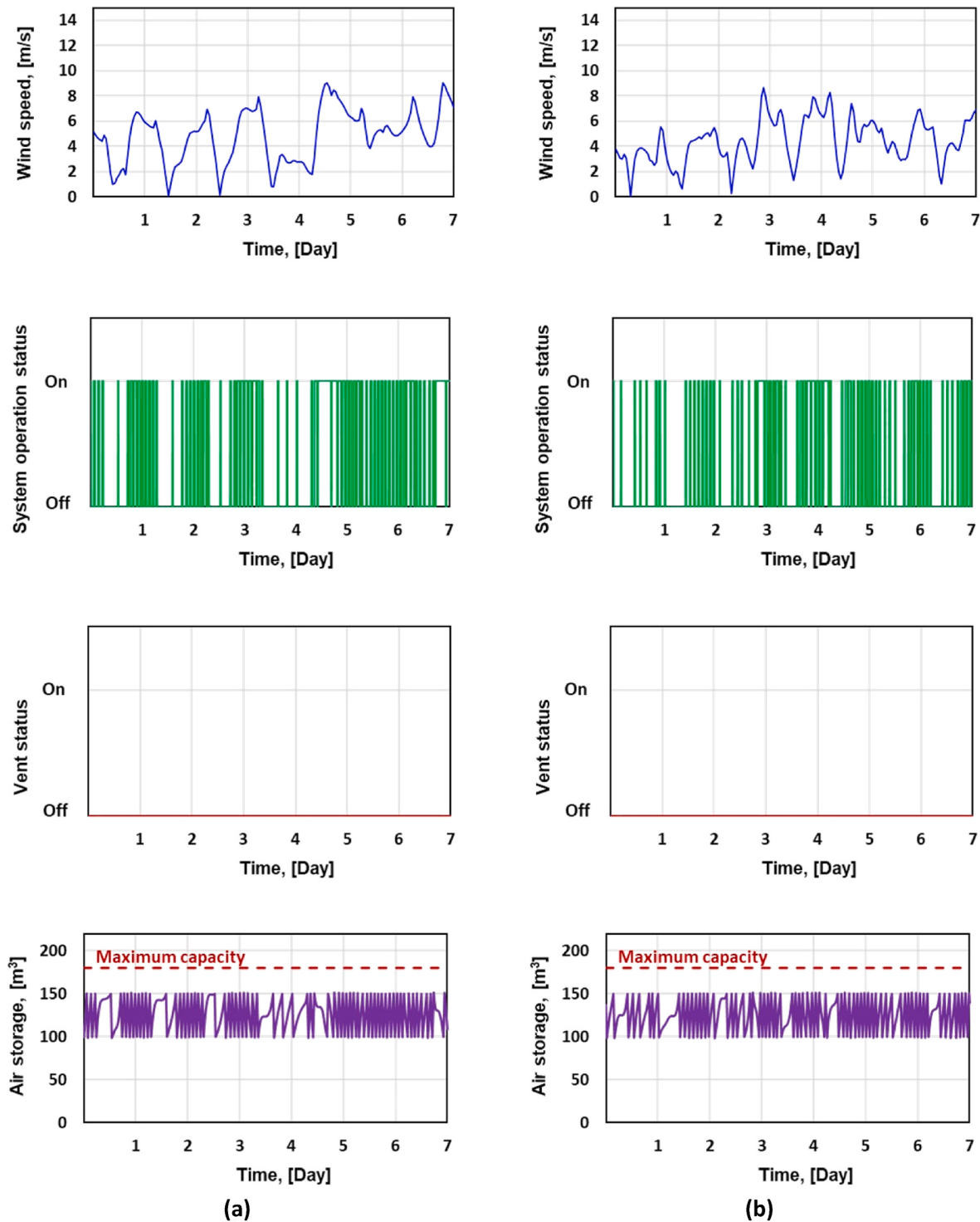


Fig. 21. Comparative operational metrics of the optimal Sharm Elsheikh system at: (a) Mid-Winter and (b) Mid-Summer.

increase of 20 % in CapEx results in approximately a 10 % rise in LCOW, while a similar decrease leads to a roughly 10 % reduction. This indicates that capital costs are a significant driver of the LCOW, underlining the importance of optimizing initial investment costs. Similarly, operational costs exhibit a parallel trend, with a 20 % change in OpEx leading to a comparable change in LCOW. This highlights the necessity for efficient operational management to maintain economic viability. In contrast, the interest rate and system lifetime have more complex, non-linear impacts on the LCOW. A 20 % increase in the interest rate leads to an approximately 5 % increase in LCOW, while a 20 % decrease

reduces LCOW by a similar magnitude. This suggests that financing conditions are critical to the cost-efficiency of desalination projects. Markedly, the system lifetime expectancy exerts an inverse influence on LCOW: increasing the system's lifespan by 20 % can decrease the LCOW by around 10 %, whereas reducing the lifespan has the opposite effect. This underscores the value of durable and long-lasting system components in reducing overall water production costs. Overall, these results emphasize the importance of balanced investments in both capital and operational efficiencies, alongside encouraging financing conditions and extended system lifespans, to achieve sustainable and economically

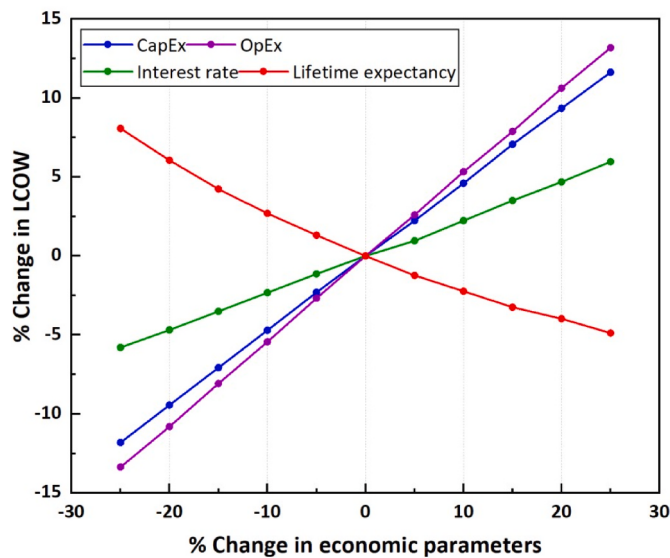


Fig. 22. Sensitivity analysis: Impact of the relative change of different economic parameters on the LCOW.

viable desalination solutions.

4. Conclusions

This paper presents a comprehensive techno-economic evaluation of a novel wind-powered desalination (WE-SWRO) system designed for arid regions such as Egypt. The system integrates two advanced technologies: reverse osmosis (RO) desalination powered by small hybrid vertical-axis wind turbines (HVAWTs) and compressed air energy storage (CAES) based on oil-free air compressor to address wind variability. A detailed mathematical model using MATLAB/Simulink optimizes the system to achieve minimal levelized cost of desalinated water (LCOW). A sensitivity analysis further explores system responses to parameter fluctuations. This research yields several key findings with significant implications for sustainable water production.

- CAES is crucial for maintaining consistent desalination operation despite wind speed variability, ensuring reliable performance during low or fluctuating wind conditions.
- The techno-economic evaluation confirms the viability of the WE-SWRO system with CAES is not only technically feasible but also cost-effective for desalination in arid regions. Optimization revealed a critical balance between turbine number, system efficiency, and cost, with optimal numbers varying significantly across locations in Egypt. This highlights the need for site-specific system configuration for maximized performance and economic viability.
- Hurghada emerged as the optimal location with 206 turbines, achieving the lowest desalination cost (\$0.65/m³) and the highest annual water production (19,500 m³). In contrast, Suez exhibited the highest cost at \$1.35/m³. This highlights the system's efficiency under favourable wind conditions. Other locations like El Gouna, Ras Shukeir, Ras Ghareb, and Safaga also show promise due to lower LCOW driven by advantageous wind patterns, providing valuable insights for regional water security planning and cost-effective system deployment.
- Seasonal variations impacted system performance, with mid-winter exhibiting more frequent system on-off cycles and air storage fluctuations compared to the more stable mid-summer wind speeds. The research quantified these variations, demonstrating the system's robustness and adaptability across different seasonal conditions.
- The sensitivity analysis underscores the critical importance of optimizing capital and operational costs, as a 20 % variation in CapEx or

OpEx leads to a 10 % shift in LCOW, while a ± 20 % change in interest rates impacts LCOW by around 5 %, and altering the system lifespan by ± 20 % results in a 10 % change in LCOW, emphasizing the need for advantageous financing conditions and extended system lifespans to ensure the economic viability and sustainability of WE-SWRO desalination systems.

- While the system demonstrates promising results for Egypt, further research is needed to explore its scalability and adaptability across diverse coastal environments worldwide, considering variations in environmental and economic factors.

Overall, this research lays the groundwork for future advancements in sustainable desalination technology. Future studies can explore advanced control algorithms to optimize system operation and minimize energy losses. Additionally, long-term durability and maintenance requirements, particularly for CAES components, warrant further investigation to ensure the system's sustainability.

CRedit authorship contribution statement

Mohamed Mohamed Elsakka: Conceptualization, Methodology, Investigation, Validation, Visualization, Software, Writing – original draft. **Ahmed Refaat:** Conceptualization, Methodology, Validation, Visualization, Software, Writing – original draft. **Khalid M. Alzahrani:** Methodology, Investigation, Software, Writing – review & editing. **Jee Loong Hee:** Writing – review & editing. **Lin Ma:** Project administration, Supervision, Writing – review & editing. **Yasser Elhenawy:** Conceptualization, Methodology, Investigation, Writing – review & editing. **Thokozani Majozi:** Writing – review & editing. **Ahmed Gharib Yosry:** Writing – original draft. **Ahmed Amer:** Validation, Visualization. **Gamal Hafez Moustafa:** Project administration, Supervision, Writing – review & editing. **Asmaa Ahmed:** Methodology, Investigation, Validation, Visualization, Formal analysis, Data curation, Writing – review & editing.

Declaration of competing interest

This article doesn't have any conflict of interest with the authors listed and beyond. This article we have submitted to the Energy Journal for review is original and has been written by the stated authors and has not been previously published. This article was not submitted for review to another journal while under review by this journal and will not be submitted to any other journal. The article does not infringe any copyright, violate any other intellectual property, privacy, or other rights of any person or entity.

Data availability

Data will be made available on request.

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