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Mathematical Modelling and Performance Review of Desalination Technology Based Renewable Energy

Irwan*, Muhammad Zohri

Department of Physics Education, Universitas Islam Negeri Mataram, Mataram 83116, Indonesia

Corresponding Author Email: irwan@uinmataram.ac.id

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ABSTRACT

This research aims to provide a comprehensive overview and review of the utilization of renewable energy in desalination technology. The study classifies the various methods employed in desalination systems, which encompass both thermal and membrane techniques. The analysis of desalination methods incorporates the concepts of energy, exergy, and economic considerations. A crucial aspect of this study is developing a mathematical model encompassing thermal and membrane desalination methods. The advancement and progress of desalination technology are elucidated and integrated using renewable energy sources. The findings of this review indicate that the thermal desalination method consumes more energy than the membrane method, particularly during the water evaporation process. The wave-based reverse osmosis (RO) technique exhibits a lower production cost among the different methods. This is followed by the solar-powered multi-effect distillation (MED) system, the solar-powered multi-stage flash (MSF) system, and the wind-powered mechanical vapor compression (MVC) system. The mathematical models developed in this study could predict both membrane and thermal desalination systems' performance, thereby assisting readers in modeling and planning environmentally friendly and sustainable desalination technology based on renewable energy sources.

1. INTRODUCTION

Water consumption worldwide is rising, with an expected 50% increase in consumption by 2030 due to population growth [1]. This surge in demand for water is anticipated to result in a concerning situation by 2025, where there may be insufficient water supply for drinking and other essential purposes [2]. Even though seawater covers about 70% of the Earth's surface, it must first undergo treatment. One highly effective method for purifying water is through the desalination process. Desalination involves the removal of salt from seawater, making it suitable for drinking. Desalinated water can be utilized for various purposes, such as agricultural irrigation, daily household needs, and industrial applications. Recent data indicates a significant increase in desalination capacity, rising from 66.4 million m^3/day to 99.7 million m^3/day over the past six years [3].

There are 21,123 operational desalination plants worldwide, catering to the clean water requirements of over 300 million individuals [4, 5]. Countries in the Middle East, which have arid and sandy terrain, primarily use desalination technologies [6]. The expansion of this industry has resulted in an increased demand for energy to power the desalination process. Unfortunately, fossil fuel energy remains the primary source, which is both environmentally unfriendly and costly. The desalination process using fossil fuels emits approximately 25 kg/m^3 of fresh water in the form of CO_2 emissions [7, 8]. Consequently, adopting renewable energy sources to power the desalination process is highly suitable for safeguarding the environment [9].

Renewable energy sources are defined as sources of energy that have the ability to be replenished. These sources include geothermal energy, sunlight, tidal water, and wind power [10]. Numerous countries currently rely on renewable energy for 20% to 50% of their national energy needs. The global trend is moving towards increasing renewable energy utilization, particularly in the desalination process [11]. However, some desalination technologies that rely on renewable energy are still relatively expensive. Nevertheless, ongoing research in desalination technology, coupled with advancements in solar collectors, storage systems, and control systems, aims to enhance the competitiveness and environmental friendliness of renewable energy-based desalination processes.

Numerous studies and literature reviews have been conducted on conventional and renewable energy-based desalination. In 2015, one such study focused on reviewing desalination systems that utilize geothermal and solar energy as energy sources [12]. Similarly, in 2017, another review explored the potential application of renewable energy in the desalination process, specifically in India [13]. Furthermore, the same year, a study extrapolated the integration of desalination with renewable energy alongside conventional approaches, highlighting the potential benefits, energy requirements, and associated costs [14]. In 2018, a review centered on desalination methods utilizing ocean, wind, and geothermal energy sources [15]. Additionally, another review specifically examined membrane-based desalination processes powered by renewable energy in the same year. Moving on to 2019, a review focused on using renewable energy in desalination applications within Iran [16]. In 2020, a comprehensive review assessed the potential of membrane, thermal, and renewable energy sources for desalination [17]. The subsequent year, 2021, witnessed a review that delved into competent renewable energy sources in the desalination process, encompassing the classification, distribution, and evaluation of financing [18]. Finally, in 2023, another review revisited the concept of the energy-water correlations, analyzing the four latest criteria while accounting for the operation and modeling process [19].

This article aims to comprehensively analyze desalination technology, encompassing its benefits and drawbacks and a detailed breakdown of the various methods employed in the desalination process. It explores the potential integration of renewable energy sources with desalination technology, examining both the combination of renewable energy with conventional desalination methods and the advancements made in developed desalination techniques. Developing a mathematical model that effectively represents desalination's design and operational aspects, encompassing thermal and membrane-based methods, is of particular significance. This mathematical model holds immense potential for offering valuable insights for designing and predicting optimal desalination systems, particularly those integrated with renewable energy sources.

2. DESALINATION TECHNOLOGY CLASSIFICATION INTEGRATED WITH RENEWABLE ENERGY

Figure 1 illustrates a schematic concept of the current research and development in desalination technology methods. Typically, these methods can be categorized into two groups: thermal methods and membrane methods. The thermal process involves heating seawater or salt water to a specific temperature. Various heat sources such as fossil fuels, geothermal energy, solar energy, and nuclear energy can be utilized for this purpose. Examples of thermal methods include multiple-effect distillation, Freezing Desalination [20, 21], Adsorption Desalination, Multi-Stage Flash, and Humidification Dehumidification [22]. On the other hand, the membrane method utilizes a membrane to separate seawater or salt water into fresh water. This method encompasses techniques such as electrodialysis, Membrane Distillation, Capacitive Deionization, Reverse osmosis, and Forward Osmosis [23, 24].

Thermal and membrane methods each have their own set of advantages and disadvantages. The membrane method offers benefits such as low capital costs and energy consumption, a high recovery ratio process, and low levels of corrosion and scale. Additionally, it allows for the reduction of membrane contamination caused by microbes [25]. On the other hand, the thermal method has its own advantages. This technique has been tested and established, producing better quality water. Furthermore, the control process for the thermal method is not overly strict. Factors such as material and operational costs must be considered when selecting the appropriate desalination technique. It is crucial to design a technology that is both suitable and efficient, especially when integrated with renewable energy sources [26, 27]. Its sustainability and environmental friendliness greatly influence the development of desalination technology. By combining desalination technology with renewable energy, efforts are made towards achieving an environmentally friendly and sustainable energy source.

The utilization of renewable energy sources in the desalination process depends on the specific needs and requirements. Various factors come into play when considering the use of renewable energy, including the geographical location of the energy source, the size of the desalination plant concerning the desired production level, the adaptability of energy supply, the accessibility and salinity of water, the proximity of the facility to the market or end user, the presence of supporting infrastructure, particularly the electricity network for backup purposes, and the potential and nature of renewable energy in alignment with the calculated capital and operational expenses [28].

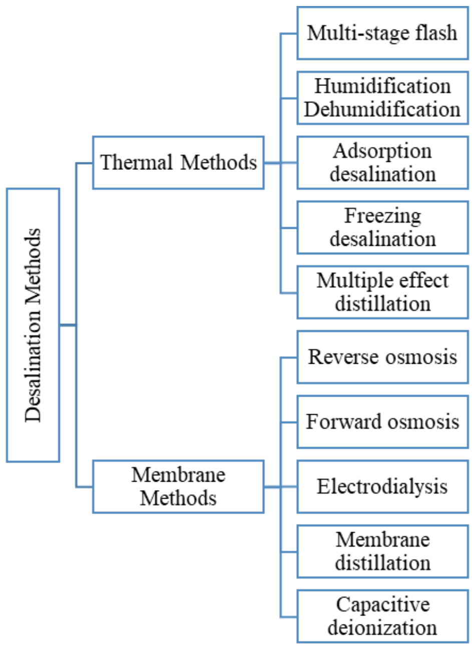

Figure 1. Classification of desalination methods technology

2.1 Reverse osmosis (RO) technologies

RO technology is currently the dominant technology in the desalination industry. It operates by drawing water through a semipermeable membrane under hydraulic pressure [29, 30]. This membrane-based desalination technology offers several advantages in the desalination process, including low production cost, low energy usage, and fast recovery. Compared to thermal-based desalination technology, RO technology has a lower production cost. The effectiveness of the membrane in RO technology has contributed to its rapid development. Additionally, RO technology excels in energy recovery and using advanced materials [31]. Another advantage of RO technology is its versatility in terms of production capacity, as it can be applied on both small and large scales, including industrial settings. RO technology is capable of treating saltwater ranging from low salinity to high salinity levels, all while consuming minimal energy [32].

RO technology's effectiveness and cost heavily rely on the quality of the water source to which it is applied. In the case of seawater RO plants, the TDS content typically falls within the range of 15,000 to 46,000 mg/L. RO technology requires a combination of various systems and multiple stages to operate on an industrial scale. However, it should be noted that this configuration consumes a significant amount of energy and generates a substantial volume of water production. Specifically, seawater RO (SWRO) plants consume energy ranging from 2.5 kWh/m^3 to 4 kWh/m^3 [33, 34]. Regarding environmental impact, RO technology boasts the lowest carbon emissions among desalination processes. The carbon emission values for RO range from 1.7 kg CO_2/m^3 to 2.8 kg CO_2/m^3 [35]. Despite its advantages, there are still challenges associated with using RO technology. These include the continued use of chemicals, the proper disposal of brine waste, and the potential impact of residual dirt on the RO membrane after operation [36, 37].

Several factors influence the power requirements in the RO process. These factors include the efficiency of the pump used, the membrane quality, the water quality produced, and the speed at which the RO system can recover. High-pressure pumps, in particular, consume significant energy in the RO system. According to a study [38], the energy consumption in RO systems ranges from 2 kWh/m^3 to 4 kWh/m^3. On the other hand, independent systems consume even higher energy, ranging from 3 to 7 kWh/m^3. This higher energy consumption can be attributed to factors such as unusual system operation, system design, operating time, and efficiency. Compared to other desalination processes, RO systems consume less energy, making them more energy-efficient. This benefit makes the RO process a promising candidate for integrating new and renewable energy technologies [39, 40].

RO systems are well suited to new and renewable energy sources. Solar energy, wind energy, and ocean waves are examples of renewable energy sources that can be exploited [41]. The energy required is approximately 44% of the cost of producing water. Energy sources such as bioenergy and hydropower are less suited for RO systems depending on the location of the desalination facility [42]. Wind and solar electricity are effectively used in RO systems. These two energy sources have benefits over other renewable energy sources. The benefits include economical operating costs, technological maturity, high accessibility, and no water usage [43, 44]. On a global basis, the utilization of solar panel sources now stands at 32%, while wind energy stands at 19%.

One of the primary goals of utilizing renewable energy sources, particularly solar panels and wind, is to mitigate emissions and decrease reliance on fossil fuels in desalination. However, a significant challenge associated with renewable energy is its intermittent or inconsistent energy supply. These drawbacks pose a problem as desalination systems require a constant and uninterrupted energy supply. Consequently, this intermittent energy supply has an adverse impact on RO systems' performance, particularly in terms of pump functionality and membrane usage [45]. Numerous previous studies have focused on the design of RO systems that incorporate energy sources from solar panels and wind. For instance, Rahal [46] conducted research on integrating a wind power plant with an RO system. This wind power plant employs a flywheel design to mitigate fluctuations in incoming wind power. This flywheel design enhances the system's overall performance by reducing wind turbulence and stabilizing the system frequency, especially fluctuations in pump pressure within the RO system.

Peñate et al. [47] conducted an investigation on the design of a stand-alone RO system plant utilizing wind power as the energy source. Their findings revealed that the production yield of this system can be increased by up to 2.8% compared to fixed operation, along with a higher-than-normal operating recovery. Another study by Carta et al. [48] demonstrated the successful combination of wind power generation with an RO system, which was directly linked to a large wind farm in the Canary Islands. Pohl et al. [49] further explored integrating wind power with RO systems through four different strategies. These strategies included maintaining a constant back pressure, implementing a constant permeate recovery process, ensuring a constant feedback rate, and establishing a stable salt flow rate. The results of these operational studies indicated that achieving stable permeate recovery can significantly reduce energy consumption.

Numerous studies have been conducted on RO plants utilizing solar energy sources or panels. One such study by Mohamed et al. [50] focused on RO systems powered by solar panels and solar panel batteries, which were able to produce approximately 0.35 m^3 of water per day. The energy consumption for this process, derived from sunlight, was around 4.5 kWh/m^3. The analysis conducted in this study revealed that the use of solar panels alone resulted in a productivity rate that was 6.5% lower compared to the utilization of solar panel batteries. In another investigation by Manolakos et al. [51] two RO generation systems incorporating solar panels were examined using a techno-economic analysis approach. The findings indicated that the energy consumption for the first system ranged from 3 to 6 kWh/m^3. On the other hand, the second system achieved a freshwater production rate of 0.1 m^3 per hour. The production costs for the first and second systems were determined to be 7.7$/$m^3$ and 12.5$/$m^3$, respectively.

Kelley and Dubowsky [52] have documented using solar panel power sources in conjunction with thermal control in osmosis desalination to produce clean water. Their research reveals that the solar panel system exhibits enhanced electricity generation capabilities at lower temperatures. By employing solar panels assisted by thermal control in the RO system, freshwater production can be achieved by up to 59%. Consequently, integrating solar panel power with thermal control significantly impacts the RO system's efficiency. Rahimi et al. [53] have investigated five scenarios involving solar panel power utilization in the RO system. These scenarios include an off-grid solar panel system with batteries, a solar panel system exporting excess power to the grid, a daytime solar panel system exporting excess power to the grid, a hybrid system utilizing solar panels during the day and grid power at night, and finally, a system solely reliant on grid power for the RO process. Among these scenarios, the most favorable outcome is observed when solar panels are utilized during the day, with excess electricity being exported to the grid.

Ghafoor et al. [54] conducted a study on integrating solar panels in RO systems and a techno-economic analysis. The implementation of solar panels in this RO system enables the production of approximately 500 L/hour of freshwater. By employing manual tracking of sunlight with three points, solar panel systems experience a notable increase in power output ranging from 20% to 25%. Additionally, a solar panel cooling system can further enhance the power output by approximately 5% to 10%. Lacroix et al. [55] designed an RO system that utilizes solar thermal energy as its heat source. This system incorporates thermal power, which aids in desalination by exerting osmotic pressure on seawater. The thermal power is harnessed through a sunlight collector with an area of 1.5 m^2. As a result of this desalination process, the system yields 750 L/day of fresh water with a concentration of 4 g per liter. García-Rodríguez and Delgado-Torres conducted an analysis on the use of Organic Rankine Cycle (ORC) and solar power in RO systems [56]. They compared an RO system powered by solar panels with an ORC system heated by the sun, both operating at the same capacity. The comparison revealed that the RO system integrated with ORC consumes less energy compared to the utilization of solar panel energy.

2.2 Electrodialysis (ED) technologies

The electrodialysis (ED) process involves an electric current to separate seawater salt ions and retain fresh water by passing them through a membrane. This process utilizes various components, including membranes, power components with direct current, and low-pressure circulation pumps. The direct current source is connected to electrodes placed in the saltwater container. Seawater flows through selective membrane channels, allowing salt removal from the seawater. As a result, positive salt ions move towards the negative electrode, while negative salt ions move through the membrane towards the positive electrode. This process encompasses two alternating channels, one for saltwater concentration and the other for producing fresh water [57-59]. Patel et al. [60] conducted a comparative study on ED and RO technology's energy consumption. Their findings indicated that the ED process exhibits higher energy efficiency in terms of salinity compared to the RO process. However, the limited removal of solutes, organic matter, and other contaminants currently affects the competitiveness of the ED process [61].

The DC power is utilized as the primary source of electrical energy in the ED system due to the utilization of DC power for the ED electrodes. Extensive research is being conducted on ED systems incorporating solar panel energy sources. These solar panel-energized ED desalination systems have been implemented worldwide to explore the possibilities and challenges, particularly in remote and hot regions [62, 63]. In Tanote, India, a solar energy source has been successfully integrated into the ED system. The solar panel system is equipped with a sunlight direction tracker to optimize electrical energy generation. This system is capable of producing 1.0 m^3 of clean water over 8 hours. Similarly, in Fukue City, Japan, a desalination plant powered by solar panels utilizing ED technology has been established [64]. This plant has a daily freshwater production capacity of up to 375 m^3, while the energy consumption per day amounts to approximately 1.9 kWh /m^3.

He et al. [65] have developed a pilot desalination technology that utilizes a solar panel energy source and an ED system. The methodology employed in this study involved the application of optimization theory and conducting field experiments in an Indian village. The research findings demonstrated a significant improvement in water production, with a remarkable increase of 45% compared to conventional designs. The freshwater production cost was estimated to be approximately 1.87 \$/m^3. However, implementing ED desalination technology with solar panels faces certain limitations, such as high initial installation expenses and limited capacity. Notably, the primary constraint lies in the elevated production cost associated with routine membrane replacement and the reduced efficiency of solar panels during cloudy or rainy conditions.

2.3 Humidification dehumidification (HDE) technologies

The process of desalinating seawater through the natural water cycle, specifically by conducting evaporation and condensation, is known as the humidification dehumidification (HDE) desalination process. This technology comprises three main components: the heating part, the dehumidifying part, and the humidifying part. The humidifier component consists of three parts, e.g., the nozzle part, which sprays hot salt water onto the material to collect and drain the salt water, and the dehumidifier part, which facilitates the condensation process [66]. The dehumidifier part is typically constructed using copper coils or fins that carry low-temperature brine to condense water vapor [67]. Dehumidifiers are commonly equipped with plate heat exchangers and finned tubes [68]. Air blowers and water pumps are employed to facilitate the transportation of seawater and air to the system [69].

This process can be categorized into two types of systems based on the energy source utilized: those that rely on electricity and those that utilize renewable energy sources such as wind, solar, geothermal, and hybrid systems. Among these renewable energy sources, solar energy is widely employed in HDE systems due to its ability to elevate the fluid temperature. Solar heating offers the advantage of increasing the air temperature, thereby enhancing the air's heat energy. This rise in air heat facilitates the system's capacity to absorb water vapor [70]. The solar water heater component is connected to the HDE unit to elevate the water temperature in the humidifier. Solar tube collectors are commonly employed to heat the water, as they expedite the increase in water temperature [71-74]. Additionally, some HDE desalination systems utilize flat plate models of solar collectors as heat sources.

Wang et al. [75] have developed a water-heating HDE system that incorporates solar panels for both cooling and increasing the solar panels efficiency. In this system, water is passed through the surface of the solar panels to facilitate the cooling process. As a result, the system generates fresh water and enhances the solar panels' performance. The system produces a daily output of 0.87 kg/m^3 of freshwater for forced or turbulent flow. The freshwater production costs range from 21.8 \$/m^3 to 2.3 \$/m^3. On a similar note, Elsafi [76] has proposed a solar thermal panel system combined with the HDE-CAOW system to generate fresh water and independent electricity. This system employs a theoretical approach and utilizes a solar panel area of 4.5 m^2. Daily freshwater production amounts to 33 kg, with a cost ranging from 10 \$/m^3 to 0.289 \$/m^3.

Gabrielli et al. [77] conducted an evaluation of the techno-economic aspects of an HDE system that utilizes solar panel energy as its source for water heating. The study reported an average 0.21 kg/m^2/hour freshwater production yield, while the production cost was estimated at approximately 0.07 kWh/kg. In a separate investigation by Giwa et al. [78], the HDE-CAOW technology was coupled with air heating and solar panels. The primary objective of this system was to generate electricity through solar panels and obtain freshwater using HDE technology. The freshwater production rate achieved was 2.28 L/day/m^2, with an electricity consumption of around 278 kWh/m^2 from the solar panels. On the other hand, integrating geothermal energy with the desalination process has gained significant attention. Geothermal energy, being continuous and abundant, proves to be highly suitable for desalination. Its consistent nature allows daily utilization, providing a 60°C to 90°C temperature range [79-82].

2.4 Multi-effect distillation (MED) technologies

Multi-effect desalination (MED) is the term used to describe the process of desalinating brackish water and seawater. This process involves the utilization of a condenser in multiple stages. Initially, seawater is introduced into the condenser tube and subjected to heating. The heated seawater then undergoes a series of stages. In the first stage, the seawater is vaporized and subsequently condensed into tubes. The subsequent stages utilize the energy derived from the condensation process to heat the water and reduce the pressure at each stage [83, 84]. Using feed water facilitates the condensation of the water vapor produced in the condenser. The number of stages employed in the MED process determines the rate at which freshwater is produced [85].

Water vapor temperature and pressure regulation in the MED process are achieved by installing a thermal vapor compressor (TVC) or mechanical vapor compressor (MVC). The implementation of vapor compression plays a crucial role in enhancing the performance of the MED process. The MED process offers several advantages, including cost-effectiveness in equipment, materials, maintenance, and low energy consumption. Additionally, its simple technology enables it to compete effectively with other desalination methods. The operating temperature range for the MED process typically falls between 70°C and 80°C, rendering it compatible with renewable energy sources. Renewable energy options such as solar panels and geothermal sources are well-suited for powering the MED process [86, 87]. El-Nashar [88]. conducted a comparative study between fossil energy and solar energy, focusing on the economic benefits of the MED system. The study concluded that the cost of producing freshwater amounts to 10$/GJ. When compared to conventional energy sources, the MED process consumes more energy.

Gholinejad et al. [89] have developed a solar power plant with a MED system incorporating a sunlight direction tracker. This innovative design utilizes an E-W sun tracing system in regions with limited solar radiation. In contrast, the N-S tracking system is employed in low-latitude areas with higher solar radiation. Meanwhile, Sharaf et al. [90] have explored integrating MED systems with TVC, MVC, and solar panel energy. In their investigation, the MED-TVC desalination process employs a parabolic trough collector to produce steam directly. The resulting freshwater output is approximately 4545 m^3/day, costing 2.1 $/$m^3$ for MED-MVC and 1.5 $/$m^3$ for MED-TVC. Palenzuela et al. conducted a study on a desalination system that utilizes MED-CSP with a thermodynamic approach. Their findings indicate that the electricity cost is approximately 0.2 $/kWh. Moser et al. [91] have also examined the hybrid desalination of RO or MED systems with CSP and conventional steam. The freshwater produced through this approach has a production cost of around 0.85 $/$m^3$.

Sharaf et al. [92] have proposed a MED desalination system that aims to obtain 100 m^3 of freshwater per day. This system consists of two models. The first model utilizes the output of Concentrated Solar Power (CSP) for heat exchange, while the second model employs turbine steam to assist the MED unit. According to the study results, freshwater production costs 5.47% per m^3 for the first model and 5.05 $ per m^3 for the second model. Bataineh has reported using a solar field with an area of 1,080,000 m^2 for solar panels in conjunction with MED model desalination. The freshwater production from this system using the ED-TVC desalination process is 50,000 m^3 per day, and it has a thermal storage capacity of 75 L per m^2. Baccioli et al. [93] have designed a MED desalination unit that utilizes waste heat in combination with solar panels. This hybrid technology aims to reduce investment and production costs. However, one drawback of this hybrid system is the long payback period. Helal and Al-Malek [94] have analyzed desalination by mechanical vapor compression hybridized with solar panels. The production capacity achieved by this system is 120 m^3 per day. A comparison with conventional desalination technology reveals that the production cost is higher.

2.5 Multi-stage flash (MSF) technologies

MSF, which stands for Multi-Stage Flash, is a widely employed thermal-based desalination process. This technology comprises various components, including the heating chamber circuit part and the brine heating part. In the MSF process, seawater is heated at a heater that operates at a standard saturation temperature. Once the seawater is heated, it is transferred to a low-pressure room. The seawater, now transformed into salt water, is then released through stages. Subsequently, it undergoes a steam production process. The resulting water vapor is condensed using salt water as a coolant [95]. In desalination, waste heat from renewable and conventional energy-based power plants can elevate the water temperature to 110°C [96]. The number of stages in the MSF system directly impacts the productivity level of the overall system. Some of the stages involved in this process include the brine heating process, the salinity water feedback process, and the process of increasing the temperature of the brine.

Darawsheh et al. [97] conducted experimental investigations on the MSF model desalination system. Their study combined the MSF model desalination with a flat plate heat absorber model solar collector. The system was tested under a pressure of 20 kPa and was found to consume approximately 35% of the energy. The results of their research indicate that this system can produce fresh water at a rate of 0.3 liters per hour per m^2 of collector area. Nafey et al. [98] focused on studying the operation of a small-scale desalination system based on the MSF model and sourced from solar energy. Their findings revealed that the system produced water at a rate of 4.2 kg/day/m^2 to 7 kg/day/m^2 during the summer and 1.45 kg/day/m^2 during the winter. Furthermore, researchers in Mexico also developed a similar system [99]. This system had a capacity to produce 10 m^3/day of water. These studies contribute to the understanding and advancement of MSF model desalination systems and their potential for sustainable water production.

Safi [100] developed a desalination unit for MSF (Multi-Stage Flash) that incorporates a parabolic collector, a flat plate collector with double tubes, and a 24-hour heat storage tank. This particular MSF unit operates with 10 stages to produce freshwater, yielding approximately 10 m^3/day when coupled with 1.0 m^2 of solar panels. To enhance the desalination performance of MSFs, researchers propose several strategies. Firstly, increasing the temperature difference between the hot salt water and the incoming seawater [101] is suggested.

Secondly, utilizing water fluid in the solar collector to expedite the production rate of the MSF system [102] is recommended. Lastly, harnessing the heat from the distillation process can optimize the exergy efficiency of the MSF system [103].

2.6 Adsorption desalination (AD) technologies

The process of utilizing low-temperature outlet heat derived from renewable energy sources to facilitate saltwater evaporation is referred to as the AD process. These outlet heat sources are typically found in renewable energy systems such as geothermal, solar panels, and industrial waste gas [104]. Once the adsorbent reaches its maximum water saturation point, it is heated to an 80℃ temperature to absorb the vapor. The resulting water vapor is subsequently condensed to produce fresh, potable water. Silica gel is commonly employed as the absorbent material in the AD system, which comprises various components, including the condenser, evaporator, and silica absorbent layer [105]. The evaporator supplies water vapor within a vacuum chamber, which is then directed to the adsorbent for absorption. On the other hand, the condenser undergoes a heat exchange process to convert pure vapor into liquid form. The silica gel adsorbent is cooled using cold water and reabsorbs the evaporated water.

The process of adsorption desalination involves the adsorption of water vapor from the air using silica gel, followed by condensation and desorption processes to produce fresh water [106]. This method primarily relies on extracting water from moist air. The freshwater obtained through this desalination process is of high quality, particularly in humid environments [107]. Renewable energy sources are well-suited for producing freshwater in the atmosphere as they require minimal heat and energy. When the humidity is sufficiently low, the absorption material affinity process can yield significant water [108]. AD desalination offers several advantages, including low energy consumption, resistance to pollution, the ability to remove pollutants and salts, minimal reliance on mechanical components, and, most importantly, its environmentally friendly nature. Ng et al. [109] have designed a waste heat energy source for the AD desalination system using silica gel, intending to obtain specific cooling power from freshwater. The waste heat generates hot water at 85℃, while the fresh water production reaches 8.0 m^3/day.

Rezk et al. [110] have designed a radial movement optimization method for AD desalination, resulting in significant improvements in SCP and SDWP, with an increase of up to 70%. The freshwater production achieved through this method is measured at 6.9 m^3/day/ton. The coefficient of performance (COP) value is determined to be 0.961, and the required cooling capacity is calculated to be 191 W/kg. Sleiti et al. [111] have conducted research on various materials, including silica gel, organic metal framework materials, and zeolite materials, to explore their potential to capture water molecules from the air and absorb low levels of heat energy. Additionally, hygroscopic salts and organic sorbents without host materials have been investigated for the AD process [112, 113]. In order to make AD desalination techniques more economical and cost-efficient, several challenges and opportunities need to be addressed. Firstly, the desalination industry should be developed from small-scale to large-scale operations to help cover production costs. Secondly, research should focus on developing more advanced and efficient adsorbents. Lastly, developing a predictive model for effective and efficient AD system performance would greatly reduce operational costs.

3. MATHEMATICAL MODELLING OF DESALINATION TECHNOLOGIES

3.1 Adsorption desalination cooling system with optimizing solar energy silica gel

Rezk et al. [110] conducted a study to investigate the most effective system for adsorption desalination cooling, utilizing a solar panel as the power source. Their research employed a mathematical modeling approach to determine the optimal performance using silica gel. Various variables were calculated, including the system cycle time, fluid flow rate, temperature of incoming cooling water, and temperature of incoming hot water. The evaluation of the system involved assessing the specific cooling power (SCP), specific daily water production (SDWP), and the coefficient of performance (COP). The results indicated that the desalinated water production reached 6.9 m^3/day/ton, while the cooling capacity was measured at 191 W/kg. The COP value was found to be 0.961, and both the SCP and SDWP values reached 70%.

For the silica gel, below is the adsorption isotherms equation:

$$w = w_o exp\left\{-\left(\frac{RT}{E} ln\left(\frac{P_{sat}}{P}\right)\right)^n\right\}$$

For the kinetic adsorption equation is:

$$\frac{dC}{dt} = a_v k_s (w_o - w)$$

where, $a_v k_s = F_o \frac{D_s}{{R_p}^2}$.

The equation for the mass balance of salt water and condenser is below:

$$\frac{dM_{sw,evap}}{dt} = \dot{m}_{sw,in} - \dot{m}_{p,cond} - \dot{m}_b$$

For salt mass balance and evaporator, the equation is as follows:

$$\frac{dM_{sw,evaporator}}{dt} = \dot{m}_{sw,in} - \dot{m}_{p,cond} - \left(\frac{d_{Cads}}{dt}\right) M_{sg}$$

$$M_{sw,eva} \frac{dX_{sw,eva}}{dt} = X_{sw,in}\dot{m}_{sw,in} - X_{sw,in}\dot{m}_b - X_D\left(\frac{d_{Cads}}{dt}\right) M_{sg}$$

For adsorption bed energy balance, the equation is as follows:

$$\left[\left(M_{Cp}\right)_{cu} + \left(M_{Cp}\right)_{al} + \left(M_{Cp}\right)_{sg} + M_{sg} cp_v C\right]^{bed} \frac{dT_{bed}}{dt} = M_{sg} H_{st} \frac{dC_{bed}}{dt} - \dot{m}_w cp_w \left(T_{w,out} - T_{w,in}\right)^{bed}$$

For heat adsorption, the equation is as follows:

$$H_{st} = h_{fg} + E\left[ln\left(\frac{C_o}{C}\right)^{1/n}\right] + \frac{ET\alpha}{n}\left[ln\left(\frac{C_o}{C}\right)^{1-n/n}\right]$$

For condenser energy balance, the equation is as follows:

$$\left[\left(M_{Cp}\right)_{cu} + \left(M_{Cp}\right)_{iron} + \left(M_{Cp}\right)_{w}\right]^{condenser} \frac{dT_{condenser}}{dt} = h_f(T_{condenser}) \frac{dM_d}{dt} + h_{fg}(T_{condenser}) \frac{dC_{des}}{dt} M_{sg} + \dot{m}_w c_{pw}(T_{cond})\left(T_{w,in} - T_{w,out}\right)^{cond} \dot{m}_b$$

For evaporator energy balance, the equation is as follows:

$$[M_{s,eva}cp_s(T_{eva}, X_{s,eva}) + M_{cu,eva}cp_{cu,eva}]\frac{dT_{eva}}{dt} = h_f(T_{eva}, X_{s,eva})\dot{m}_{s,in} - h_{fg}(T_{eva})\frac{dC_{des}}{dt}M_{sg} + \dot{m}_{ch}cp_{ch}(T_{ch,in} - T_{ch,out}) - h_f(T_{eva},X_{s,eva})\dot{m}_b$$

The outlet temperature of the heat exchanger equation is below:

$$T_{w,out} = T_{hex} + (T_{w,in} - T_{hex})exp\left(\frac{-UA_{hex}}{(m^A c_p)_w}\right)$$

For the heat of evaporation equation is below:

$$Q_{eva} = \int_0^t \dot{m}_{ch}c_{pch}(T_{ch,in} - T_{ch,out})dt$$

For the heat desorption equation is below:

$$Q_{des} = \int_0^t \dot{m}_{hw}c_{pw}(T_{hw,in} - T_{hw,out})dt$$

For the heat condensation equation is below:

$$Q_{cond} = \int_0^t \dot{m}_w c_{pw}(T_{cw,in} - T_{cw,out})dt$$

The cycle performance of the parameter's equation is below:

$$SDWP = \int_0^{t_{cycle}} \frac{\dot{m}_{ch}c_{pch}(T_{cw,out}-T_{cw,in})}{h_{fg}M_{sg}}dt$$

$$SCP = \int_0^{t_{cycle}} \frac{\dot{m}_{ch}c_{pch}(T_{ch,in}-T_{ch,out})}{M_{sg}}dt$$

$$COP = \int_0^{t_{cycle}} \frac{\dot{m}_{ch}c_{pch}(T_{ch,in}-T_{ch,out})}{\dot{m}_{hw}c_{cp}(T_{hw,in}-T_{hw,out})}dt$$

3.2 Reverse osmosis (RO) desalination system using solar power and wind turbine energy

The reverse osmosis desalination system utilizes renewable energy sources, specifically wind turbines and solar panels. The reverse osmosis units can produce fresh water by harnessing solar energy and wind power, with batteries as backup. Various strategies have been employed to optimize the system's efficiency, such as maximizing particle swarms, harmony search, annealing simulations, and tabu search algorithms. The findings of the analysis indicate that the combination of solar and wind energy in a hybrid renewable energy system (HRES) yields the highest performance. This HRES maximizes performance and reduces production costs for reverse osmosis desalination [114].

The photovoltaic panel (PV) power generation (P_{pv}) can be stated as:

$$P_{pv} = \eta_{pv}R_tA_{pv}$$

where, the efficiency of PV is η_{pv}, the surface area of PV is A_{pv} (m^2) and the representation of solar radiation is R_t (kW/m^2).

The efficiency of PV (η_{pv}) is calculated as:

$$\eta_{pv} = \eta_{ref}\eta_{pc}\left[1 - N_T\left(\left(T_a + \left[\frac{NOCT-20}{800}\right]R_t\right) - T_{ref}\right)\right]$$

where, the efficiency of power conditioning is η_{pc}, the reference efficiency of photovoltaic is η_{ref}, T_{ref} is the temperature of a cell reference, T_a is the temperature of ambient air, N_T is the efficiency temperature of the PV collector, *NOCT* is the working temperature of the insignificant photovoltaic.

The calculation of the life cycle cost (*LCC*) is the amount of the capital cost (CC_{pv}) and process and upkeep of cost (MC_{pv}) [49, 66, 67].

$$LCC_{pv} = CC_{pv} + MC_{pv}$$

$$CC_{pv} = A_{pv}C_{pv}CRF$$

$$MC_{pv} = C_{ann-pv}A_{pv}$$

$$CRF(j,n) = \frac{j(1+j)^n}{(1+j)^n-1}$$

where, *CRF* is the capital recovery factor, C_{pv} means the cost of the photovoltaic system, C_{ann-pv} means the PV system's yearly process and upkeep cost, *n* is the lifetime distance, and *j* is the interest rate.

The wind turbine's power generation can be calculated as [67, 69]:

$$\begin{cases} P_{wt}(t) = 0, & v(t) \le V_{ci} \text{ or } v(t) \ge V_{co} \\ P_{wt}(t) = a.v^3(t) - bP^r, & V_{ci} < v(t) < V_r \\ P_{wt}(t) = P_r, & V_r \le v(t) < V_{co} \end{cases}$$

where, $\begin{cases} a = \frac{P_r}{(V_r^3 - V_{ci}^3)} \\ b = V_{ci}/(V_r^3 - V_{ci}^3) \end{cases}$, $P_r = 1/2A_{wt}C_p\rho_a\eta_{wt}V_r^3$.

here, V_{ci}, V_r and V_{co} are cut-in, the rate and cut-off speed (m/s) respectively, the wind speed is *v*, for the power of wind turbines is P_r, for the power coefficient is C_p, for the area of the turbine blade is A_{wt}, for the efficiency of wind turbines is η_{wt}.

3.3 Evaluation of solar-powered electrodialysis (ED) for sustainable freshwater production

Combining renewable energy and membrane desalination presents a viable and environmentally friendly technological solution. This study explores the implementation of Electrodialysis (ED) technology in conjunction with solar panels to generate potable water from brackish water desalination in the Canary Islands. The energy consumption of ED technology for treating brackish water with a salinity range of 2500-5000 mg/L is estimated to be between 0.49-0.91 kWh/m^3. From an economic standpoint, the production cost of the ED-PV system is projected to be in the range of 0.15-0.4 $€/m^3$ [58].

For calculating the cost of obtaining water on ED/Grid is $C_{ed\text{-}grid}$ ($€/m^3$):

$$C_{ed-grid} = TAC_{ed} + TC_{0per}$$

For calculating ED annual cost is TAC_{ED} ($€/m^3$):

$$TAC_{ED} = TCC_{ED}.AF/ATV$$

For calculating amortization is *AF:*

$$AF = IR/(1 - (1 + IR)^{-DP})$$

The calculation of the total ED costs is TCC_{ED} (€):

$$TCC_{ED} = IC_{ED} + DC_{ed} = (DC_F + 1).(C_{memb} + C_{ed})$$

The membrane cost calculation is C_{memb} (€):

$$C_{memb} = A_{am}.P_{am} + A_{cm}.P_{cm}$$

For ED cost without a membrane is C_{ED} (€):

$$C_{ED} = RFPM.C_{memb}$$
$$TC_{Oper} = TC_{O\&M} + C_{Energy}$$
$$TC_{O\&M} = C_{MembR} + C_{ElectrR} + C_{Chem} + C_{Sp} + C_{Lb} + C_{Disp}$$

For membrane replacement, the cost is C_{MembR} (€/m^3):

$$C_{MembR} = RF_{Memb}.C_{Memb}.AF/ATV$$

The cost of replacing the electrode is $C_{ElectrR}$:

$$C_{ElectrR} = RF_{Elect}.P_{Elect}.A_{Elect}.AF/ATV$$

Chemical cost is C_{Chem}:

$$C_{Chem} = D_{AS}.P_{AS}$$

The Energy cost calculation is C_{Energy} (€/m^3):

$$C_{Energy} = P_E.SEC_v$$

The calculation of water costs obtained in ED-PV is $C_{ED\text{-}PV}$ (€/m^3):

$$C_{ED-PV} = TAC_{ED} + TAC_{PV} + TC_{O\&M}$$

The calculation of the PV's total annual cost is TAC_{PV}:

$$TAC_{PV} = TCC_{PV}.AF/ATV$$

The total PV cost is TCC_{PV}:

$$TCC_{PV} = IC_{PV} + DC_{PV} = (DC_F + 1).(C_{PVI} + C_{PVM})$$

For PV infrastructure cost is C_{PVI}:

$$C_{PVI} = C_{PVM}.RFPPV$$

For PV module cost is C_{PVM}:

$$C_{PVM} = AP_{PV}.P_{PV}$$

The calculation of power availability in PV is AP_{PV}:

$$AP_{PV} = SEC_V.FR/(NEH.PR_{PV})$$

3.4 Integrating thermal photovoltaic technology with humidification-dehumidification desalination system

Amin developed a system called the humidification-dehumidification-humidification (HDH) cycle integrated with concentrated photovoltaic-thermal (CPVT) to address the need for reliable fresh water and electricity generation in remote areas [76]. The main objective of this research was to analyze the energy and exergy aspects, as well as the production costs, using a mathematical modeling approach. The system achieved a freshwater yield of 12 m^3 and an electricity capacity of 960 kWh. The cost of producing fresh water was found to be 0.01 \$/L, while the cost of solar panel energy was estimated at 0.289 \$/kWh.

For high cover is:

$$S_{g1} + h_{r,g2-g1}(T_{g2} - T_{g1}) = h_{r,g1-sky}(T_{g1} - T_{sky}) + h_{c,g1-wind}(T_{g1} - T_{amb}) + h_{c,g1-f1}(T_{g1} - T_{f1})$$

For the lower cover is:

$$S_{g2} + h_{r,pv-g2}(T_{pv} - T_{g2}) = h_{r,g2-g1}(T_{g2} - T_{g1}) + h_{c,g2-f1}(T_{g2} - T_{f1})$$

For upper channel is:

$$\frac{\dot{m}C_p}{W_2}\frac{dT_{f1}}{dx} = h_{c,g2-f1}(T_{g2} - T_{f1}) + h_{c,g1-f1}(T_{g1} - T_{f1})$$

For lower channel is:

$$-\frac{\dot{m}C_p}{W_2}\frac{dT_{f2}}{dx} = h_{c,pv-f2}(T_{pv} - T_{f2}) + h_{c,bp-f2}(T_{bp} - T_{f2})$$

For the collector in PV is:

$$S_{pv}(1 - \eta_{elec}) = h_{r,pv-g2}(T_{pv} - T_{g2}) + h_{c,pv-f2}(T_{pv} - T_{f2}) + h_{r,pv-bp}(T_{pv} - T_{bp})$$

The back plate is:

$$h_{r,pv-bp}(T_{pv} - T_{bp}) = h_{c,bp-f2}(T_{bp} - T_{f2}) + U_b(T_{bp} - T_{amb})$$

where, the mass flow rate of fluid is $\dot{m}$, the heat capacity of the fluid is C_p, the occurrence of irradiance is S, convective heat transfer coefficient is h_c, for the radiative heat transfer coefficient is h_r. The calculation for the energy balance equation for each component in the humidifier and dehumidifier system is as follows:

The humidifier is:

$$\dot{m}_3 = \dot{m}_4$$
$$\dot{m}_4 = \dot{m}_3 - \dot{m}_5$$
$$\dot{m}_3 h_3 - \dot{m}_4 h_4 = \dot{m}_8(h_9 - h_8)$$
$$\dot{m}_9 = \dot{m}_8$$
$$\varepsilon_H = max\left\{\frac{h_9 - h_8}{h_{9,id} - h_8}, \frac{h_3 - h_4}{h_3 - h_{4,id}}\right\}$$

The dehumidifier is:

$$\dot{m}_7 = \dot{m}_6$$
$$\dot{m}_5 = \dot{m}_6(\varpi_6 - \varpi_7)$$
$$\dot{m}_6(h_6 - h_7) = \dot{m}_2(h_3 - h_2) + \dot{m}_5 h_5$$
$$\varepsilon_D = max\left\{\frac{h_6 - h_7}{h_6 - h_{7,id}}, \frac{h_3 - h_2}{h_{3,id} - h_2}\right\}$$

where, the enthalpy is h, the humidity of the ratio is ϖ, the usefulness of the heat exchangers is ε, and the id is the ideal of air outlet enthalpy.

For the exergy of solar intensity is:

$$Ex_{solar} = I_t.Aperture\left[1 - \frac{4}{3}\left(\frac{T_0}{T_{sun}}\right) + \frac{1}{3}\left(\frac{T_0}{T_{sun}}\right)^4\right] T_{sun} \approx 6000K$$

The asset cost per hour is estimated ($\dot{Z}_k$) as:

$$\dot{Z}_k = \left[\frac{CRF.\varphi}{H_{opr}}\right] Z_k$$

where, the asset price of the *k*th component is Z_k, the capital retrieval factor is *CRF*, the maintenance factor is φ, and yearly process hours is H_{opr}.

For the economic factor (ξ) and the effect of *CRF* are estimated as:

$$\xi = CRF \frac{\varphi}{H_{opr}}$$

3.5 Multi-effect distillation-vapor compression (MED-VC) desalination using solar thermal power

Sharaf et al. [90] have developed a solar thermal-based multi-effect distillation-vapor compression (MED-VC) system. The analysis conducted in this study adopts an exergy and tempo-economic methodology. The research employs a combination of multi-effect thermal distillation and mechanical vapor compression techniques. The steam compressor is also powered by electrical energy generated from organic diesel. The system achieves a distillate production output of 4545 m^3/day. The system effectively reduces energy consumption costs, solar panel area requirements, and thermo-economic costs by reducing the compression ratio.

For the exergy destruction or loss in the solar collector $\dot{Ex}_{Collector}$ is calculated as:

$$\dot{Ex}_{Collector} = A_{collector} G_b \left(1 + \frac{1}{3}\left(\frac{T_{amb}}{T_{sun}}\right)^4 - \frac{4}{3}\left(\frac{T_{amb}}{T_{sun}}\right)\right) + \dot{m}_{col}[h_i - h_o - T_{amb}(s_i - s_o)]$$

$$\dot{Ex}_{turbine} = \dot{m}[\Delta h_{i-o} - T_{amb} \times \Delta S_{i-o}] - W_{turbine}$$

$$\dot{Ex}_{rec,cond} = \dot{m}_{hot}[\Delta h_{i-o} - T_{amb} \times \Delta S_{i-o}]_{hot} + \dot{m}_{cold}[\Delta h_{i-o} - T_{amb} \times \Delta S_{i-o}]_{cold}$$

$$\dot{Ex}_{pump} = \dot{m}[\Delta h_{i-o} - T_{amb} \times \Delta S_{i-o}] - W_{pump}$$

$$\dot{Ex}_{MED} = \Delta\dot{Ex}_{steam} = W_{pumps} - W_{turbine} + \dot{Ex}_f + \dot{Ex}_b - \dot{Ex}_d$$

where, the exergy stream of the vapor disorder is $\dot{Ex}_{steam}$, for the chemical and physical exergy stream is $\dot{Ex}_d$, the exergy stream related to brine and deserted as damage stream is $\dot{Ex}_b$, the chemical and physical exergy of seawater food watercourse to the MED belongings is $\dot{Ex}_f$.

$$W_{f,d,b} = h_0 + \left(A \times T + \frac{B}{2} \times T^2 + \frac{C}{3} \times T^3 + \frac{D}{4} \times T^4\right)$$

where,
$h_0 = 9.6296 \times S - 0.4312402 \times S^2$;
$A = 4206.8 - 6.6197 \times S + 1.2288 \times 10^{-2} \times S^2$;
$B = -1.1262 + 5.4178 \times 10^{-2} \times S - 2.2719 \times 10^{-4} \times S^2$;
$C = 1.2026 - 5.3566 \times 10^{-4} \times S - 1.8906 \times 10^{-6} \times S^2$;
$D = 6.8774 \times 10^{-7} + 1.517 \times 10^{-6} \times S - 4.4268 \times 10^{-9} \times S^2$.

The physical exergy equation for any salty watercourse (kg/s) is calculated as follows:

$$\dot{Ex}_{ph} = m\left(C_p(T,S) \times (T - T_o) \times C_p(T,S) log \frac{T}{T_o}\right),$$
$$(T_o = \text{reference temperature})$$

The chemical share of the exergy watercourse (kg/s) is calculated as follows:

$$\dot{Ex}_{ch} = m(N_{mol}(S, M_w, M_s) \times 10^{-3} \times 8.314 \times T_o\{-X_w \times logX_w - X_s \times logX_w\})$$

The Overall stream exergy rate is calculated as follows:

$$\dot{Ex}_{total} = \dot{Ex}_{ph} + \dot{Ex}_{ch}$$

where,
$X_w = N_{pure}(S, M_w)/N_{mol}(S, M_w, M_s)$;
$X_s = N_{salt}(S, M_w)/N_{mol}(S, M_w, M_s)$;
$N_{pure} = (1000 - S)/M_w$; $N_{salt} = S/M_s$.

The number of particles is the combination of N_{salt}+N_{pure}, the portion of water and salt are X_w and X_s respectively. And the molar weight $M_{w,s}$.

For the exergy efficiency of this study is:

$$\eta_{ex} = 1 - \frac{\dot{Ex}_{total}}{Ex_{in}}$$

3.6 Flat plate solar collector desalination process with multi-stage flash (MSF)

The advancement of desalination technology persists due to the increasing scarcity of clean water in various regions, particularly arid areas. The traditional desalination industry heavily relies on fossil fuels, which not only have a negative impact on the environment but also come at a significant cost. Consequently, this study focuses on developing multi-stage flash (MSF) solar desalination technology, which utilizes renewable energy sources. The research findings indicate that this technology offers optimal cost and performance compared to conventional desalination methods. It reduces atmospheric pressure by up to 20% compared to traditional techniques while increasing the evaporation ratio by up to 53% and reducing energy consumption by up to 35%. The most efficient desalination ratio achieved is 0.5L/min [97].

For the energy input equation of the solar MSF, desalination ($\dot{Q}_{insol}$) is calculated as:

$$\dot{Q}_{insol} = IA_a$$

For the thermal energy engrossed by the mixing saltwater ($\dot{Q}_b$) is assessed as:

$$\dot{Q}_b = \dot{m}_b C_p(T_4 - T_3)$$

The efficiency of solar collectors is:

$$\eta = \frac{\dot{Q}_b}{\dot{Q}_{insol}}$$

The leading energy equation at the boiler basis is:

$$\dot{Q}_b = \eta \dot{Q}_{insol}$$

The specific thermal energy input is:

$$\frac{\dot{Q}_b}{\dot{m}_d} = \frac{\dot{m}_b C_p(T_4 - T_3)}{\dot{m}_d}$$

The specific available energy consumption is:

$$E = \frac{W_{wp} + W_{vp}}{\dot{m}_d}$$

For the specific feed flow rate $= \frac{\dot{m}_b}{\dot{m}_d}$:

$$\sum_{i=1}^{n} \dot{m}_{vn} = \sum_{i=1}^{n} \frac{\dot{m}_{bn} C_p (T_{bn} - T_{vn})}{\lambda_n}$$

The water efficiency in the chamber is defined as:

$$\eta_{distillation} = \frac{\sum_{i=1}^{n} \dot{m}_{bn}}{\sum_{i=1}^{n} \dot{m}_{nv}}$$

4. CONCLUSIONS

Desalination technology is continuously evolving and progressing in response to the growing global population and the increasing demand for clean water. However, the cost of implementing desalination technology remains relatively high. As a result, the integration of desalination technology with renewable energy sources holds great promise, particularly in remote areas. Despite the higher cost associated with desalination using renewable energy, it still competes with conventional energy sources due to its environmentally friendly and sustainable nature. Among the different desalination methods, thermal methods, such as Multi-Effect Distillation (MED) and Multi-Stage Flash (MSF), consume a significant amount of energy, primarily due to the large energy requirement for evaporation. On the other hand, the membrane method, specifically Reverse Osmosis (RO), has proven to be more efficient compared to other methods. The average production cost of the RO process is approximately 0.45$/m^3, making it a cost-effective option. Wave-powered RO, utilizing renewable energy, offers the lowest cost among other renewable energy sources, estimated at around 0.95$/m^3. The solar-powered MED system follows with a cost of 2.55 $/m^3, the solar-powered MSF system at 3.0 $/m^3, and the wind-powered RO at 3.6 $/m^3. It is worth noting that the highest cost is associated with the RO system integrated with solar panels. This review provides mathematical models for both thermal and membrane desalination methods. These models offer an overview of the variables and analysis required in a desalination system incorporating renewable energy. It is hoped that this review will assist readers in developing environmentally friendly and sustainable desalination technology in the future.

REFERENCES

[1] Mekonnen, M.M., Hoekstra, A.Y. (2016). Sustainability: Four billion people facing severe water scarcity. Science Advances, 2(2). https://doi.org/10.1126/sciadv.1500323

[2] Gökçek, M., Gökçek, Ö.B. (2016). Technical and economic evaluation of freshwater production from a wind-powered small-scale seawater reverse osmosis system (WP-SWRO). Desalination, 381: 47-57. https://doi.org/10.1016/j.desal.2015.12.004

[3] Alawad, S.M., Ben Mansour, R., Al-Sulaiman, F.A., Rehman, S. (2023). Renewable energy systems for water desalination applications: A comprehensive review. Energy Conversion and Management, 286: 117035. https://doi.org/10.1016/j.enconman.2023.117035

[4] Shatat, M., Worall, M., Riffat, S. (2013). Opportunities for solar water desalination worldwide. Sustainable Cities and Society, 9: 67-80. https://doi.org/10.1016/j.scs.2013.03.004

[5] Lattemann, S., Kennedy, M.D., Schippers, J.C., Amy, G. (2010). Global desalination situation. Sustainability Science and Engineering, 2: 7-39. https://doi.org/10.1016/S1871-2711(09)00202-5

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

[7] Lattemann, S., Höpner, T. (2008). Environmental impact and impact assessment of seawater desalination. Desalination, 220(1-3): 1-15. https://doi.org/10.1016/j.desal.2007.03.009

[8] Dawoud, M.A. (2012). Environmental impacts of seawater desalination: Arabian Gulf case study. International Journal of Environment and Sustainability, 1(3): 96. https://doi.org/10.24102/ijes.v1i3.96

[9] Wenten, I.G., Ariono, D., Purwasasmita, M., Khoirudin, K. (2017). Integrated processes for desalination and salt production: A mini-review. AIP Conference Proceedings, 1818(1): 020065. https://doi.org/10.1063/1.4976929

[10] Mendez, D.L.M., Castel, C., Lemaitre, C., Favre, E. (2018). Membrane distillation (MD) processes for water desalination applications. Can dense selfstanding membranes compete with microporous hydrophobic materials? Chemical Engineering Science, 188: 84-96. https://doi.org/10.1016/j.ces.2018.05.025

[11] Müller-Holst, H. (2007). Solar thermal desalination using the multiple effect humidification (MEH)-method. In Solar Desalination for the 21st Century: A Review of Modern Technologies and Researches on Desalination Coupled to Renewable Energies, pp. 215-225. https://doi.org/10.1007/978-1-4020-5508-9_16

[12] Ghaffour, N., Bundschuh, J., Mahmoudi, H., Goosen, M.F. (2015). Renewable energy-driven desalination technologies: A comprehensive review on challenges and potential applications of integrated systems. Desalination, 356: 94-114. https://doi.org/10.1016/j.desal.2014.10.024

[13] Manju, S., Sagar, N. (2017). Renewable energy integrated desalination: A sustainable solution to overcome future fresh-water scarcity in India. Renewable and Sustainable Energy Reviews, 73: 594-609. https://doi.org/10.1016/j.rser.2017.01.164

[14] Alkaisi, A., Mossad, R., Sharifian-Barforoush, A. (2017). A review of the water desalination systems integrated with renewable energy. Energy Procedia, 110: 268-274. https://doi.org/10.1016/j.egypro.2017.03.138

[15] Abdelkareem, M.A., Assad, M.E.H., Sayed, E.T., Soudan, B. (2018). Recent progress in the use of renewable energy sources to power water desalination plants. Desalination, 435: 97-113. https://doi.org/10.1016/j.desal.2017.11.018

[16] Ali, A., Tufa, R.A., Macedonio, F., Curcio, E., Drioli, E. (2018). Membrane technology in renewable-energy-driven desalination. Renewable and Sustainable Energy Reviews, 81: 1-21. https://doi.org/10.1016/j.rser.2017.07.047

[17] Nassrullah, H., Anis, S.F., Hashaikeh, R., Hilal, N. (2020). Energy for desalination: A state-of-the-art review. Desalination, 491: 114569. https://doi.org/10.1016/j.desal.2020.114569

[18] Bundschuh, J., Kaczmarczyk, M., Ghaffour, N., Tomaszewska, B. (2021). State-of-the-art of renewable energy sources used in water desalination: Present and future prospects. Desalination, 508: 115035. https://doi.org/10.1016/j.desal.2021.115035
[19] Ifaei, P., Charmchi, A.S.T., Santamouris, M., Yoo, C. (2023). Comprehensive performance evaluation of water and power production technologies using water-exergy nexus analysis. Energy Conversion and Management, 284: 116960. https://doi.org/10.1016/j.enconman.2023.116960
[20] Rahman, M.S., Ahmed, M., Chen, X.D. (2006). Freezing-melting process and desalination: I. Review of the state-of-the-art. Separation & Purification Reviews, 35(02): 59-96. https://doi.org/10.1080/15422110600671734
[21] Badawy, S.M. (2016). Laboratory freezing desalination of seawater. Desalination and Water Treatment, 57(24): 11040-11047. https://doi.org/10.1080/19443994.2015.1041163
[22] Franchini, G., Padovan, L.E., Perdichizzi, A. (2015). Design and construction of a desalination prototype based on HD (Humidification-Dehumidification) process. Energy Procedia, 81: 472-481. https://doi.org/10.1016/j.egypro.2015.12.121
[23] Wang, Y.N., Goh, K., Li, X., Setiawan, L., Wang, R. (2018). Membranes and processes for forward osmosis-based desalination: Recent advances and future prospects. Desalination, 434: 81-99. https://doi.org/10.1016/j.desal.2017.10.028
[24] Li, Z., Linares, R.V., Sarp, S., Amy, G. (2018). Direct and indirect seawater desalination by forward osmosis. In Membrane-Based Salinity Gradient Processes for Water Treatment and Power Generation, pp. 245-272. https://doi.org/10.1016/B978-0-444-63961-5.00009-2
[25] Eltawil, M.A., Zhengming, Z., Yuan, L. (2009). A review of renewable energy technologies integrated with desalination systems. Renewable and Sustainable Energy Reviews, 13(9): 2245-2262. https://doi.org/10.1016/j.rser.2009.06.011
[26] Elsaid, K., Sayed, E.T., Yousef, B.A., Rabaia, M.K.H., Abdelkareem, M.A., Olabi, A.A. (2020). Recent progress on the utilization of waste heat for desalination: A review. Energy Conversion and Management, 221: 113105. https://doi.org/10.1016/j.enconman.2020.113105
[27] Gholizadeh, T., Vajdi, M., Rostamzadeh, H. (2020). A new trigeneration system for power, cooling, and freshwater production driven by a flash-binary geothermal heat source. Renewable Energy, 148: 31-43. https://doi.org/10.1016/j.renene.2019.11.154
[28] Tomaszewska, B., Pająk, L., Bundschuh, J., Bujakowski, W. (2018). Low-enthalpy geothermal energy as a source of energy and integrated freshwater production in inland areas: Technological and economic feasibility. Desalination, 435: 35-44. https://doi.org/10.1016/j.desal.2017.12.032
[29] Lee, H.J., Sarfert, F., Strathmann, H., Moon, S.H. (2002). Designing of an electrodialysis desalination plant. Desalination, 142(3): 267-286. https://doi.org/10.1016/S0011-9164(02)00208-4
[30] Mathioulakis, E., Belessiotis, V., Delyannis, E. (2007). Desalination by using alternative energy: Review and state-of-the-art. Desalination, 203(1-3): 346-365. https://doi.org/10.1016/j.desal.2006.03.531
[31] Curto, D., Franzitta, V., Guercio, A. (2021). A review of the water desalination technologies. Applied Sciences, 11(2): 670. https://doi.org/10.3390/app11020670
[32] Amy, G., Ghaffour, N., Li, Z., Francis, L., Linares, R.V., Missimer, T., Lattemann, S. (2017). Membrane-based seawater desalination: Present and future prospects. Desalination, 401: 16-21. https://doi.org/10.1016/j.desal.2016.10.002
[33] Zarzo, D., Prats, D. (2018). Desalination and energy consumption. What can we expect in the near future? Desalination, 427: 1-9. https://doi.org/10.1016/j.desal.2017.10.046
[34] Voutchkov, N. (2018). Energy use for membrane seawater desalination–current status and trends. Desalination, 431: 2-14. https://doi.org/10.1016/j.desal.2017.10.033
[35] Shahzad, M.W., Burhan, M., Ang, L., Ng, K.C. (2017). Energy-water-environment nexus underpinning future desalination sustainability. Desalination, 413: 52-64. https://doi.org/10.1016/j.desal.2017.03.009
[36] Jiang, S., Li, Y., Ladewig, B.P. (2017). A review of reverse osmosis membrane fouling and control strategies. Science of the Total Environment, 595: 567-583. https://doi.org/10.1016/j.scitotenv.2017.03.235
[37] Sagiv, A., Avraham, N., Dosoretz, C.G., Semiat, R. (2008). Osmotic backwash mechanism of reverse osmosis membranes. Journal of Membrane Science, 322(1): 225-233. https://doi.org/10.1016/j.memsci.2008.05.055
[38] Shemer, H., Semiat, R. (2017). Sustainable RO desalination–Energy demand and environmental impact. Desalination, 424: 10-16. https://doi.org/10.1016/j.desal.2017.09.021
[39] Carta, J.A., González, J., Cabrera, P., Subiela, V.J. (2015). Preliminary experimental analysis of a small-scale prototype SWRO desalination plant, designed for continuous adjustment of its energy consumption to the widely varying power generated by a stand-alone wind turbine. Applied Energy, 137: 222-239. https://doi.org/10.1016/j.apenergy.2014.09.093
[40] Subiela, V.J., Carta, J.A., González, J. (2004). The SDAWES project: Lessons learnt from an innovative project. Desalination, 168: 39-47. https://doi.org/10.1016/j.desal.2004.06.167
[41] National Research Council, Division on Earth, Life Studies, Water Science, Technology Board, Committee to Review the Desalination, & Water Purification Technology Roadmap. (2004). Review of the desalination and water purification technology roadmap. National Academies Press. https://doi.org/10.17226/10912
[42] World Energy Council. (2015). World energy resources: Charting the upsurge in hydropower development 2015.
[43] Gude, V.G., Nirmalakhandan, N., Deng, S. (2010). Renewable and sustainable approaches for desalination. Renewable and Sustainable Energy Reviews, 14(9): 2641-2654. https://doi.org/10.1016/j.rser.2010.06.008
[44] Astariz, S., Iglesias, G. (2015). The economics of wave energy: A review. Renewable and Sustainable Energy Reviews, 45: 397-408. https://doi.org/10.1016/j.rser.2015.01.061
[45] Lai, W., Ma, Q., Lu, H., Weng, S., Fan, J., Fang, H. (2016). Effects of wind intermittence and fluctuation on

reverse osmosis desalination process and solution strategies. Desalination, 395: 17-27. https://doi.org/10.1016/j.desal.2016.05.019
[46] Rahal, Z. (2001). Wind powered desalination. Loughborough University.
[47] Peñate, B., Castellano, F., Bello, A., García-Rodríguez, L. (2011). Assessment of a stand-alone gradual capacity reverse osmosis desalination plant to adapt to wind power availability: A case study. Energy, 36(7): 4372-4384. https://doi.org/10.1016/j.energy.2011.04.005
[48] Carta, J. A., Gonzalez, J., Subiela, V. (2003). Operational analysis of an innovative wind powered reverse osmosis system installed in the Canary Islands. Solar Energy, 75(2): 153-168. https://doi.org/10.1016/S0038-092X(03)00247-0
[49] Pohl, R., Kaltschmitt, M., Holländer, R. (2009). Investigation of different operational strategies for the variable operation of a simple reverse osmosis unit. Desalination, 249(3): 1280-1287. https://doi.org/10.1016/j.desal.2009.06.029
[50] Mohamed, E.S., Papadakis, G., Mathioulakis, E., Belessiotis, V. (2008). A direct coupled photovoltaic seawater reverse osmosis desalination system toward battery based systems—A technical and economical experimental comparative study. Desalination, 221(1-3): 17-22. https://doi.org/10.1016/j.desal.2007.01.065
[51] Manolakos, D., Mohamed, E.S., Karagiannis, I., Papadakis, G. (2008). Technical and economic comparison between PV-RO system and RO-Solar Rankine system. Case study: Thirasia island. Desalination, 221(1-3): 37-46. https://doi.org/10.1016/j.desal.2007.01.066
[52] Kelley, L.C., Dubowsky, S. (2013). Thermal control to maximize photovoltaic powered reverse osmosis desalination systems productivity. Desalination, 314: 10-19. https://doi.org/10.1016/j.desal.2012.11.036
[53] Rahimi, B., Shirvani, H., Alamolhoda, A.A., Farhadi, F., Karimi, M. (2021). A feasibility study of solar-powered reverse osmosis processes. Desalination, 500: 114885. https://doi.org/10.1016/j.desal.2020.114885
[54] Ghafoor, A., Ahmed, T., Munir, A., Arslan, C., Ahmad, S. A. (2020). Techno-economic feasibility of solar based desalination through reverse osmosis. Desalination, 485: 114464. https://doi.org/10.1016/j.desal.2020.114464
[55] Lacroix, C., Perier-Muzet, M., Stitou, D. (2019). Dynamic modeling and preliminary performance analysis of a new solar thermal reverse osmosis desalination process. Energies, 12(20): 4015. https://doi.org/10.3390/en12204015
[56] García-Rodríguez, L., Delgado-Torres, A.M. (2007). Solar-powered Rankine cycles for fresh water production. Desalination, 212(1-3): 319-327. https://doi.org/10.1016/j.desal.2006.10.016
[57] Al-Karaghouli, A., Renne, D., Kazmerski, L.L. (2010). Technical and economic assessment of photovoltaic-driven desalination systems. Renewable Energy, 35(2): 323-328. https://doi.org/10.1016/j.renene.2009.05.018
[58] Fernandez-Gonzalez, C., Dominguez-Ramos, A., Ibañez, R., Irabien, A. (2015). Sustainability assessment of electrodialysis powered by photovoltaic solar energy for freshwater production. Renewable and Sustainable Energy Reviews, 47: 604-615. https://doi.org/10.1016/j.rser.2015.03.018
[59] Gonzalez, A., Grágeda, M., Ushak, S. (2017). Assessment of pilot-scale water purification module with electrodialysis technology and solar energy. Applied Energy, 206: 1643-1652. https://doi.org/10.1016/j.apenergy.2017.09.101
[60] Patel, S.K., Biesheuvel, P.M., Elimelech, M. (2021). Energy consumption of brackish water desalination: Identifying the sweet spots for electrodialysis and reverse osmosis. Acs Es&T Engineering, 1(5): 851-864. https://doi.org/10.1021/acsestengg.0c00192
[61] Shi, L., Rossi, R., Son, M., Hall, D.M., Hickner, M.A., Gorski, C.A., Logan, B.E. (2020). Using reverse osmosis membranes to control ion transport during water electrolysis. Energy & Environmental Science, 13(9): 3138-3148. https://doi.org/10.1039/d0ee02173c
[62] Lundstrom, J.E. (1979). Water desalting by solar powered electrodialysis. Desalination, 31(1-3): 469-488. https://doi.org/10.1016/S0011-9164(00)88551-3
[63] Ortiz, J.M., Expósito, E., Gallud, F., García-García, V., Montiel, V., Aldaz, A. (2008). Desalination of underground brackish waters using an electrodialysis system powered directly by photovoltaic energy. Solar Energy Materials and Solar Cells, 92(12): 1677-1688. https://doi.org/10.1016/j.solmat.2008.07.020
[64] Ishimaru, N. (1994). Solar photovoltaic desalination of brackish water in remote areas by electrodialysis. Desalination, 98(1-3): 485-493. https://doi.org/10.1016/0011-9164(94)00175-8
[65] He, W., Amrose, S., Wright, N.C., Buonassisi, T., Peters, I.M. (2020). Field demonstration of a cost-optimized solar powered electrodialysis reversal desalination system in rural India. Desalination, 476: 114217. https://doi.org/10.1016/j.desal.2019.114217
[66] Chafik, E. (2004). Design of plants for solar desalination using the multi-stag heating/humidifying technique. Desalination, 168: 55-71. https://doi.org/10.1016/j.desal.2004.06.169
[67] Chafik, E. (2003). A new type of seawater desalination plants using solar energy. Desalination, 156(1-3): 333-348. https://doi.org/10.1016/S0011-9164(03)00364-3
[68] El-Agouz, S.A., Abugderah, M. (2008). Experimental analysis of humidification process by air passing through seawater. Energy Conversion and Management, 49(12): 3698-3703. https://doi.org/10.1016/j.enconman.2008.06.033
[69] Müller-Holst, H., Engelhardt, M., Herve, M., Schölkopf, W. (1998). Solarthermal seawater desalination systems for decentralised use. Renewable Energy, 14(1-4): 311-318. https://doi.org/10.1016/S0960-1481(98)00083-4
[70] Antar, M.A., Sharqawy, M.H. (2013). Experimental investigations on the performance of an air heated humidification–Dehumidification desalination system. Desalination and Water Treatment, 51(4-6): 837-843. https://doi.org/10.1080/19443994.2012.714598
[71] Ho, C.D., Yeh, H.M., Wang, R.C. (2005). Heat-transfer enhancement in double-pass flat-plate solar air heaters with recycle. Energy, 30(15): 2796-2817. https://doi.org/10.1016/j.energy.2005.01.006
[72] Zubair, M.I., Al-Sulaiman, F.A., Antar, M.A., Al-Dini, S.A., Ibrahim, N.I. (2017). Performance and cost assessment of solar driven humidification dehumidification desalination system. Energy Conversion and Management, 132: 28-39. https://doi.org/10.1016/j.enconman.2016.10.005
[73] Khalil, A., El-Agouz, S.A., El-Samadony, Y.A.F., Abdo,

A. (2015). Solar water desalination using an air bubble column humidifier. Desalination, 372: 7-16. https://doi.org/10.1016/j.desal.2015.06.010
[74] Behnam, P., Shafii, M.B. (2016). Examination of a solar desalination system equipped with an air bubble column humidifier, evacuated tube collectors and thermosyphon heat pipes. Desalination, 397: 30-37. https://doi.org/10.1016/j.desal.2016.06.016
[75] Wang, J.H., Gao, N.Y., Deng, Y., Li, Y.L. (2012). Solar power-driven humidification–dehumidification (HDH) process for desalination of brackish water. Desalination, 305: 17-23. https://doi.org/10.1016/j.desal.2012.08.008
[76] Elsafi, A.M. (2017). Integration of humidification-dehumidification desalination and concentrated photovoltaic-thermal collectors: Energy and exergy-costing analysis. Desalination, 424: 17-26. https://doi.org/10.1016/j.desal.2017.09.022
[77] Gabrielli, P., Gazzani, M., Novati, N., Sutter, L., Simonetti, R., Molinaroli, L., Manzolini, G., Mazzotti, M. (2019). Combined water desalination and electricity generation through a humidification-dehumidification process integrated with photovoltaic-thermal modules: Design, performance analysis and techno-economic assessment. Energy Conversion and Management: X, 1: 100004. https://doi.org/10.1016/j.ecmx.2019.100004
[78] Giwa, A., Fath, H., Hasan, S.W. (2016). Humidification–dehumidification desalination process driven by photovoltaic thermal energy recovery (PV-HDH) for small-scale sustainable water and power production. Desalination, 377: 163-171. https://doi.org/10.1016/j.desal.2015.09.018
[79] Mohamed, A.M.I., El-Minshawy, N.A.S. (2009). Humidification–dehumidification desalination system driven by geothermal energy. Desalination, 249(2): 602-608. https://doi.org/10.1016/j.desal.2008.12.053
[80] Bourouni, K., Martin, R., Tadrist, L., Tadrist, H. (1997). Experimental investigation of evaporation performances of a desalination prototype using the aero-evapo-condensation process. Desalination, 114(2): 111-128. https://doi.org/10.1016/S0011-9164(98)00003-4
[81] Bourouni, K., Martin, R., Tadrist, L., Tadrist, H. (1998). Modelling of heat and mass transfer in a horizontal-tube falling-film evaporator for water desalination. Desalination, 116(2-3): 165-183. https://doi.org/10.1016/S0011-9164(98)00193-3
[82] He, W.F., Han, D., Wen, T. (2018). Energy, entropy and cost analysis of a combined power and water system with cascade utilization of geothermal energy. Energy Conversion and Management, 174: 719-729. https://doi.org/10.1016/j.enconman.2018.08.089
[83] Ghalavand, Y., Hatamipour, M.S., Rahimi, A. (2015). A review on energy consumption of desalination processes. Desalination and Water Treatment, 54(6): 1526-1541. https://doi.org/10.1080/19443994.2014.892837
[84] Khawaji, A.D., Kutubkhanah, I.K., Wie, J.M. (2008). Advances in seawater desalination technologies. Desalination, 221(1-3): 47-69. https://doi.org/10.1016/j.desal.2007.01.067
[85] Sharon, H.K.S.R., Reddy, K.S. (2015). A review of solar energy driven desalination technologies. Renewable and Sustainable Energy Reviews, 41: 1080-1118. https://doi.org/ 10.1016/j.rser.2014.09.002
[86] Saldivia, D., Rosales, C., Barraza, R., Cornejo, L. (2019). Computational analysis for a multi-effect distillation (MED) plant driven by solar energy in Chile. Renewable Energy, 132: 206-220. https://doi.org/10.1016/j.renene.2018.07.139
[87] Mezher, T., Fath, H., Abbas, Z., Khaled, A. (2011). Techno-economic assessment and environmental impacts of desalination technologies. Desalination, 266(1-3): 263-273. https://doi.org/10.1016/j.desal.2010.08.035
[88] El-Nashar, A.M. (2001). The economic feasibility of small solar MED seawater desalination plants for remote arid areas. Desalination, 134(1-3): 173-186. https://doi.org/10.1016/S0011-9164(01)00124-2
[89] Gholinejad, M., Bakhtiari, A., Bidi, M. (2016). Effects of tracking modes on the performance of a solar MED plant. Desalination, 380: 29-42. https://doi.org/10.1016/j.desal.2015.11.015
[90] Sharaf, M.A., Nafey, A.S., García-Rodríguez, L. (2011). Thermo-economic analysis of solar thermal power cycles assisted MED-VC (multi effect distillation-vapor compression) desalination processes. Energy, 36(5): 2753-2764. https://doi.org/10.1016/j.energy.2011.02.015
[91] Moser, M., Trieb, F., Fichter, T., Kern, J., Hess, D. (2015). A flexible techno-economic model for the assessment of desalination plants driven by renewable energies. Desalination and Water Treatment, 55(11): 3091-3105. https://doi.org/10.1080/19443994.2014.946718
[92] Sharaf, M.A., Nafey, A.S., García-Rodríguez, L. (2011). Exergy and thermo-economic analyses of a combined solar organic cycle with multi effect distillation (MED) desalination process. Desalination, 272(1-3): 135-147. https://doi.org/10.1016/j.desal.2011.01.006
[93] Baccioli, A., Antonelli, M., Desideri, U., Grossi, A. (2018). Thermodynamic and economic analysis of the integration of Organic Rankine Cycle and Multi-Effect Distillation in waste-heat recovery applications. Energy, 161: 456-469. https://doi.org/10.1016/j.energy.2018.07.150
[94] Helal, A.M., Al-Malek, S.A. (2006). Design of a solar-assisted mechanical vapor compression (MVC) desalination unit for remote areas in the UAE. Desalination, 197(1-3): 273-300. https://doi.org/10.1016/j.desal.2006.01.021
[95] Al-Othman, A., Tawalbeh, M., Assad, M.E.H., Alkayyali, T., Eisa, A. (2018). Novel multi-stage flash (MSF) desalination plant driven by parabolic trough collectors and a solar pond: A simulation study in UAE. Desalination, 443: 237-244. https://doi.org/10.1016/j.desal.2018.06.005
[96] Shaaban, S. (2019). Performance optimization of an integrated solar combined cycle power plant equipped with a brine circulation MSF desalination unit. Energy Conversion and Management, 198: 111794. https://doi.org/10.1016/j.enconman.2019.111794
[97] Darawsheh, I., Islam, M.D., Banat, F. (2019). Experimental characterization of a solar powered MSF desalination process performance. Thermal Science and Engineering Progress, 10: 154-162. https://doi.org/10.1016/j.tsep.2019.01.018
[98] Nafey, A.S., Mohamad, M.A., El-Helaby, S.O., Sharaf, M.A. (2007). Theoretical and experimental study of a small unit for solar desalination using flashing process. Energy Conversion and Management, 48(2): 528-538.

https://doi.org/10.1016/j.enconman.2006.06.010
[99] Manjarrez, R., Galvan, M. (1979). Solar multistage flash evaporation (SMSF) as a solar energy application on desalination processes. Description of one demonstration project. Desalination, 31(1-3): 545-554. https://doi.org/10.1016/S0011-9164(00)88557-4
[100] Safi, M.J. (1998). Performance of a flash desalination unit intended to be coupled to a solar pond. Renewable Energy, 14(1-4): 339-343. https://doi.org/10.1016/s0960-1481(98)00087-1
[101] Moustafa, S.M.A., Jarrar, D.I., El-Mansy, H.I. (1985). Performance of a self-regulating solar multistage flash desalination system. Solar Energy, 35(4): 333-340. https://doi.org/10.1016/0038-092X(85)90141-0
[102] Hanafi, A. (1991). Design and performance of solar MSF desalination systems. Desalination, 82(1-3): 165-174. https://doi.org/10.1016/0011-9164(91)85180-3
[103] Al-Weshahi, M.A., Anderson, A., Tian, G. (2013). Exergy efficiency enhancement of MSF desalination by heat recovery from hot distillate water stages. Applied Thermal Engineering, 53(2): 226-233. https://doi.org/10.1016/j.applthermaleng.2012.02.013
[104] Wang, X., Ng, K.C. (2005). Experimental investigation of an adsorption desalination plant using low-temperature waste heat. Applied Thermal Engineering, 25(17-18): 2780-2789. https://doi.org/10.1016/j.applthermaleng.2005.02.011
[105] Thu, K., Saha, B.B., Chakraborty, A., Chun, W.G., Ng, K.C. (2011). Study on an advanced adsorption desalination cycle with evaporator–Condenser heat recovery circuit. International Journal of Heat and Mass Transfer, 54(1-3): 43-51. https://doi.org/10.1016/j.ijheatmasstransfer.2010.09.06
[106] Alnajdi, O., Wu, Y., Kaiser Calautit, J. (2020). Toward a sustainable decentralized water supply: Review of adsorption desorption desalination (ADD) and current technologies: Saudi Arabia (SA) as a case study. Water, 12(4): 1111. https://doi.org/10.3390/W12041111
[107] Patel, J., Patel, K., Mudgal, A., Panchal, H., Sadasivuni, K.K. (2020). Experimental investigations of atmospheric water extraction device under different climatic conditions. Sustainable Energy Technologies and Assessments, 38: 100677. https://doi.org/10.1016/j.seta.2020.100677
[108] Kim, H., Rao, S.R., Kapustin, E.A., Zhao, L., Yang, S., Yaghi, O.M., Wang, E.N. (2018). Adsorption-based atmospheric water harvesting device for arid climates. Nature Communications, 9(1): 1191. https://doi.org/10.1038/s41467-018-03162-7
[109] Ng, K.C., Thu, K., Saha, B.B., Chakraborty, A. (2012). Study on a waste heat-driven adsorption cooling cum desalination cycle. International Journal of Refrigeration, 35(3): 685-693. https://doi.org/10.1016/j.ijrefrig.2011.01.008
[110] Rezk, H., Alsaman, A.S., Al-Dhaifallah, M., Askalany, A.A., Abdelkareem, M.A., Nassef, A.M. (2019). Identifying optimal operating conditions of solar-driven silica gel based adsorption desalination cooling system via modern optimization. Solar Energy, 181: 475-489. https://doi.org/10.1016/j.solener.2019.02.024
[111] Sleiti, A.K., Al-Khawaja, H., Al-Khawaja, H., Al-Ali, M. (2021). Harvesting water from air using adsorption material–Prototype and experimental results. Separation and Purification Technology, 257: 117921. https://doi.org/10.1016/j.seppur.2020.117921
[112] Asim, N., Badiei, M., Alghoul, M.A., Mohammad, M., Samsudin, N.A., Amin, N., Sopian, K. (2021). Sorbent-based air water-harvesting systems: Progress, limitation, and consideration. Reviews in Environmental Science and Bio/Technology, 20: 257-279. https://doi.org/10.1007/s11157-020-09558-6
[113] Jarimi, H., Powell, R., Riffat, S. (2020). Review of sustainable methods for atmospheric water harvesting. International Journal of Low-Carbon Technologies, 15(2): 253-276. https://doi.org/10.1093/ijlct/ctz072
[114] Peng, W., Maleki, A., Rosen, M.A., Azarikhah, P. (2018). Optimization of a hybrid system for solar-wind-based water desalination by reverse osmosis: Comparison of approaches. Desalination, 442: 16-31. https://doi.org/10.1016/j.desal.2018.03.021