

**OPTIMIZING HYBRID RENEWABLE ENERGY SYSTEM WITH
DIFFERENT STORAGE OPTIONS FOR REVERSE OSMOSIS
DESALINATION**

BY

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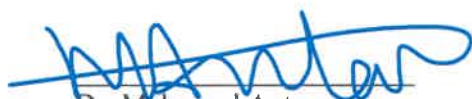
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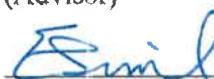


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DEDICATION

TO

**TO MY PARENTS, WIFE, SISTERS, AND BROTHER—YOUR STEADFAST
SUPPORT AND UNWAVERING ENCOURAGEMENT HAVE BEEN THE
CORNERSTONE OF MY ACADEMIC PURSUIT.**

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LIST OF ABBREVIATIONS

Nomenclature

$C_{batt}(t)$:	: The Available Energy Storage Capacity of a Battery Bank (Wh)
$C_{batt,max}$	: Battery Storage System's Maximum State of Charge (Wh)
$C_{batt,min}$	: Battery storage's minimal charge state (Wh)
C_{BT}	: The Capital Cost of The Battery Storage System (\$)
$C_{BT,rep}$	: The Replacement Cost for The Batteries (\$)
$C_{O\&M}$	: Annual Operating and Maintaining Cost for the System (\$)
$C_{O\&M,inv}$	: Annual Operating and Maintaining Cost of Inverter (\$)
$C_{O\&M,PV}$	: Annual Operating and Maintaining Cost for PV Module (\$)
$C_{O\&M,RO}$	: Annual Operating and Maintaining Cost for RO system (\$)
$C_{O\&M,WT}$	: Annual Operating and Maintaining Cost for Wind Turbine (\$)
C_P	: The Capital Cost for Water Pump (\$)
C_{PV}	: The Capital Cost of PV System (\$)
C_{PS}	: The Capital Cost of The Pumped Storage System (\$)
$C_{PS,rep}$	: The Replacement Cost for The Water Pump (\$)
C_T	: The Capital Cost for The Water Turbine (\$)
$C_{T,rep}$	: The Replacement Cost for Water Pump (\$)
C_{UR}	: The Capital Cost for The Upper Reservoir. (\$)
C_{WT}	: The Capital Cost of Wind Turbine System (\$)
C_{WST}	: The Capital Cost for Water Tank Storage (\$)
$CRF(i, N)$	: Capital recovery factor

DOD	: the maximum depth to which the battery can be discharged (%)
$E_{PV}(t)$	: The Total Energy Generation of The PV Array (kWh)
$E_{WT}(t)$	: The Total Energy Generation by Wind Turbine System (kWh)
$G(t)$	: the global solar radiation at the horizontal surface at hour t (kW/m ²)
$G_b(t)$	: The Beam Radiation at Hour t (kW/m ²)
$G_d(t)$	: The Diffuse Radiation at Hour t (kW/m ²)
$G_d(t)$	: The Diffuse Radiation at Hour t (kW/m ²)
$G_T(t)$	: The Solar Radiation on A Tilted Surface at Hour (t) (kW/m ²)
LCOE	: The Levelized Cost of Electricity (\$/kWh)
LOC	: Level of Charge for The Upper Reservoir (%)
LPS(t)	: The Loss of Power Supply at Hour t
LPSP	: The Loss of Power Supply Probability
LWC	: The Levelized Water Cost (\$/m ³)
LWS(t)	: The Hourly Shortage of Freshwater (m ³ /h)
LWSP	: The Loss of Water Supply Probability
NPV	: The Net Present Value for the System (\$)
$P_c(t)$	: The Hourly Converter Power (kW)
$P_{PV}(t)$	: The Hourly Power Production of a PV Module (kW)
$P_{WT}(t)$	: The Hourly Power Production from Wind Turbine (kW)
$P_{total}(t)$	: The Total Power Produced Per Hour (t) By PV and Wind Turbine (kW)
$Q(t)$	: The Hourly Status of The Water Storage Tank (m ³)
$Q_D(t)$	: The Volumetric Flow Rate of Sweet Water Demand (m ³ /d)
$Q_P(t)$	: The Volumetric Flow Rate of Produced Sweet Water (m ³ /d)

$Q_{\text{upp}}(t)$	: The water upper reservoir level at time t (m^3)
$Q_{\text{upp,max}}$	: The maximum capacity for upper reservoir
$Q_{\text{upp,min}}$	: The minimum capacity for upper reservoir
$q_{\text{pm}}(t)$	: The Flow Rate That is Pumped from The Lower to The Upper Reservoir (m^3/s)
$q_{\text{tu}}(t)$	: The Turbine Water Flow Rate (m^3/s)
$T_A(t)$	: The Ambient Temperature ($^{\circ}\text{C}$)
$T_C(t)$	: The PV Cell Temperature at Operating Conditions ($^{\circ}\text{C}$)

Greek

σ	: Self-discharge rate of the battery (%)
η_{bc}	: The Efficiency of Charging Battery (%)
η_{c}	: The Efficiency of The Converter (%)
η_{bd}	: The efficiency of Discharging Battery (%)
η_{pm}	: The Overall Efficiency of The Water Pump (%)
η_{tu}	: The Overall Water Turbine Efficiency (%)
i	: The interest rate (%)

Acronyms

DE	: Differential Evolution
HRES	: Hybrid Renewable Energy System
HOMER	: Hybrid Optimization of Multiple Energy resources
PS	: Pumped Storage
PV	: Photovoltaic

RES	: Renewable Energy Sources
RO	: Reverse Osmosis
SE	: Surplus Energy
WT	: Wind Turbine

ABSTRACT

Full Name : AZEEZ MOHAMMAD QUDAH
Thesis Title : Optimizing Hybrid Renewable Energy System with Different Storage
Options for Reverse Osmosis Desalination
Major Field : MECHANICAL ENGINEERING
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Access to clean water, a fundamental human right, is hindered by the high operational costs of reverse osmosis (RO) desalination systems. This M.S.C thesis focuses on optimizing RO systems integrated with renewable energy sources (RES), specifically wind and photovoltaic (PV) systems using the Differential Evolution (DE) algorithm. Three distinct storage methods—battery systems, pumped storage Hydro (PSH), and water tank storage—are explored to enhance the economic viability and sustainability of RO operations. Surplus energy (SE) from the optimized system is utilized in two scenarios: firstly, it is either sold back to the grid, contributing to the reduction of water production costs; secondly, it is employed to desalinate additional water, thereby increasing the capacity and stability of the RO unit while concurrently lowering the cost of water production. The results show that the most cost-effective alternative, HRES with water tank storage, has the lowest levelized water cost (LWC) at 1.29 \$/m³ for a variable water demand case. The excess energy produced by the system improves desalination efficiency and adds to the grid's supply. According to economic research, desalination capacity expansion may strategically reduce Levelized Water Cost (LWC) by 26.35%, while excess energy can be resold to reduce LWC by 6.2%. Furthermore, the study explores the impact of varying RO capacity on LWC, shedding light on the scalability and efficiency of the proposed hybrid system.

ملخص الرسالة

الاسم الكامل: عزيز محمد عبد العزيز قضاة

عنوان الرسالة: تحسين نظام الطاقة المتجددة الهجين مع خيارات تخزين مختلفة لتحلية المياه بالتناضح العكسي

التخصص: الهندسة الميكانيكية

تاريخ الدرجة العلمية: يونيو ٢٠٢٤

إن الوصول إلى المياه النظيفة، وهو حق أساسي من حقوق الإنسان، يعوقه ارتفاع تكاليف التشغيل لأنظمة تحلية المياه بالتناضح العكسي. تركز أطروحة الماجستير هذه على تحسين أنظمة التناضح العكسي المتكاملة مع مصادر الطاقة المتجددة، وخاصة أنظمة الرياح والطاقة الكهروضوئية باستخدام خوارزمية التطور التفاضلي. يتم استكشاف ثلاث طرق تخزين مميزة - أنظمة البطاريات، وتخزين الطاقة الكهرومائية بالضخ، وتخزين خزان المياه - لتعزيز الجدوى الاقتصادية والاستدامة لعمليات التناضح العكسي. يتم استخدام الطاقة الفائضة من النظام المحسن في سيناريوهين: أولاً، يتم بيعها مرة أخرى إلى الشبكة، مما يساهم في تقليل تكاليف إنتاج المياه؛ ثانياً، يتم استخدامها لتحلية المياه الإضافية، وبالتالي زيادة سعة واستقرار وحدة التناضح العكسي مع خفض تكلفة إنتاج المياه في نفس الوقت. تظهر النتائج أن البديل الأكثر فعالية من حيث التكلفة، أنظمة تحلية المياه بالتناضح العكسي مع تخزين خزان المياه، لديه أدنى تكلفة مياه مستوية (LWC) عند 1.29 دولارًا أمريكيًا / م³ لحالة الطلب المتغير على المياه. إن الطاقة الزائدة التي ينتجها النظام تعمل على تحسين كفاءة تحلية المياه وتضيف إلى إمدادات الشبكة. ووفقًا للبحوث الاقتصادية، فإن توسيع قدرة تحلية المياه قد يقلل استراتيجيًا من تكلفة المياه المستوية (LWC) بنسبة 26.35٪، في حين يمكن إعادة بيع الطاقة الزائدة لتقليل تكلفة المياه المستوية بنسبة 6.2٪. علاوة على ذلك، تستكشف الدراسة تأثير سعة التناضح العكسي المتغيرة على تكلفة المياه المستوية، مما يلقي الضوء على قابلية التوسع وكفاءة النظام الهجين المقترح.

CHAPTER 1

INTRODUCTION

1.1 Background

Energy and water are essential needs of modern society. However, despite only 3% of the world's water being freshwater, an alarming 25% of the world's population lacks sufficient access to this vital resource [1]. The global community is currently facing a significant challenge of water scarcity, which is primarily caused by the exponential growth of populations and economies, resulting in a surge in demand for high-quality water in numerous regions [2]. Fortunately, many of these areas often have access to renewable energy sources like wind and solar power.

To reduce costs and enable desalination technology in areas with limited energy access, recent efforts have focused on combining renewable energy sources like photovoltaic cells, wind turbines, and battery-based storage systems with desalination technology[2],[3],[4] . Desalination is a process that removes salt from saltwater to make it drinkable, and it has expanded over the past 40 years due to water security concerns [5]. The world's desalination capacity has steadily increased since 1965, with a significant expansion in the last decade. By 2018, the capacity expanded to 99.7 million m³/day, compared to 66.4 million m³/day in 2012.

To obtain freshwater with low salt content, desalination employs various techniques to remove salts from feedwater, which generally contains a high salt concentration (brine) [6].

Nowadays, the most commonly utilized method of desalination is reverse osmosis (RO), which produces fresh water by removing contaminants from seawater using a semi-permeable membrane and hydraulic pressure. [6],[7],[8],[9],[10]. Figure 1 shows that as of the end of 2016, RO formed 65% of the built desalination capacity worldwide [11].

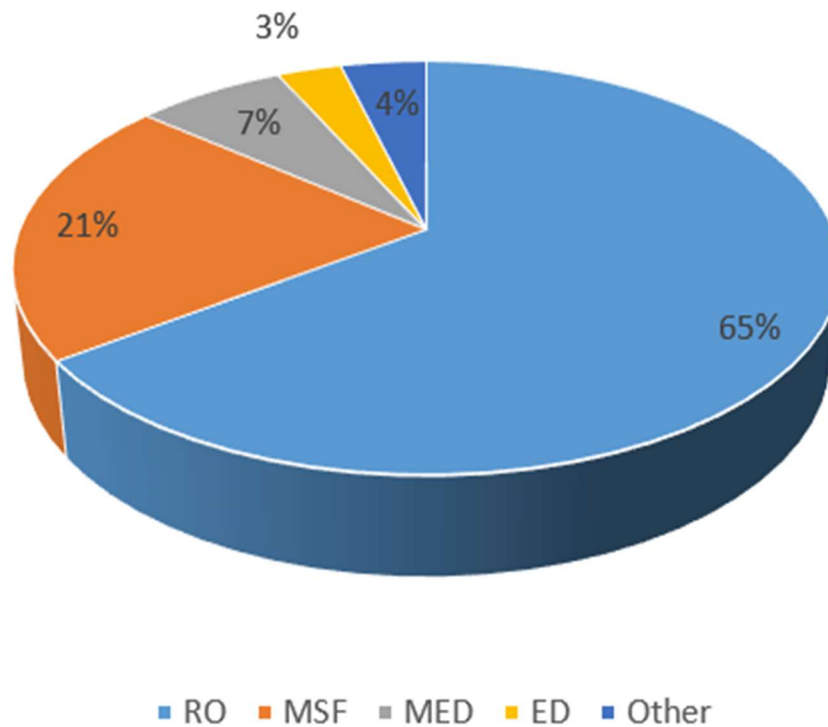


Figure 1: World Production and The Significance of Desalination Technologies.

Despite progress in reverse osmosis (RO) desalination, two significant environmental issues remain. First, RO desalination still requires a significant quantity of energy compared to other water delivery methods [12],[13]. Second, the release of concentrated brine and chemicals from large RO desalination systems poses a risk to marine ecosystems

[14] . To enhance the viability of commercial RO desalination facilities, reduce carbon emissions generated by water production, and improve access for societies with limited financial and natural resources, alternative energy sources must be identified to power them [15],[16].

1.2 Desalination Technology and Renewable Energy

Integrating renewable energy (RE) offers several advantages, including minimizing the carbon footprint of RO units, reducing operational expenditures, and eliminating the link between water prices and fuel costs [12]. Since it is widely accessible, RE generally provides a practical alternative to using fossil fuels. The global capacity of solar panels and wind turbines rose from 177 GW to 227 GW and from 370 GW to 433 GW, respectively, between 2014 and 2015 [17]. Additionally, the expense of RE is slowly dropping, with solar photovoltaic module costs decreasing from \$33.44 per watt in 1979 to approximately \$0.35 per watt in 2017 [18]. In the USA, the price of wind turbines decreased by one-third between 2008 and 2011 [19]. Figure.2 shows various combinations of RESs and desalination technology.

Desalination systems powered by small-scale renewable energy sources hold significant promise for regions with limited water resources. Studies have demonstrated the efficiency and minimal maintenance requirements of these systems in various locations of the globe, [20],[21],[22],[23],[24] . Additionally, the generated renewable sources can be used for other applications, such as powering air conditioning systems, further enhancing their overall value.

Although the expense of water generated by existing renewable desalination systems is still greater than traditional methods..., their applicability in remote or arid areas is undeniable. Furthermore, technological advancements anticipated to become a feasible option for large-scale use in the near future.

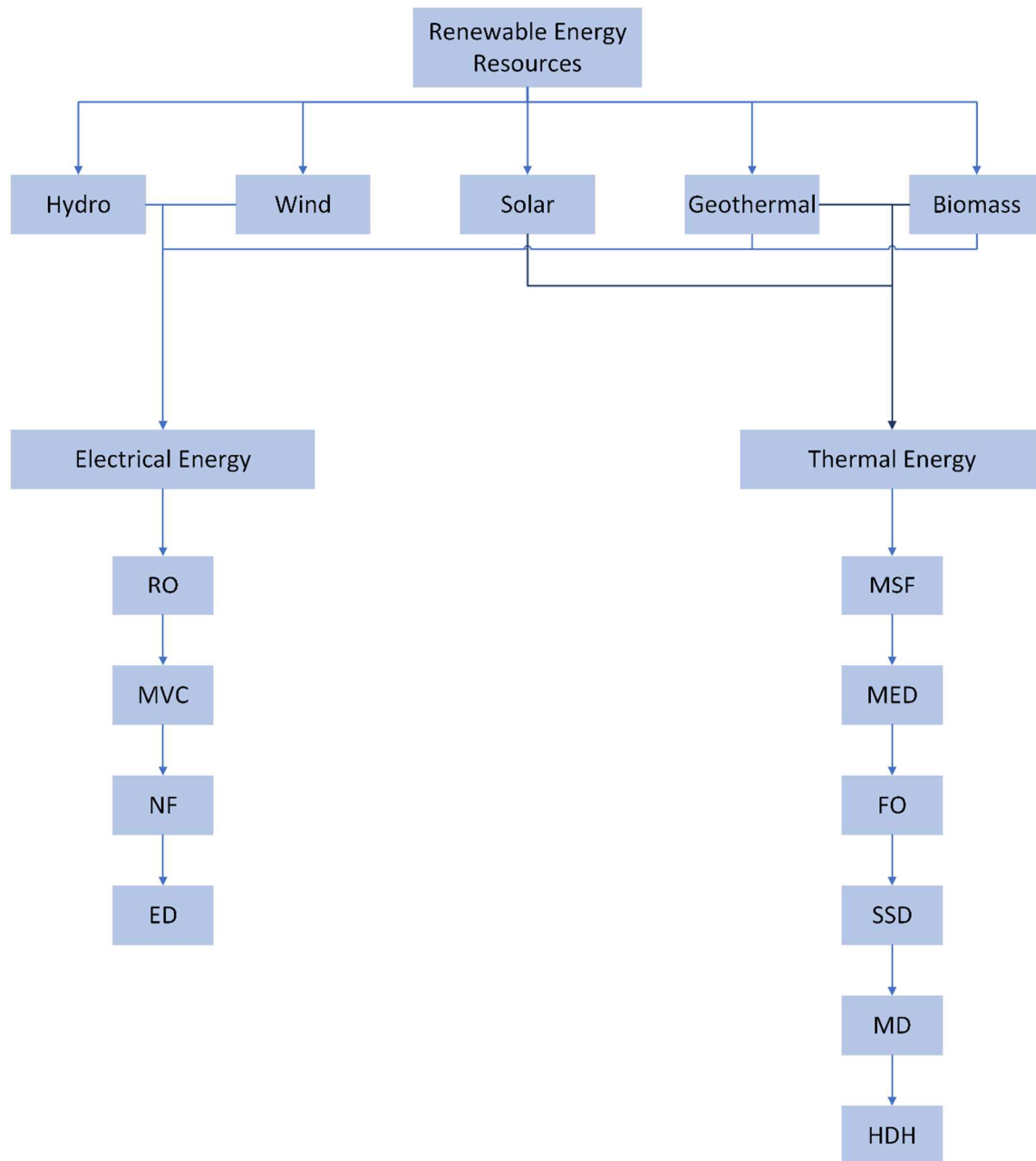


Figure 2: Several Possible Combinations of Renewable Energy Sources (RESs) and Desalination Technologies that Could be Used.

The cost of electrical energy, accounting for 44% of the water price in RO desalination, can be reduced by directly generating electricity using renewable energy sources such as solar, wind, or wave energy converters [25]. While hydro- and bio-energy are also renewable energy sources, they are not widely applicable in desalination-required countries due to the scarcity of natural water resources [26] . Wind and wave energy have the potential to generate mechanical power for the High-Pressure Pump. Nonetheless, it is not recommended to employ directly powered wind-RO systems for seawater reverse osmosis (SWRO) due to the high osmotic pressure involved [27] ,[28] .

Several studies suggest that wind and solar-PV systems are suitable for powering RO units due to their cost-effectiveness, widespread accessibility, technological maturity, and low water usage compared to other renewable energy sources [29], [30], [31]. The frequently employed desalination systems powered by renewable energy sources are PV-RO and wind-RO, which represent of 32% and 19% in the field, respectively Fig. 3.

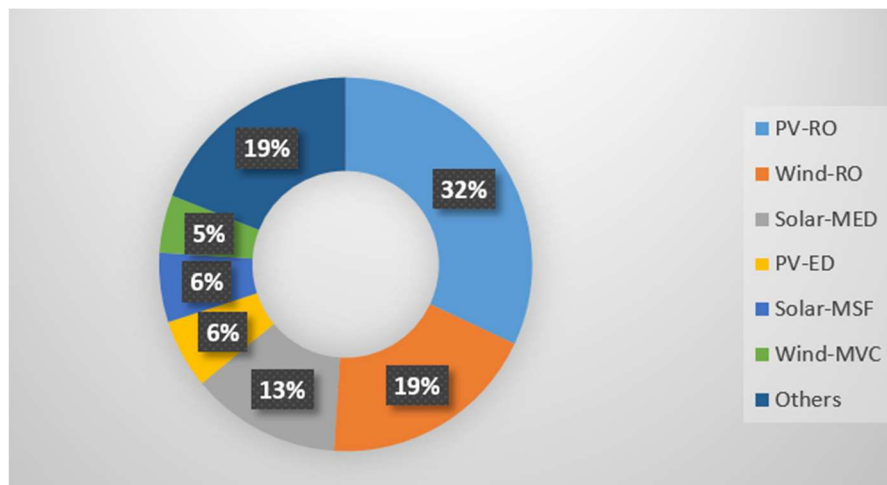


Figure 3: Global Desalination with Renewable Energy at Today.

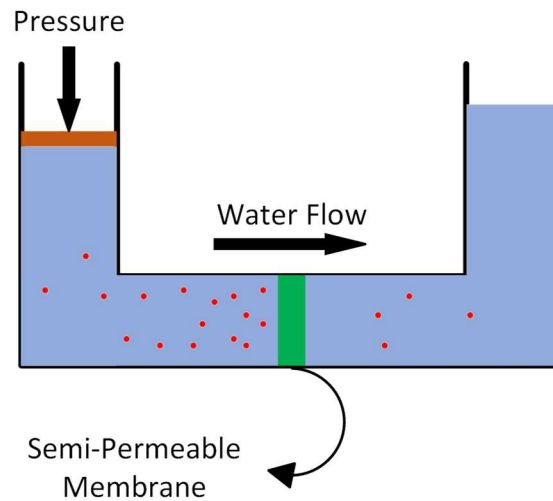
In the past decade, significant Emerging seawater desalination technology have shown advancements, which have the potential to lower specific energy consumption compared to traditional methods such as SWRO. SWRO requires a large amount of energy with a specific energy need, based exclusively on electrical energy and energy recovery, is around 3-4 kWh/m³. In comparison, multi-stage flash (MSF) and multi-effect distillation (MED) consume more energy, with MSF ranging from 10-16 kWh/m³ thermal and 2.5-4 kWh/m³ electrical energy. Meanwhile, MED varies from 5.5 to 9 kWh/m³ thermal and 1.5 to 2 kWh/m³ electrical energy [32] .

To address these energy concerns, desalination operations can be driven by RES, with the energy transformed into either electrical or thermal energy. Electrical energy powers RO and ED techniques, while thermal energy is used for methods like MSF, MED, MD, solar still, and humidification-dehumidification (HD)[33].

1.3 Reverse Osmosis (RO) Desalination Technology

The technique of Reverse Osmosis (RO) involves pushing a solvent, such as water, to move across a semi-permeable membrane Against the natural osmotic flow direction. The process occurs when the exerted hydrostatic pressure surpasses the inherent osmotic pressure. RO is mainly employed as a water purification technique, segregating dissolved ions, molecules, and larger particles from saline water through a permeable membrane. Reverse Osmosis (RO) is a economical and sustainable water desalination technique is known for effectively removing a large quantity of salt while keeping a moderate water flow rate. The process includes pre-treatment phases, such as coagulation and filtration, to reduce membrane fouling [34]. While energy-intensive, RO incorporates devices for

recovering energy to reclaim energy from the brine. Disinfection and mineral replenishment are part of the post-treatment procedure. RO is extensively used, effective, and shows potential for further breakthroughs in energy efficiency, as shown in the schematic representation of a RO system (Fig. 4) [35].



Reverse Osmosis (RO) Process

Figure 4: Schematic of Reverse Osmosis (RO) process.

Reverse Osmosis (RO) membranes are made up of a homogeneous polymer layer that is selective enough to prevent large molecules from passing through, only allowing water molecules to pass through. RO desalination systems require energy in electricity form, which is used to power pumps that pressurize saline water. The pressurized saline water then flows across the RO membrane, where the separation takes place because the membrane permits water molecules to pass through while restricting salt molecules. High pressure is required for the RO process to overcome the osmotic pressure of the saline water, which typically ranges from 2-17 bar (30-250 psi) for brackish water and 40-70 bar (600-1000 psi) for seawater[36].

1.4 Storage Ways for Hybrid Renewable Energy Systems (HRES)

Hybrid renewable energy systems, combining multiple energy sources like photovoltaic (PV) and wind turbine (WT), have gained prominence for their combined reliability and efficiency. This section focuses on the integration for powering desalination processes, leveraging the strengths of both solar and wind energy to provide a diverse and complementary energy mix [37].

To produce consistent daily freshwater production, desalination plants powered by renewable sources like hydro, wind, and solar require a steady and predictable electricity supply daily. However, these sources are naturally intermittent, unpredictable, and weather-dependent, making it challenging to achieve consistent power[38]. Energy storage systems address this challenge by storing excess power when supply exceeds demand and then discharge it during periods of net load, providing a resilient backup for intermittent renewable energy sources [39], [40]. This approach can increase system flexibility and dependability, while also reducing the variability of renewable sources by integrating pumped storage hydropower, which takes advantage of the complementary nature between different renewable resources [41].

While large-scale energy storage presents challenges for powering RO desalination plants with renewable energy sources, these sources are irregular and unpredictable in nature. To ensure a constant electricity supply, energy storage systems are required but they are often impractical due to their high capital cost, need for additional hardware, and space requirements [42]. Using batteries in hybrid systems is a major contributor to the high cost, significantly increasing the price of water production.

In contrast, hydropower holds untapped potential due to its complementary nature with other renewable sources, making it a vital player in the energy transition. Pumped hydro storage serves a suitable technology for supporting both grid-connected and standalone hybrid hydro-wind-solar systems. To overcome the high cost of energy storage systems, several studies have focused effectively using renewable energy sources to power RO systems without relying on energy storage solutions [43],[44]. These approaches have been successfully implemented in many small-scale systems over the past decade [45].

Numerous storage options are available, each with its unique characteristics and advantages. Selecting an appropriate storage solution becomes a nuanced process, guided by considerations that encompass scalability, efficiency, geographical constraints, and cost implications. The synergy between Hybrid Renewable Energy Systems (HRES) and Reverse Osmosis (RO) desalination unfolds a rich tapestry of storage options, each intricately designed to enhance system reliability and efficiency. In this dynamic landscape, traditional stalwarts like batteries, pumped storage, hydrogen tanks, and water tank storage form the bedrock of energy storage. Yet, beyond these established solutions, an ever-expanding array of emerging applications is pushing the boundaries of innovation, promising to elevate the resilience of HRES-RO desalination systems to new heights.

1.5 Problem Statement

In the pursuit of sustainable and reliable energy solutions, the integration of hybrid renewable energy systems, specifically combining photovoltaic (PV) and wind turbine technologies, has gained prominence. This approach holds great potential for powering critical infrastructure such as reverse osmosis (RO) desalination plants. However, a

significant challenge to the widespread adoption of such systems is the high cost associated with energy storage. Storage solutions are integral components that influence the overall effectiveness and economic viability of hybrid renewable energy systems.

To optimize a hybrid renewable energy system for an RO desalination plant, this research goes in-depth with three different storage alternatives—batteries, pumped storage systems, and water tank storage. These options have distinct features, considerations, and related costs that impact the overall economic viability of the energy system.

Considering the crucial role that storage plays in renewable energy systems, this research seeks to explore the specifics of each form of storage, with a focus on Dhahran, Saudi Arabia, as a case study. The investigation's unusual backdrop is provided by Dhahran's unique patterns of energy consumption, environmental circumstances, and high-water demand for desalination. The main objective is to maximize the performance of the whole hybrid renewable energy system, lowering overall expenses and guaranteeing a steady and dependable power supply to the RO desalination plant.

By identifying the most cost-effective storage solution tailored to Dhahran's specific needs, the study not only enhances the economic viability of renewable energy systems but also contributes to the region's sustainable energy development. By meticulously analyzing batteries, pumped storage, and water tank storage options, this research aims to pave the way for an optimized, economically feasible, and sustainable hybrid renewable energy system in Dhahran City.

1.6 Thesis Objectives

This study aims to optimize three different storage systems integrated with Hybrid Renewable Energy Systems (HRES), utilized for Reverse Osmosis (RO) desalination. These systems include PV, WT, and pumped hydro storage systems, a system comprised of battery storage, WT, and PV systems, and system includes PV, WT, and water tank storage. The system's optimal size and combination will be estimated based on the differential evolution (DE) optimization approach, aiming to attain minimum Levelized Cost of Electricity (LCOE) and Levelized Water Cost (LWC).

The following are the specific aims of this thesis proposal:

1. Develop and implement an innovative approach to optimize renewable energy systems for Reverse Osmosis (RO) desalination using Saudi Arabia's specific weather data. Quantify the improvement in the cost of RO desalination systems achieved through this new approach.
2. Evaluate and compare various storage alternatives to optimize the cost of renewable energy systems driving RO desalination in the Saudi Arabian context. Assess the impact of different storage options on the overall expenditure of renewable energy-driven desalination systems.
3. Identify and choose the most economical renewable energy system with a storage option for RO desalination. Quantify the cost reduction achieved in water production using the selected system.
4. Compare the LWC achieved through the optimized system with findings from same studies in the literature. Assess the competitiveness and effectiveness of the proposed solution by benchmarking against existing research.

CHAPTER 2

LITERATURE REVIEW

Several studies have investigated the integration of reverse osmosis (RO) desalination systems with various RES. Wind energy [46],[47] and solar energy [48],[49] systems have been utilized in these studies. One study by Ahmad et al.[48] modeled and verified experimentally utilizing photovoltaic (PV) systems to generate energy for RO water desalination plants. The model was used to investigate the effect of the PV panel's slope and the impact of azimuth angle on the permeate flow rate in Dhahran, Saudi Arabia.

Furthermore, another study by Qiblawey [49] worked on the incorporation of RO water desalination and photovoltaic energy production with battery storage system. The study examined the effectiveness of the RO-PV system in the ADIRA project, which was designed, built, and operated successfully in the Hartha in Jordan. The study examined the impact of the impacts of operational pressure and temperature on recuperation percentage, salt exclusion, and particular energy consumption, as well as the correlation between system efficiency and meteorological factors such as solar irradiance, air temperature, and daily sunlight duration, were examined. Table 1 outlines different storage options employed in the hybrid renewable energy system to power reverse osmosis.

Table Keys: PV: Photovoltaics, WT: Wind Turbine, DG: Diesel Generator, RO: Reverse Osmosis, BG: Biomass Generator, EZ: Electrolyzer, FC: Fuel Cell, CSP: Concentrating Solar Power, BS: Battery Storage, WS: Water Storage,							
Reference	Location	System configuration	Storage system	Specific energy consumption (kWh/m ³)	Capacity (m ³ /day)	Economic criteria	Analysis aspects
[50]	Egypt	PV/WT/RO	Battery	7.68	3500	0.5305 \$/m ³	Energy and economic
[51]	Egypt	PV/WT/DG/RO	Battery	2.928	1500	0.164 \$/kWh	Energy, economic
[52]	South Korea	PV/RO	Water tanks	2.4	1000	1.74 \$/m ³	Energy and economic
[53]	Greece	PV/WT/RO	Pumped storage	3	160	1.58-3.17 \$/m ³	Energy and economic
[54]	Spain	PV/WT/DG/RO	Battery	5	50	0.404 \$/kWh	Energy, economic
[55]	India	PV/WT/BG/EZ/FC	Hydrogen	4.38	30	0.86 \$/m ³	Social, economic,
[56]	Turkey	PV/WT/DG/RO	Battery	4.38	24	2.20 \$/m ³	Energy and economic
[57]	Bangladesh	PV/WT/DG/RO	Battery	4.38	20	1.37 \$/m ³	Energy, economic
[58]	Indonesia	PV/RO	Water tanks	2.3	11.6	9 \$/m ³	Energy and economic
[59]	Iran	PV/WT/EZ/FC	Hydrogen/Battery	NA	10	NA	Energy and economic
[60]	Saudi Arabia	PV/WT/RO	Battery	5	5	1.98 – 2.16 \$/m ³	Energy and economic
[61]	France	PV/RO	Without battery	4.2	1	NA	Energy
[62]	Egypt	PV/WT	Pumped Storage	NA	NA	0.216 \$/kWh	Energy and economic

Table 1 Synopsis of research articles examining water desalination systems powered by renewable energy sources.

2.1 Hybrid Renewable Energy System (HRES) with battery system-driven RO desalination.

Various optimization approaches were employed to identify the hybrid PV-wind systems with battery storage optimal configuration for powering RO desalination plants. Mokheimer et al. [63], describe the scheme of simulation software capable of optimizing the components of an isolated, hybrid RO desalination plant driven by wind and solar power, therefore making it appropriate for Saudi Arabia's environment.

According to the results, several wind turbines must be used to minimize the LCOE of the specified system component. Maleki et.al [64], d constructed an integrated PV/WT/battery/RO systems optimization approach to stand-alone, renewable desalination facilities in Davarzan, Khorasan, Iran. The model includes a practical approach for predicting RES and utilizes a harmony search (HS) method for optimal system design.

Additionally, the model is improved by incorporating a chaotic search (CS) algorithm, leading to the development of the HSBCS algorithm for further optimization. Zhang et al. [65] presented a novel hybrid optimization methodology to find the optimum installation for a self-contained solar and wind power system using simulated annealing, chaotic search (CH), and harmonic search (HS). When assessing the feasibility of a hybrid renewable energy system, its reliability is considered even though the main aim is to minimize the total life cycle cost (LCC).

Meanwhile, to supply Arar City in northern Saudi Arabia with freshwater, Eltamaly et al. [66] designed an efficient a plant for (RO) desalination that uses RES. The size of the plant as estimated by the authors using a model with a single objective and the particle swarm

and bat heuristics Abdelshafy et al. [67] developed an optimization method called PSO-GWO, which combines Particle Swarm Optimization and Grey Wolf Optimization, determine the optimum hybrid system size that can effectively operate a RO system and include either battery storage or hydrogen storage. Kumar et al.[68] introduced the Biogeography Based Optimization (BBO) approach to estimate the most appropriate size factor for PV/wind hybrid energy systems in distant areas. The BBO approach was employed to assess the best component sizing and operational technique, to reduce a hybrid energy system's overall cost while still ensuring energy availability. Maleki [59]also, has formulated an enhanced variant of the bee algorithm to optimize the HRES sizing in the distant eastern Iranian region of South Khorasan. The outcomes of this upgraded algorithm have been compared to those achieved with the harmony search algorithm [69].

Another approach has been done by Ghaithan [70]. Ghaithan built an algorithm that sizes grid-connected photovoltaic-wind systems using mixed-integer programming. The model's aims include decreasing the total cost throughout the duration of the system's lifetime as well as emissions of greenhouse gases and reliance on the electricity grid. The system is designed to power a RO desalination system that provides clean water to a Saudi residential area. By using a genetic algorithm, Kumarasamy et al. [71] were able to size the suggested hybrid system. Without accounting for the utilization of a power storage system, their research focused on attaining the best possible running of a desalination facility powered by solar energy for the supply of water to a rural area. Bourouni et al. [72] published a study about the growth of a hybrid PV-wind system with batteries and RO technology in Tunisia. The authors presented a system that was designed using an innovative

evolutionary heuristic approach (EHM), highlighting the importance of renewable energy technologies.

Moreover, Smaoui and Krichen [73] devised a strategy to construct and operate an autonomous HRES that supplies Tunisia's desalination plant with what it needs. The system is made up of many RES, including fuel cells, electrolyzers, wind turbines, solar generators, and wind turbines, each scaled to assure both technological and financial viability. Their model aims to achieve optimal efficiency and profitability of the system. In Turkey, Gökçek [56] investigated the performance of off-grid energy options that supplied electricity for a small reverse osmosis plant, using an integration of PV, wind, battery, and diesel generators. Gökçek used the HOMER program to assess the system's economic viability. The study's findings revealed that the hybrid system is an affordable approach, particularly in conditions where solar and wind power are abundant. To choose the proper size for a microgrid that includes an RO system while also optimizing the operation of the RO system and the sizes of other components, Prathapaneni and Detroja [74] established a method called coordinate sizing. This strategy involves decomposing the problem into a leader-follower optimization process. According to the study's outcomes, coordinate sizing is a more economical method than conventional ones. Anoune et al. [75] designed a HRES to fulfill the requirements for the electrical demand using particular designs made using the TRNSYS program. Their suggested approach replicates the yearly effectiveness of several PV-Wind hybrid system configurations and selects the most effective setup that guarantees the delivery of the necessary energy at the lowest cost. They compared the size deterministic approaches of the worst and average months on an annual basis.

Furthermore, Acuna [76] introduced a novel reliability metric that employs a probabilistic approach and relies on solar and wind energy's least expensive hourly electric power production. This metric was compared to other measures, and results demonstrate that by utilizing RES to its full potential, system reliability is improved. A Mixed Integer Nonlinear Program (MINLP) framework was recommended by Klaimi [77] for the designing of desalination systems that must meet specific carbon emission objectives. The primary goal of the model was to lower the overall cost of the desalination plant while attaining a range of desires and restrictions related to energy generation, power, and recovered water. The suggested method has proven to be capable of considering a variety of optimal desalination and RES that might meet certain water and energy requirements. The method has also been proven to be reliable for directing decision-making processes. To establish the best design for an HRES that includes a turbine for wind power, PV array, battery bank, and RO desalination unit, Peng [78] used 19 distinct algorithms for evolution to select the HRES' optimal configuration, these algorithms, both single and hybrid optimization algorithms, are employed, with using solar and wind power being the primary sources of power for the desalination unit. Batteries are used as backup units to ensure continuous operation. Ultimately, the study aims to identify the most efficient HRES setup for generating fresh water. The study employs various optimization approaches, including particle swarm optimization, bee swarm optimization, harmony search, simulated annealing, chaotic search, and tabu search algorithm, to achieve optimal performance for the (HRES). Among the evolutionary algorithms taken into consideration, It has been observed that these hybrid strategies for optimizing perform the best. Implementing HRES decreases system costs and improves the reliability of the system, leading to increased

availability of fresh water. Different methods have been employed in recent times to figure out an appropriate HRES size for RO desalination, Liu for example, studied the impact of dispatch techniques on the optimal HRES arrangement with PV panels, storage batteries, diesel generators, and RO desalination and designed to supply all the freshwater and energy requirements of a single region. The goal is to reduce the overall net yearly cost, LCOE, capacity shortfall cost, and reliability index. The tabu search technique is used to identify the optimum system size, considering two dispatch techniques, namely, load following and cycle charge. According to the outcomes, utilizing the tabu search algorithm instead of the harmony search algorithm has the potential to cut down on both average simulation time and overall cost by about 1.8% and 1.65%, respectively.

Earlier studies focused on using renewable energy for water desalination by assuming the size of the desalination unit remains fixed, while The Net Present Value (NPV) of the power supply parts is kept to a minimum. However, this approach does not accurately represent the actual cost of producing water. In contrast, Saboori [79] proposed a novel linear formulation that simultaneously optimizes the components of the power supply and to reduce the Levelized Cost of Water, the size of the desalination system. In addition, this strategy optimizes energy and water storage while reducing carbon emissions. The study's optimization framework is robust and, in addition, the results highlight the crucial factors that have the greatest impact on water cost. This analysis provides valuable insights for future research to explore and reduce water costs.

2.2 Hybrid Renewable Energy System (HRES) with Pumped Storage

(PS) driven RO desalination.

Using of hybrid PV and wind turbine systems with pumped storage (PS) technology has gained considerable attention as a viable solution to power reverse osmosis (RO) unit desalination processes [80]. The key challenge lies in ensuring a stable and continuous power supply to desalination plants, given the variability of solar and wind energy resources [81]. This necessitates the development of robust optimization methods to design and operate such hybrid systems efficiently [82]. The optimization process involves determining the appropriate sizing and configurations of the components.

Various optimization approaches were employed to identify the hybrid system's optimal configuration with (PS) system. Abdelshafy et al. [83] proposed optimizing a grid-connected solar-wind hybrid system with double pumped and battery storage alongside PS hydro-power, leveraging the SSR and ISSR algorithms for configuration selection. Their study explored the impact of uncertain rainy season inflows on system design, previously unexplored in optimal sizing studies. Incorporating random inflow data revealed a substantial decrease in the cost per unit of energy generated.

Notably, the Levelized Cost of Energy (LCOE) is 0.1935 for the grid-connected system with double pumped and battery storage and 0.249 for pumped storage alone. Bhimaraju et al. [84] optimized grid-connected solar-wind hybrid systems with a PS hydro-power station, aiming to minimize LCOE and enhance reliability. Using search space reduction SSR and improved space reduction ISSR algorithms, they achieved a lower LCOE of 0.1870 (\$/kWh) with ISSR outperforming other methods. An uncertainty analysis reducing

solar irradiance and speed of wind by 30% resulted in an LCOE of 0.2495 (\$/kWh), showcasing the system's robustness to variable inputs. Furthermore, Diab et al. [62] introduced an optimization strategy to determine the appropriate dimensions of a hybrid system comprised of PV panels, wind turbines, and a hydroelectric PS system. They evaluated different optimization methods, such as Whale Optimization (WO), Water Cycle (WC), Salp Swarm (SS), and Grey Wolf (GW) algorithms, to attain the best sizing for grid-connected HRES. The findings reveal that the Whale Optimization Algorithm (WOA) predicts the system's minimum LCOE with the lowest NPV and LPSP, resulting in the best LCOE value of 0.216089 \$/kWh.

For a rural Bangladeshi society, Das et al. [85] presented a thorough examination of hybrid energy system (HES) systems. In this study, Hybrid Optimization of Multiple Energy Resources (HOMER) computer software was utilized to assess various combinations, including PV/Pump-hydro storage (PHS), Diesel/PHS, and PV/Diesel/Battery systems. The optimized PV/Diesel/PHS system beats out the PV/PHS (0.43 \$/kWh) and Diesel/PHS (0.41 \$/kWh) choices with a cost of energy (LCOE) of 0.27 \$/kWh. It turns out to be more cost-effective than PV/Diesel/Battery (0.34 \$/kWh). Results demonstrated that in comparison to HOMER software, Genetic Algorithm (GA) offers solutions that are enduring and economically sustainable. The study emphasizes the advantages of the PV/Diesel/PHS system for rural electrification with significant cost savings. The implementation of the HOMER software is also demonstrated by Yimen et al.'s [86] research, where they optimize a pumped-hydro energy storage-based 100%-renewable off-grid hybrid energy system for electrifying Djoundé village in Cameroon. Employing the (HOMER) software, their optimal configuration integrates an 81.8-kW PV array and a 15-

kW biogas generator, resulting in an LCOE of \$0.28/kWh and a total NPC of \$399,444. The study highlights the system's feasibility, emphasized by projected declines in photovoltaic installation costs, making it a viable option in parts of Sub-Saharan Africa (SSA), though substantial investment subsidies would be necessary in other areas.

Moreover, Makhdoomi et al. [87] optimized a PV/diesel/pumped hydro storage (PHS) hybrid energy system to minimize fuel consumption, employing a modified Crow Search Algorithm (CSA) employing adaptable chaotic awareness probability. (CSAAC-AP). The objective links to fuel consumption across the assessment period, while the decision variable manages PHS-supplied power during shortages. Simulations highlight CSAAC-AP's superiority over CSA, genetic algorithm (GA), and particle swarm optimization (PSO), optimizing shortfall power distribution and lowering operational costs. Jurasz et al. [88] introduced a mathematical model for district-level optimization of a solar-wind hybrid with *PS*, incorporating simplified grid costs. The model considers energy distribution and fluctuating solar/wind production, optimizing CO₂ prices using the local consumption index (LCI) to boost renewables' share. LCI highlights PV and wind cost competitiveness, particularly with low CO₂ prices. Shabani et al. [89] examined the combination of micro-pumped storage with battery storage in small scale RES. Through optimization in a Swedish rural setting, the hybrid PV-wind-battery storage system demonstrated an 18.61% reduction in life cycle costs and a 6.12% decrease in oversupply compared to PV-wind-micro PHS. Key variables, including PV modules, wind turbines, reservoir parameters, and battery capacity, were optimized using a modified Genetic Algorithm. Notably, the Levelized Cost of Energy (LCOE) for the battery storage system is 0.19 \$/kWh, while for the pumped storage, it is 0.2 \$/kWh, highlighting economic advantages and reliability.

In desalination technology, a PV-wind hybrid system with *PS* optimizes revenue by synergizing solar and wind sources for a consistent energy supply [90]. Currently, PHES is utilized for desalinating seawater when coupled with renewable energy sources (RES) like wind and solar photovoltaics [91]. Spyrou et al. [53] analyzed a hybrid desalination setup for remote coastal areas, using wind, solar, and PS for freshwater supply. Their customized algorithm optimized the plant's design, aiming to minimize costs and maximize water availability. The stand-alone system can meet water demands in areas like Greek islands, boasting an appealing water production cost (1.61–3.23\$/m³). A system for planning a PV-Wind-pumped storage-seawater desalination (PV-WT-PS-D) system was introduced by Liu et al. [92]. Thoroughly analyzing the cost-benefit ratio and clarifying the system configuration, they got the process started. Mixed-integer linear programming was used to solve a formula that was designed to maximize economic gains while taking restrictions into account. The practicality of the suggested approach was supported by a real-world case study.

2.3 Hybrid Renewable Energy System (HRES) with water tank storage driven RO desalination.

Several studies have explored the integration of renewable energy sources for desalination with water tank storage. In a study conducted on King Island in southern Australia, Tafesh et al. [93] investigated the feasibility of powering a reverse osmosis (RO) plant using renewable energy sources. The study considered four scenarios: PV-Battery storage, PV-Water tank storage, PV with two wind turbines-water tank storage, and PV with four wind

turbines-Water tank storage. Among these scenarios, it was found that the first option, which involved battery storage, incurred the highest cost of water production. This was primarily due to the inclusion of batteries, which contributed to increased capital and replacement costs, along with a shorter lifespan. It found that using a water storage tank is more economical compared to batteries.

Additionally, Mentis et al. [94] created a tool to optimize the sizing of hybrid PV/wind turbine systems with water tank storage for powering reverse osmosis units on three distinct islands in the South Aegean Sea, Greece. The modeling outcomes reveal a noteworthy range in water selling prices. On the larger island, the cost is as low as 1.54 \$/m³, while on the smaller island, it hovers around 2.76 \$/m³. These figures represent a substantial reduction compared to the current water cost, which is at a high (7.42-9.54) \$/m³ for these particular islands.

Nevertheless, to explore the potential of using renewable energy systems powering RO plants to meet the water demand in 2030 which is estimated to be 2374 million/day, Caldera et al. [95] used Hybrid PV-wind – battery storage- water storage tank to feed the RO plant with the required electricity to produce the required water. In regions with desalination demand in 2030, the levelized cost of water (LWC) ranges from 0.59 €/m³ to 2.81 €/m³, influenced by factors like renewable resources and water transport costs. This suggests that in the near future, desalinated water costs may become comparable to those from fossil fuels.

CHAPTER 3

METHODOLOGY

The primary aim of this study is to evaluate the feasibility of a standalone Hybrid Renewable Energy Storage System (HRESS) for running a Reverse Osmosis (RO) desalination plant. The HRESS will integrate photovoltaic (PV) and wind turbine technologies, with three distinct storage options: battery, pumped storage, and water tank storage. To achieve this, a mathematical model is constructed using MATLAB, followed by the implementation of the Differential Evolution (DE) method to identify the optimal configuration for each storage option.

In the first scenario, the study explores utilizing a battery storage system to store excess energy, employing the DE algorithm to optimize the system for RO unit operation.

In the second scenario, pumped storage acts as an alternative to battery storage.

In the third case, a unique approach is adopted by employing water tank storage. Instead of conventional storage, excess energy is used to produce additional water, which is then stored in a water tank for later use during periods of lower production.

Finally, as illustrated in Fig.5, the study unfolds in four distinct steps, the pre-assessment phase involves defining the problem, and specifying the study location, load demand, and system component specifications. Subsequent steps include simulation and analysis, covering both energy and economic assessments. The results are then thoroughly evaluated

and discussed, culminating in the identification of overall performance indicators and the provision of corresponding recommendations.

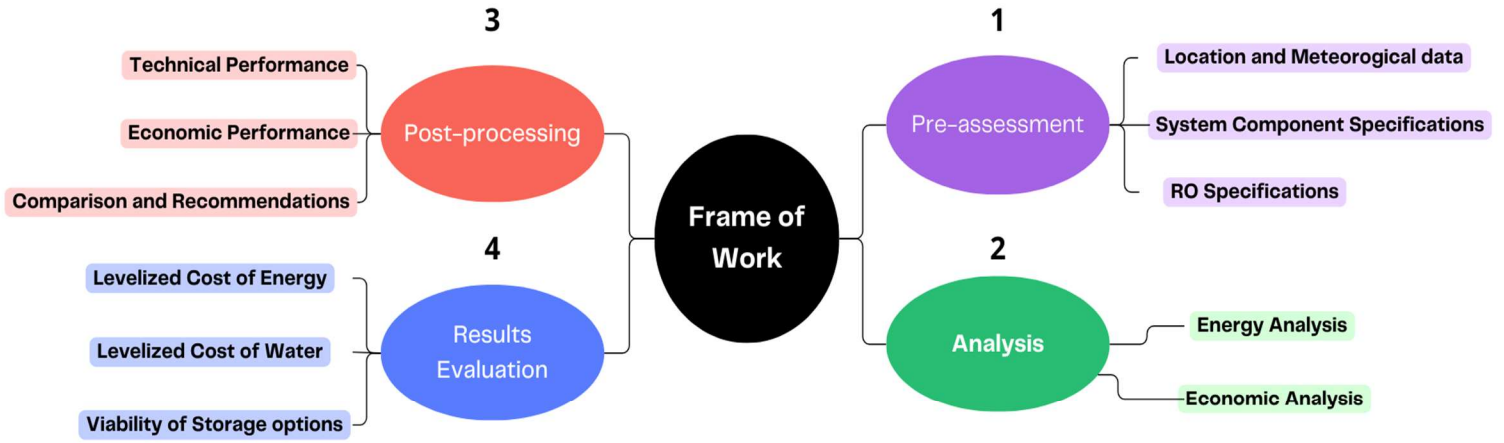


Figure 5: Frame of work of the current thesis' study.

3.1 Meteorological data

This study examines the performance of an RO unit powered by a standalone hybrid renewable PV-wind system with different storage options. This study focuses on Dhahran City, located in the eastern region of Saudi Arabia (Latitude: 26° 23' N, Longitude: 50° 04' E).

Due to its location in the equatorial sunbelt, the Kingdom of Saudi Arabia (KSA) has one of the highest average daily solar radiation rates in the entire globe. As illustrated in Fig. 6, the daily average global radiation on horizontal planes ranges from 5.6 to 6.6 kWh/m² [96],[97]. This feature highlights the region's potential for the installation of solar-powered devices.

In Fig. 7, the hourly data for solar irradiance, wind speed, and temperature in Dhahran City's [98] are presented. With only a minor difference between summer and winter, the hourly global sun irradiation on the horizontal planes of Dhahran is rather constant all year. Solar radiation levels vary from 0.3 to 0.8 kW/m² in the winter and from 0.8 to 1.1 kW/m² in the summer. This consistently high level of sun radiation throughout the year demonstrates the region's suitability for solar-powered technologies. Dhahran experiences hot summers with highs exceeding 40 °C and mild winters with lows ranging from 10 and 25 °C.

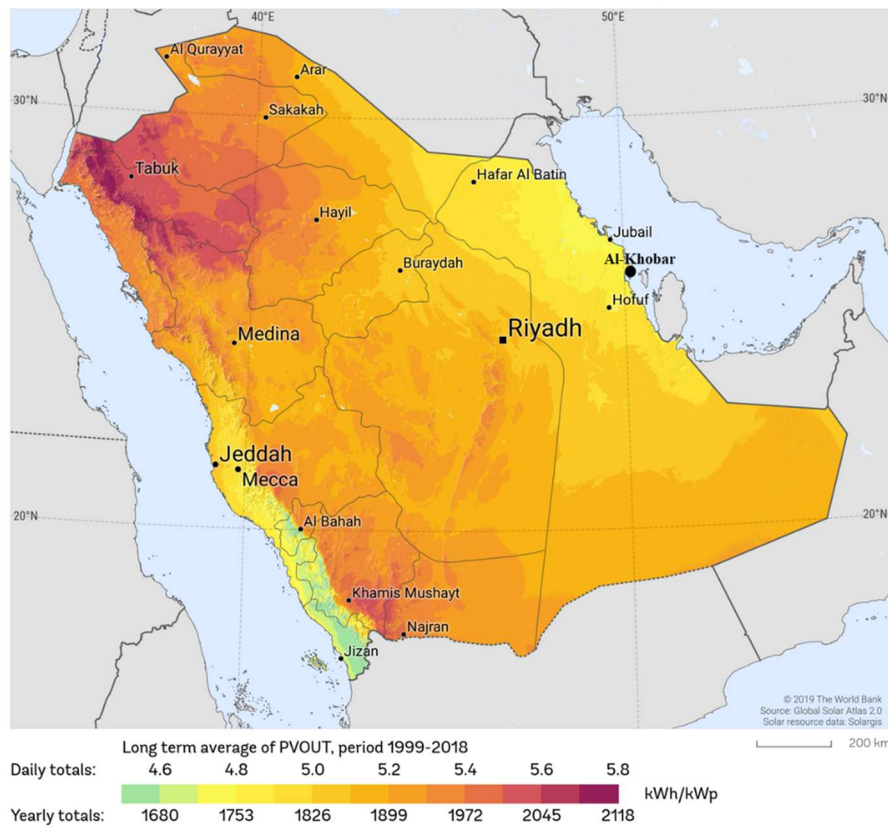


Figure 6: Kingdom of Saudi Arabia's horizontal global irradiance [98] .

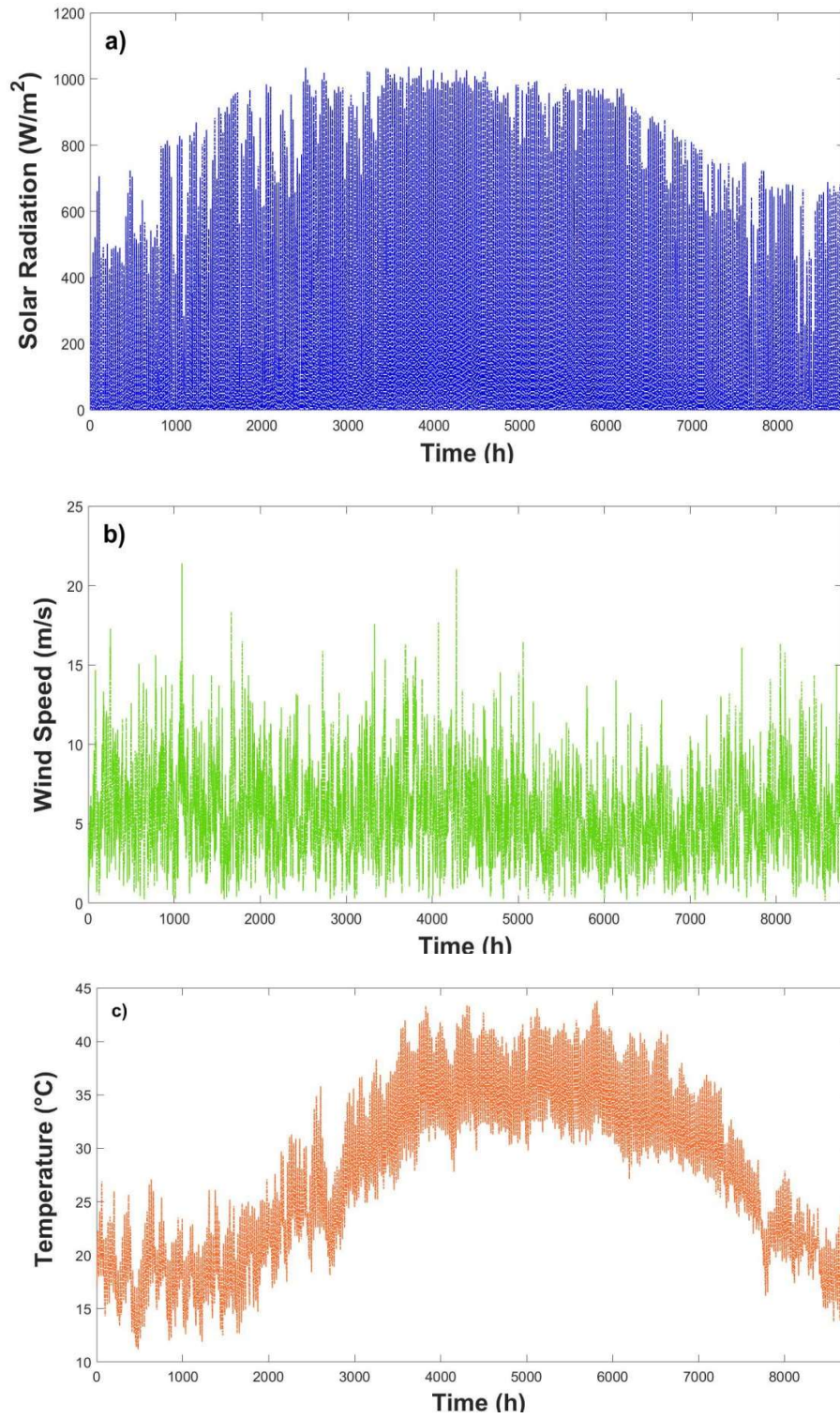


Figure 7: Hourly weather data for Dhahran city: a) Global horizontal irradiance (W/m^2), b) Hourly wind speed, and c) Hourly temperature variation ($^{\circ}\text{C}$).

3.2 System Description

3.2.1 Hybrid Renewable Energy System (HRES) with battery system-driven

RO desalination.

The first proposed system in this study incorporates a state-of-the-art battery storage system to enhance its overall efficiency, specifically tailored for powering a Reverse Osmosis (RO) desalination unit. The hybrid system, as illustrated in Fig. 8, comprises a photovoltaic (PV) panel, a wind turbine, a battery backup storage, and a DC/AC inverter. Serving as the primary power sources, the PV panel and wind turbine generate electricity for the system.. However, the inherent fluctuations in solar irradiance and wind speed can lead to variability in power output.

To counteract this, a storage battery has been integrated into the system, ensuring a consistent power supply throughout the year. The DC/AC converter and inverter are pivotal components, converting the DC electricity from the PV panel into AC electricity suitable for the RO desalination unit. This means that the battery storage system plays a crucial role in maintaining an uninterrupted power supply during periods of low power generation, ensuring the continuous operation of the desalination process. By seamlessly integrating these various components and power sources, this hybrid system not only provides reliability but also presents a sustainable solution for powering RO desalination applications.

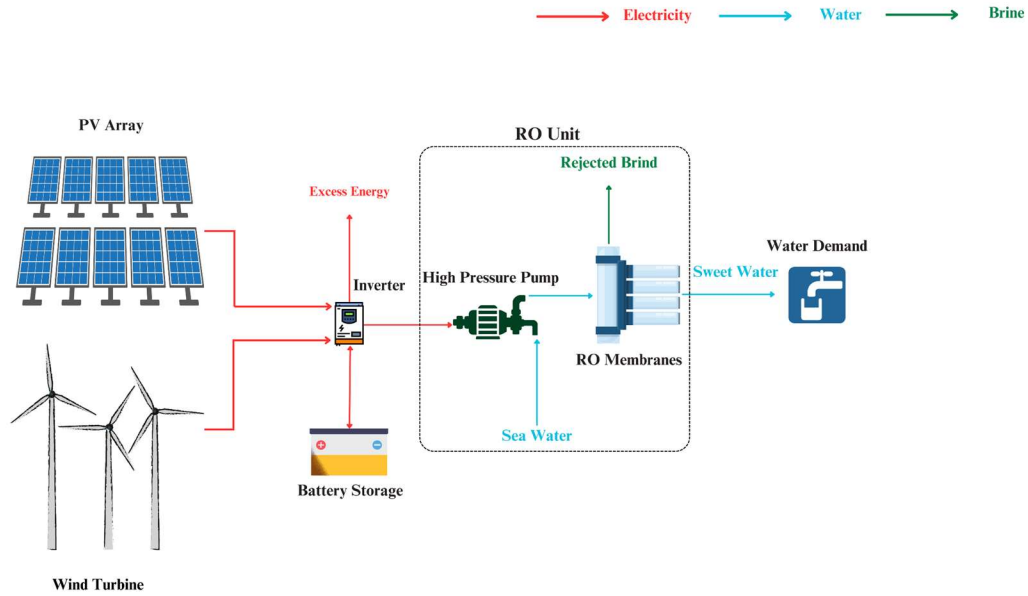


Figure 8: Schematic diagram represents a Hybrid Renewable Energy System for Reverse Osmosis Desalination with battery storage system.

3.2.2 Hybrid Renewable Energy System (HRES) with Pumped Storage (PS)

driven RO desalination.

In this study, the (HRES) encompasses both PV panels and wind turbines. To diverge from conventional battery storage, the current investigation adopts a micro hydro *PS* system. Design and analysis considerations for this hydro *PS* configuration hinge on several factors, including the elevation difference between the upper reservoir (UR) and lower reservoir (LR), reservoir volumes, pumps, hydro turbines, and pipe systems.

Within the context of the optimization process pursued in this analysis, the parameter of upper reservoir height is fixed at 50 meters ($h = 50$ m). The exclusive variable of interest in this study pertains to the volume of the upper reservoir within the system. In this

investigation, the lower reservoir is identified as a lake existing in the vicinity of the hybrid system. Consequently, the construction of an extra lower reservoir is deemed unnecessary. In Figure 9, an illustration of the hybrid system used in this study is shown. This system operates by utilizing the PV panel and wind turbine as its primary sources of power. It is made up of a photovoltaic (PV) panel, a wind turbine, a hydro *PS*, a DC/AC converter, and an inverter.

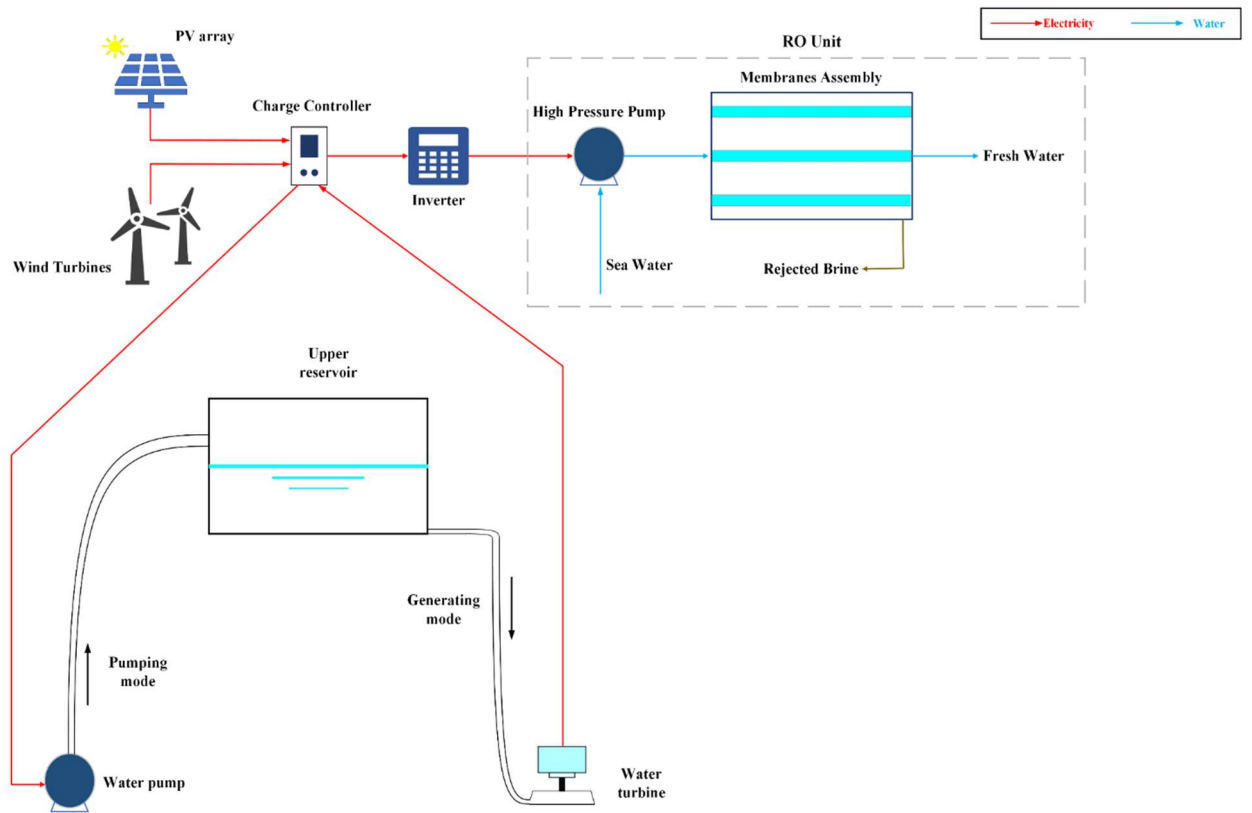


Figure 9: Schematic diagram of a hybrid PV and wind turbine system with a hydro-pumped storage system powering a reverse osmosis (RO) unit.

3.2.3 Hybrid Renewable Energy System (HRES) with water tank storage driven RO desalination.

In the third case, a Hybrid Renewable Energy System (HRES) is implemented, combining optimized Photovoltaic (PV) and Wind Turbine (WT) components through the Differential Evolution (DE) algorithm to power a Reverse Osmosis (RO) desalination system in Dhahran City, Saudi Arabia. Tailored to the city's unique weather patterns., the system addresses the intermittent nature of renewable energy sources. Recognizing the need for enhanced reliability and continuous operation, this case introduces a water tank storage system instead of conventional battery storage. During periods of surplus energy, the system generates additional water, storing it in a water tanks a valuable reserve for times of low HRES production and daytime hours when meeting water production might be challenging. To optimize water production, a variable operating Reverse Osmosis (RO) unit is integrated into the Hybrid Renewable Energy System (HRES). This dynamic RO unit efficiently adapts to the fluctuating inputs from renewable energy sources, ensuring optimal performance during peak periods and resilience during lower energy output scenarios.

Figure 10 presents a schematic diagram of the Hybrid Renewable Energy System (HRES) configuration. It visually represents the dynamic interactions among components such as the Photovoltaic (PV) array, Wind Turbine (WT), and Variable Operating Reverse Osmosis (RO) unit. The diagram emphasizes the adaptability of the system showcasing electrical energy flow, and the strategic use of surplus energy for water production in the Water Tank Storage system.

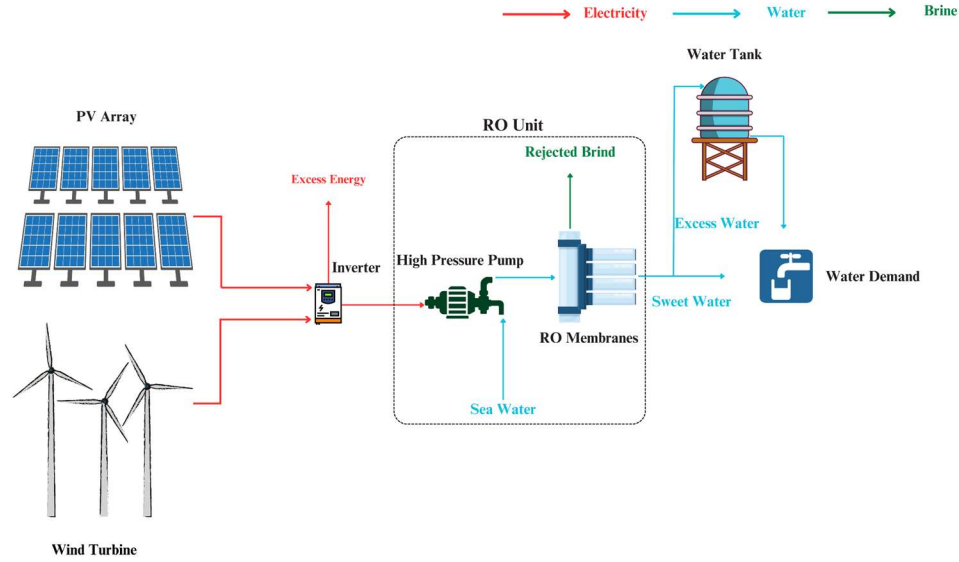


Figure 10: Schematic diagram of the Hybrid Renewable Energy System Configuration with Water Tank Storage and Variable RO Operation.

3.2.4 RO System Description

This thesis investigates the optimal configuration of a Hybrid Renewable Energy System (HRES) to power various Reverse Osmosis (RO) desalination capacities, ranging up to 50,000 m³/day. Focusing on Dhahran city, the study explores the effectiveness of three storage options to determine the most economically viable option for this specific context. The cost of desalinated water from an RO system varies based on several parameters, including system size, water supply, and electricity cost. Typically, RO systems produced desalinated water at a cost of \$(532-1400)/m³/day [99] and consume 3-5 kWh of electricity per cubic meter of water produced [100].

Thus, for this study's HRES optimization, an RO desalination unit with a 5 kWh/m³ consumption was selected. Table 2 details the RO system's capital cost, operating costs, membrane replacement costs, and chemical expenses. Consequently, the capital expenses

of the RO system fall between \$2660 and \$7000 and with an assumed bi-annual replacement, the annual replacement cost is \$0.6 per cubic meter.

Table 2: Costs for RO desalination unit [63] .

Capital cost (\$/m ³ /day)	532-1400
Operational and maintenance cost (\$/year)	365
Membrane replacement cost (\$/replacement)	0.3
Chemical cost (\$/year)	109.5

3.3 Mathematical Modeling

This study's renewable energy system comprises of a PV solar module, a wind turbine (WT), three different storage systems, and a converter. This power system's size and performance are optimized using the mathematical models shown below.

3.3.1 Photovoltaic (PV) System Design

Solar monocrystalline PV modules with a rated power of 295 W and a module efficiency of 18.02 % are employed in this investigation [101]. Furthermore, the PV module has a 25-year lifespan, a 1200 \$/kW initial and replacement cost, and a 17 \$/kW operating and maintenance cost. The PV module's hourly energy generation $P_{PV}(t)$ [102] is:

$$P_{PV}(t) = P_R \times \left(\frac{G_T(t)}{G_{ref}} \right) \times [+\tau_p \times (T_C(t) - T_{ref})] \quad (3.1)$$

where P_R stands for the rated capacity (kW) of the PV module, $G_T(t)$ is the hourly solar radiation on slanted PV panels (kW/m²), G_{ref} indicates solar radiation at standard test conditions (STC), which is equivalent to 1 kW for the selected modules[101], τ_p represents the power temperature coefficient, whose value is 0.0039 (1/^oC), T_{ref} indicates the PV cell temperature during standard test circumstances, which is equivalent to 25°C, and $T_C(t)$

is the PV cell temperature at operating conditions. The solar radiation on a tilted surface is given by [103]:

$$G_T(t) = G_b(t)R_b(t) + G_d(t)\left(\frac{1+\cos\beta}{2}\right) + G(t)\rho_g\left(\frac{1-\cos\beta}{2}\right) \quad (3.2)$$

where $G_b(t)$ is the beam radiation at hour (t), $G_d(t)$ is the diffuse radiation at hour (t), $G(t)$ denotes the global solar radiation at the horizontal surface at hour (t), $R_b(t)$ refers to the geometry factor, β is the PV tilt angle, and ρ_g is the ground reflectivity.

Under working circumstances, the temperature of the PV cell is given by [102] :

$$T_c(t) = T_A(t) + \left(\frac{T_{NOCT}-20}{G_{NOCT}}\right) \times G_T(t) \quad (3.3)$$

where T_A relates to the surrounding temperature ($^{\circ}\text{C}$), T_{NOCT} indicates the temperature at nominal working module conditions ($^{\circ}\text{C}$) and G_{NOCT} represents the 0.80 kW/m^2 standard solar radiation under nominal circumstances. For a PV array containing N_{PV} panels, the total energy produced is expressed by:

$$E_{PV}(t) = N_{PV} \times P_{PV}(t) \quad (3.4)$$

where $E_{PV}(t)$ represents the PV array's overall energy production and N_{PV} represents the number of PV panels. Table 3 contains the specifications considered for the PV panels.

Table 3: PV panel specifications [101].

Panel Specifications	value
Efficiency (%)	18.02
Rated power (kW)	0.295
Coefficient of temperature (%)	-0.39
Open circuit voltage V_{oc} (V)	39.5
Short circuit current I_{sc} (A)	9.75
Temperature of nominal operation ($^{\circ}\text{C}$)	45
Mechanical Data	
Cell type	Mono-crystalline
Dimensions (mm)	1650×992×40
Weight (Kg)	18.2
Life time (year)	25

3.3.2 Wind Turbine Model Power Output

A wind turbine with a rated power of 1 kW, a rotor diameter of 2.5 m, and a hub height of 10 m is employed for the present study [104]. Additionally, the rated, cutoff and cut-in wind speeds are 3 m/s, 11 m/s, and 25 m/s, respectively. The wind turbine is designed to operate for a period of 25 years., a total installation cost of \$3125/kW [105], and yearly operating and maintenance costs of \$156/kW. The hourly energy production from wind turbine $P_{WT}(t)$ is:

$$P_{WT}(t) = \begin{cases} 0 & v(t) < v_{ci} \\ a_1 v^3(t) + b_1 v^2(t) + c_1 v(t) + d_1 & v_{ci} \leq v(t) < v_1 \\ a_2 v^3(t) + b_2 v^2(t) + c_2 v(t) + d_2 & v_1 \leq v(t) < v_2 \\ a_3 v^3(t) + b_3 v^2(t) + c_3 v(t) + d_3 & v_2 \leq v(t) < v_{co} \\ 0 & v(t) > v_{co} \end{cases} \quad (3.5)$$

The wind turbine's hourly electricity production, denoted as $P_{WT}(t)$, depends on the wind speed $v(t)$ during that specific hour, falling within the range between the cut-in speed (v_{ci}) and cut-out speed (v_{co}). For enhanced precision, intermediate wind speeds (v_1 and v_2) are

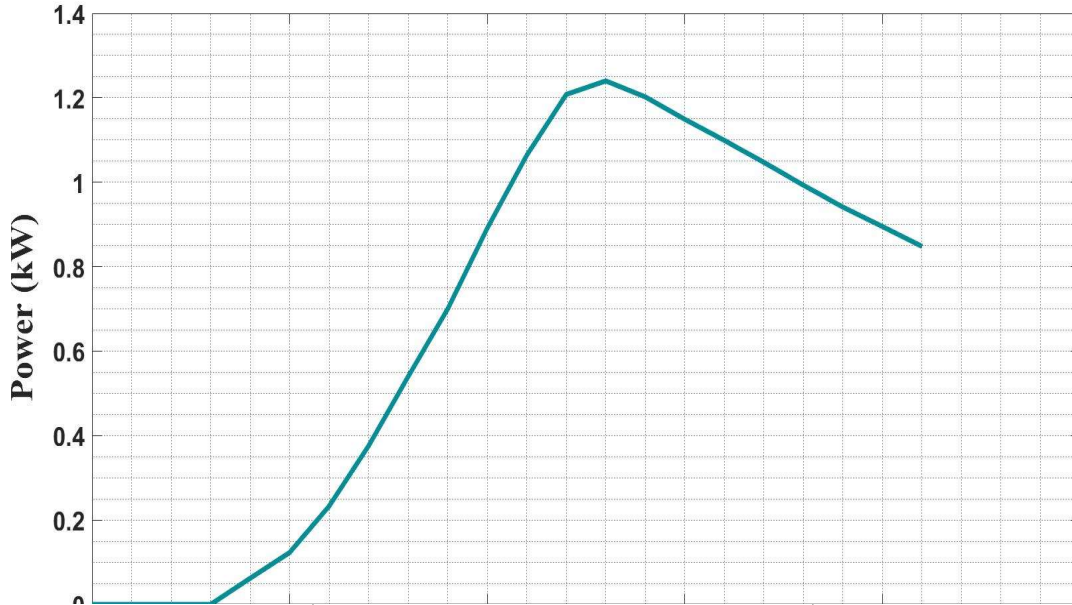


Figure 11: Performance Curve of Wind Turbine.

incorporated into the curve fitting procedure. This study utilized the Bergey BWC XL.1 wind turbine for electricity generation, showcasing its power output at varying wind speeds in Figure 11.

The estimated value for the constants related to the wind turbine Bergey BWC XL.1 is shown in Table 4. In addition, Table 5 summarizes the technical specifications of the wind turbine used [104].

Table 4: Estimated Constants for Wind Turbine Bergey BWC XL.1.

Constant	Value
a_1	-0.0015
b_1	0.0433
c_1	-0.23
d_1	0.385
a_2	0.0036
b_2	-0.1664
c_2	2.5131
d_2	-11.19
a_3	0.002
b_3	-0.0077
c_3	0.0728
d_3	1.2658

Table 5: Technical Details of Wind Turbine

Wind Turbine specifications	Value
Rated Capacity (kW)	1
Wind speed at start-up (m/s)	3
Rated wind speed (m/s)	11
Wind speed cut-off (m/s)	25
Rotor diameter (m)	2.5
Hub height (m)	10
Capital cost (\$)	2500
Lifetime (year)	25

To precisely estimate a wind turbine's hourly power, its characteristic curve is constructed using the least squares method, incorporating a minimum of three binomial expressions for accuracy. The total energy produced by wind turbines is:

$$E_{WT}(t) = N_{WT} \times P_{WT}(t) \quad (3.6)$$

where $E_{WT}(t)$ Signifies the overall energy generated by the wind turbine system. and N_{WT} donate the number of wind turbines.

3.3.3 Converter System

In the Hybrid Renewable Energy System (HRES), to change DC electricity into AC power, converters are utilized. The converter efficiency is used to indicate the AC power demand, which is [106]:

$$P_C(t) = \frac{E_{Load}(t)}{\eta_c} \quad (3.7)$$

where $P_C(t)$ is the conversion power that reflects AC, power required in an hour(t) in order to meet the demand (kW), $E_{Load}(t)$ is the hourly load demand (kW) and η_c represents the efficiency of the converter (%). A converter with a rated power of 0.5 kW,

an efficiency of 95%, and a 15-year lifespan has been selected for the present study. Operating and maintenance expenditures are 10 \$/ year, whereas capital and replacement costs are 650 \$/ kW.

3.3.4 Battery Storage Model

Battery storage is required in hybrid systems that incorporate PV and wind technologies to balance intermittent energy production and consumption. It provides a backup power supply and enables energy to be stored during low demand and released during high demand. The hourly power output generated by the PV system and the wind turbine together is:

$$P_{total}(t) = P_{PV}(t) + P_{WT}(t) \quad (3.8)$$

where $P_{total}(t)$ is the total electricity produced per hour (t) by PV and wind turbines.

If the energy generated by PV panels and wind turbines during a certain hour (t) exceeds the energy needed at that time, the excess energy will be stored in a battery. The equation for determining the state of charge of a battery is provided by [107]:

$$C_{batt}(t) = C_{batt}(t - 1) \times (1 - \sigma) + (P_{total}(t) - P_C(t))\Delta t \times \eta_{bc} \quad (3.9)$$

Nevertheless, the battery will be in a discharged state if the amount of electricity produced by the wind and solar panels is insufficient to meet the demand. As a result, the following equation [107] may be used to show how much energy the battery bank has at hour t.

$$C_{batt}(t) = C_{batt}(t - 1) \times (1 - \sigma) - (P_C(t) - P_{total}(t))\Delta t \times \eta_{bd} \quad (3.10)$$

The value of Δt , which denotes the time increment used in the computation, is set to one hour in this work ($\Delta t = 1$). At time t and t-1, the available energy storage capacity (in watt-hours) of a battery bank is represented by $C_{batt}(t)$ and $C_{batt}(t - 1)$, respectively. The

battery manufacturer provides information on the self-discharge rate of the battery denoted as σ , which is 25% over six (6) months for a storage temperature of 20°C. In other words, the daily self-discharge rate is 0.14% [108]. The efficiency of charging a lead acid battery, denoted as η_{bc} , is approximately 85% [109]. Additionally, the discharging efficiency of the battery, denoted as η_{bd} , reflects the ratio of the energy taken out of the battery during discharge to the energy stored in the battery.

The energy in the battery must not be more than its maximum state of charge, according to one of the optimization constraints ($C_{batt,max}$). By doing this, the battery's energy-storage capacity is protected against being overcharged, which can cause damage and decrease its performance:

$$C_{batt}(t) \leq C_{batt,max} \quad (3.11)$$

Once the battery becomes fully charged, any additional energy generated beyond its capacity is considered surplus energy (SE) and can be quantified using [110]:

$$SE(t) = P_{total}(t)\Delta t - \left(P_C \Delta t + \left(\frac{C_{batt,max} - C_{batt}(t-1)}{\eta_{batt}} \right) \right) \quad (3.12)$$

Surplus energy, which accounts for more than 50% of the overall production in certain cases [111], refers to the energy that cannot be stored in batteries due to limitations in the capacity of the storage system. In a hybrid PV/wind turbine system, this surplus energy can be effectively utilized in various ways. Firstly, it can be sold back to the grid, allowing for its integration into the larger energy network [112]. Additionally, it can be employed for hydrogen production [113], which presents a valuable opportunity for storing and utilizing energy in the form of hydrogen gas. Furthermore, the surplus energy can be utilized for deferrable loads like a bank of light bulbs or a resistive heater, where it can be directed to

power energy-consuming activities during periods of low demand [114]. Also, it can be utilized to dump loads in the type of heating or cooling loads in residential applications, which could increase the reliability of the system [115]. Lastly, it can also be harnessed to support other energy-intensive processes, providing a sustainable and cost-effective solution. In this study, the surplus energy generated by the optimized system will be reintegrated into the grid, allowing us to harness this surplus power to both lower the Levelized Cost of Energy (LCOE) and reduce the Levelized Water Cost (LWC).

Also, the minimum energy constraint ensures that the battery always has a minimum amount of energy available for use, preventing depletion beyond safe limits and reducing the risk of damage and decreased lifespan.

$$C_{batt}(t) \geq C_{batt,min} \quad (3.13)$$

The battery's minimum permitted level of charge ($C_{batt,min}$) is determined by [111]:

$$C_{batt,min} = DOD \times C_{batt,nominal} \quad (3.14)$$

The value of DOD, which represents the maximum depth to which the battery can be discharged without causing damage, typically falls within the range of 30-50% [116]. Table 6 Presents The battery specifications used in the current simulation.

Table 6: Battery specifications. [117]

Specifications	Value
Type	Lead-Acid
Voltage (V)	12
Maximum capacity (Ah)	359
Nominal Capacity (kWh)	4.31
Capital cost (\$)	800
Replacement (\$)	600

3.3.5 Hydro Pumped Storage Model

This section explores an integrated approach that combines energy storage with renewable sources, such as solar and wind. This synergy ensures a continuous and reliable power supply for a variety of applications with fluctuating energy demands and renewable energy generation. The section also covers the efficient use of excess energy in this system.

In the pump operation, the excess energy is used to run a pump as follows [118]:

$$P_{pm}(t) = \frac{\rho g h q_{pm}(t)}{\eta_{pm}} \quad (3.15)$$

Where: $P_{pm}(t)$ is the pump power at time t , ρ is the density of the water, g is the gravitational acceleration ($g = 9.81 \text{ m/s}^2$), h is the elevation difference between the lower and upper reservoirs, $q_{pm}(t)$ is the flow rate (m^3/s) that is pumped from the lower to the upper reservoir, and η_{pm} is the overall efficiency of the pump.

If there is an electricity shortage in the system, the water turbine will turn on to compensate for the deficiency using this formula [118]:

$$P_{tu}(t) = \eta_{tu} \rho g h q_{tu}(t) \quad (3.16)$$

Where $P_{tu}(t)$ represents turbine power, η_{tu} denotes overall turbine efficiency, and $q_{tu}(t)$ is turbine water flow rate (m^3/s). The water level in the upper reservoir fluctuates while the pumping or generating mode is in operation:

$$Q_{upp}(t) = Q_{upp}(t-1) + \int_{t-1}^t q_{pm}(t) - \int_{t-1}^t q_{tu}(t) \quad (3.17)$$

The water upper tank level at time t , and $t-1$ is represented by $Q_{upp}(t)$ and $Q_{upp}(t-1)$ in (m^3). During the operation, the water level for the upper reservoir is expressed by the Level of Charge (LOC):

$$LOC = \frac{Q_{upp}(t)}{Q_{upp,max}} \quad (3.18)$$

During the operation of the system, various scenarios may unfold as follows:

- **Scenario I:** When the system's power output exceeds the demand, excess energy ($P_{excess}(t)$) is utilized to switch on the pump and pump the water to the upper reservoir. This occurs when $Q_{upp}(t - 1) < Q_{upp,max}$ and $Q_{upp,max} - Q_{upp}(t - 1) > \int_{t-1}^t q_{pm}(t)$.
- **Scenario II:** The upper reservoir is at full capacity and the power production is larger than the system demand, hence in this case, $P_{excess}(t)$ is regarded as surplus power. This surplus energy can be effectively sold back to the grid.
- **Scenario III:** The power generated by the system is greater than the demand, and $Q_{upp,max} - Q_{upp}(t - 1) < \int_{t-1}^t q_{pm}(t)$. As a result, the pump will continue to operate until the upper reservoir is completely filled, and any further $P_{excess}(t)$ is considered surplus power.
- **Scenario IV:** The power generation is less than the system's demand ($P_{loss}(t)$), hence the water turbine will be in ON mode and any deficit will be covered by the water turbine when $Q_{upp}(t - 1) > Q_{upp,min}(t)$.

Table 7 encapsulates the entirety of specifications and cost details pertinent to pumped storage.

Table 7: Overview of Pumped Storage Specifications and Costs

Component	Unit	Cost (\$)	Lifetime (years)
Variable Speed Water Pump [119]	kW	850	10
Water turbine [120]	kW	518	10
Upper Reservoir [121]	m3	60	30

3.3.6 Water Tank Storage Model

The water storage tank plays a critical role in the HRES powering the RO plant. It stores excess sweet water flowing from the RO unit to keep the water demand always satisfied when the HRES is not able to produce enough energy to meet the RO load. Therefore, the hourly status of the water storage tank is expressed as follows:

$$Q(t) = Q(t - 1) + Q_p(t) - Q_D(t) \quad (3.19)$$

where $Q(t)$ is the water tank capacity in the current hour, $Q(t - 1)$ is the water tank capacity in the previous hour, Q_p is the volumetric flow rate of produced sweet water flowing from the RO unit, Q_D represents the volumetric flow rate of sweet water demand. The capital cost of the water tank is 90 \$/m³ with a lifetime of 25 years [122].

3.4 Assessment Criteria

Two assessment and evaluation criteria are used in this study. A detailed description of each criterion is given in the following subsections.

3.4.1 Reliability Assessment

The reliability of the hybrid system is a crucial factor to consider, as it has an impact on the system's capacity to deliver a constant and steady source of power. Factors that can affect the reliability of the system include the availability of sunlight and wind, the consistency of the individual components, and the overall design and configuration of the integrated system.

3.4.1.1 Power Reliability

When assessing the performance of a hybrid PV and wind system linked with energy storage systems like battery storage and pumped storage, as well as other energy storage systems, power reliability is of the utmost importance. A significant evaluation of system reliability is provided by Loss of Power Supply Probability (LPSP), which plays a crucial role. It represents the number of hours that the integrated PV and wind system, along with energy storage systems like battery storage and pumped storage, fails to supply the power demand [123]. This measure is a key indicator for analyzing the system's dependability and resilience, and it may be calculated using the equation below:

$$LPSP = \frac{\sum_{t=1}^{8760} LPS(t)}{\sum_{t=1}^{8760} P_d(t) \Delta t} \quad (3.20)$$

Where $(\sum_{t=1}^{8760} LPS(t))$ is the sum of the HRES's total loss of power supply during the year and $(\sum_{t=1}^{8760} P_d(t))$ is the total demand load within the same interval of time. The value of LPSP has a limit that is specified by the application being utilized. As a result, it is important to consider this factor and implement a system limitation to guarantee that the LPSP does not exceed the allowable limit.

$$LPSP \leq LPSP_{desired} \quad (3.21)$$

The desired value for LPSP denoted as $(LPSP_{desired})$, is considered to be zero in this study.

3.4.1.2 Water Supply Reliability

To keep the end-user demand for freshwater always satisfied, a novel performance indicator is developed in this study called: Loss of Water Supply Probability (LWSP).

$LWSP$ is represented by a number ranging from 0 to 1. $LWSP = 0$ indicates that there is no

water shortage, and that demand is always satisfied. However, $LWSP = 1$ indicates that there is no water supply, and the system is always unable to fulfill demand. The RO freshwater output should be sufficient to prevent the discharging of the water tanks to a level lower than their minimal capacity. Therefore, to ensure that the end-user water demand is 100% covered by RO unit production, the loss of water supply should be always zero. To account for this, a novel expression called Loss of Water Supply (LWS) is developed in this study and it is expressed as:

$$LWS(t) = Q_D(t) - (Q_P(t) + Q(t - 1) - Q_{min}) \quad (3.22)$$

where $LWS(t)$ represents the hourly shortage of freshwater in (m^3/h), $Q_D(t)$ denotes the hourly water demand in (m^3/h), $Q(t - 1)$ is the water tank state of charge in the previous hour in (m^3) and Q_{min} is the minimum allowable state of charge. The Loss of water is calculated hourly for 8760 hours (full year). Then, the LWSP is expressed as:

$$LWSP = \frac{\sum_{t=1}^{8760} LWS(t)}{\sum_{t=1}^{8760} Q_D(t)} \quad (3.23)$$

where $LWSP$ denotes the shortage of water supply probability, $\sum_{t=1}^{8760} LWS(t)$ is the summation of hourly shortage of water supply for a full year and $\sum_{t=1}^{8760} Q_D(t)$ is the summation of hourly water demand for the same year.

3.5 Economic Assessment

Regarding a power production system, the Levelized Cost of Electricity (LCOE) is used to rank the feasible PV/Battery configurations. LCE indicates the cost of one kWh generated by the PV/Battery system in (\$/kWh) and it is expressed by[124]:

$$LCOE = \frac{CRF \times NPV}{\sum_{t=1}^{8760} P_{req}(t) \Delta t} \quad (3.24)$$

Where NPV is the net present value, and CRF is the capital recovery parameter. NPV represents the net present value for the system and can be expressed as:

$$NPV = C_{RO} + C_{PV} + C_{WT} + C_{inv} + C_{storage} + C_{rep} \quad (3.25)$$

where C_{RO} is the capital cost of an RO unit which has a cost of \$532/m³ [63], C_{PV} represents the capital cost of the PV module, C_{WT} accounts for the capital cost of wind turbine systems, C_{inv} is the capital cost of the inverter, and $C_{storage}$ donates the capital cost of the storage system, and C_{rep} is the replacement cost for the system. The Capital Recovery Factor can be written:

$$CRF(i, N) = \frac{i \times (1+i)^N}{(1+i)^N - 1} \quad (3.26)$$

where i relates to the percentage of interest and N refers to the duration of project (years).

In the current study, $i = 6\%$, and $N = 25$ years.

The annual operation and maintenance cost $C_{O\&M}$ are described by:

$$C_{O\&M} = C_{O\&M,RO} + C_{O\&M,PV} + C_{O\&M,WT} + C_{O\&M,inv} \quad (3.27)$$

where $C_{O\&M,RO}$ is the annual $O\&M$ cost of RO unit, which in this study is equal to \$73/m³, $C_{O\&M,PV}$ signifies the yearly $O\&M$ of the PV module, $C_{O\&M,WT}$ represents annual $O\&M$ for wind turbine systems, and $C_{O\&M,inv}$ is $O\&M$ of inverter.

In addition, the Levelized Water Cost (LWC) [79] is an important indicator that provides the cost of each m³ produced by the RO desalination system. It can be expressed by:

$$LWC = \frac{(NPC \times CRF(i, N)) + C_{O\&M} + C_{chm}}{\sum_{t=1}^{8760} Q_P(t)} \quad (3.28)$$

Where C_{chm} accounts for the annual chemical cost required for the RO unit. $\sum_{t=1}^{8760} Q_P(t)$ is the summation of hourly water production for one full year.

Equation (3.28) does not consider the cost of returning surplus energy (SE) to the grid, though. If this SE were sold to the grid, calculate the Levelized Water Cost after selling back LWC_s , the following expression is used [125]:

$$LWC_s = \frac{(NPC \times CRF(i, N)) + C_{O\&M} + C_{rep} + C_{chm} - SB \times \sum_{t=1}^{8760} SE(t)}{\sum_{t=1}^{8760} Q_P(t)} \quad (3.29)$$

where SB denotes the benefit of selling back surplus energy to the grid, measured in (\$/kWh). This cost is set at 0.05 \$/kWh in Saudi Arabia [126]. $\sum_{t=1}^{8760} SE(t)$ is the summation of the hourly surplus energy during one year.

3.4.2.1 Cost Analysis for Photovoltaic (PV) system

The cost of one PV panel is denoted here as μ_{pv} , the total number of PV panels is N_{PV} and λ_{pv} refers to the additional cost associated with structural, support, and other components for PV panels. Thus, the capital cost of PV system (C_{PV}) can be expressed as:

$$C_{PV} = N_{PV} \times \mu_{PV} + \lambda_{PV} \quad (3.30)$$

And λ_{PV} is set equal to [127]:

$$\lambda_{PV} = 0.5 \times (N_{PV} \times \mu_{PV}) \quad (3.31)$$

Moreover, assuming that the maintenance cost for a PV system is equal to 1% of C_{PV} [107] and that the project life is equal to ($r = 25$), the following is the net present value of the maintenance throughout the project's lifespan:

$$C_{O\&M, PV} = \sum_{N=1}^N 0.01 \times C_{PV} \times (1 + i)^{-N} \quad (3.32)$$

3.4.2.2 Cost Analysis for Wind Turbine

Following the same process as PV systems, C_{WT} for wind turbines will be determined using the same concept, considering the additional capital costs of wind turbines, such as support,

foundation, and other related costs, as well as the annual maintenance cost, which is set equal to 25% and 5%, respectively [107].

$$C_{WT} = N_{WT} \times \mu_{WT} + \lambda_{WT} \quad (3.33)$$

$$\lambda_{WT} = 0.25 \times (N_{WT} \times \mu_{WT}) \quad (3.34)$$

$$C_{O\&M,WT} = \sum_{N=1}^N 0.05 \times C_{WT} \times (1 + i)^{-N} \quad (3.35)$$

Where N_{WT} represents the total number of wind turbines, μ_{WT} is the capital cost per wind turbine, and λ_{WT} denotes extra costs for the wind turbine's construction, support, and other components. Since the wind turbine's lifetime equals the project's lifespan, no replacement cost is added in the wind cost analysis.

3.4.2.3 Cost Analysis for Battery Storage System

The capital cost of the battery storage system can be calculated by:

$$C_{BT} = N_{BT} \times \mu_{BT} \quad (3.36)$$

where N_{BT} is the number of batteries and μ_{BT} is the battery's cost.

The lifetime of batteries varies depending on the type and usage but typically ranges from one to five years. Therefore, the replacement of the batteries represents additional cost adding to the system's overall net present value. The life of the battery selected in this study is five years and the project has a 25-year lifespan, so the batteries need to be replaced four times. It follows that the battery replacement's net present value is estimated by:

$$C_{BT,rep} = \sum_{N=5,10,15,20}^N C_{BT,rep} \times (1 + i)^{-N} \quad (3.37)$$

where $C_{BT,rep}$ represents the replacement cost for the batteries.

3.4.2.4 Cost Analysis for Hydro Pumped Storage System

The capital cost for a pumped storage system is described by:

$$C_{PS} = C_P + C_T + C_{UR} \quad (3.38)$$

Where C_{PS} is the capital cost of the pumped storage system, C_P is the capital cost for the water pump, C_T is the capital cost for the water turbine, and C_{UR} is the capital cost for the upper reservoir.

The replacement cost for the PS system is shown:

$$C_{P,rep} = \sum_{N=10,20}^N C_P \times (1 + i)^{-N} \quad (3.39)$$

$$C_{T,rep} = \sum_{N=10,20}^N C_T \times (1 + i)^{-N} \quad (3.40)$$

Where $C_{P,rep}$, $C_{T,rep}$ are the replacement costs for the water pump and water turbine respectively.

3.4.2.5 Cost Analysis for Water Tank Storage

The capital cost for water tank storage including support, foundation, and other things is provided [122]. In this study, the optimization process commences with the water tank's initial status, Q_i , set at 10% of its full capacity. Since the water inside the tank is entirely pure, there's a requirement to purchase sweet water to fill half of the tank, incurring a cost C_{water} of \$ 0.92/m³ for sweet water in the Dhahran city region [128]. So, the capital cost for water tank storage:

$$C_{WST} = C_{WST} + C_{water} \times Q_i \quad (3.41)$$

3.5 Differential Evolution Algorithm

Differential evolution (DE) is a heuristic, population-based algorithm that searches for the global optimal solution. Due to its robustness, speed of convergence, and ease of implementation, DE has been utilized in many engineering optimization problems[129]. Differential Evolution (DE) is a widely used population-based stochastic optimization algorithm. It is effective for solving optimization problems with multiple variables and can handle both single-variable and multi-variable optimization. It is also characterized by two key parameters, which are the mutation factor (F) and the crossover constant (CR). The four fundamental steps of the DE algorithm are as follows:

- 1) Initialization: at this stage, x is the representative vector of the optimized parameters, and with a population size of NP , the initial vectors are randomly generated as:

$$x_{i,j} = x_j^{min} + g \times (x_j^{max} - x_j^{min}) \quad (3.42)$$

where $i = 1, 2, \dots, NP$; $j = 1, 2, \dots, P$; P is the number of optimized parameters; x_j^{max} and x_j^{min} are the upper and lower bounds of the corresponding $x_{i,j}$; g is a randomly generated number with a uniform distribution with a range of $(0, 1)$.

- 2) Mutation: at the mutation stage, each individual x_i in the population produces a mutant vector v_i based on a certain mutation operation. Although there are several mutation operations in the DE algorithm[130], the mutant vector v_i in this study was produced as follows:

$$v_i = x_{R1} + F \times (x_{R2} - x_{R3}) \quad (3.43)$$

Where $R1$, $R2$, and $R3$ are arbitrary integer numbers within the range $[1, NP]$ and they must satisfy $R1 \neq R2 \neq R3$.

3) Crossover: after creating NP mutant vectors, a trial vector t_i is produced by crossovering the mutant vector v_i with the individual vector x_i . In this work, t_i is produced as follows:

$$t_{i,j} = \begin{cases} v_{i,j} & \text{if } r \leq CR \\ x_{i,j} & \text{otherwise} \end{cases} \quad (3.44)$$

4) Selection: finally, the number of $x_{i,j}$ and $t_{i,j}$ vectors are $2NP$. However, we need NP vectors x_i^{new} to be selected for the next generation. F_o is the objective function that must be reduced, and it is accomplished as follows:

$$x_i^{new} = \begin{cases} t_i & \text{if } F_o(t_i) \leq f(x_i) \\ x_i & \text{otherwise} \end{cases} \quad (3.44)$$

It is worth mentioning that there is a final sub-step in the DE, i.e., the fitness evaluation. In the differential evolution algorithm, fitness is the evaluation function that measures the quality of a potential solution in the population. It presents the solution and quantifies how well a solution performs concerning the desired outcome. This is needed to store the best fitness out of the generated population for the termination criterion.

Figure 12 illustrates the flowchart which summarizes the main steps of the DE algorithm, starting with initialization, and ending with the stopping criterion which is to have the same fitness for a certain number of generations.

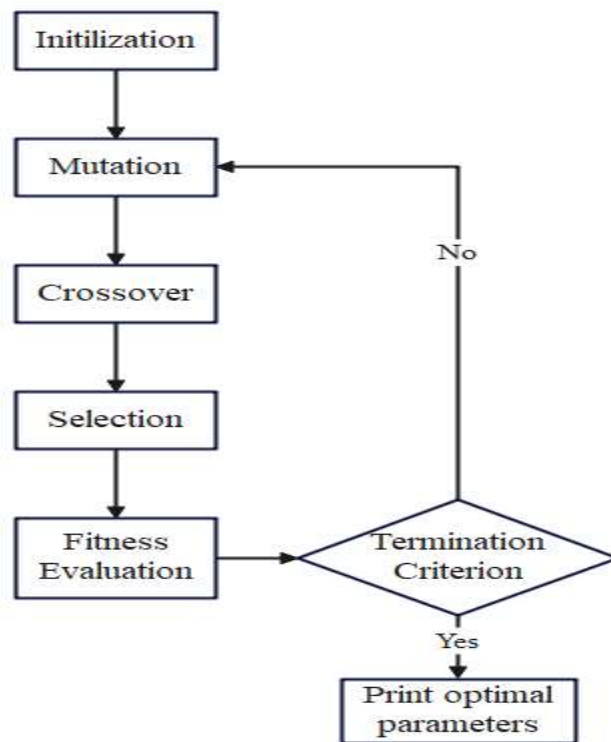


Figure 12: Flowchart of the DE optimization process.

CHAPTER 4

OPTIMIZATION RESULTS FOR HYBRID

RENEWABLE ENERGY SYSTEM (HRES) WITH

BATTERY STORAGE

Based on the aforementioned literature, limited research has conducted the application of the Differential Evolution (DE) algorithm to optimize Hybrid Renewable Energy Systems (HRES) for RO desalination, particularly in the Gulf region. This study addresses this gap by implementing the DE algorithm to determine the optimal configuration of a hybrid PV/Wind turbine system for powering a 1kW RO desalination in Dhahran City, Saudi Arabia. The feasibility will be evaluated using Levelized Cost of Energy (LCOE) and Levelized Water Cost (LWC) as objective functions.

To achieve this objective, weather data for Dhahran City will be gathered and utilized to simulate the performance of 158 model configurations involving various combinations of PV panels, wind power turbines, and battery storage systems. Additionally, data on the cost of each component will be collected. Subsequently, the Differential Evolution algorithm will be employed to search for the optimal configuration that minimizes both LCOE and LWC.

4.1 Model Validation

To ensure the accuracy and reliability of the mathematical model used for powering the RO desalination with a combined wind, PV, and battery storage system, it was first validated using HOMER software. The validation involved comparing the model's results with those generated by HOMER for the same type of system configuration. The validation results demonstrated an excellent agreement between the two, indicating that the presented model is suitable for optimization using the DE algorithm. Table 8 summarizes the characteristics of the validated system and the results obtained from the mathematical model that includes PV, wind, and battery storage system.

While both MATLAB and HOMER simulate identical configuration of the wind-PV hybrid system, slight differences in results can occur due to variations in underlying modeling algorithms, data sources, and assumptions. These discrepancies in handling parameters and calculating performance metrics can result in slight variations in total energy production, total net present value, and LCOE, as indicated in the table.

Table 8: Model validation with HOMER software.

Configuration	PV module load (kW)	Number of wind turbines	Number of batteries	Total energy production (kWh/yr)	Total net present value (\$)	LCOE (\$/kWh)
HOMER	6.47	1	13	13,859	44,995.74	0.398
Present code	6.47	1	13	13,909	45,253	0.4
Difference %	0	0	0	0.36	0.56	0.5

With the validated mathematical model, the DE algorithm can now be implemented to find the optimal values of the decision variables. This optimization aims to minimize the LCOE while satisfying the pre-defined constraints. By improving the hybrid system's overall

efficiency and sustainability, this optimization method can assist in determining the hybrid system's cost-effective design.

4.2 Optimization Procedure

The differential evolution (DE) algorithm plays an important role to optimize the size of a hybrid system designed to power an RO desalination unit. This system consists of PV panels, wind turbines, and battery storage systems to meet the unit's energy demands. The ultimate goal of the optimization is to minimize system's levelized cost of energy (LCOE). The optimization process includes a four-step process: defining the objective function, determining decision variables, applying the algorithm to generate and evaluate potential solutions, and selecting the best solution.

Figure 13, which is a typical process diagram used in computer programming, further illustrates the implementation of Differential Evolution (DE) for optimizing the (LCOE) of (HRES).

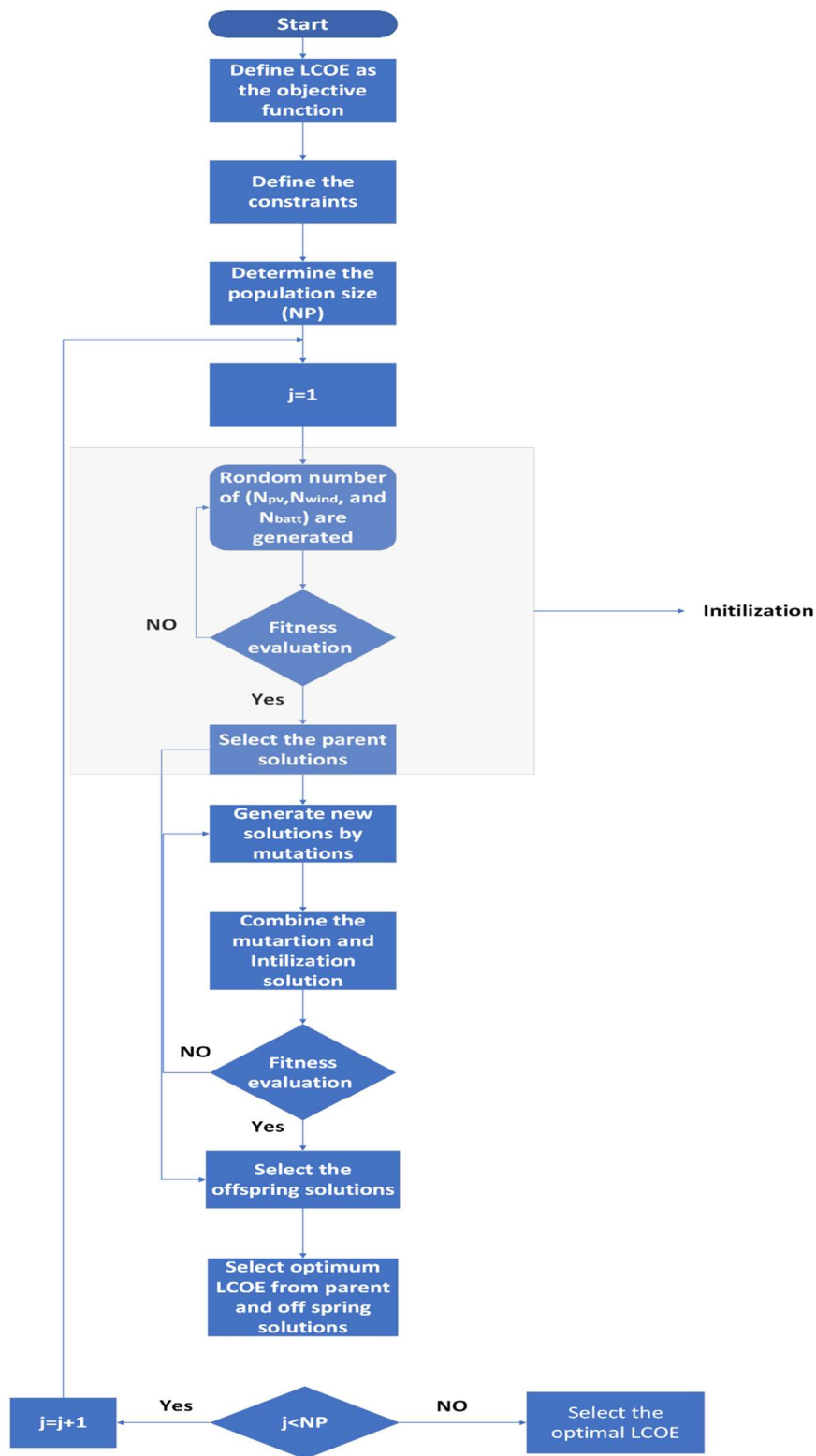


Figure 13 Flow Chart: Differential Evolution Optimization for RO Desalination in PV and Wind Hybrid System LCOE.

4.3 Objective function and constraints

In a hybrid system that uses wind and photovoltaic (PV) power for reverse osmosis (RO) desalination, the primary objective is for minimizing the Levelized Cost of Electricity (LCOE) and Levelized Water Cost (LWC). To achieve this goal, particular restrictions pertaining to wind turbines, photovoltaic panels, batteries, energy production, and LPSP must be followed. It may be stated as follows in a more symbolic sense:

$$P_{PV}(t) + P_{WT}(t) + C_{batt}(t) \geq P_d(t) \quad (4.1)$$

$$0 \leq N_{PV} \leq N_{PV,max} \quad (4.2)$$

$$0 \leq N_{WT} \leq N_{WT,max} \quad (4.3)$$

$$0 \leq N_{batt} \leq N_{batt,max} \quad (4.4)$$

$$LPSP \leq LPSP_{desired} \quad (4.5)$$

$N_{PV,max}$, $N_{WT,max}$, and $N_{batt,max}$ denote the maximum possible number of photovoltaic (PV) panels, wind turbines, and batteries, respectively.

The mathematical model for the PV and wind-based hybrid system for RO desalination was built in MATLAB. The DE algorithm was then implemented to find the optimal values of N_{PV} , N_{WT} , and N_{batt} that minimize the LCOE and LWC ensuring compliance with constraints on LPSP, wind turbines, PV panels, batteries, and electricity output.

4.4 Optimization Results

In this study, DE is implemented to optimize the HRES powering RO desalination unit. The approach seeks to reduce the levelized cost of electricity (LCOE) while also ensuring that the Levelized Water Cost (LWC) falls within an acceptable range. The DE algorithm was used to a case study of Dhahran, Saudi Arabia, which suffers serious water scarcity issues. Table 9 lists the parameters of the DE technique that were employed in the study's optimization approach.

Table 9: DE Algorithm Parameters for Optimization in the Study.

Pop. Size	Crossover constant (<i>CR</i>)	Mutation factor (<i>F</i>)	Generations
30	0.85	0.05	900

For an RO capacity of 5 m³/day, The outcomes illustrate that for an RO capacity of 5 m³/day and an RO load requirement of 1 kW, the optimum hybrid system configuration comprises a PV producing capacity of 7.67 kW, a 2 kW wind turbine, and a battery size of 38.79 kWh. The LCOE for Dhahran stands at \$0.39 per kWh. Figure 14 depicts the LCOE (Levelized Cost of Electricity) values for these configurations, with the optimal solution of ($N_{pv}=26$, $N_{wind}=2$, and $N_{batt}=9$) yielding the lowest LCOE of 0.39 \$/kWh.

It has been observed that as the number of iterations increases, the graph (Fig. 13) representing the behavior of the objective function tends to converge towards its lowest value. This convergence phenomenon becomes more pronounced with an increasing number of iterations. Eventually, the graph reaches a point at which the objective function's value becomes constant, and this occurs after a total of 693 iterations.

In other words, the iterative process results in a stable value for the objective function beyond the 693th iteration. This behavior can be interpreted as the optimization algorithm reaching a point of minimum value for the objective function, which cannot improve further beyond a certain point.

Through the DE algorithm with a population size of 30, a total of 30 HRES configurations were obtained, satisfying the system constraints. However, the configuration with the lowest LCOE was selected as the final solution, providing a reliable and cost-effective option for powering the RO desalination system using HRES. Table 10 presents all candidate configurations. However, the configuration with the lowest LCOE value was selected through the DE algorithm, providing a reliable and cost-effective solution for RO desalination systems powered by HRES.

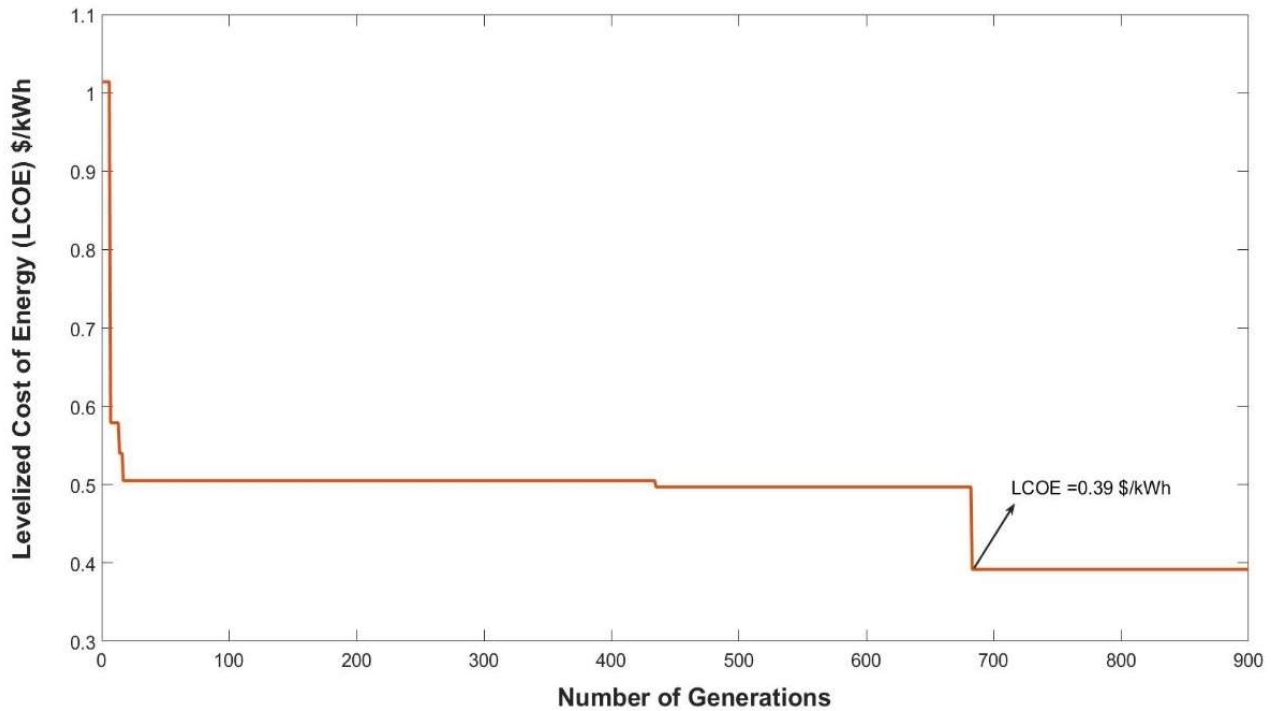


Figure 14: Convergence Results of DE Algorithm Optimization for HRES-Powered RO Desalination.

Table 10: The optimum configurations for HRES powering RO desalination generated by the DE algorithm.

Optimum configuration#	N_{pv}	N_{wind}	N_{batt}	LCOE (\$/kWh)
1	60	6	13	0.829
2	21	4	28	0.897
3	53	1	23	0.588
4	34	5	5	0.503
5	20	3	10	0.43
6	27	4	10	0.511
7	24	3	10	0.45
8	17	8	11	0.66
9	26	2	9	0.39
10	12	2	25	0.612
11	43	3	25	0.819
12	36	1	9	0.402
13	58	6	26	1.02
14	13	7	10	0.575
15	24	2	10	0.404
16	8	5	10	0.458
17	35	1	10	0.417
18	18	2	14	0.447
19	18	6	7	0.509
20	17	4	10	0.461
21	13	7	10	0.573
22	31	1	8	0.541
23	30	2	11	0.455
24	50	1	24	0.748
25	16	4	10	0.456
26	33	1	10	0.407
27	14	2	17	0.480
28	35	1	11	0.435
29	74	1	11	0.639
30	37	1	18	0.573

A detailed comparative investigation has been conducted to compare the efficacy of the presently developed Differential Evolution (DE) algorithm and the MATLAB code with that of the well-known HOMER software in optimizing a hybrid system that would achieve

a 0% Loss of Power Supply Probability (LPSP) in a controlled environment. The optimization function of both the Differential Evolution (DE) based-developed code and the HOMER Software was to achieve the lowest possible Levelized Cost of Electricity (LCOE).

The results of the optimization as obtained by the two software's are presented in Table 11. The DE algorithm excels by outperforming HOMER's LCOE of 0.4 \$/kWh and obtaining an LCOE of 0.39 \$/kWh. Despite preserving parity in energy production and storage (2 wind turbines and 9 batteries), a subtle difference between DE and HOMER's photovoltaic (PV) panels (26 vs. 27) is observed. Consequently, the overall techno-economic performance of the optimized system is affected by this slight difference and DE's solution has the lower LCOE.

Table 11: Comparative Analysis of Differential Evolution and HOMER Methods for System Reliability and Economic Efficiency.

Method	LPSP	Optimum LCOE (\$/kWh)	N_{pv}	N_{wind}	N_{batt}
DE algorithm	0	0.39	26	2	9
HOMER software	0	0.40	27	2	9

Table 12 thoroughly comprise the performance of the Differential Evolution (DE) algorithm and the HOMER software in optimizing system configurations to achieve an LPSP of 0.01. The analysis highlights the superior efficiency of the DE algorithm in generating solutions that offers more cost-effective solutions. These results shed light on the distinct advantages of DE in providing more efficient energy system configurations under stringent reliability constraints.

Table 12: Comparative Analysis of Differential Evolution and HOMER Methods for System Configurations at LPSP = 0.01.

Method	N_{pv}	N_{wind}	N_{batt}	LCOE (\$/kWh)
DE	39	1	5	0.343
Optimum of HOMER	23	2	8	0.358

Therefore, the Differential Evolution (DE) algorithm and the MATLAB code developed during this work fall under the category of developing reliable and cost-effective energy solutions.

Figure 15 illustrates the hourly energy generation of the optimum Hybrid Renewable Energy System (HRES) throughout the year. This system consists of 26 photovoltaic (PV) panels, two wind turbines (WT), and nine battery storage systems. As expected, energy generation fluctuates due to variations in sunlight and wind availability. However, the presence of a battery storage system reduces these fluctuations by storing excess energy during peak production periods for utilization during lower energy generation.

Furthermore, the graph highlights the total power consumption of a reverse osmosis (RO) desalination facility with a consistent 1-kilowatt (kW) capacity all year round. The energy generated by the HRES system can be utilized to fulfill the needs of the RO plant, with any remaining energy available for other applications [131], [132], [133]. Alternatively, if the energy produced exceeds the requirements of the RO plant, it can be considered as surplus from the system.

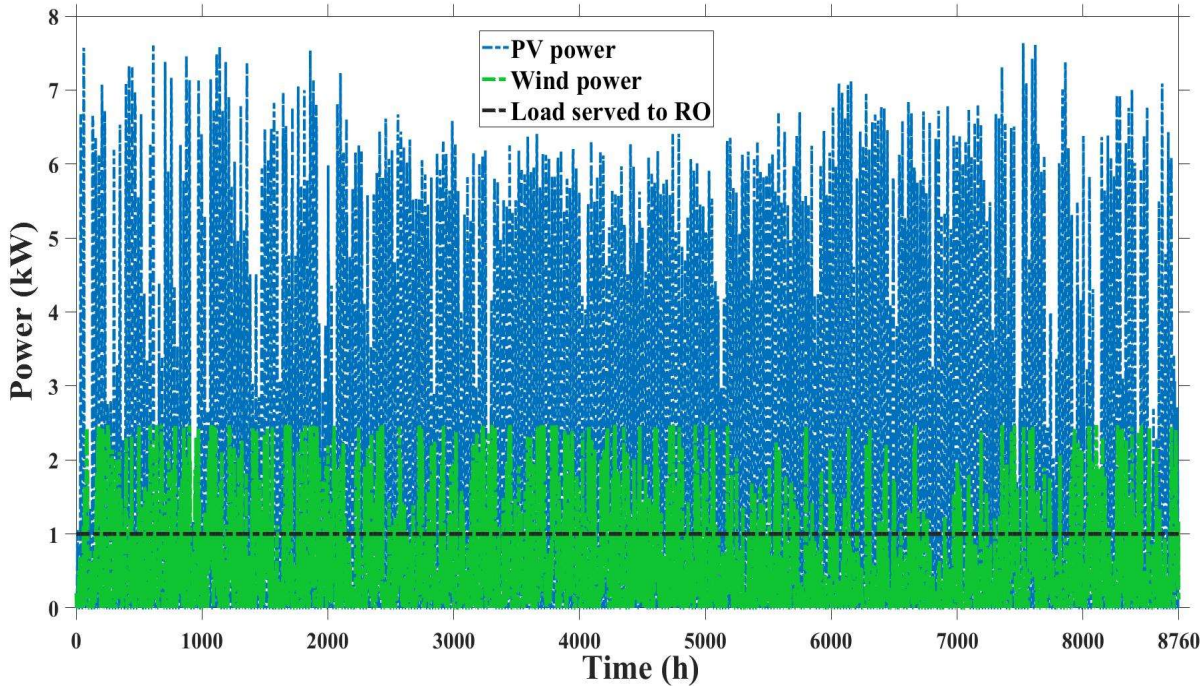


Figure 15: Hourly power production and served to RO from the optimum HRES with battery storage configuration during one year.

Figure 16 presents the state of charge (SOC) of the battery storage system in the optimized system over a year, revealing how it balances the variable renewable energy production and demand. The data clearly shows that the batteries are at a maximum state of charge during peak production hours of PV and wind, indicating that excess energy is being stored. However, the SOC fluctuates during mornings and nights because of reduced renewable

energy production, demonstrating the batteries' ability to supply energy to meet the load demand. Notably, during the day, surplus energy from PV and wind is wasted as it cannot be stored in the battery storage system due to its maximum state of charge. This highlights the importance of the battery storage system in optimizing the use of renewable energy and reducing reliance on fossil fuels.

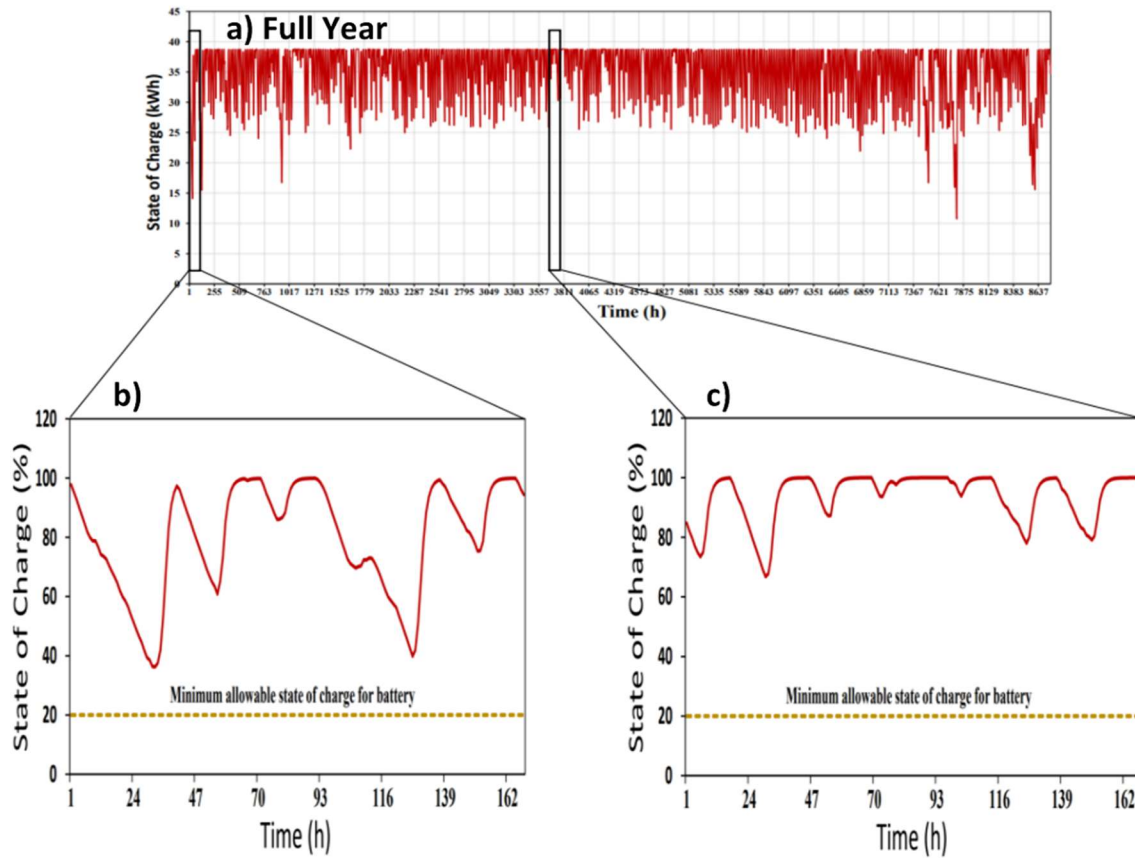


Figure 16: Battery storage system's State of Charge (SOC) throughout: a) 12-month period, b) First week of January, c) First week of June.

The weekly power production from the optimum hybrid system based on PV/wind turbine, along with the battery state of charge and load served to the RO unit are shown in Fig.17 for the third week of January and the second week of June. As seen in Fig.16.a, the optimum hybrid system utilized both PV panels and a wind turbine for power generation during the third week of January.

The system's power production varied throughout the week due to factors like weather conditions, sunlight availability, and wind strength. The battery's state of charge, representing stored energy, fluctuated during this period. Starting at a specific level on Monday, it changed gradually as power was generated, consumed, and battery efficiency played a role. The load served to the RO unit, essential for water purification, remained constant, relying on a stable power supply throughout the week.

In the second week of June, as shown in Fig.17.b, the hybrid system displayed a unique power production pattern compared to January. The varying amounts of electricity generated by the PV panels and wind turbine were influenced by changing environmental conditions. The battery's state of charge also fluctuated throughout the week, reflecting the interplay of power production, energy consumption, and battery efficiency.

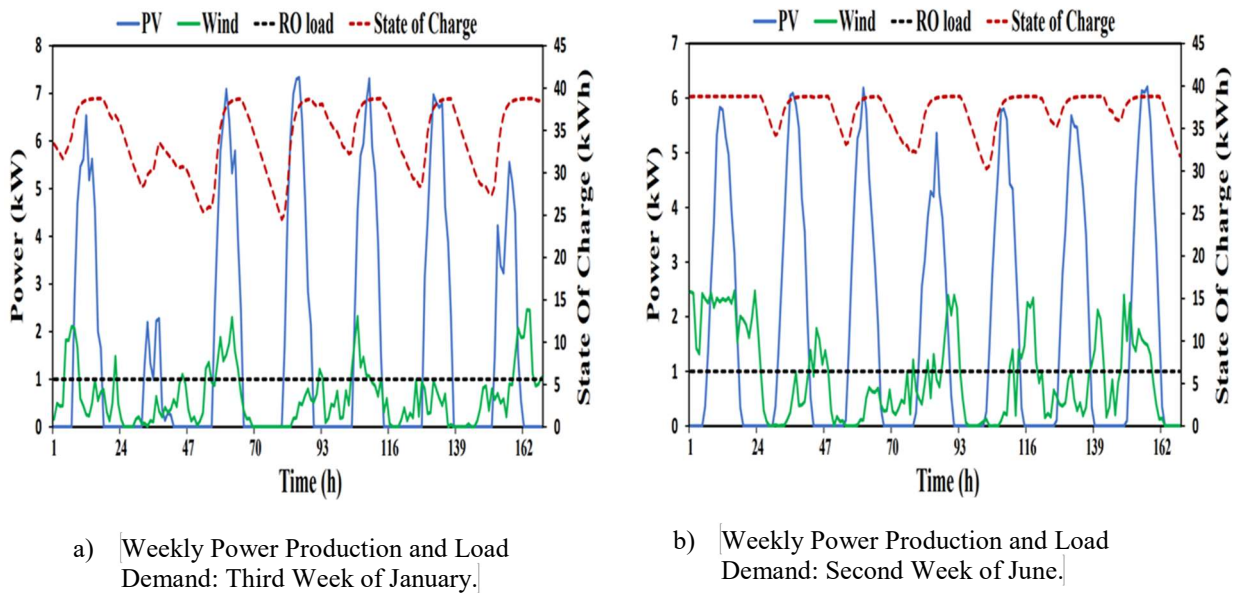


Figure 17 Weekly Power Production and Load Demand Comparison: January vs. June

Figure 18 compares the power production, surplus energy, load served, and load demand for a typical day in January and June, as generated from an optimum Hybrid Renewable

Energy System (HRES) operating a Reverse Osmosis (RO) unit. The bar chart represents the varying power generation from PV panels and wind turbines, influenced by factors such as sunlight and wind speed. Power values are indicated on the y-axis in kilowatts (kW). The load served to the RO unit is represented by a horizontal line, indicating the constant 1 kW load demand for the RO unit.

In January, the comparison reveals limitations in charging capacity or system design, which impede the efficient utilization and storage of excess energy. As a result, there is wastage or curtailment of excess electricity, indicating that the system cannot fully utilize or store the power produced by the PV panels and wind turbines.

Conversely, the figure for June demonstrates an improved system design. Enhanced factors such as charging efficiency, increased battery capacity, or optimized control strategies enable better utilization and storage of excess energy. This enhanced system design allows for efficient utilization and storage of the constant excess energy, leading to improved overall system performance.

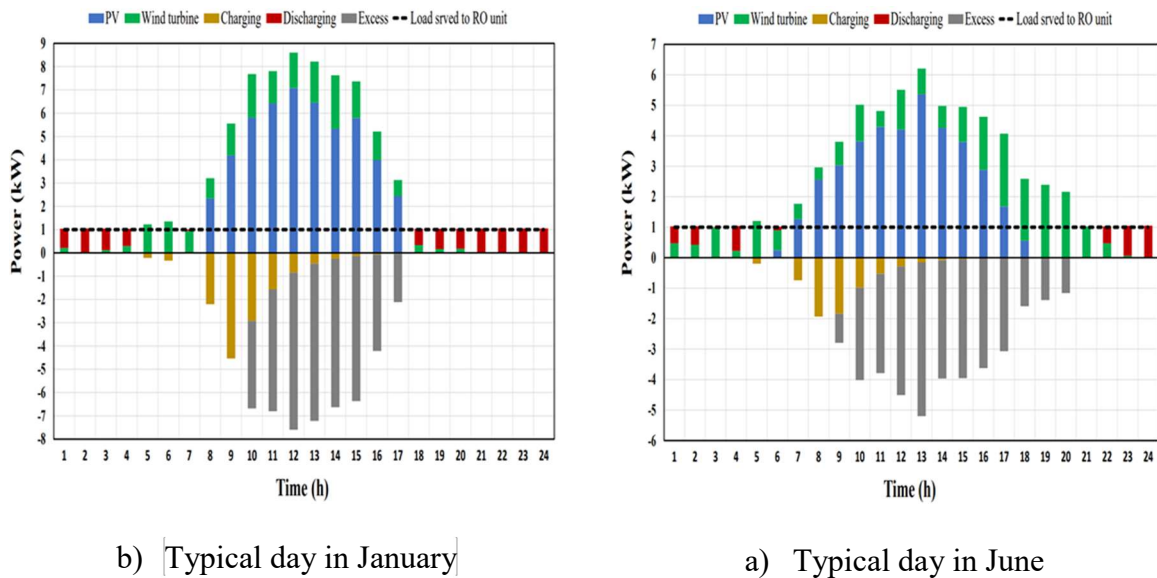


Figure 18: Comparative Analysis of Energy Flow in Hybrid Renewable Energy Systems: a) January, b) June.

The comparison in Figure 18 highlights disparities in surplus energy utilization and overall system performance between January and June. Battery efficiency in energy storage systems can vary based on factors such as temperature, state of charge, and age. In January, lower temperatures and other factors could lead to reduced battery performance, potentially resulting in more wasted energy when excess energy is not efficiently stored. However, in June, the system demonstrated improved utilization and storage of the excess energy, suggesting that the batteries may have performed more efficiently during this period. This improved efficiency could contribute to the enhanced overall system performance observed in June compared to January. This means that temperature significantly impacts battery performance in energy storage systems. During winter days, as temperatures drop, the chemical reactions within the battery slow down. This slowdown increases the battery's internal resistance, restraining both charging and discharging efficiency, resulting in decreased overall performance of the battery. In contrast, summer's warmer temperatures accelerate these chemical reactions, reducing internal resistance and resulting to improved battery performance and efficiency [69].

Figure 19 represents the hourly water production from the optimized configuration of a Hybrid Renewable Energy System (HRES) running a Reverse Osmosis (RO) unit. In this investigation, the water demand is $5 \text{ m}^3/\text{day}$, which is equivalent to $0.208 \text{ m}^3/\text{h}$. Thus, Figure 19.a demonstrates the RO water output for the entire month of June. It appears that the RO unit provides a consistent water output per hour that meets the demand throughout the month. On the other hand, Figure 19. b illustrates the hourly water production for a

typical day in June. This graph likely showcases the variations in water production throughout the day, highlighting the specific hourly outputs of the RO unit.

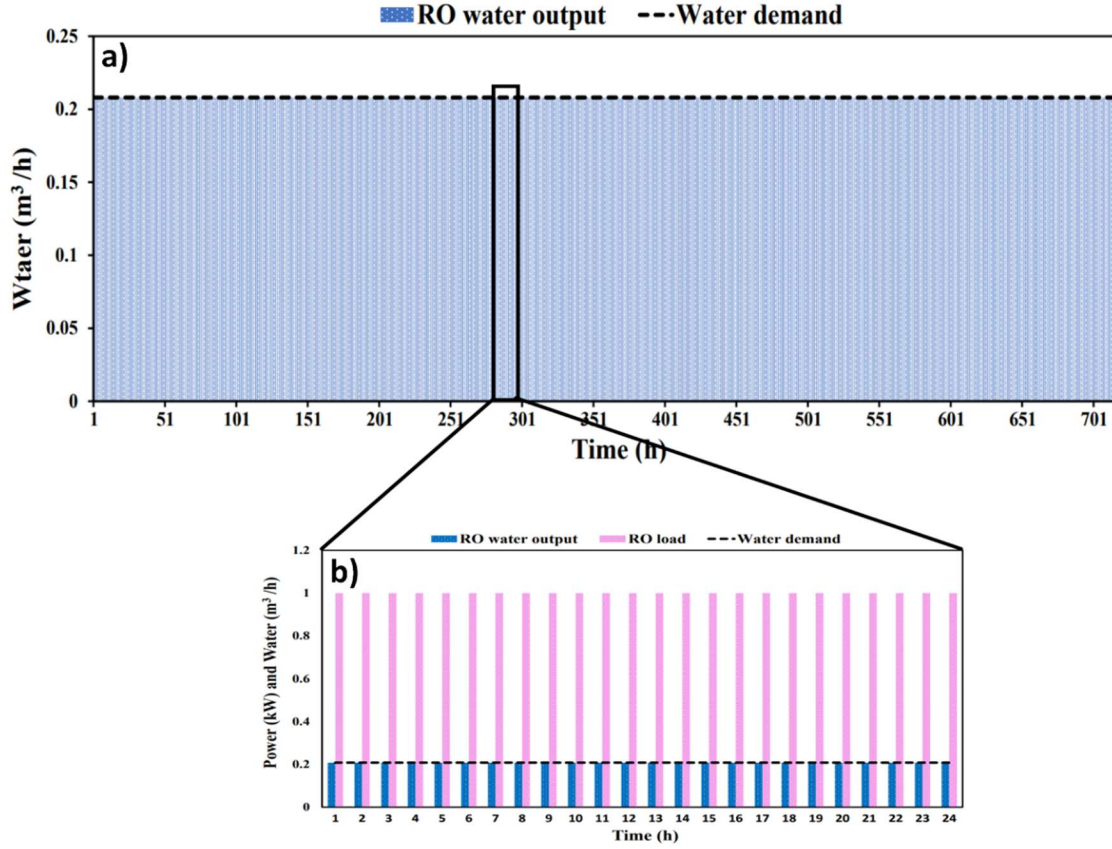


Figure 19: RO Unit Water Production and Demand: a) June, b) Typical June Day.

4.4.1 Levelized Water Cost

Using the LCOE resulting from the optimal HRES configuration, and the RO system costs and capacity, we were able to estimate the Levelized water cost (LWC) using Eq. (3.28). The resulting LWC is in the \$(2.24-2.43)/\text{m}^3\$ range. It is crucial to realize that these LWCs only account for water production by the optimal HRES utilized in Dhahran city and do not consider any surplus energy produced within the system.

4.4.2 Savings on desalination water costs by selling surplus energy.

The optimal system configuration's surplus energy was estimated to be approximately 9,775 kWh/year, accounting for 51% of the total energy production, a significant amount that should be utilized effectively. Equation (3.29) is used to calculate the levelized water cost after reselling the excess energy to the grid. The results show that the LWC becomes \$1.98/m³ when the RO capital cost is \$2,660, and increases to \$2.16/m³ when the capital cost is \$7,000. Table 13 further explains the cost comparison of desalinated water with and without selling surplus energy, along with the corresponding percentage reduction.

Table 13: The Surplus Energy Impact on the LWC.

RO capital cost (\$)	LWC without selling back (\$/m ³)	LWC with selling back (\$/m ³)	Savings (%)
2660	2.24	1.98	11.61
7000	2.43	2.16	11.11

4.4.3 Savings on desalination water cost by using surplus energy to desalinate more water.

In the second scenario, surplus energy is harnessed to enhance the economic efficiency of the system. This surplus energy (SE) is directed towards augmenting water production by integrating new modules into the Reverse Osmosis (RO) unit to absorb the excess energy. The additional water generated during the utilization of surplus energy is stored for future use, thus minimizing wastage. The estimated value of the wasted energy stands at \$0.39/kWh.

By employing this strategy, waste energy is significantly reduced, leading to a more sustainable operation. Approximately 49.4% of the surplus energy is allocated to enlarging the RO unit, thereby increasing water production. The remaining 1.6% of energy is considered unused.

The implementation of surplus energy for desalination purposes results in a reduction in the Levelized Water Cost (LWC) and enhances the overall economic feasibility of the system. A comparative analysis, presented in a table 14, illustrates the impact of utilizing surplus energy on LWC, highlighting the benefits over the scenario where surplus energy is not utilized for desalination.

Table 14 Comparison of Levelized Water Cost (LWC) with and without Surplus Energy Utilization for Desalination.

RO capital cost (\$)	LWC/ no surplus energy (\$/m³)	LWC/ more desalination (\$/m³)	Savings (%)
2660	2.24	1.6	29.8
7000	2.43	1.77	27.9

Additionally, to ensure the model's effectiveness, the analysis is extended to two more RO systems with varying capacities (2.2 m³/day and 10 m³/day) while maintaining their 5 kWh/m³energy consumption. Table 15 shows the DE algorithm results for two RO capacities, including those driven by a hybrid PV/wind turbine with battery storage. Evidently, the primary advantage of the employed DE algorithm is its capacity to locate global optima, even in situations where there are several local optima. This leads to the identification of distinct HRES configurations for every requested energy demand or desalinated water capacity. This is because the DE uses a mutation operator, which generates new candidate solutions by combining a weighted set of multiple parent solutions. This enables DE to efficiently explore a large search space while avoiding becoming stuck in local optimal.

Table 15 DE Algorithm Results for Hybrid PV/Wind Turbine with Battery Storage: Optimization of Two RO Capacities.

RO capacity (m³/day)	PVs (kW)	WT (kW)	Battery capacity (kWh)	LWC/no selling back (\$/m³)	LWC/selling back (\$/m³)
2.2	3.84	1	12.93	2.57	2.26
5	7.67	2	38.79	2.24	1.98
10	21.8	3	56.03	2.06	1.72

CHAPTER 5

OPTIMIZATION RESULTS FOR HYBRID

RENEWABLE ENERGY SYSTEM (HRES) WITH

HYDRO PUMPED STORAGE

This chapter describes the findings of a study, using Dhahran's meteorological data to derive a Reverse Osmosis (RO) unit using a hybrid PV and wind turbine system combined with a pumped storage system. The Differential Evolution (DE) algorithm is utilized by the MATLAB-based mathematical model to find the optimal values for the Levelized Cost of Electricity (LCOE) and the Levelized Water Cost (LWC).

The Differential Evolution (DE) algorithm starts the optimization process with a population size of $NP=200$. To meet the demand load of the RO unit while maintaining a POD limitation of zero, a detailed investigation of possible combinations for PV panels, wind turbines, and the upper reservoir volume is conducted at this point. The process then progresses to the stages of crossover and mutation. Finally, the selection process concludes with the discovery of the ideal arrangement for the upper reservoir volume, wind turbines, and solar panels.

Figure 20 shows the flowchart of a computer simulation program developed using the MATLAB to simulate and analyze the techno-economic performance of the hybrid power

system with a PS unit. Figure 20 provides a visual aid for comprehending the functioning of the code by outlining the phases and procedures within the simulation model.

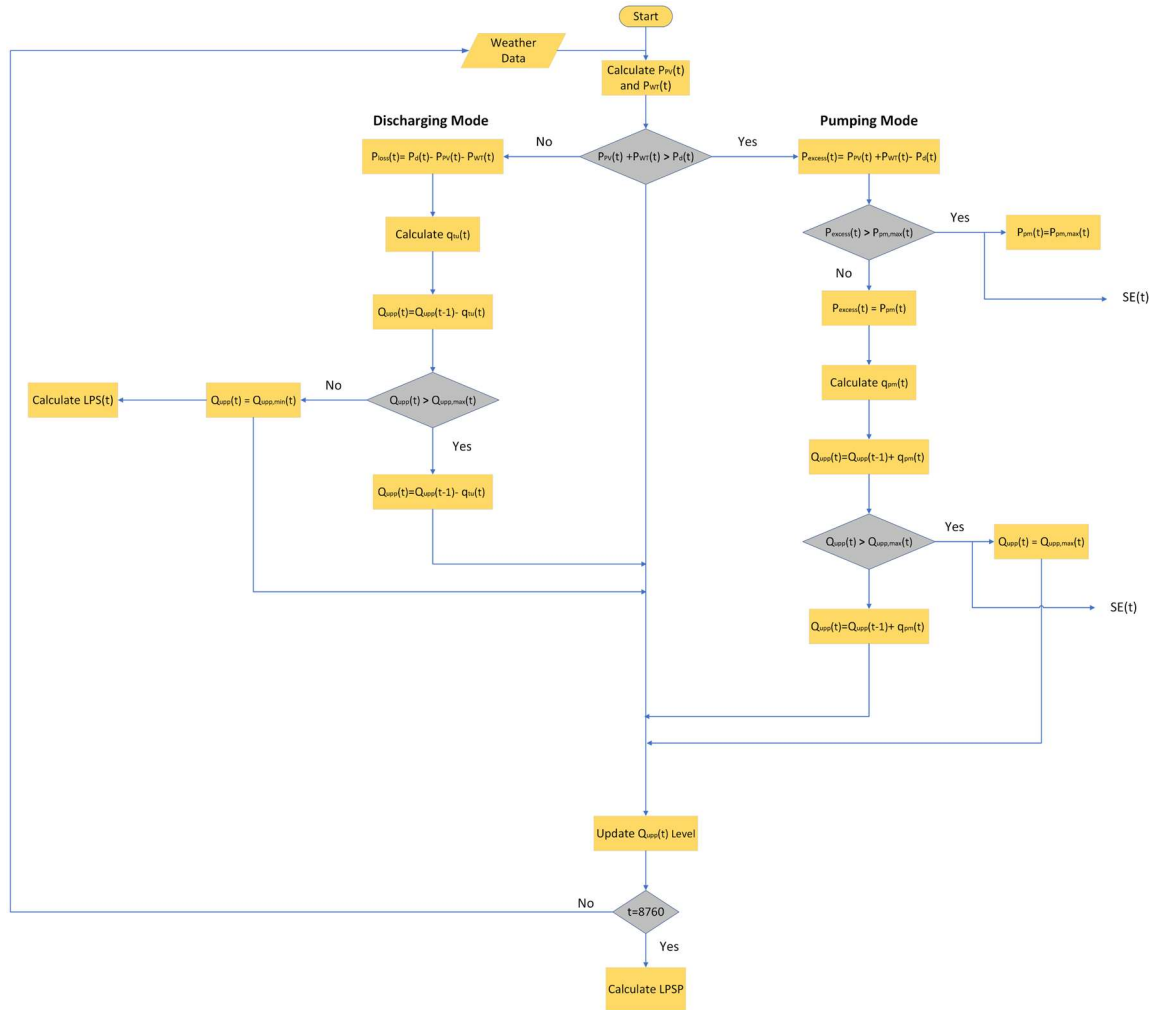


Figure 20: Flowchart of MATLAB Simulation for Hybrid Power System with Pumped Storage.

5.1 Verification of the Mathematical Mode

To ensure the accuracy and reliability of the proposed hybrid renewable energy system (HRES) model incorporating pumped hydro storage (PHS), a comprehensive verification was conducted using the HOMER software. The same input parameters and configurations used in the MATLAB model were replicated in HOMER to simulate the system's

performance. The comparison focused on key metrics such as total energy production, Levelized Cost of Energy (LCOE). The results showed a high degree of consistency between the two models, with energy production variance of less than 1%, storage utilization closely matched, and LCOE values within 1% of each other. This validation confirms the robustness and reliability of our MATLAB model. The detailed comparison is shown in Table 16.

Table 16 Comparative Analysis of HRES Model Performance in MATLAB and HOMER.

Configuration	PV Module Output (kW)	WT Output (kW)	PHS (kWh)	Total energy production (kWh/yr)	Total net present value (\$)	Surplus Energy (kWh)	LCOE (\$/kWh)
HOMER	31.5	6	245	70,258	160,984	20305	0.284
Present code	31.5	6	245	70,352	158,540	20,466	0.283
Difference %	0	0	0	0.13	1.5	0.79	0.352

5.2 Optimization Results for 5m³/day RO Unit

For RO capacity 5m³/day, and with LPSP = 0, the convergence curve is shown in Figure 21 and sheds light on how the optimization procedure is progressing in its search for the ideal system size. After approximately 150 iterations, the graph demonstrates a notable convergence behaviour where the Levelized Cost of Electricity (LCOE) stabilizes at around 0.428 \$/kWh. The LCOE value cannot increase any more after this point. This convergence pattern implies that an optimal and stable solution has been found through optimization. The system's most effective configuration for satisfying the RO unit's energy

and water production needs while lowering costs consists of 23 PV panels, 3 wind turbines, and an upper reservoir with a volume of 230.7 m³.

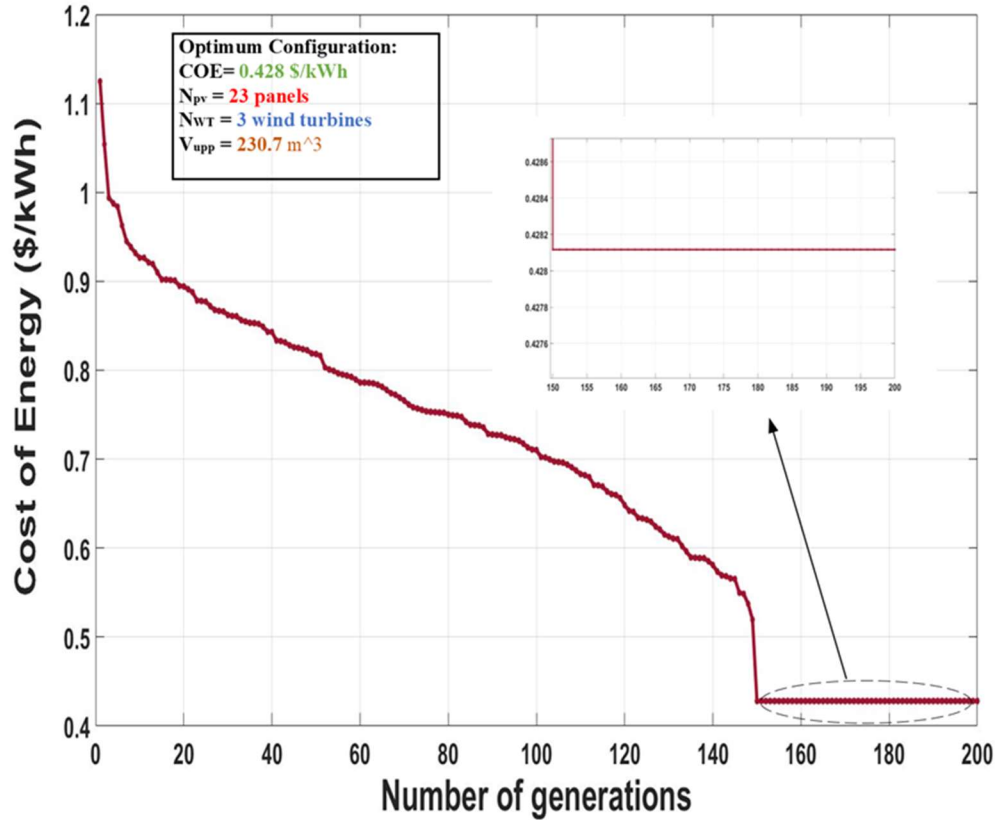
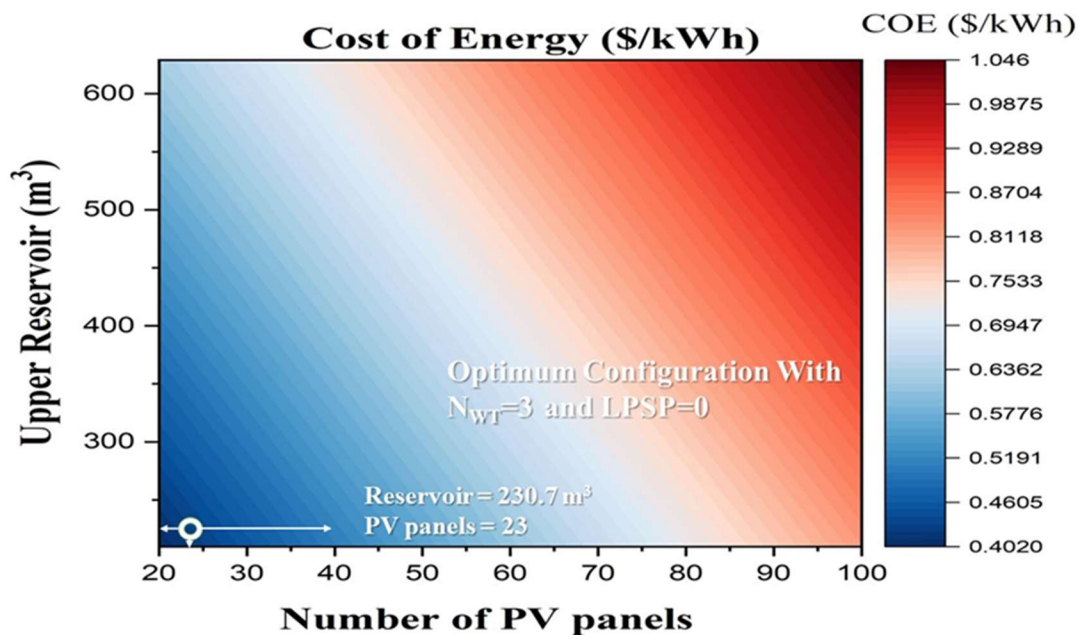


Figure 21: DE Convergence Curve of Optimization Process for Optimal System Configuration.

Figure 22 presents the synergistic relationship between two crucial parameters: the quantity of PV panels and the upper reservoir volume. It explores their combined effect on the (LCOE) within a hybrid system configuration. This analysis assumes fixed design of three wind turbines and a Loss of Power Supply Probability (LPSP) of zero. Despite these constraints, this thorough study remains valid. The x-axis skillfully depicts fluctuations in the numbers of PV panel, which directly the system's solar energy generation. The y-axis represents the upper reservoir levels, representing a varied range of energy storage capacities. The study reveals that adding PV panels has a more substantial effect on the

(LCOE) compared to changing the upper reservoir volume in this specific scenario with three wind turbines. This means that the number of photovoltaic (PV) panels has a more significant effect on the (LCOE) than the upper reservoir volume. As a direct contributor to overall energy production, PV panels are crucial to the process of producing electricity. However, as the number of PV panels increases, the increased electricity production could reach a point where it offers diminishing returns. Adding more panels could potentially lead to higher costs without proportionate gains in energy efficiency. In contrast, because it doesn't directly affect electricity output, the higher reservoir has a greater impact on energy storage capacity and a less significant impact on LCOE in this situation.

Figure 23 illustrates the annual energy distribution for the optimum configuration. The RO unit is powered by a combined total of 19,390 kWh of electricity produced by the PV panels and wind turbines. The system produces more energy during the day than it consumes, resulting in excess power. By using this extra energy to power a pump, the system can fill the upper reservoir for water storage. Once the pump reaches its maximum capacity or the



[Figure 22: LCOE Variations with the Number PV Panel and Upper Reservoir Volume in a 3-Wind Turbine Hybrid System.]

reservoir is fully charged, any excess energy is sent back to the grid and is considered SE, increasing the system's economic efficiency. Notably, in the optimal configuration, wind turbines contribute 38.75% and the PV system contributes 61.25% of the total annual energy production. The RO unit is powered by about 45.2% of the system's total yearly energy output. This consumption includes 31.44% considered surplus energy and 20.83% dammed excess energy, demonstrating efficient resource utilization. Moreover, approximately 2.5% of energy is lost during the conversion of power and electricity in pumps and turbines.

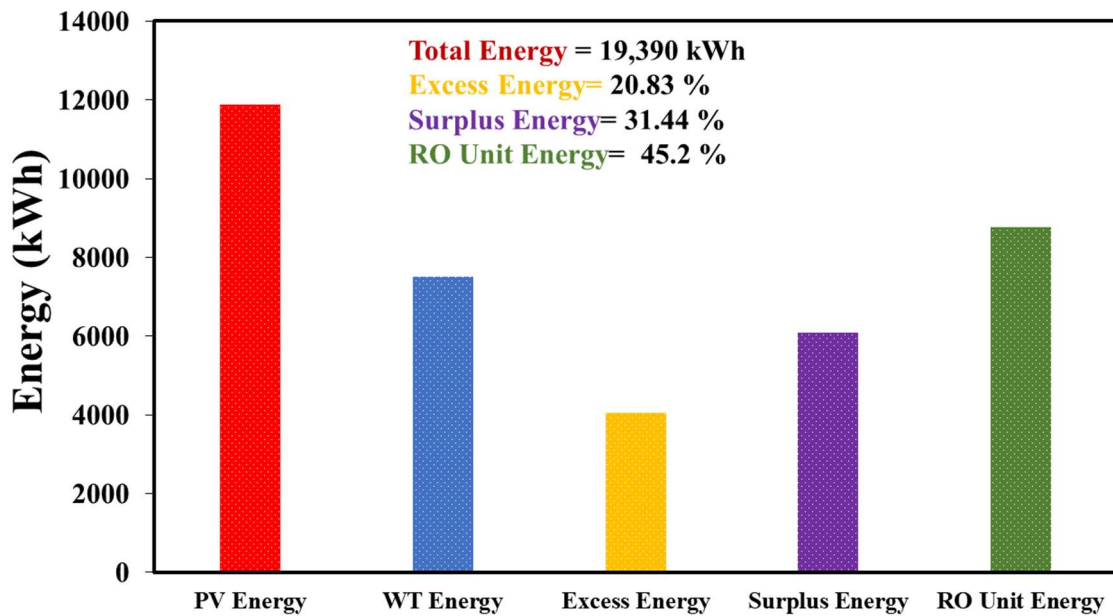


Figure 23: Annual Energy Distribution in the Optimal Hybrid System Configuration.

Figure 24 illustrates the Level of Charge (LOC) dynamics for an optimized upper reservoir, operating within a capacity range of 0% to 100%. Notably, the LOC exhibits a distinct diurnal pattern, with an increase during daylight hours, prompting the activation of the pump to balance energy supply, and a decrease during night time hours to offset energy deficits. Remarkably, under the condition of Lower Pump Storage Power (LPSP) set at 0%, the upper reservoir's LOC fluctuates between 100% and a minimum of 3.7%, never reaching 0% due to operational constraints. This minimum LOC value occurs at hour 8258, coinciding with December's low solar radiation period, emphasizing the importance of reservoir management to ensure a consistent energy supply amidst varying environmental conditions and energy demands.

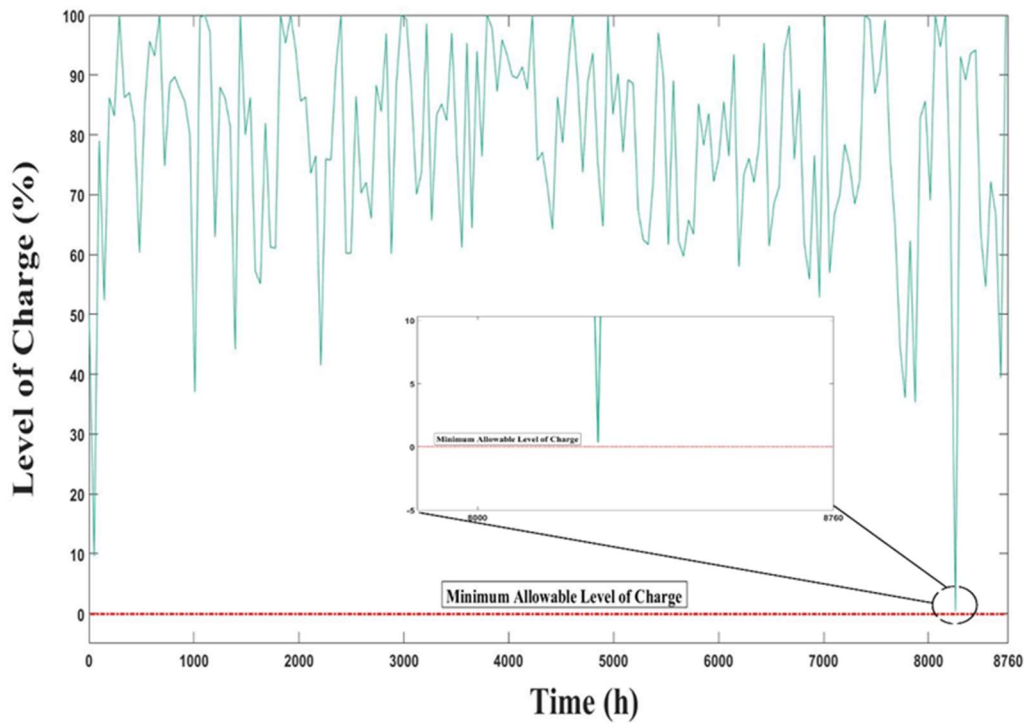


Figure 24: Hourly Level of Charge Variations in an Optimized Upper Reservoir.

The daily system performance, specifically in terms of the Level of Charge (LOC) and excess power utilization, is depicted in Figure 25. Figure 25 a, shows the daily variations

in LOC and the excess power employed for pumping water to the upper reservoir. During winter days, LOC steadily declines until it nears the minimum permissible level for the upper reservoir. Conversely, during summer days, the LOC of the upper reservoir fluctuates within the range of 60% to 100%. The excess energy used for pumping operations varies in response to both the overall power generated by the hybrid system and the water level in the upper reservoir.

Figure 25 b shows the hourly dynamics of the Level of Charge (LOC) and charging/discharging (measured in m^3) into the upper reservoir throughout a typical day in January. Notably, the upper reservoir consistently maintains near-full capacity during daylight hours. As evening descends, the turbine operates from 6:00 pm to 4:00 am, extracting energy from the upper reservoir during these night periods. Following this, from 5:00 am to 7:00 am, the wind turbine takes over, generating sufficient power to meet the system's demand. Any SE generated during this interval is effectively utilized to pump water into the upper reservoir. Starting at 8:00 am, the photovoltaic (PV) system initiates electricity generation, working in tandem with the wind turbine until 10:00 am. This ensures the upper reservoir is fully recharged by daylight hours, considering the absence of solar radiation post-sunset.

A typical day in July is depicted in Figure 25 c, which shows the daily dynamics of the Level of Charge (LOC) and the inflow/outflow of water measured in cubic meters (m^3) within the upper reservoir. Notably, throughout the daytime, the top reservoir continuously reaches its maximum capacity, leaving the pump and turbine systems in the OFF position. The turbine starts to operate when sunset approaches (from 7:00 pm to 3:00 am), when solar energy is not available, and it draws water from the upper reservoir to supply the

system. The wind turbine still runs on its own during this time, but it is not able to fully handle the load. From 4:00 am to 6:00 am, the wind turbine creates extra electricity, completing the load and using the extra energy to run the pump and move water to the upper reservoir. The hybrid system's total energy output rises by 7:00 am when the PV system turns on, enabling the pump to keep running. Excess energy is then directed towards replenishing the upper reservoir, achieving full capacity by 10:00 am. Beyond this point, any additional surplus energy generated is considered for grid feed-in, contributing to the overall energy supply.

A stark contrast exists between winter and summer days operations. During winter, with fewer hours of sunlight, the turbine and discharging mode operate for extended periods compared to summer days. This necessity arises from the fact that wind turbines alone cannot fully satisfy the energy demand during nighttime hours.

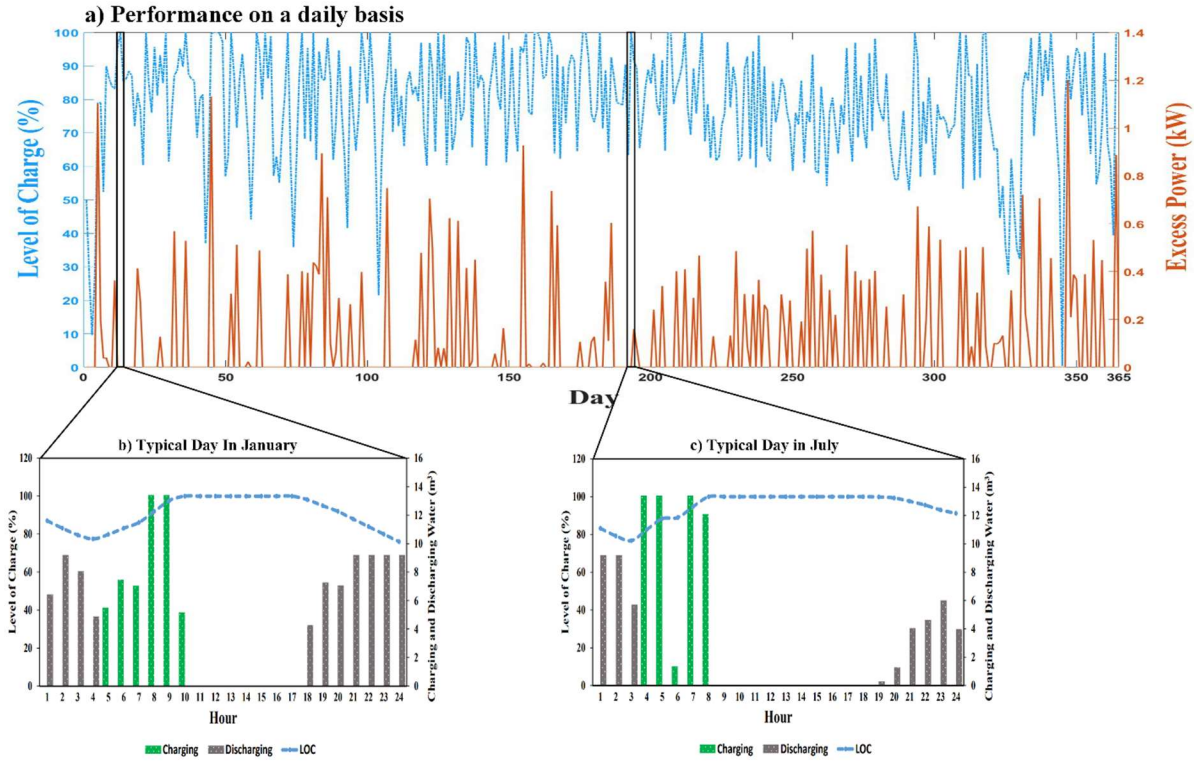


Figure 25: Performance of the Optimized Hybrid System in terms of LOC and Excess Power, a) daily performance during one year, b) Hourly Charging and Discharging of upper reservoir with LOC: Typical Day in January, and c) Hourly Charging and Discharging of upper reservoir

Figure 26 illustrates daily fluctuations in surplus energy from an optimized hybrid PV and wind turbine system with pumped storage over a year. Peaks in the graph correspond to periods of surplus energy production, potentially due to favorable weather conditions or system efficiency. In summer, the figure reveals increased surplus energy production from the hybrid PV-wind turbine system, likely due to extended daylight hours and favorable weather conditions. Conversely, during winter, there may be a reduction in surplus energy generation due to shorter days and potentially less favorable weather.

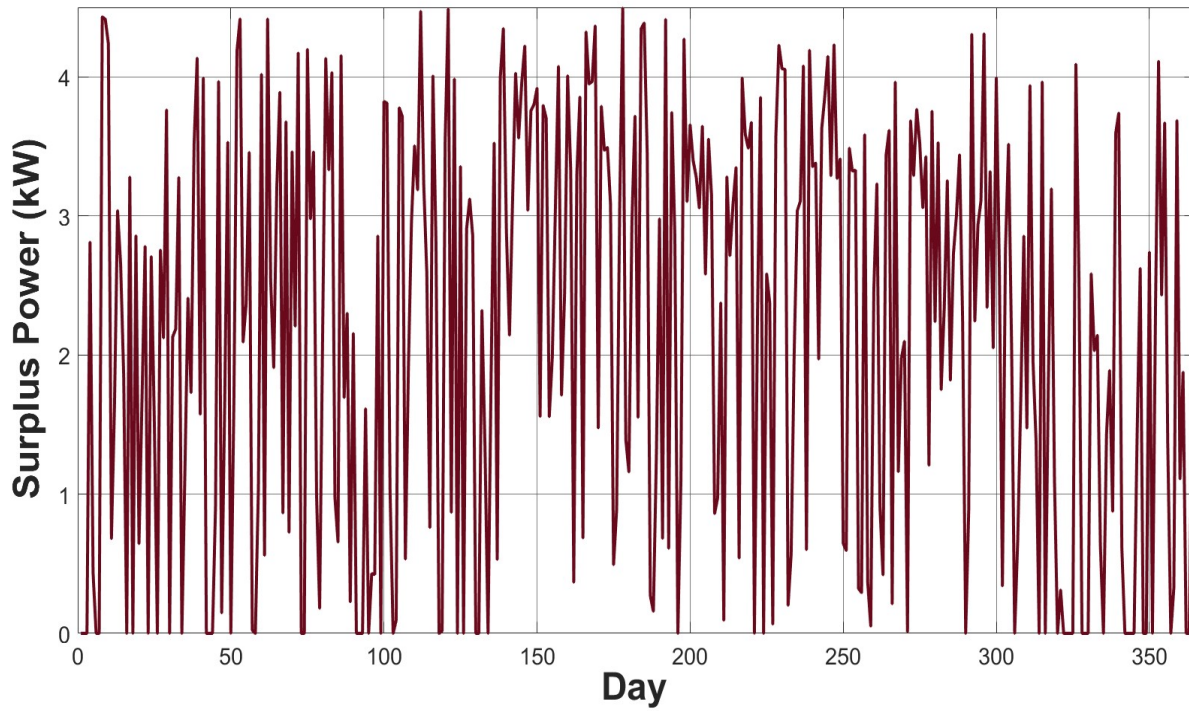


Figure 26: Daily Surplus Energy Fluctuations in Optimized Hybrid PV-Wind Turbine System.

2.2.1 Cost of Water by Selling Back Surplus Energy

The convergence map for the Levelized Water Cost (LWC) under different scenarios of RO capital costs, with as well as without selling back SE to the grid, is shown in Fig 27. Notably, after roughly 150 iterations, the convergence diagram presents a consistent pattern, indicating that achievement of the optimal LWC. Furthermore, the graph obviously shows that RO systems with \$2660 - \$7000 capital expenses produce an optimum LWC of \$2.43 and \$2.61/m³. The optimum LWC is instead reduced to a range of \$2.26 to \$2.44 /m³ in scenarios involving *SE* sales to the grid.

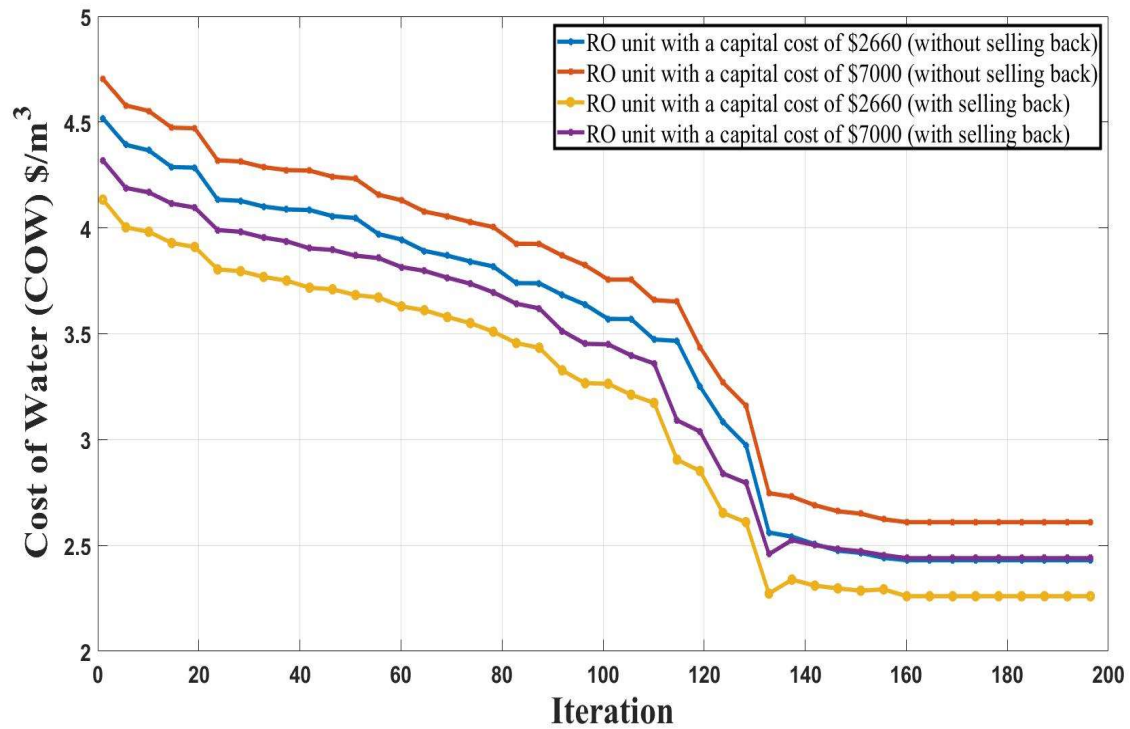


Figure 27: Convergence of optimum Levelized Water Cost (LWC) for RO Units under Different Capital Costs with and without Grid Surplus Energy Sales.

Table 17 outlines how Reverse Osmosis (RO) capital costs influence the Cost of Water (COW), with and without excess energy (SE) selling.

Table 17 Comparison of COW with and without SE Selling for Different RO Capital Cost Scenarios

RO Capital Cost (\$)	LWC without SE selling (\$/m ³)	LWC with SE Selling (\$/m ³)	Saving (%)
2660	2.43	2.26	7
7000	2.61	2.44	6.51

2.2.2 Cost of Water by Utilizing Surplus Energy to Produce More Water

Another approach to using the SE from the optimum system for 5 m³/day is to use this energy to increase the capacity of the RO unit. Therefore, this study proposes an approach to capitalize on surplus energy generated by an optimally designed Hybrid Renewable

Energy System (HRES) powered Reverse Osmosis (RO) unit. The surplus energy can be utilized to increase the water production capacity beyond immediate demand. This is achieved by expanding the RO unit's capacity through the addition of more RO modules. Consequently, these extra modules play a pivotal role in absorbing surplus energy, particularly during peak daytime hours.

In the context of this study, the optimal configuration for a 5m³/day RO unit powered by HRES involves surplus energy equivalent to 6096 kWh annually. This surplus energy exhibits fluctuations from one hour to another. The additional capital cost for the RO unit in this case is \$532/m³/day [63]. The excess water generated during surplus energy utilization is stored and used for other purposes. The utilization of this strategy is beneficial in minimizing waste energy, which is estimated to be worth \$0.428/kWh. This, in turn, lowers the Levelized Water Cost (LWC) and raises the system's overall economic feasibility.

In Figure 28, the variations in surplus energy (SE) are depicted. This energy is utilized both for the enhanced production of water through additional modules and for the energy considered wasteful due to the incapability of operating the high-pressure pump. The pump is crucial for elevating the pressure of saline water, facilitating its passage through the membrane. Adopting this method results in a noteworthy decrease in the waste energy percentage from the optimum system, reducing it to 2.4%. Simultaneously, the useful SE percentage, contributing to increased water production, constitutes 28.7% of the total energy generated by the optimal system. Table 18 shows LWC with and without considered SE to increase the production.

In this scenario, the surplus energy is used to produce additional water. This extra water will not be sold but used for other purposes. Equation 4.1 shows the new value for LWC in this scenario.

$$LWC = \frac{(NPC \times CRF(i, N)) + C_{O\&M} + C_{chm}}{\sum_{t=1}^{8760} Q_P(t) + \sum_{t=1}^{8760} Q_{extra}(t)} \quad (4.1)$$

Where $\sum_{t=1}^{8760} Q_{extra}(t)$ is the total extra water production from the optimum system.

Table 18: Comparison of Water Production Costs with and without Surplus Energy.

RO capital cost (\$)	LWC/ no surplus energy (\$/m ³)	LWC _s / surplus energy (\$/m ³)	Savings (%)
2660	2.43	1.85	23.86
7000	2.61	1.97	24.52

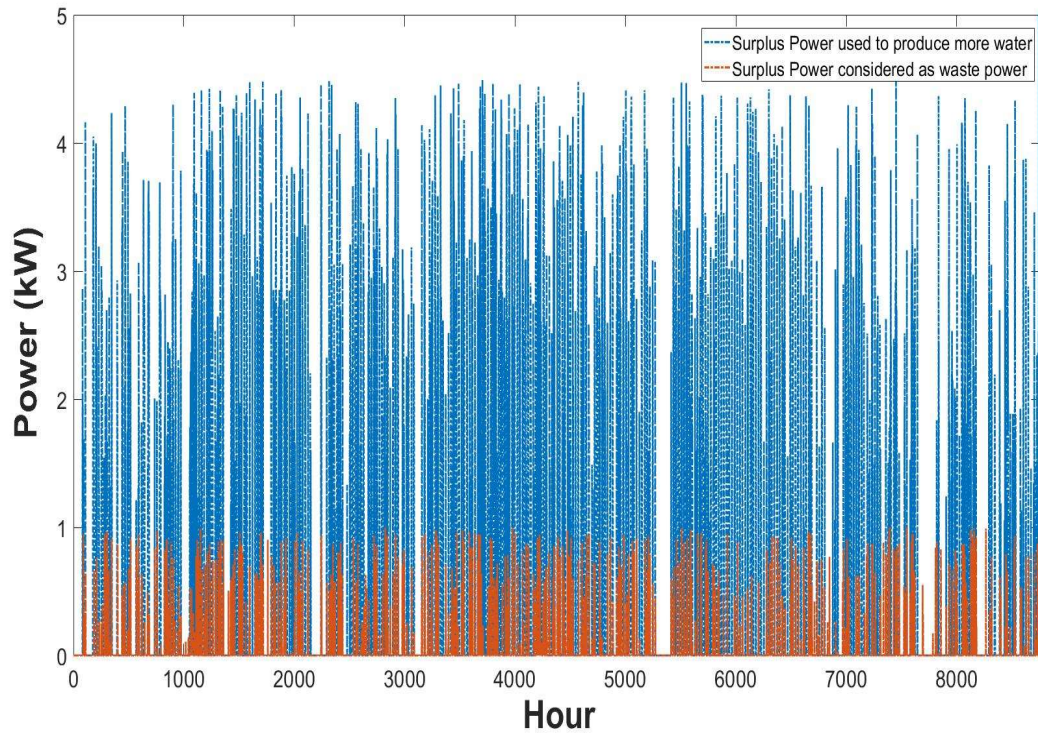


Figure 28: Surplus Power Distribution in RO Production System.

5.2 Optimization of the Hybrid System for Varied RO Loads

This research evaluates the effectiveness of the Differential Evolution (DE) algorithm, in optimizing different capacities of Reverse Osmosis (RO) units driven by a Hybrid Renewable Energy System (HRES). Particularly, Reverse Osmosis which regularly produces $24 \text{ m}^3/\text{day}$ —serves as a case study for utilizing the DE algorithm to optimize the HRES. The convergence diagram in Figure 29 shows the results of optimizing the HRES-powered RO unit with a $24 \text{ m}^3/\text{day}$ output rate.

The optimum system, as shown in the picture, consists of an upper reservoir with a volume of 1111.4 m^3 , a 15-kW wind turbine, and an 18.8 kW PV generation system. According to the DE algorithm, the RO unit with a capacity of $24 \text{ m}^3/\text{day}$ has an optimum (LCOE) of \$0.408/kWh. There is a significant disparity when the optimum LCOE values of two RO units with a capacity of 5 and $24 \text{ m}^3/\text{day}$ are compared.

Despite its higher power requirements due to the larger system's operation, the 24 m³/day capacity Reverse Osmosis (RO) unit has a lower (LCOE). The reason for this result may be traced back to the yearly energy demand increasing proportionately with the capacity of RO units. The improved system achieves an optimal balance between running costs and power by producing more power in response to the increased energy demand. The link between the two variables is complex, but it highlights the economic feasibility of higher RO capacities. This clarifies the fundamental causes of the lower LCOE that has been observed in the 24 m³/day RO unit.

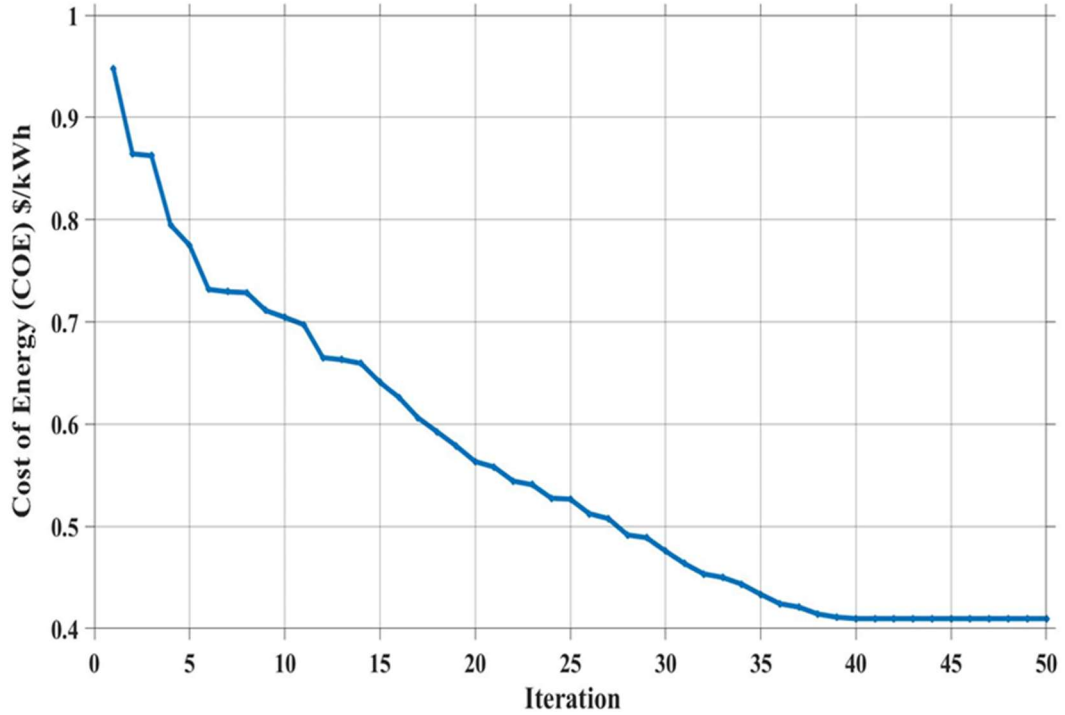


Figure 29: Convergence Diagram of DE Algorithm for 24 m³/day RO Desalination Powered by HRES. |

Using equ.3.28 the optimum LWC is estimated to be within the range of \$(2.006-2.192)/m³. This cost represents the cost of production of water from the optimum HRES powering RO unit with a capacity of 24 m³/day without selling back the surplus energy from this optimum system which equals 16270 kWh/year which accounts for 22 % of the total energy from the optimum HRES. Considering this surplus energy to sell it back to the

grid and using equation (3.29), the LWC produced from the system is found to be within the range \$ (1.91-2.09)/m³.

An alternative method involves employing surplus energy (SE) to enhance the efficiency of reverse osmosis (RO) units, thereby increasing water production for various applications. The Levelized Cost of Water (LWC) fluctuates within the \$(1.44-1.62)/m³ range. Notably, the residual SE, accounting for 0.27% of the total energy, is classified as unused or wasted energy.

Comparing the optimum LWC for two RO units with 5 and 24 m³/day, it is clear that an RO unit with high capacity has a lower value of LWC with and without selling back. The scale advantage allows larger RO systems to distribute energy and capital costs more efficiently, contributing to their cost-effectiveness and making them a more economically viable choice.

Figure 30 displays the relationship between the (LCOE) and Levelized Water Cost (LWC) in a large-scale Reverse Osmosis (RO) system powered by a (HRES) with *PS*. This configuration represents the result of an optimized design achieved through the application of the Differential Evolution (DE) algorithm. It is obvious that the RO system's feasibility and economic allure change dramatically as its scale increases. With the increase in RO capacity and the corresponding load in kW, the LCOE shows an ongoing declining trend.

This phenomenon can be linked to the HRES's increased annual power production, which rises along with the system's expanded size. This leads to a higher cost-to-benefit ratio than what is seen in smaller-scale implementations as the system develops into a larger-scale design, with total energy production surpassing total cost. Additionally, as the RO capacity is increased, the LWC exhibits the same declining tendency. The higher capacity of Reverse Osmosis (RO) units reduces the cost of water due to economies of scale. Larger systems distribute energy costs more efficiently over a greater water volume, resulting in enhanced energy efficiency. Additionally, the initial capital cost, though higher for larger units, is spread across a larger production capacity, reducing the overall cost per unit of water. The combination of these factors makes higher-capacity RO units more cost-effective in terms of both energy and capital costs.

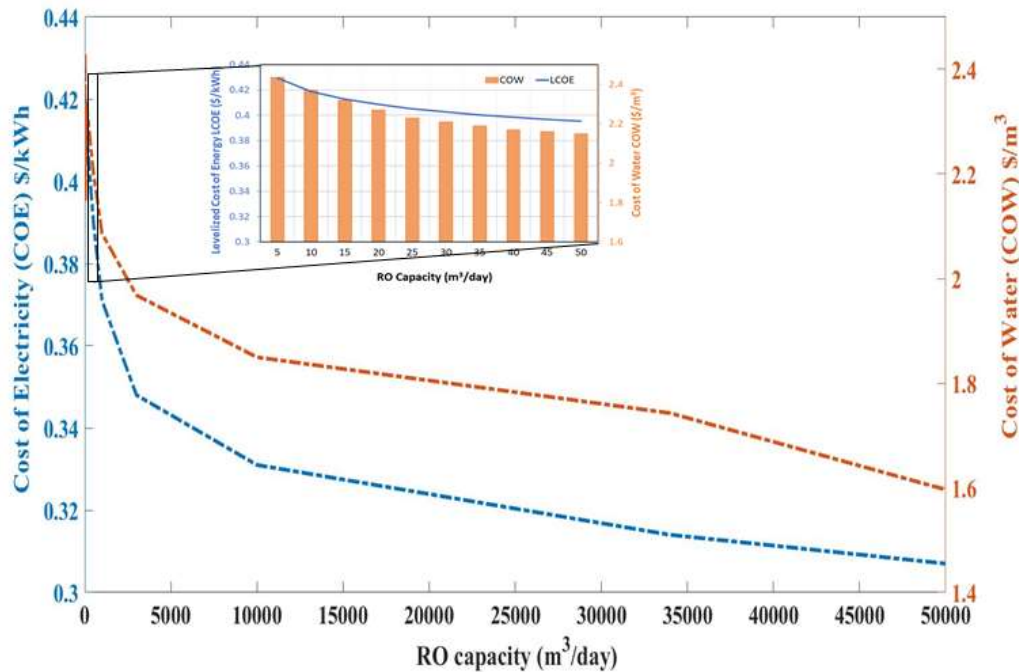


Figure 30: Variation of the LWC and LCOE of Large-Scale HRES-Powered RO Systems.

Table 19 provides a comprehensive comparison of desalination costs for 5 m³/day and 24 m³/day reverse osmosis (RO) units under various approaches, including no action, selling surplus energy to the grid, and increasing RO capacity. The ranges of optimum Levelized Water Cost (LWC) for each scenario are outlined, revealing the economic implications of different strategies in achieving cost-effective desalination.

Table 19: Comparison of Desalination Costs and Strategies for 5 m³/day and 24 m³/day RO Units.

Consideration description	RO Size (m³/day)	Optimum LWC (\$/m³)
Baseline scenario (no utilization for the SE)	5	2.43 – 2.61
	24	2.006 – 2.192
Selling the SE to the grid	5	2.26 – 2.44
	24	1.91- 2.09
Leveraging the SE for additional desalination	5	1.85 – 1.97
	24	1.44- 1.62

CHAPTER 6

OPTIMIZATION RESULTS FOR HYBRID

RENEWABLE ENERGY SYSTEM (HRES) WITH

DESALINATED WATER TANK STORAGE

The flowchart that shows the DE algorithm's optimization process for hybrid renewable energy systems (HRES) with water tank storage is shown in Figure 31.

For an RO unit with a capacity of 5 m³/day, in this case, the community's water demand is 0.208 m³/h. To meet this demand, a variable reverse osmosis (RO) unit is utilized. The Differential Evolution Algorithm is used to optimize the hybrid photovoltaic/wind turbine (PV/WT) system with water tank storage.

6.1 Optimization Results of RO unit with constant 5 m³/day Water Demand

Figure 32 illustrates the convergence diagram for the Differential Evolution (DE) algorithm, depicting the optimization process for determining the optimal configuration of the Hybrid Photovoltaic/Wind Turbine (PV/WT) system with a water storage tank. This configuration is designed to power a variable Reverse Osmosis (RO) unit with a water demand of 0.208 m³/h. The convergence diagram shows how the optimization changed during the course of 31 generations. As the generations continue, the convergence curve

stabilizes, indicating that the DE algorithm has reached an optimal point. Beyond this point, the Levelized Water Cost (LWC) remains unchanged, signifying that further iterations do not result in improvements and confirming the attainment of the optimum system configuration.

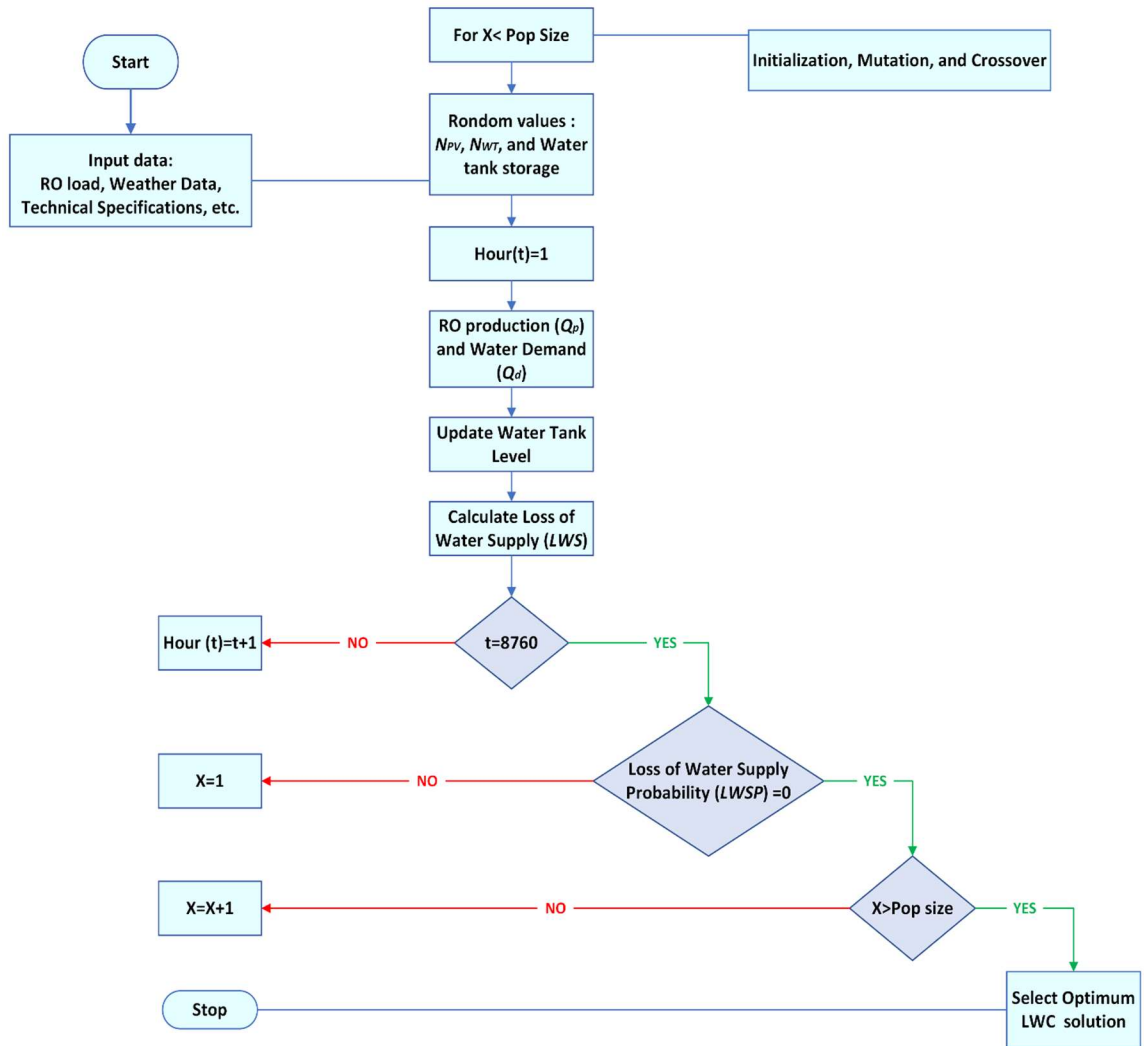


Figure 31: Optimization Process Flowchart for HRES with Water Tank Storage Using DE Algorithm.

The optimized configuration entails a PV production capacity of 6.8 kW, a WT generation capacity of 2 kW, and a water tank volume of 10.5 m³. The Levelized Water Cost at this optimal configuration is reported to be \$1.44/m³, providing a clear insight into the cost-effectiveness of the proposed system.

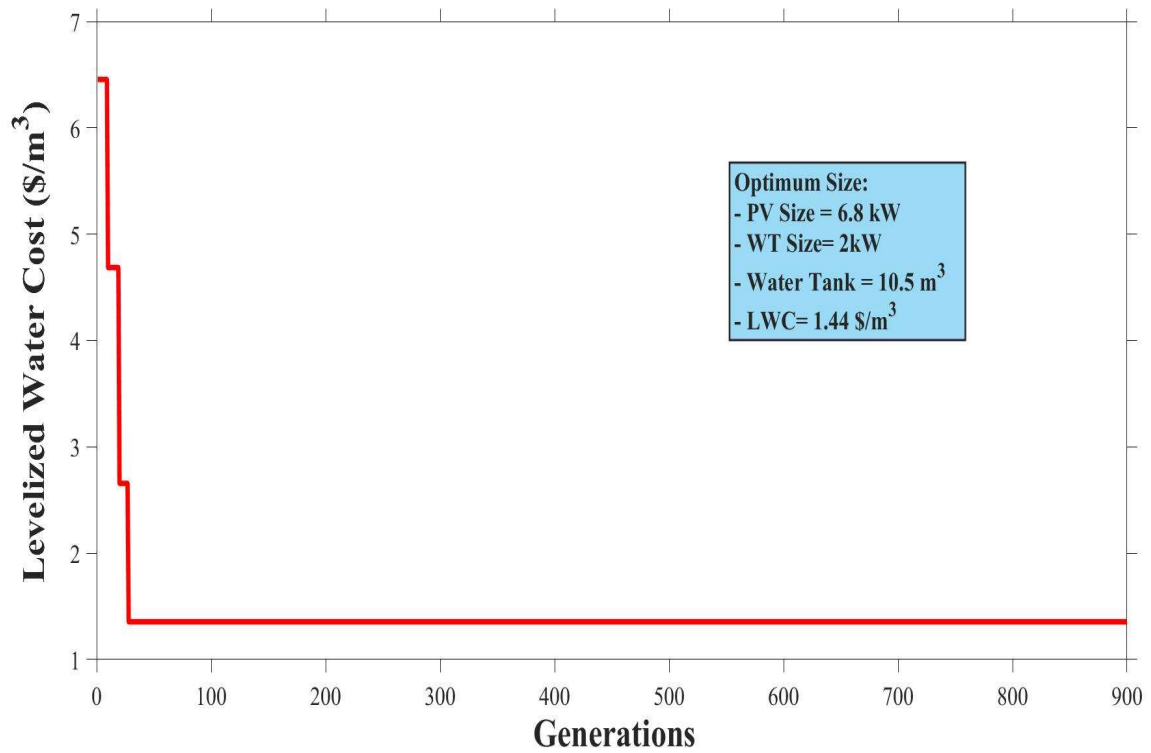


Figure 32: Optimization Convergence Diagram for Hybrid PV/WT System with Water Storage Powering Variable RO Unit under 0.208 m³/h Demand.

The detailed depiction of optimal system performance is presented in Figure 33, illustrating both daily and hourly trends. In Figure 33a, the average daily performance is showcased in terms of Reverse Osmosis (RO) water production and the water tank storage level. Initially set at 10% of its capacity, the RO production satisfies the water requirement during the first nighttime hours of operation, keeping the water tank level at 10%. As daylight approaches, the RO output exceeds, leading to the surplus water being stored in the tank, resulting in a gradual increase to nearly 85% of its full capacity. Throughout the winter season, the water level within the tank fluctuates between 10% and 100 % of its full capacity, while in the summer, it ranges from 77% to full capacity. Notably, Figure 33a emphasizes that the water tank level during winter is consistently lower than in the summer months.

Figure 33b displays the hourly performance of the Reverse Osmosis (RO) unit for a typical day in January. During the night hours, from 20:00 to 7:00, the RO unit relies solely on the power generated by the wind turbine, as solar energy is not available. At this time, the RO output is not sufficient to meet the water demand. As daylight becomes available, the Hybrid Photovoltaic/Wind Turbine (PV/WT) system optimally combines to power the RO unit, resulting in an output that exceeds the water demand. The excess water produced during this period is stored in the tank, reaching its full capacity between 8:00 and 13:00. Subsequently, although the Hybrid PV/WT system continues to generate more water than required by the RO unit, the water tank remains at full capacity. As a result, between 14:00 and 19:00, the RO unit produces water only to meet the demand, while the surplus energy from the optimal Hybrid PV/WT system is sold back to the grid. Figure 33d depicts the water tank's hourly performance on a typical January day. The tank is discharged during the night hours, from 20:00 to 7:00, following the same reason depicted in Figure 33b. As a result, between 8:00 and 13:00, the tank is charging and will be fully charged by the end of this period.

In comparison, Figures 33c and 33e provide an insight into the hourly performance of the Reverse Osmosis (RO) unit and the water tank during a typical day in June. The summer season, known for its heightened solar energy potential, results in the optimal system consistently producing more power than the RO unit requires throughout most of the day (excluding night hours). This surplus energy translates to a greater excess of water from the RO unit compared to winter days, swiftly filling the water tank to its full capacity in a shorter period between 7:00 and 11:00.

After that between 12:00 to 21:00, the optimal system continues to generate more power than the RO unit demands during this period. The RO unit utilizes part of this excess power to meet the water demand. Since the water tank is already at full capacity, the remaining surplus power is then directed towards the grid for resale. Consequently, during the summer, the water tank maintains a high and stable level, fluctuating within that range, while in winter, the water level remains below this threshold. Additionally, the excess energy from the optimal hybrid Photovoltaic/Wind Turbine (PV/WT) system is notably higher in the summer season due to the increased potential for power output.

Figure 34 presents the power performance of the Hybrid Photovoltaic/Wind Turbine (PV/WT) system integrated with the Reverse Osmosis (RO) unit, addressing a water demand of ($Q_d = 0.2083 \text{ m}^3/\text{h}$). In Figure 34a, the average daily performance over one year is depicted, showcasing Hybrid PV/WT power generation, excess power from the optimal system, and the power directed to the RO unit for freshwater production. During winter days, a substantial portion of the total generated power is allocated to meet the RO load for sweet water production and to fill the water tank, and a small portion is considered excess power.

Conversely, on summer days, a noteworthy fraction of the total power constitutes excess energy. This surplus arises from the fact that the RO unit requires only a small portion to fulfill the demand and maintain the water tank, which, during daylight hours, is consistently at or near full capacity. Figure 34b depicts the power performance of the system on a typical day in January.

During the night hours, when solar radiation is absent, the Wind Turbine (WT) serves as the only power source for the Reverse Osmosis (RO) unit. Due to fluctuating wind speeds,

WT power production falls short of the RO power demand, triggering water tank discharge to compensate for the deficiency. This discharge occurs between 20:00 and 7:00.

In daylight hours, when solar radiation is available, the Photovoltaic/Wind Turbine (PV/WT) system collaborates to fulfill the RO power demand and utilize excess water to fill the water tank. Once the tank is filled, a portion of the power production is used to meet the RO power demand, and the remainder becomes excess energy sold back to the grid between 13:00 and 20:00.

In contrast, for a typical day in July, as shown in Figure 34c, the period of excess hours (between 11:00 and 21:00) is higher than in Figure 34b. During this period, the water tank is filled with sweet water, and the RO power demand is met by the optimal PV/WT system.

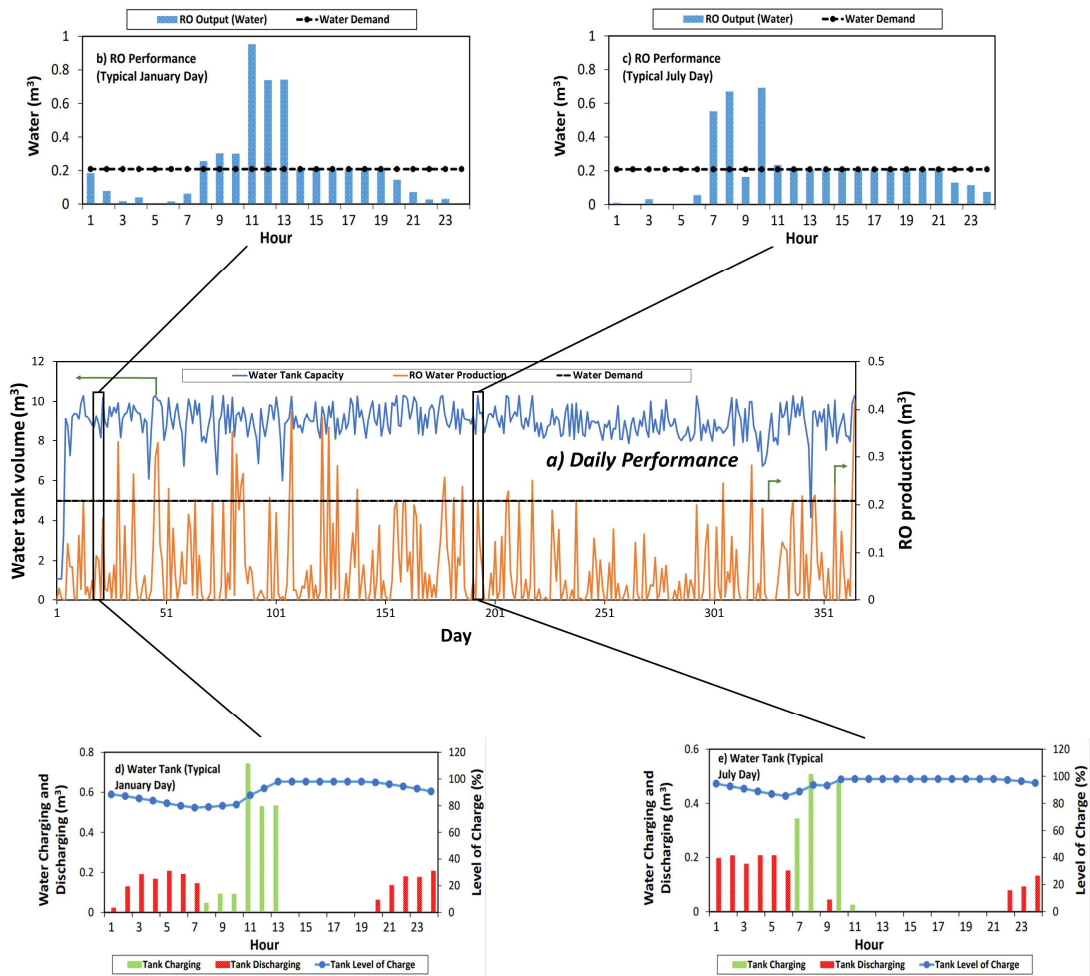


Figure 33: Hourly performance of the RO/Water-Tank system, a) Full year indicators water production and tank level, b) Hourly performance in January day, c) Hourly performance in July day, d) Hourly performance in January day, and e) Hourly performance in July day

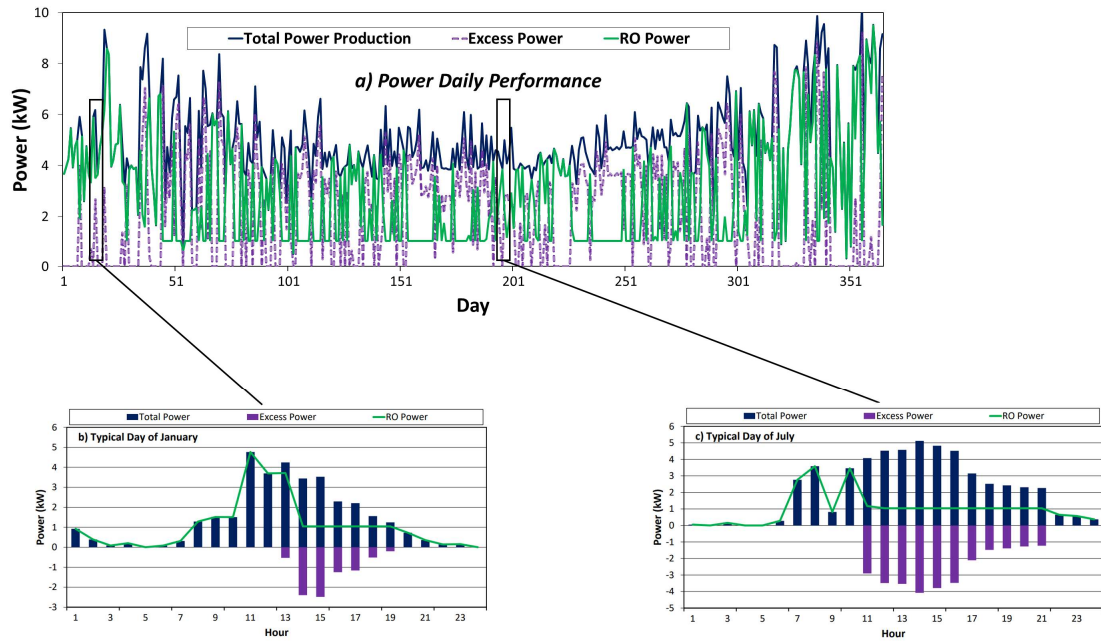


Figure 34 Hourly performance of PV/WT with water tank storage powering RO unit, a) Full year indicators of PV/WT power generation, Excess power and RO power, b) Hourly performance for January day and, c) Hourly performance for July day.

6.1.1 Cost of Water Management through Surplus Energy Utilization

One strategy to make the most of the surplus electricity produced by the optimal system in this study is to sell it back to the grid. Figure 35 displays the power distribution in the optimal PV/WT system. In the ideal configuration, 53.9% of the total generated power is utilized to operate the RO unit, leaving 46.1% as surplus electricity. This surplus arises from the water tank's constrained capacity, reaching its maximum limit for storing the sweet water produced by the RO unit. Beyond this capacity, any remaining power is considered excess.

Equation (3.29) is employed to calculate the Levelized Water Cost (LWC) after incorporating the resale of surplus energy. Table 20 outlines the optimal Levelized Water

Cost, both with and without the consideration of surplus power, showcasing a 14.6% reduction when surplus energy is factored in.

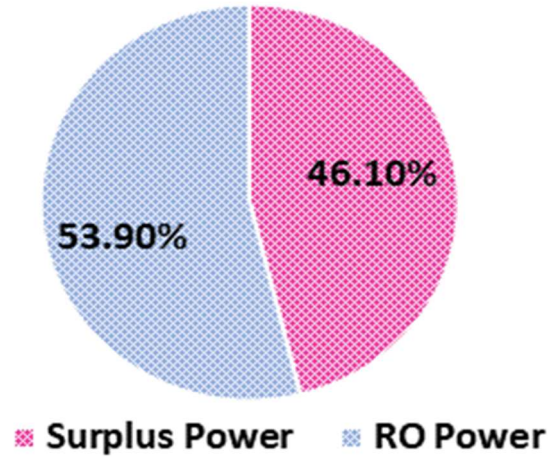


Figure 35: Distribution of power generated by optimal PV/WT system for RO desalination.

Table 20: The surplus energy impact on the LWC.

RO capital cost (\$)	LWC without selling back (\$/m ³)	LWCs with selling back (\$/m ³)	Savings (%)
2660	1.44	1.23	14.6

An alternative method harnesses surplus energy (SE) to further enhance water desalination capabilities, thereby expanding the capacity of Reverse Osmosis (RO) units. This innovative approach leverages excess energy to augment water production. The process involves integrating additional modules into the RO unit, enabling the absorption of surplus energy and consequent amplification of water output. Illustrated in Figure 36 is the allocation of surplus energy for the purpose of desalinating more water. Notably, a minor fraction of SE (approximately 4.9%) remains untapped due to insufficient power to drive the RO module pumps. Consequently, SE utilization is optimized to a rate of 2.2%, with

the remaining energy either dissipated or redirected through heating mechanisms to ensure system stability.

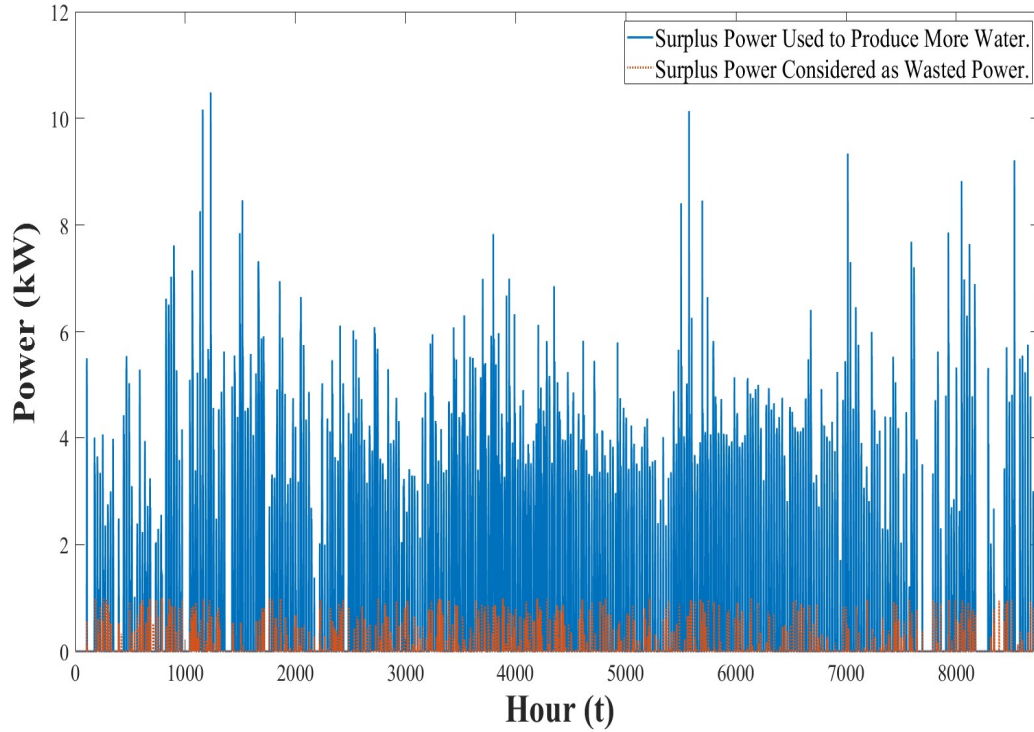


Figure 36: Surplus Power Distribution in RO Production System

The LWC based on using SE to desalinate more water is calculated using equation (4.1). Table 21 shows a comparison between the LWC with and without consider SE for further desalination.

Table 21: Comparative Analysis of Water Production with and without Additional Desalination.

RO capital cost (\$)	LWC/ no surplus energy (\$/m ³)	LWC/ more desalination (\$/m ³)	Savings (%)
2660	1.44	0.96	33.33
7000	1.63	1.144	29.8

To further enhance the effectiveness of the DE algorithm, the study extends its investigation to explore the applicability of the DE algorithm in determining optimal sizes for Photovoltaic (PV) and wind turbine components, along with water storage tank volume,

across varying capacities of RO units, including 24, 100, and 1000 cubic meters per day. In Fig.37, the optimization findings for LWC and LWCs for varied RO capacities are displayed, together with the excess energy associated with each system size. The greater $\sum_{t=1}^{8760} SE(t)$ indicates that more energy is sold back to the grid as the system size increases. This is due to the larger size of the optimal system. Second, increased RO capacity results in a larger system size but reduced water costs (both LWC and LWCs), making the larger system more affordable and efficient. Furthermore, the benefit of selling extra energy back to the grid is demonstrated, which helps to reduce water costs.

Table 22 shows the optimization results for different RO capacities (5,14,00, and 1000) m³/day using the DE algorithm. It includes economic metrics like (LWC, LWC_s), PV generation, WT generation, water tank size, and the total excess energy associated with each system.

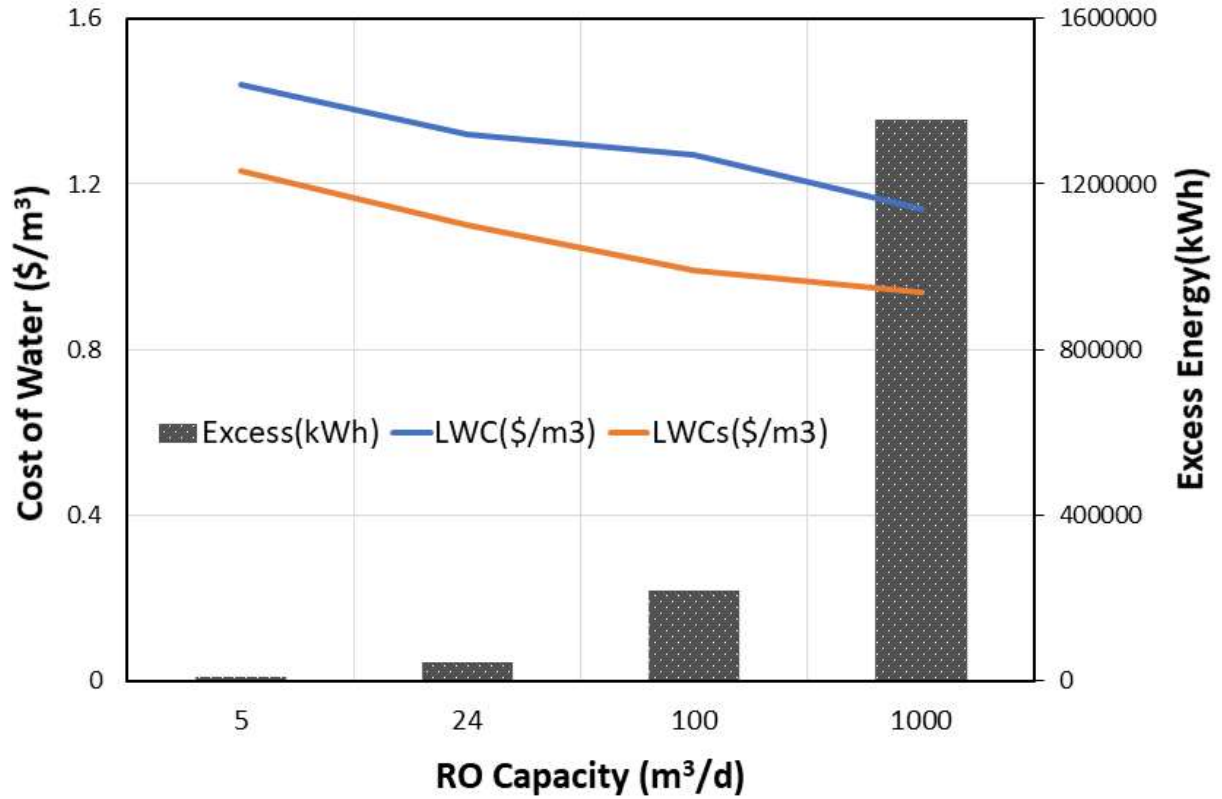


Figure 37: Economic Optimization and Excess Energy Analysis for Different Reverse Osmosis Capacities.

Table 22: Optimization Results for Different RO Capacities.

RO capacity	PV generation	WT generation	Water tank	LWC	LWC _s	$\sum_{t=1}^{8760} SE(t)$
5 m³/day	6.8 kW	2 kW	10.5 m³	1.44 \$/m³	1.23 \$/m³	7818.9 kWh
24 m³/day	39.8 kW	8 kW	81.6 m³	1.33 \$/m³	1.1 \$/m³	46200 kWh
100 m³/day	193.52 kW	23 kW	280 m³	1.27 \$/m³	0.99 \$/m³	216000 kWh
1000 m³/day	1294.46 kW	461 kW	461 m³	1.14 \$/m³	0.94 \$/m³	13560000 kWh

6.2 Optimization Results of RO unit with Variable Water Demand

This scenario considers variable daily water demand throughout the year, as illustrated in Fig. 38. The study employs the Differential Evolution (DE) algorithm to optimize both

cases, utilizing different Reverse Osmosis (RO) capacities to meet the specific water needs of the communities.

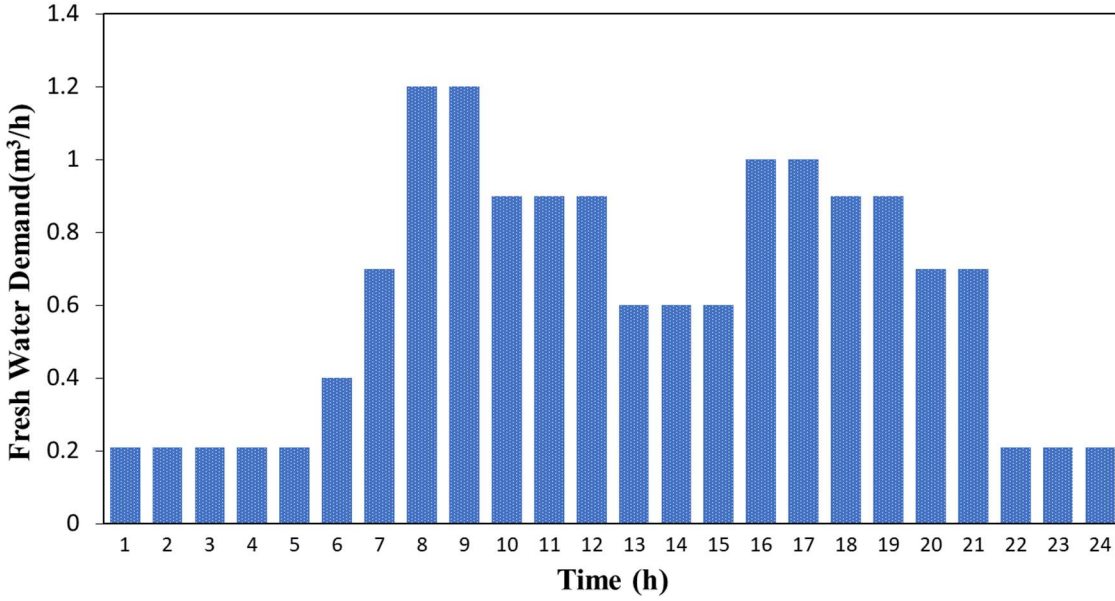


Figure 38 Daily Variable Water Demand Profile.

In this scenario, the optimization addresses the variable daily water demand observed throughout the year, as depicted in Fig. 38. The DE algorithm is utilized to adapt the RO unit capacity to this fluctuating demand, ensuring the community's water needs are met regardless of daily variations.

The convergence diagram from the DE algorithm, shown in Figure 39, illustrates the optimization process over 400 iterations. Notably, the algorithm converges at 311 iterations, indicating the point at which the optimal solution is identified. This optimal solution results in a Levelized Water Cost (LWC) of 1.29 \$/m³, demonstrating the cost-effectiveness of the optimized system. The optimum installed capacity for this scenario includes a photovoltaic (PV) array of 12.4 kW, a wind turbine (WT) capacity of 7 kW, and

a water tank volume of 42.8 m³. These components efficiently manage variable water demand, using renewable energy to ensure sustainability and reduce costs.

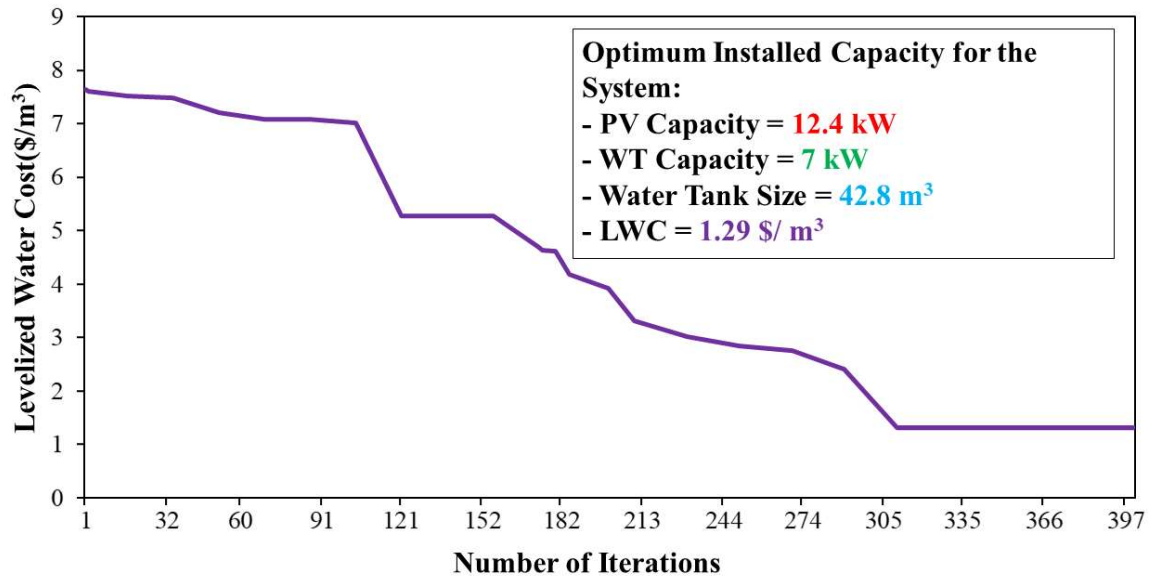


Figure 39 Convergence Diagram of the DE Algorithm for Variable Water Demand Optimization.

The state of charge (SOC) for the water tank is a critical metric for assessing the performance and reliability of the water supply system. Figure 40 illustrates the SOC variations over the course of a year, highlighting distinct seasonal patterns. During the winter months (December to February), the SOC fluctuates significantly between 10% and 90%. This variability is primarily due to the reduced power production from the photovoltaic (PV) array and wind turbine (WT) during this period. Shorter daylight hours and lower solar irradiance limit the energy output of the PV system, while calm weather conditions often reduce wind speeds, thereby decreasing the efficiency of the WT. Additionally, during the night hours, the SOC decreases further to meet the water demand as there is no solar energy available. As a result, the energy available to operate the Reverse Osmosis (RO) system is diminished, leading to greater fluctuations in the SOC as the tank struggles to maintain a consistent supply amid these constraints.

In contrast, the summer months (June to August) exhibit a much more stable SOC, ranging between 70% and 100%. The increased solar irradiance during longer daylight hours significantly boosts the energy output from the PV array. Additionally, summer winds tend to be more consistent, enhancing the performance of the WT. This abundant and steady energy supply allows the RO system to operate at optimal capacity, ensuring the water tank is frequently refilled and maintaining a high SOC. Despite the decrease in SOC during night hours due to the lack of solar energy, the system can quickly recover during the day thanks to the strong renewable energy input. This mitigates fluctuations and supports a reliable water supply during periods of peak demand.

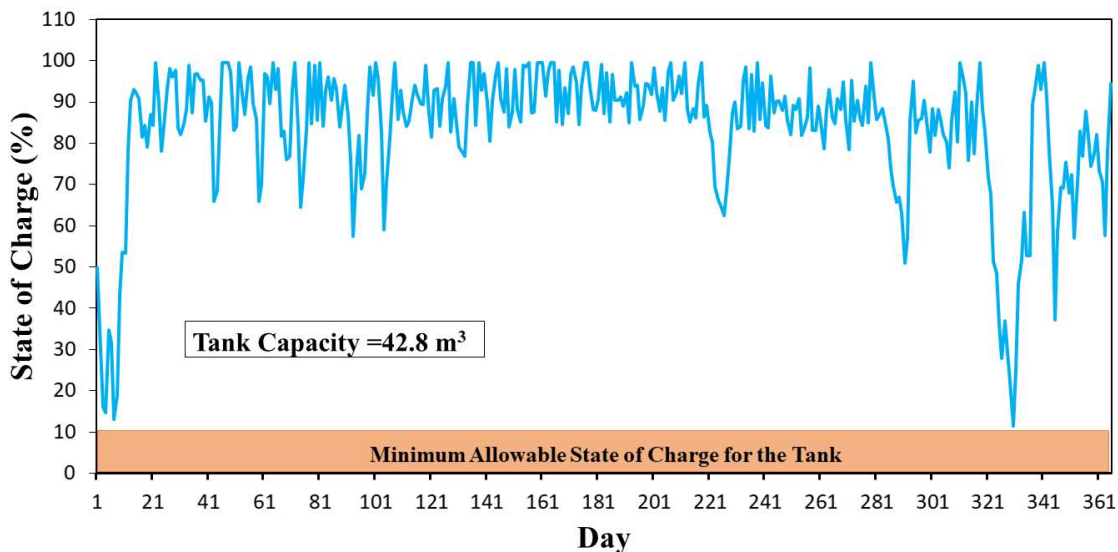


Figure 40 Daily State of Charge (SOC) Variations of the Water Tank Over One Year.

The system performance on both a daily and hourly basis is detailed in Fig. 41. Figure 41a illustrates the average daily performance in terms of reverse osmosis (RO) water production and the state of charge (SOC) of the water tank. During winter, the water tank's SOC decreases due to reduced solar and wind energy availability, approaching its minimum limit. This occurs because shorter days and lower wind speeds reduce energy

input. Conversely, in summer, the SOC reaches 100% as increased sunlight and stronger winds provide more energy, resulting in higher RO water production. The daily variation in RO water production depends on fluctuations in solar and wind energy availability and changes in water demand.

Figure 41b depicts the hourly performance of the RO unit on a typical January day. From 23:00 to 4:00, the system cannot meet the power demand for the RO unit due to the absence of solar radiation and insufficient wind power. At 5:00, as the sun rises, the system starts supplying the required power to the RO unit. All the generated energy is used for desalination, with excess water stored in the tank (Fig. 41d). Between 5:00 and 19:00, the system produces more water than needed because of sufficient solar and wind energy, charging the water tank. At 20:00 and 21:00, after sunset, the PV panels produce no energy, and the wind turbine alone cannot meet the water demand. Any production shortfall is covered by discharging the water tank. Consequently, the tank discharges from 20:00 to 21:00 and from 23:00 to 4:00, with SOC fluctuating between 12% and 37%. The discharging occurs because energy production is insufficient during these hours, and stored water is needed to meet demand.

Figure 41c and 41e show the system performance on a typical June day. From 00:00 to 1:00, the system exceeds water demand, storing surplus water until the tank reaches full capacity (100%) at 1:00. This is due to continued wind energy production at night. Afterward, the system continues to meet water demand, but any surplus energy is considered unused as the tank is already full. Between 6:00 and 8:00, the tank discharges slightly (Fig. 41e) because of higher water demand in the morning. For the rest of the day, the system meets water demand efficiently due to high solar and wind energy availability.

During the day, the tank's SOC remains high, fluctuating between 97% and 100%, as the system consistently produces more water than needed, maintaining a high level of stored water.

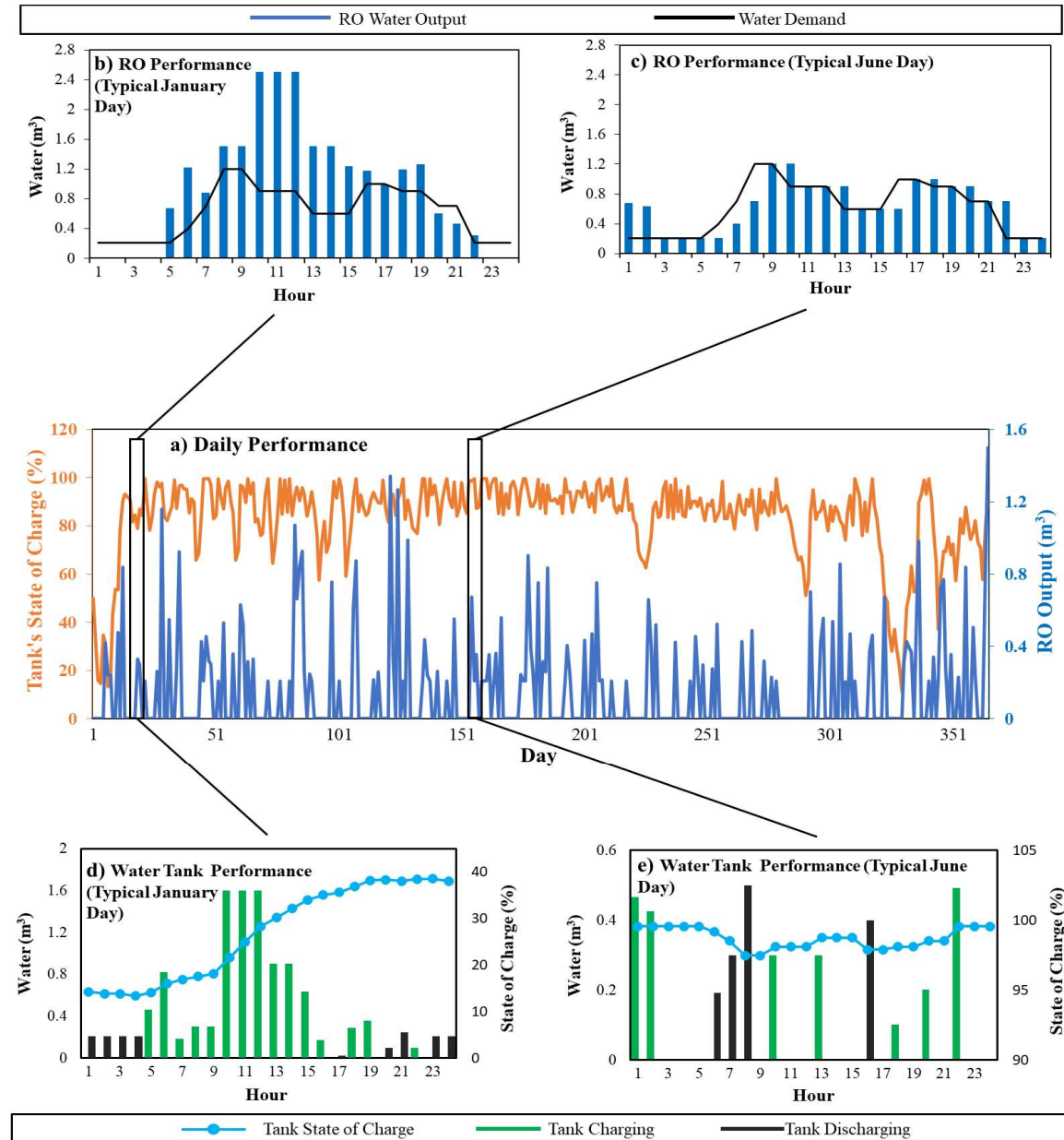


Figure 41 Detailed System Performance Analysis (a) daily RO Water & Tank Status Analysis, hourly RO unit performance on a typical (b) January day, (c) June day, hourly water tank charging and discharging on a typical (d) January day, and (e) June day.

Figure 42 demonstrates the performance of the optimum system on both a daily and hourly basis. In Figure 42a, the total power produced, power consumed by the RO unit, and surplus

power are depicted. Figure 42b illustrates the hourly total power produced, power consumed by the RO unit, and surplus power for a typical day in January. During the night hours, the system relies solely on wind turbines (WT). However, between 23:00 and 04:00, the wind turbines do not generate sufficient power to operate the RO unit, resulting in zero power consumption by the RO unit during these hours. As the sun rises, the PV system begins to contribute, increasing the total power produced by the system. From 08:00 to 10:00, the power consumed by the RO unit follows the total power produced, utilizing the maximum capacity available, with any additional energy classified as surplus power. For the remaining hours, the system harnesses the total power produced to generate water. At 04:00, 14:00, and 00:00, the total power produced is less than the minimum required to operate the RO unit, thus this energy is considered surplus. Figure 42c shows the hourly power performance for a typical day in June. The same trend is observed, but with higher surplus energy compared to the January day.

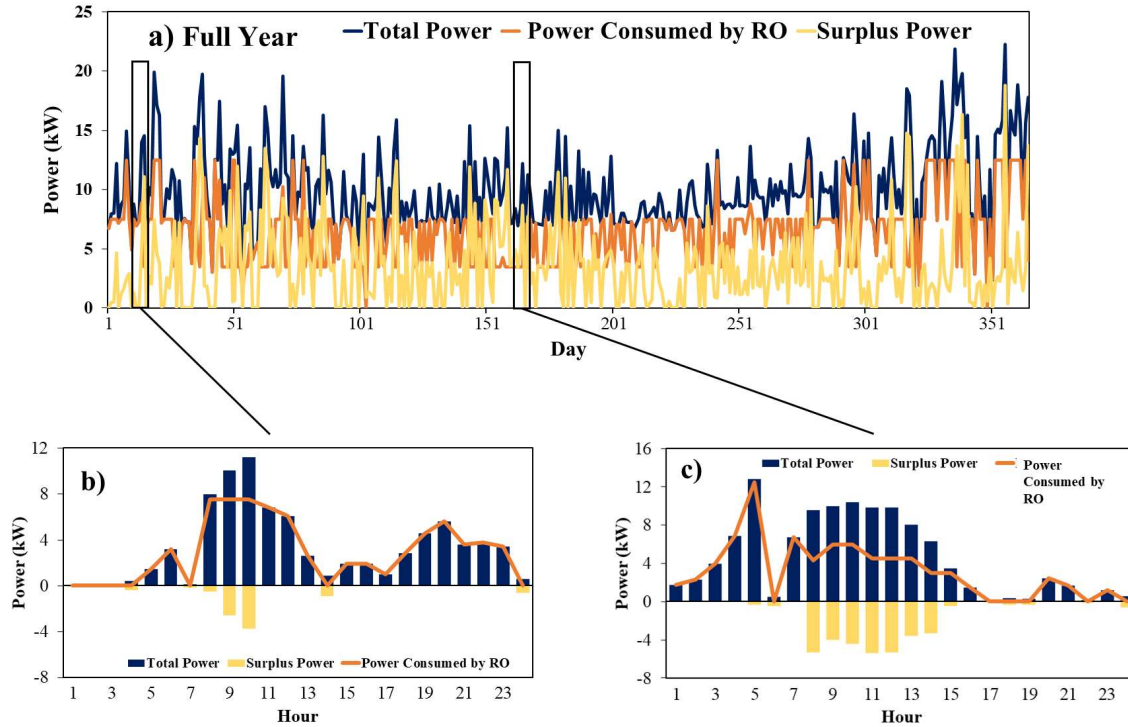


Figure 42 Performance of Optimal System with RO Unit Integration a) Comprehensive Annual Overview: PV/WT Generation, Surplus Power, and RO Utilization, b) January Insights: Hourly Power Dynamics, and c) July Insights: Hourly Power Dynamics.

6.2.1 Cost of Water Production Considering Surplus Energy Utilization

The surplus power obtained from the optimum system has a total value of 11,073 kWh/year, which accounts for about 27% of the total energy produced by the system annually. The remaining energy is harnessed by the RO unit.

Two approaches for utilizing this surplus energy are considered. In the first approach, the surplus energy is sold back to the grid. In the second approach, the surplus energy is used to desalinate more water. The results for these two approaches, including the variables RO production and water demand, are presented in Table 23.

Table 23 Comparison of Levelized Cost of Water for Two Approaches (Variables: RO Production and Water Demand)

LWC/ no surplus energy (\$/m ³)	LWCs with selling back (\$/m ³)	Savings (%)	LWC/ more desalination (\$/m ³)	Saving (%)
1.29	1.21	6.2	0.95	26.35

CHAPTER 7

OPTIMIZATION RESULTS FOR PHOTOVOLTIC (PV)

SYSTEM WITH BATTERY STORAGE SYSTEM

The mathematical model for a renewable energy system incorporating photovoltaic (PV) technology and a battery storage system to drive a variable reverse osmosis (RO) desalination unit with a minimum water production capacity of 5 m³/day is executed using MATLAB. Subsequently, the system is optimized using the Differential Evolution (DE) algorithm. The optimization process, depicted in Figure 43, follows a systematic flow. Initially, the specifications of the system components and battery capacity are defined.

The convergence of the Differential Evolution algorithm towards optimizing the Levelized Cost of Electricity (LCE) is evident in the graphical representation (Fig.44). As the iterations progress, the graph showcases a clear trend towards minimizing the objective function, with its value decreasing steadily. This trend becomes more pronounced with an increasing number of iterations, indicating the algorithm's persistent effort in fine-tuning system parameters. After 361 iterations, the graph stabilizes, reaching a constant value for the objective function, which remains unchanged beyond this point. This stabilization signifies the algorithm's achievement of a minimum value for the LCE of \$0.203/kWh, indicating an optimal configuration for the PV/battery system powering the RO desalination unit. The optimum system consists of 22.4 kW PV generation and 112.1 kWh battery capacity.

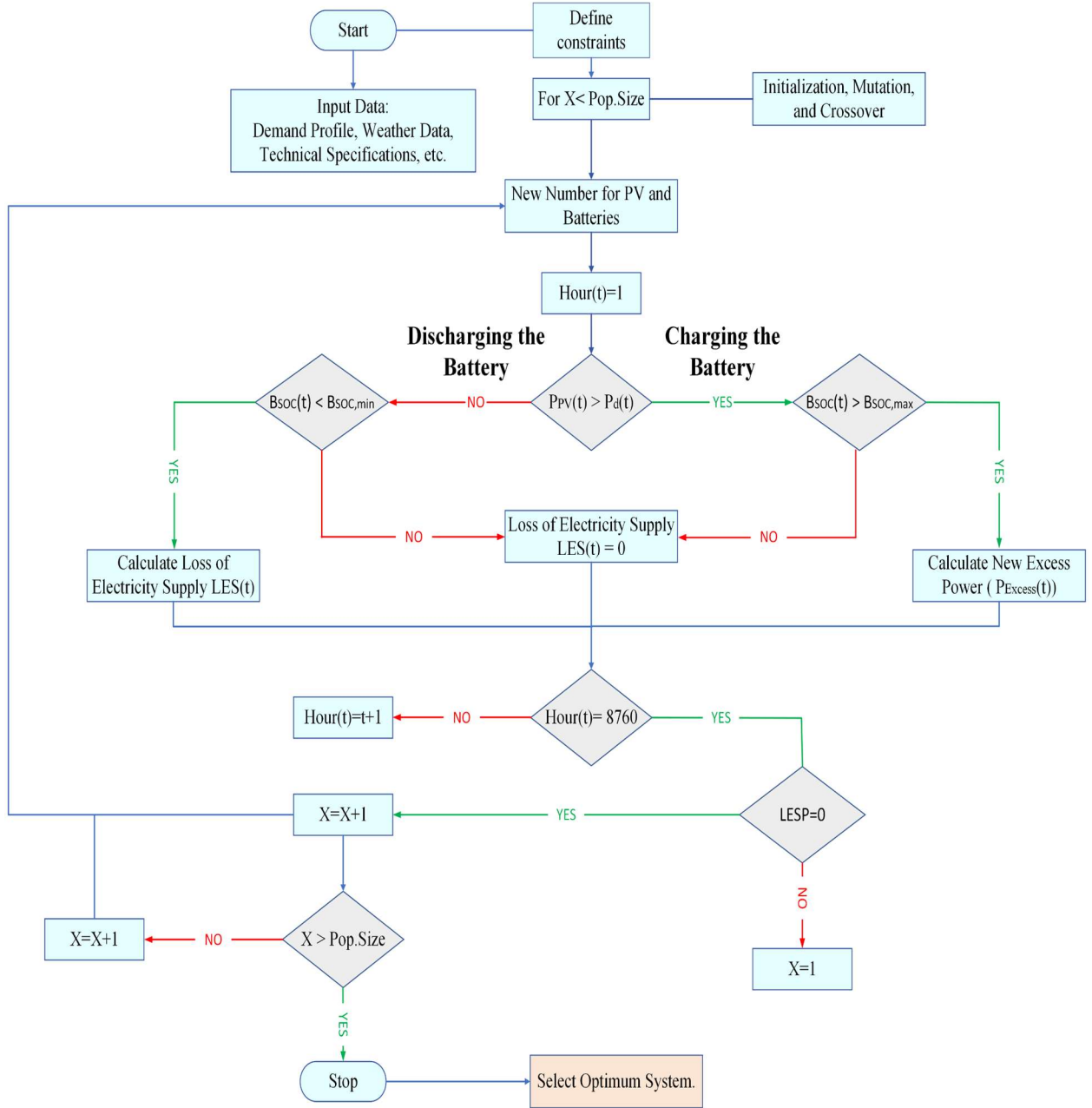


Figure 43: Optimization Process Flowchart for PV/Battery System Using Differential Evolution (DE) Algorithm

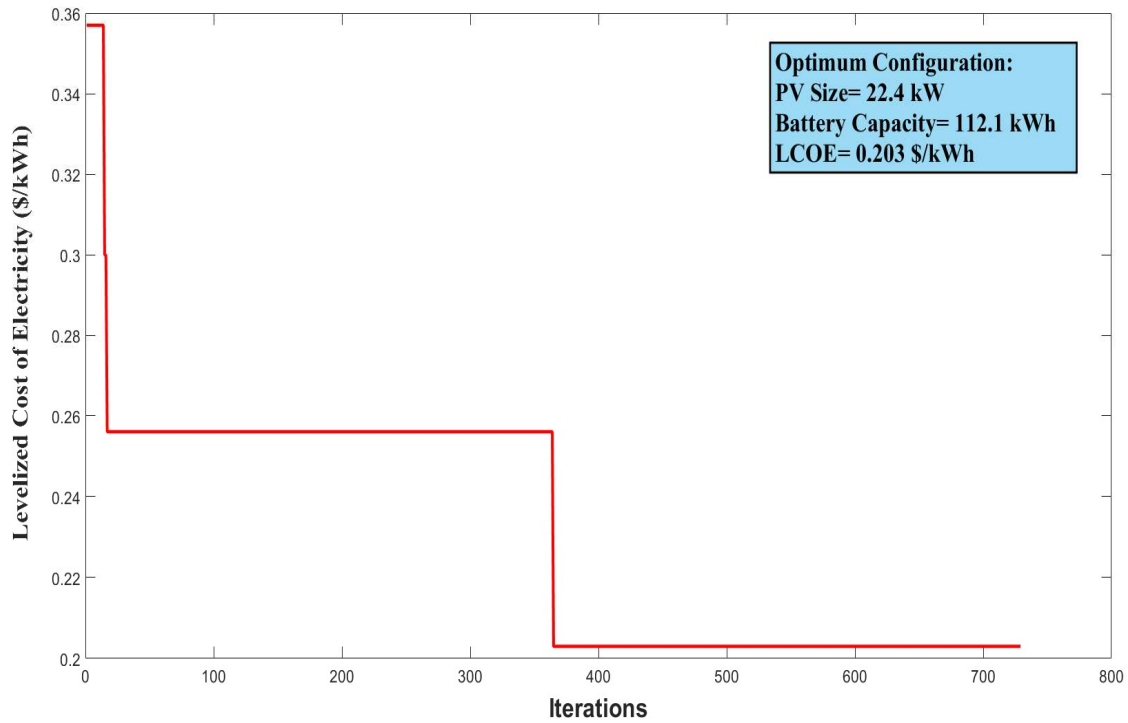


Figure 44: Convergence Analysis of the Differential Evolution Algorithm for Optimizing the Levelized Cost of Energy (LCE) in the PV/Battery System for RO Desalination.

Figure 45 presents the performance of the optimized PV/Battery system tailored to meet the electricity needs of RO unit. In Figure 45a, the system's average daily performance over a year is depicted, highlighting PV power generation, surplus electricity, and battery state of charge. Notably, during summer days, the battery state of charge remains consistently high as the system efficiently utilizes PV power generation to meet electricity demands and replenish the battery with any excess energy. When the battery is full, the additional excess energy remains unused. In other words, it is considered an additional excess energy which is named a surplus energy. Conversely, in winter, the battery state of charge declines, sometimes reaching as low as 40%, due to insufficient PV power generation necessitating the discharge of stored energy to fulfill demand. The correlation between PV power generation and battery state of charge is evident in the surplus energy profile, with surplus

energy observed on days with higher battery state of charge and minimal surplus on days when the battery is depleted due to increased demand. Figure 45b further details the system's performance on a typical January day, with PV power generation available during daylight hours. During this period, a portion of PV power directly meets the RO load, while the remaining energy is stored in the batteries. After sunset, power is drawn from the batteries to satisfy demand, with the battery state of charge peaking at midday and gradually decreasing thereafter as energy is discharged to meet load requirements. Lastly, Figure 45c illustrates the hourly performance for a typical June day, showcasing a similar profile to January. By comparing Fig. 45b and 45c, the hourly PV power generation in July is lower than the hourly PV power production in January because the PV panel temperature in the summer is high and for sure higher than cell temperature in the January, this lead to decrease in panel's efficiency contribute to decrease in power production.

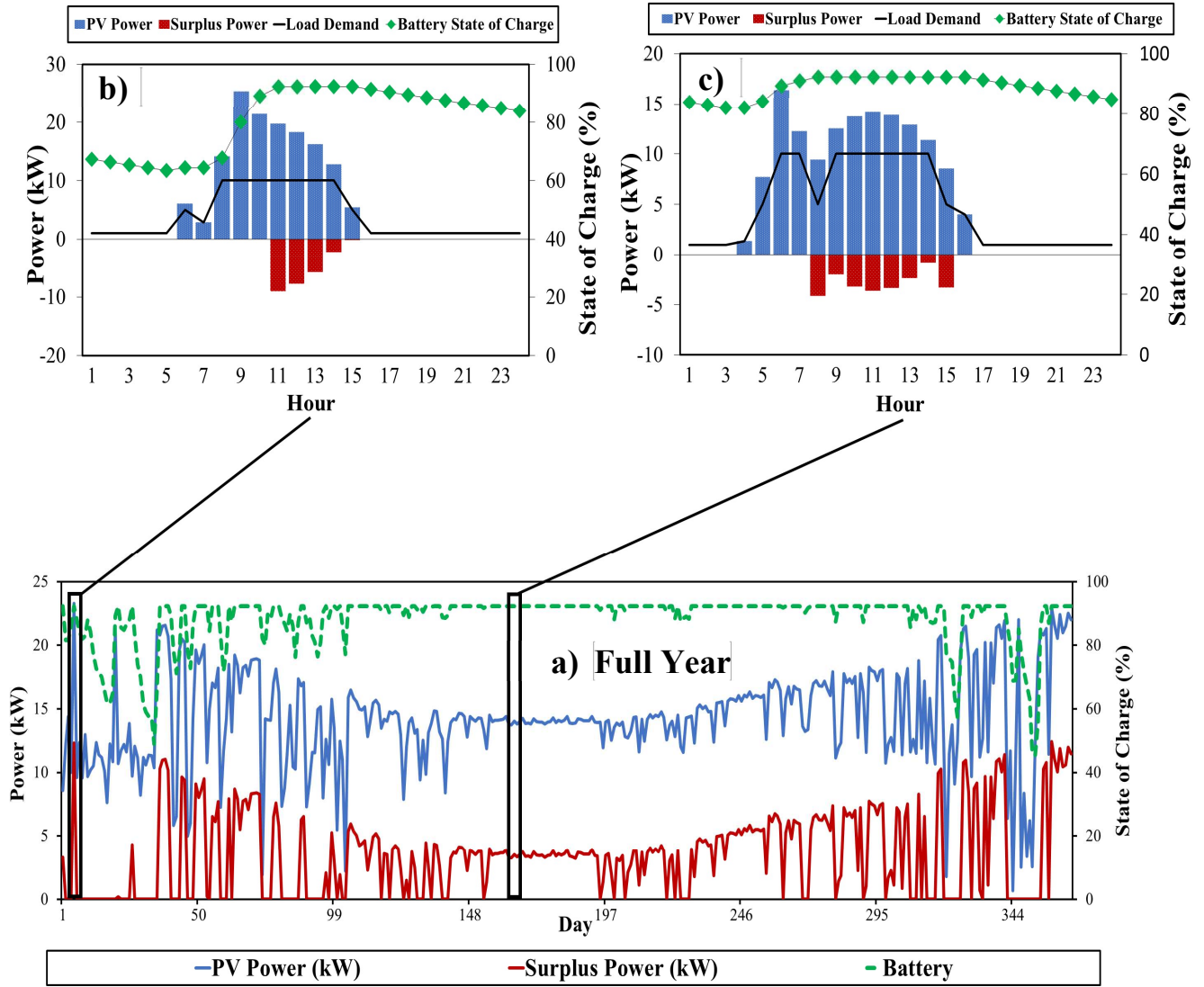


Figure 45: Hourly performance of PV/Battery system supplying electric load of RO unit, a) Full year indicators of PV power, Surplus energy and battery state of charge, b) Hourly performance for January day and, c) Hourly performance for June day.

Figure 46a illustrates the average daily performance of the optimized PV/Battery-driven RO unit, displaying freshwater production from the RO system, the state of charge of the PV/Battery system, and PV generation. The minimum freshwater production of the RO unit is recorded at $0.208 \text{ m}^3/\text{h}$, while its maximum capacity stands at $2 \text{ m}^3/\text{h}$. In Figures 40b and 40d, the hourly performance of the RO unit integrated with the optimized PV/Battery

and RO-Battery configurations, respectively, is depicted for a typical January day. Figure 46b presents the RO power demand, freshwater production, and freshwater demand, demonstrating the continuous operation of the RO unit to meet water demand both day and night. During nighttime, when PV production is absent, the RO unit utilizes electricity from the battery storage to maintain freshwater production at $0.208 \text{ m}^3/\text{h}$, matching the water demand. With PV power available from 6:00 to 15:00 (Figure 46b), it is utilized first to fulfill the RO demand, with any surplus energy stored in the RO-Battery (Figure 41d). Once the battery reaches full capacity around 11:00 (Figure 46b), any excess energy thereafter is considered surplus. After sunset, the RO power demand is met by discharging power from the RO-Battery. Conversely, for a typical June day, depicted in Figures 46c and 46e, the hourly performance of the RO unit integrated with the optimized PV/Battery and RO-Battery configurations, respectively, showcases higher battery state of charge values compared to a January day, although the daytime performance remains similar. PV power is available from 4:00 to 18:00, with the battery state of charge starting to increase during this period.

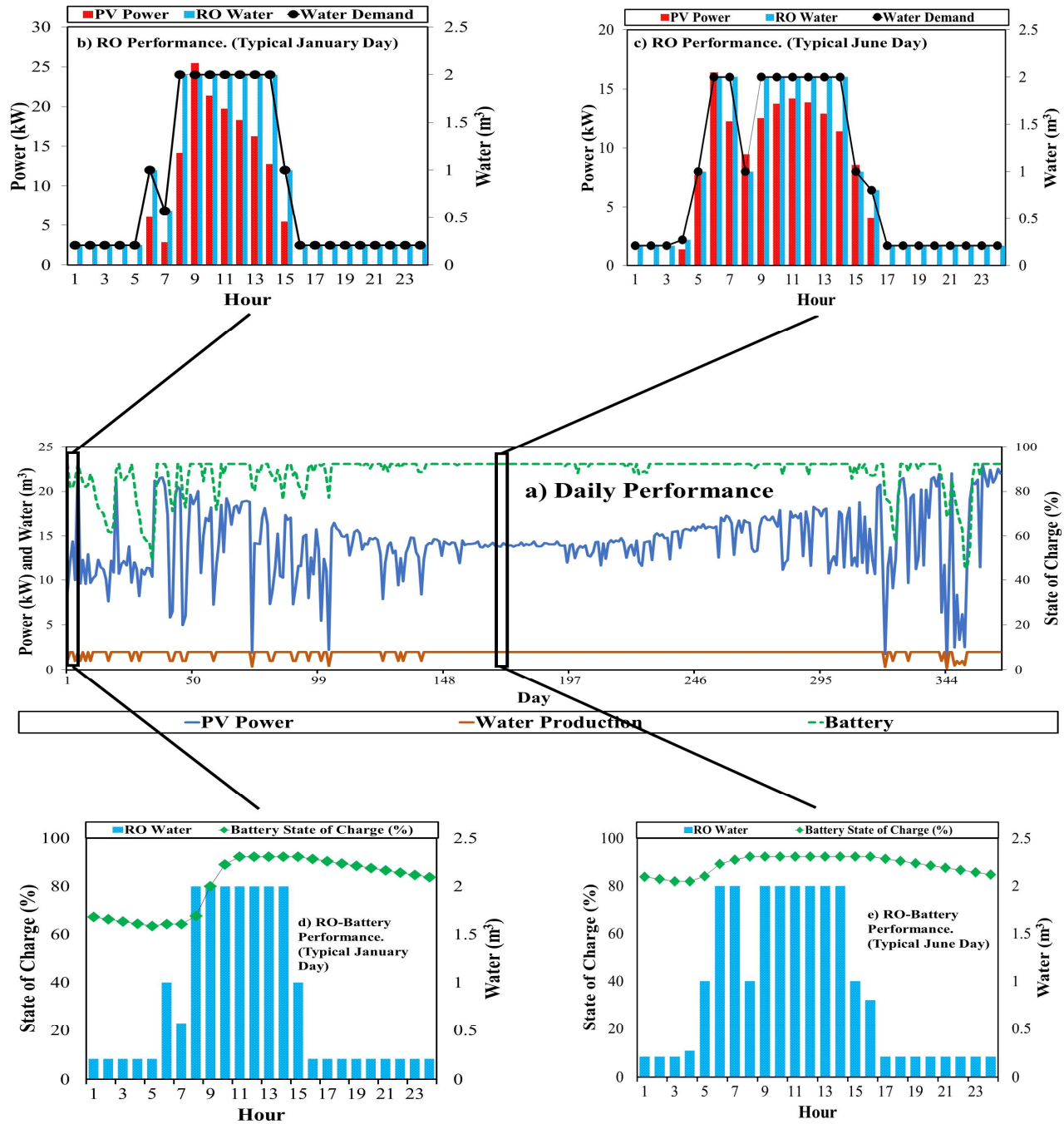


Figure 46: Performance Analysis of Optimized System, (a) Average Daily Performance, Hourly Performance for a: (b) Typical January Day (PV/Battery), (c) Typical June Day (PV/Battery), (d) Typical January Day (RO-Battery), and (e) Typical June Day (RO-Battery)

The surplus energy harnessed by the optimal system in this study serves dual purposes. Firstly, it is redirected back to the grid after being harnessed, effectively contributing to the overall energy supply. Secondly, this excess energy is strategically employed to bolster the desalination process, thereby augmenting the capacity of the Reverse Osmosis (RO) unit. Within the optimal Photovoltaic (PV), a significant proportion—81.1% of the total generated power—is allocated to powering the RO unit, with the remaining 18.9% classified as surplus. This surplus arises due to the limitations of battery storage, which can only retain a finite amount of energy produced by the PV/ Battery. Once the storage reaches its capacity, any additional power is designated as surplus.

In the first scenario, the Levelized Water Cost after selling back (LWCs) the surplus energy is determined using equation (3.29). Table 24 outlines the optimal Levelized Water Cost both with and without the resale of surplus power. Notably, there is a decrease of 2.7% in the Levelized Water Cost when factoring in the surplus energy.

Table 24: The surplus energy impact on the LWC.

RO capital cost (\$/m³)	LWC without selling back (\$/m³)	LWCs with selling back (\$/m³)	Savings (%)
532	2.61	2.54	2.7

In the second scenario, the recalculated Levelized Water Cost focused on utilizing surplus energy for desalination (LWC) is derived using equation (3.30). Table 25 illustrates the comparison between LWC and the standard LWC, shedding light on how water production costs are influenced by desalinating additional water. Expanding the desalination capacity involves augmenting the size of the Reverse Osmosis (RO) unit by incorporating new modules to harness *SE*. Notably, a significant 8.5% reduction in LWC is evident through the strategic use of surplus energy for increased desalination.

Table 25: Comparison of Levelized Water Costs with and without Surplus Energy Utilization for Desalination

RO capital cost (\$/m³)	LWC without desalinate more water (\$/m³)	LWC/ with more desalination (\$/m³)	Savings (%)
532	2.61	2.39	8.5

CHAPTER 8

CONCLUSION AND RECOMMENDATION WORKS

In this study, a techno-economic and optimization analysis of standalone hybrid renewable energy system (HRES), which is made up of a photovoltaic array and wind turbines driven Reverse Osmosis (RO) desalination system are conducted under the meteorological characteristics of Dhahran City, Kingdom of Saudi Arabia. To exploit excess energy, three different alternative storage options are investigated for the RO desalination unit: Battery, Pumped hydro, and Water-Tank, storage system. Surplus energy (SE), representing extra or unused energy from the system, can be harnessed to improve the economic viability of the system through two approaches. Firstly, it can be sold back to the grid, contributing to grid stability and reducing the Levelized Water Cost (LWC). Secondly, it can be used to increase the size of the RO unit, enabling the desalination of more water, which also contributes to lowering the LWC. Mathematical models are built and implemented in MATLAB software where the optimization is conducted. Differential Evolution (DE) algorithm is utilized to optimize the size of the HRES. In addition, reliability and economic metrics are used to evaluate each system's performance. The reliability of the power generation system is evaluated in terms of the Loss of power supply probability (LPSP), whereas the reliability of the desalination system is evaluated in terms of the Loss of water supply probability (LWSP), which is introduced in this study. In addition, levelized cost of electricity (LCE) and levelized cost of water (LCW) are used in the cost modeling process. The findings of this study can be summarized in the following points:

- In the first case, where a battery is utilized as a storage system for an RO unit producing 5 m³/day, the optimized hybrid system comprises a 7.67 kW PV generation capacity, a 2 kW wind turbine, and a 38.79 kWh battery. Achieving a Levelized Cost of Electricity (LCE) of \$0.39/kWh and a Levelized Water Cost (LWC) of \$2.14/m³, selling surplus energy back to the grid results in an 11.61% decrease in LWC. Additionally, employing surplus energy to augment desalination capacity yields a remarkable 29.8% reduction in LWC.
- In the second case, utilizing pumped hydro as a storage system for the same RO unit, the optimal hybrid system configuration integrates a 6.8 kW PV array, 3 kW wind turbines, and an upper reservoir volume of 230.7 m³ at a 50-meter height. This configuration results in an LCE of \$0.428/kWh and an LWC of \$2.43/m³. Selling surplus energy to the grid reduces LWC by 7%, while utilizing surplus energy for increased desalination lowers LWC by 23.9%.
- In the third case, where a water tank is implemented as the storage system for the reverse osmosis (RO) unit, two approaches to water demand are employed: constant and variable water demand. For the constant water demand scenario, with a daily demand 5m³/day, the optimal system configuration comprises a 6.8 kW photovoltaic (PV) array, 2 kW wind turbines, and a water tank with a volume of 10.5 m³. The resulting levelized water cost (LWC) for this optimal system is \$1.44/m³. When surplus energy is sold back to the grid, the LWC is reduced by 14.6%. Alternatively, utilizing the surplus energy for expanded desalination reduces the LWC by 33.33%. In contrast, for the variable water demand scenario, the optimal system configuration consists of a 12.4 kW PV array, 7 kW wind

turbines, and a water tank with a volume of 42.8 m³. This configuration ensures a consistent water supply despite fluctuating daily demands, achieving an LWC of \$1.29/m³. When surplus energy is sold back to the grid, the LWC decreases by 6.2%. Utilizing the surplus energy for additional desalination further reduces the LWC by 26.3%.

- Another case explores a variable size RO unit driven by a PV/battery system. Findings indicate that optimal LCE of \$0.203/kWh is achieved with a 22.4 kW PV generation and 112.1 kWh battery capacity, resulting in an LWC of \$2.61/m³. Economic analysis reveals a 2.7% decrease in LWC through surplus energy resale and an 8.5% reduction in LWC by strategically expanding desalination capacity.

The table 26 below summarizes the results obtained from various cases exploring hybrid renewable energy systems integrated with RO desalination unit.

Table 26: Comprehensive Comparison of Hybrid Renewable Energy System Scenarios and Their Influence on Desalination Costs for Driven RO Uni

System Configuration	Scenario (RO Size)	Storage System	PV Capacity (kW)	Wind Turbine Capacity (kW)	Storage Capacity	Surplus Energy (SE) Percentage (%)	LCE (\$/kWh)	LWC (\$/m³)	LWC/ resale SE (\$/m³)	LWC/ desalinate more water (\$/m³)
PV/WT/RO	Constant (5m³/day)	Battery	7.67	2	38.9 kWh	51	0.39	2.24	1.98	1.6
PV/WT/RO	Constant (5m³/day)	Pumped Hydro	6.8	3	230.7 m³	31.4	0.428	2.43	2.26	1.85
PV/WT/RO	Constant (5m³/day)	Water Tank	6.8	2	10.5 m³	46.1	-	1.44	1.23	0.96
PV/WT/RO	Variable	Water Tank	12.4	7	42.8 m³	27 %	-	1.29	1.21	0.95
PV/RO	Variable	Battery	22.4	-	112.1 kWh	18.9	0.203	2.61	2.54	2.39

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