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REVIEW OF SOLAR ENERGY APPLICATIONS FOR WATER TREATMENT; A GLOBAL AND AFRICAN PERSPECTIVE

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Abstract

Solar energy is energy derived from the sun's radiation. The sun's energy can be exploited using a variety of technologies, including (a) photovoltaic (PV)/concentrator photovoltaics (CPV) systems that convert photons to electricity; and (b) solar thermal technologies that capture thermal energy from the sun's radiation using solar collectors or concentrated solar power systems (CSP). Due to the quest for power supply from renewable, cheap, and non-gaseous emission sources coupled with the attempts to combat the shortage of potable water in rural areas, much research on the interface of solar energy power systems with water treatment plants has been reported. However, the greater part of the existing reports are based on theoretical modelling, with only minimal experimental, cost analysis, pilot projects and strategic studies. Also, even though solar-powered water treatment technologies are still in the early stages of research, and very rare studies based on real plants have been conducted, existing publications are mostly focused on single principles, making it impossible to assess and compare several technologies. Globally, this review has particularly highlighted the recent advances in the application of solar energy technologies in desalination and wastewater treatments. It likewise highlighted the key research findings and the critical gaps in the existing achievements. It further highlighted the attempts made on hybrid techniques with other renewable energy sources such as wind and geothermal energies which are paramount for scaling up and commercialization uses. However, the findings revealed that most of these studies were restricted to particular parts of the globe without candid evidence from the African perspective, especially

Sub-Saharan Africa. Thus, due to the paucity of information concerning this topic within the region, there is a need for further studies on the application of solar energy for water treatment, especially on a pilot scale level for sustainable development.

Keywords: desalination, wastewater, renewable energy, photovoltaic and sustainability

PRZEGLĄD ZASTOSOWAŃ ENERGII SŁONECZNEJ DO OCZYSZCZANIA ŚCIEKÓW; PERSPEKTYWA GLOBALNA I AFRYKAŃSKA

Abstrakt

Energia pochodząca z promieniowania słońca może być eksploatowana przy użyciu różnorodnych technologii, w tym (a) fotowoltaiki (PV)/skoncentrowanej fotowoltaiki (CPV), systemów, które przekształcają fotony w energię elektryczną; i (b) słoneczne technologie cieplne, które wychwytują energię cieplną z promieniowania słonecznego przy pomocy kolektorów słonecznych lub skoncentrowanych systemów energii słonecznej (CSP). Z powodu poszukiwań dostaw energii ze źródeł odnawialnych, tanich i nie emitujących zanieczyszczeń gazowych, a także wysiłków na rzecz walki z niedoborem wody pitnej w obszarach wiejskich, opublikowano wiele badań na temat systemów pozyskiwania energii słonecznej dla obsługi oczyszczalni ścieków. Jednakże większość istniejących opracowań oparta jest o modelowanie teoretyczne, jedynie z minimalną częścią eksperymentalną, analizą kosztów, projektami pilotażowymi i studiami strategicznymi. Co więcej, technologie oczyszczania wody zasilane energią słoneczną wciąż są na wczesnym etapie, a prace dotyczące badań w prawdziwych oczyszczalniach są rzadkie, publikacje w większości skupiają się na pojedynczych przypadkach, uniemożliwiając porównywanie kilku technologii wykorzystujących energię słoneczną do odsalania wody i oczyszczania ścieków. Wskazuje również kluczowe wyniki badań oraz istotne braki w istniejącym stanie zaawansowania. Ponadto przedstawia próby z technikami hybrydowymi, wykorzystującymi inne odnawialne źródła energii, takie jak wiatr i energia geotermalna, które są kluczowe w zwiększaniu skali produkcji i komercjalizacji. Jednakże wyniki badań wskazują, że większość prac ograniczona jest do innych kontynentów; brak jest jasnej afrykańskiej perspektywy, szczególnie dotyczącej Afryki subsaharyjskiej. Tak więc, z powodu skąpych informacji na ten temat, które dotyczą tego regionu, istnieje potrzeba dalszych badań nad zastosowaniem energii słonecznej do oczyszczania ścieków, szczególnie w skali pilotażowej, które przyczynią się do zrównoważonego rozwoju.

Słowa kluczowe: odsalanie, ścieki, energia odnawialna, fotowoltaika, zrównoważony rozwój

1. INTRODUCTION

It is no longer a gain-say that renewable energy technologies are indeed contributing significantly to widespread access to carbon-free energy. Renewable energy capacity is currently added annually at a faster rate than all fossil fuel capacity combined [1]. This will also have a significant influence on water availability. Only 84 percent of the world's population have access to electricity, suggesting that about 1.2 billion people are still without it, as stated by several authors [2, 3].

Water and energy are reciprocally linked: fulfilling energy needs requires water in mining, fuel production, hydropower, power plant cooling, pumping, collection, treatment, and the discharge of wastewater. "This interrelationship is often referred to as the energy-water nexus, or the water-energy nexus" [4, 5]. Power and water supply are widely recognized as the two major issues mankind will have to face and solve during this century [6]. While it is evident that oil will lose its dominance in the next decades, it is unclear what energy source will take its place. Simultaneously, water shortage, which is currently a major worldwide issue, will become crucial in the first half of this century. Energy and water issues are perhaps the most difficult to handle scientifically, and they will have the greatest long-term repercussions of all the present environmental issues. Water shortage issues, as well as the slow loss and pollution of fresh water supplies, are becoming more prevalent in many parts of the world, creating alarm even in countries that have not previously had such issues [6]. The treatment of wastewater containing pesticides and organochlorine compounds has recently attracted a growing commitment from the scientific community because of their high toxicity and persistent character, which can affect not only the ecosystems but also human health [7–9].

Recently, proposals have been made for the powering of electrochemical processes with green energy sources, like solar photovoltaic or wind [10–12].

The most promising hybrid systems are those that integrate multiple desalination methods and energy sources [13]. Novel hybrid solar (or wind) energy driven systems combined with highly efficient desalination processes offer promise in areas with increasing water scarcity and high solar radiation [14]. This paper addresses the applications of solar power for water treatment on a global scale and an African perspective. It does so by highlighting important research discoveries as well as major gaps in the present literature. A brief introduction and description of the procedures employed are offered for each solar technique. Finally, there is a complete conclusion as well as a list of requirements.

2. SOLAR ENERGY

Solar energy is solar radiation that can be used in a variety of ways, including solar thermal technologies that use solar collectors or concentrated solar power (CSP) to extract thermal energy from the sun's radiation, and solar electricity – photovoltaic (PV)/concentrator photovoltaics (CPV) – solar modules that use photons to convert solar energy into electricity [14].

2.1. Solar thermal – solar collector and CSP

By the middle of the century, solar thermal electricity, or STE (also known as CSP or Concentrating Solar Power), is predicted to have a significant influence on the world's bulk power supply [15, 16]. Today, commercial initiatives in Spain, the United States, and other nations such as Israel, India, Italy, China, Algeria, and Australia are quickly boosting high-temperature thermal conversion of concentrated solar energy [16].

One of the most prominent, ubiquitous, and oldest Renewable Energy Systems (RES) applications in the world is thermal desalination. The heat created by solar radiation is used in a variety of technologies like; Multi-stage Flash (MSF), Vapour Compression Distillation (VCD), and Multi Effect Distillation (MED). These are energy-intensive systems, especially when utilized in places with higher salinity (up to 45 g/L), such as the Middle East [17].

CSP is a method of generating electricity that uses concentrated solar energy in a small area, as well as mirrors to focus and convert sunlight into heat. The four CSP technologies include parabolic trough collector systems, linear Fresnel reflectors, solar/power towers, and parabolic dish collectors. Power towers and parabolic trough collectors are the most often used [18]. The working principles of the parabolic trough power plants, and the potentials of concentrating solar power in Algeria has been reviewed by [19]. The review highlights the competitive viability of CSP plants. According to [19], Algeria prioritizes economical CSP power generation due to the high-quality insolation, land availability, and extensive transmission and power grid. According to [14], when compared to alternative options, this technique requires large areas, which might be a barrier to investment. While the performance and efficiency of solar parabolic trough collector has been presented by [20], highlighting the pertinent applications in air heating system, desalination, refrigeration, industrial heating purposes and power plants.

A technoeconomic model to evaluate the feasibility of combining solar collectors with thermal desalination systems has been developed by [21]. The model took into account how system lifespan and size, unit pricing and functional properties for each component, as well as local market and environmental constraints at the plant site, influenced discounted water production costs and payback periods [21]. They believe that this strategy overcomes technological and geographic constraints. The goal of the technoeconomic model was to estimate the expenses of a multi-stage solar flash distillation system. The subsidized water production cost for a plant generating 1000 m^3/day is \$0.97/m^3 if a solar collector unit costs \$100/m^2 and runs at 40% efficiency. According to commercial and environmental criteria, Miami, Florida is the most economically feasible geographic location for a solar desalination plant among seven coastal cities in the United States [21]. As indicated in Fig. 1, a desalination facility has two distinct income streams: (i) brine-derived freshwater, and (ii) brine-derived value-added goods.

A research on a thermal concentrated multistage distiller for solar desalination has been carried out [22]. A thermal concentrator was coupled to a multistage evaporator-condenser arrangement in the distiller. On the upper surface of the thermal concentrator, which has a high solar absorptance of 0.935 and a low emittance of 0.150, solar energy may be efficiently converted into heat for high temperature vapor formation while reducing radiation loss [22]. The multistage distiller with concentric expansion evaporator-condenser construction recovers the latent heat of vapor effectively while

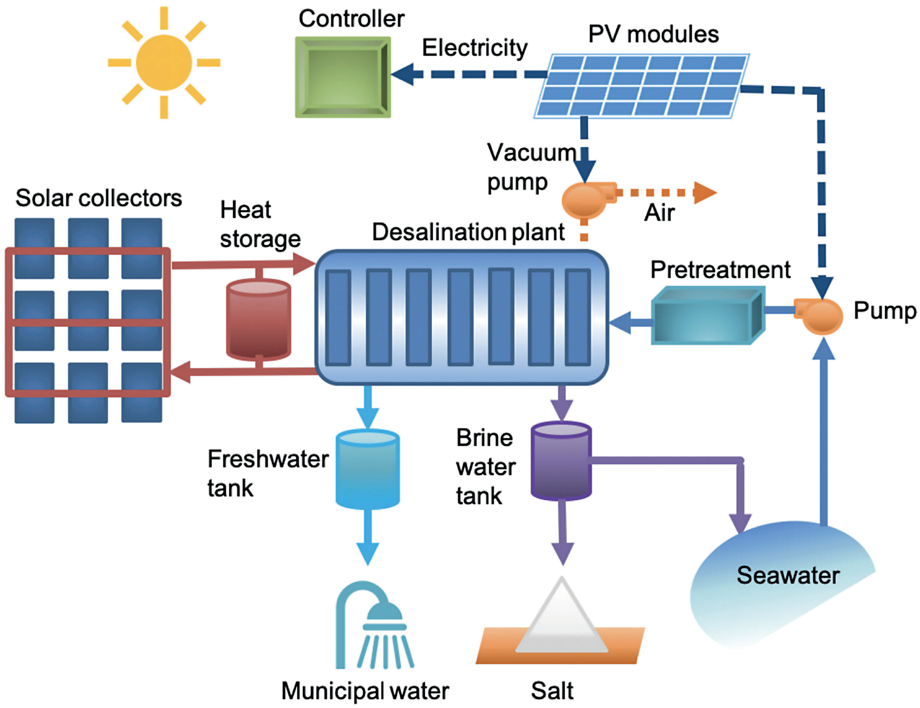

Fig. 1. Schematic of solar thermal integrated desalination plant which shows the economic considerations adapted from [21]
Ryc. 1. Schemat zintegrowanej słoneczno-cieplnej odsalarni wody, biorącej pod uwagę aspekty ekonomiczne, opracowanie na podstawie [21]

reducing heat losses and water diffusion resistance. As a consequence, a 6-stage distiller with a solar intensity of 1 kW m^2 and 3 times thermal concentration was able to provide a high water output of 2.2 kg m^2 h1. Even with a modest solar intensity of 415 W m^2, outdoor studies on rooftops showed that the water production may reach 3.9 kg m^2 per day. This innovative design with increased water production offers a viable solution for harvesting sunlight for small-scale solar desalination in isolated areas [22].

Likewise, an overview of Thermal Energy Storage (TES) systems as well as an update on the most recent breakthroughs in various TES technologies that are either commercially available or under study has been provided by [23]. The limits of each technology, as well as several creative approaches for improving heat transfer efficiency, the primary applications, and environmental issues associated with TES integration in solar thermal CSP systems, were all discussed [23]. In terms of the environment, a case study on Moroccan CSP quantified the possibility of integrating TES in CSP facilities for electricity production in order to reduce greenhouse gas emissions considerably [23].

In order to analyse system integration and performance constraints, [24] developed a thermodynamic model of a perfect concentrating solar distillation process (specific water production). Three different heating topologies were used to evaluate the impacts of solar collector absorber temperature, concentration ratio, and recovery ratio on system performance. The authors discovered that they must utilize proper heating designs and regulate absorber temperatures, system recovery ratios, and system irreversibilities for the optimal integration of solar collectors with thermal desalination systems [24]. The table 1 compares the latest researches on solar thermal technology.

Table 1 reveals that up till this moment, theoretical modelling remains the main investigation approach for solar thermal integrated water plant systems with minimal experimental study and critical reviews. Thus, it is obvious that, solar thermal – solar collector and CSP integrated water treatments systems have been utilized in few places around the world (Fig. 1). Again, the few experimental studies were performed majorly on a small scale level with no evidence of commercial scale recently.

Table 1. Summary of key findings and achievements from studies on solar thermal – solar collector and CSP
Tabela 1. Zestawienie kluczowych wynalazków i osiągnięć badań nad energią słoneczną do produkcji ciepła –kolektor słoneczny i skoncentrowane systemy energii społecznej

Author, Year	Study Aim	Technique	Findings and Achievements
[24]	To investigate the performance limitations of a thermal desalination process with three alternative solar collector heating topologies (direct, lumped and cascade,), a thermodynamic model was developed.	Modelling	Solar collectors were effectively incorporated with thermal desalination systems.
[21]	To develop a techno-economic model that assesses the viability of integrating solar collectors with thermal desalination systems.	Modelling	Solar thermal desalination plants are ideal for regions where there is plenty of sunlight but not enough water.
[22]	For solar desalination, a thermal concentrated multistage distiller was reported.	Experimental	This novel design with enhanced water yield provides an effective approach to harvest sunlight for small-scale solar desalination in remote regions.
[23]	Review on Thermal Energy Storage (TES) systems and the latest developments on the different TES that are commercially available or under investigation	Review	Many characteristics and limitations of each technology, as well as the primary uses and environmental concerns related with their discussion on integrating TES with solar thermal CSP systems.
[25]	The main goal of this study was to provide a detailed review of the Moroccan parabolic trough solar thermal power plant Noor 1, which is considered one of the best in Africa and the Middle East.	Case Study--Review	The key reasons for the site selection were discussed, as well as a full technical description of the facility. For the first time, similar parabolic trough solar thermal power plants from around the world were studied and compared for the first time. It was also determined that Noor 1 specific energy generation is among the best of the plants studied (superior to 61.5 percent of other plants).

2.2. Solar electricity – PV and CPV

Two types of solar technology include flat-plate PV modules, which are the most extensively used, and concentrated photovoltaic (CPV) technology, which is still in development [26]. The key distinction between the two technologies is that CPV uses DNI (define) as a sun source rather than Global Irradiation (GI). PV installations have the undeniable benefit of being simple to install in practically any place as long as the local solar radiation levels are sufficient [14]. It is also worth noting that most regions with a lack of freshwater have relatively high amounts of solar irradiance, enabling for the generation of the energy required for desalination operations [27].

A feasibility analysis on the desalination of water in the Egyptian deserts utilizing solar energy as the major source of energy was investigated by [28]. A design of a PV powered small scale reverse osmosis water desalination system was studied including its economic values. The cost of generating 1 m^3 of fresh water with tiny PV-powered RO water desalination devices was determined to be $3.73. This estimate was based on a small system that only runs during the day. As a result, increasing the system's capacity and length of operation lowers the cost of providing fresh water. The authors further suggested that employing renewable energy sources in feeding the different systems (what system) in the rural areas would maintain their clean environment clean.

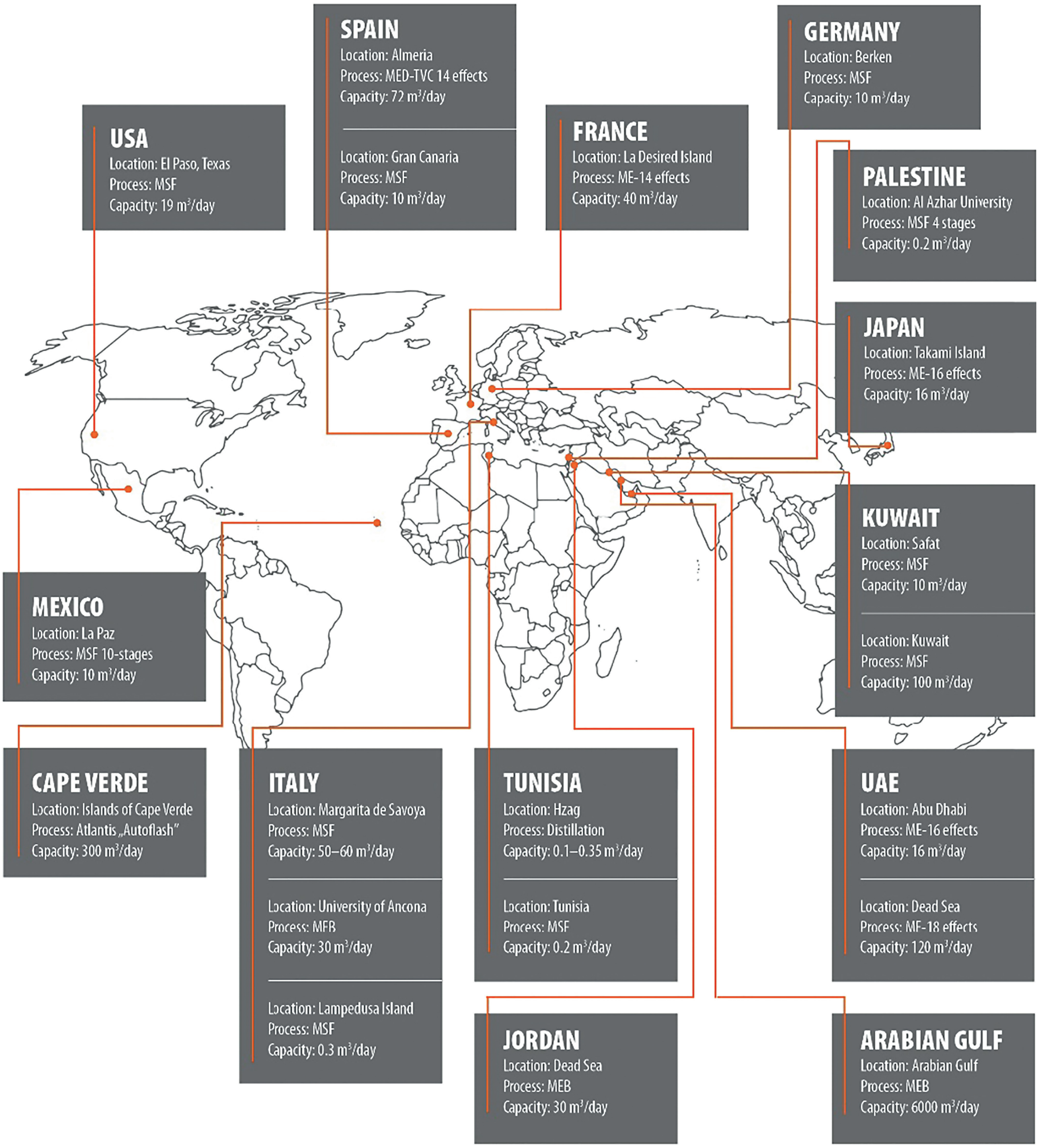

Fig. 2. Various solar thermal desalination plants across the world (Adapted from [14]).
Ryc. 2. Różne słoneczne odsalarnie termiczne w świecie (opracowane na podstawie [14])

In order to power a Sea Water Reverse Osmosis (SWRO) desalination plant in the tiny town of Ginostra in Sicily, [29] created a diesel-powered PV. Using a suggested energy management approach, an hourly simulation of the hybrid system with the desalination plant was done. When comparing energy usage with and without the proposed energy management strategy, the number of diesel operational hours was used as a differentiating measure [29].

The possibility of desalinating brackish water using an electrodialysis system powered by photovoltaic energy, as well as the impact of experimental parameters was investigated by [30]. Likewise, a mathematical simulation model was developed that allows for the

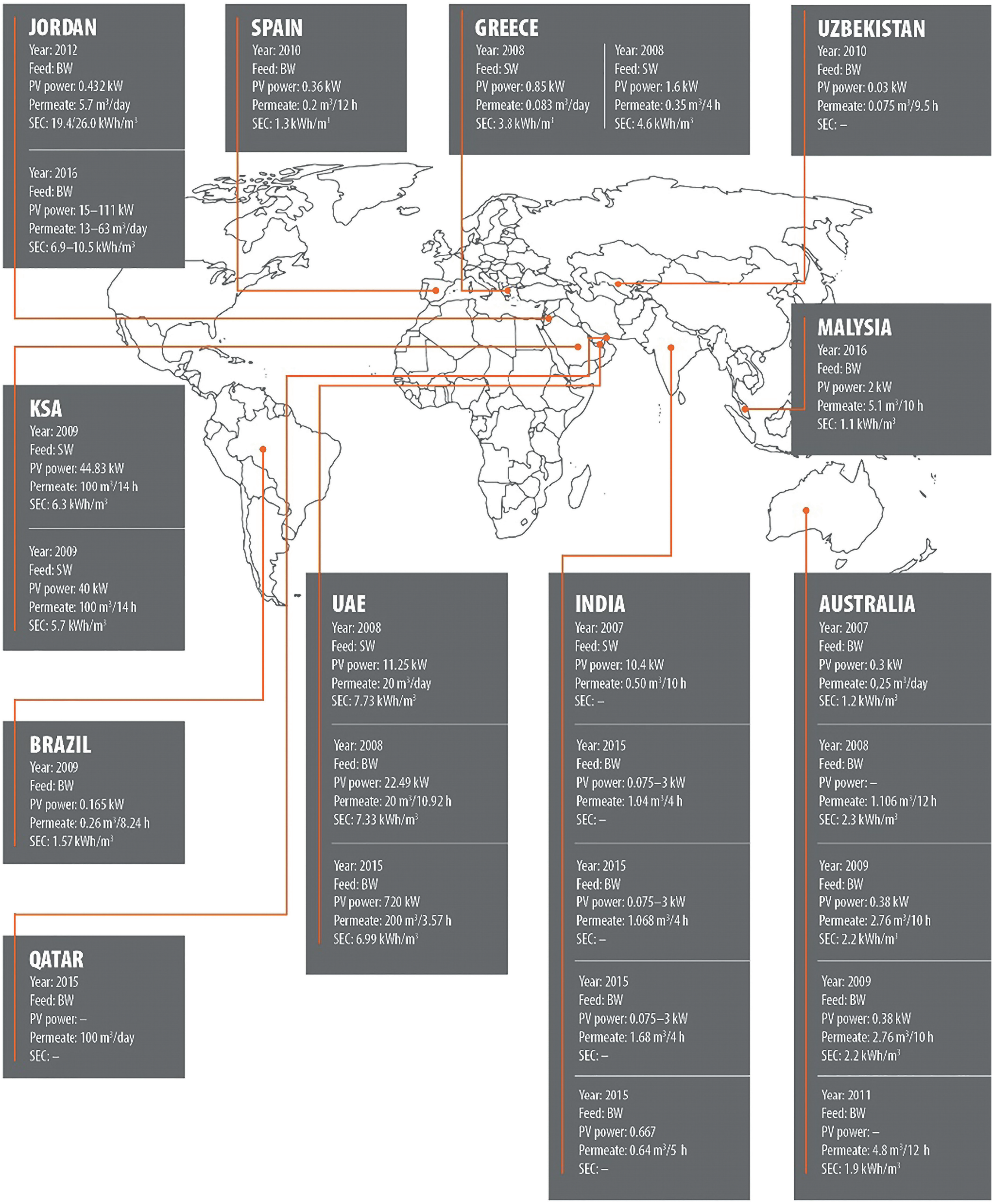

Fig. 3. Selected PV desalination installations worldwide (Adapted from [14]).
Ryc. 3. Wybrane odsalarnie fotowoltaiczne w świecie (opracowane na podstawie [14])

prediction and simulation of the system's operation under various meteorological conditions. The model was successfully used to the desalination of a NaCl solution under various experimental settings. To assess the model's dependability, data from the mathematical simulation model were compared to experimental results, and excellent agreement was found [30]. The use of this model facilitated the creation of an electrodialysis system driven by solar energy (electrodialyzer size and number and configuration of PV modules) for the desalination of brackish water, as well as the investigation of its suitability in various geographical areas.

In another study according to [31], using reverse osmosis desalination in conjunction with brine-operated pump storage units, driven by integrated wind and (PV) photovoltaic facilities reveals could help Jordan address its environmental and energy concerns. In their research, the authors proposed six possibilities for the growth of Jordan's energy system until 2050. According to the authors, desalination plants can provide much-needed water while also acting as a flexible demand to help increase the penetration of intermittent renewables supported by brine-operated pump storage units. Furthermore, the findings revealed that the presented configuration can enhance the contribution of intermittent renewables in electricity production by up to 76%, leading to significant fuel savings, CO_2 emissions, and cost savings [31].

Meanwhile, an overview on the use of solar energy in operating desalination systems was presented by [32]. The expense of implementing desalination plants integrated with photovoltaic (PV)-driven RO systems,

Table 2. Summary of the key findings and achievements from studies on solar electricity – PV and CPV
Tabela 2. Zestawienie kluczowych wynalazków i osiągnięć w badaniach nad wykorzystaniem energii słonecznej do produkcji elektryczności – PV i CPV

Author, Year	Study Aim	Approach	Findings and Achievements
[32]	Present a summary of how solar energy may be used to power desalination facilities.	Review	When the cost of electric energy storage in batteries is combined with the intermittent solar energy supply that lasts about one-third of the day, the PV-RO desalting system has the greatest specific capital outlay for cost among the studied systems, according to the research.
[31]	Reverse osmosis desalination integrated with wind and (PV) photovoltaic power for tackling environmental and energy related issues in Jordan.	Case-Study Modelling	Desalination plants can generate the water that is desperately required.
[28]	In the Egyptian deserts, a preliminary study of water desalination utilizing solar energy as the principal source of energy was carried out.	Cost analysis	It was stated that the cost of producing 1 m^3 of fresh water with small PV-powered RO water desalination units was $3.73. The authors also proposed that employing renewable energy sources to power various systems in these rural regions will help to keep the environment cleaner.
[29]	In the small Sicilian settlement of Ginostra, the construction of a PV-diesel energy management approach for a Sea Water Reverse Osmosis (SWRO) desalination plant.	Modelling	Using the energy management approach given, an operational simulation of the hybrid system with the desalination plant was performed. When comparing energy consumption with and without the suggested energy management technique, the number of diesel operational hours was chosen as the distinguishing metric.
[30]	The feasibility of the desalination of brackish water using electrodialysis system powered by photovoltaic energy and the influence of experimental parameters were investigated.	Modelling	According to the authors, using this model, they were able to construct an electrodialysis system powered by solar energy (electrodialyzer size, quantity, and PV module arrangement) for the desalination of brackish water, as well as studying its behavior in different geographical areas.

as well, the study also included thermally driven MSF and ME facilities that were powered by steam generated directly by solar collectors or recovered steam from solar steam power plants powered by concentrated solar collectors. Because of the expense of storing electric energy in batteries, as well as the fact that solar energy supply only lasts about one-third of the day, while of the technologies investigated, the PV-RO desalting system has the greatest specific capital outlay for cost. Table 2 collected the latest achievements on the application of solar electricity – PV and CPV in water treatment plants (desalination).

Here, majority of the studies carried out as seen in table 2 were modeling followed by cost analysis, then critical reviews. However, there seem to be paucity of recent studies done with regards to PV and CPV for solar desalination owing to the high expense of storing electric energy in batteries, and the limited solar energy availability (approximately one-third of the day).

3. DESALINATION OF WATER

Desalination of seawater and brackish water is one of the most promising techniques for addressing global water problems [33]. Its use has climbed 6.8% per year over the previous decade, equating to an annual increase in fresh water output of 4.6 million m^3/day, and, while high-capacity facilities are not numerous, they account for the majority of installed capacity [34].

Desalination plant capacity worldwide reached 99.8 million m^3/day in 2017, according to the International Desalination Association (IDA), with 18,500 units constructed in 150 countries [35]. In China alone, some 142 plants operating with seawater were installed during 2018 [36]. Between January 2019 and February 2020, some 155 new plants were put in operation, increasing the installed capacity by up to 5.2 million m^3/day [34].

To address the increased demand for freshwater, desalination plants are required. One way to eliminate the need for fossil fuel energy sources is to combine desalination systems with solar energy technology [37, 21].

3.1. Solar Desalination

The process in which the sea water is converted to fresh water is referred as desalination process [20, 38]. By far the most often used renewable energy source for desalination is solar energy, and it has therefore been used to power a variety of current desalination methods, including MSF, ED, RO, VC, and NF [39]. Solar energy can be harvested directly as electricity or used in power turbines as solar thermal energy. PV and solar thermal technologies are two types of solar energy [40].

The viability of establishing a combined electric power and saltwater desalination plant in Wilayat Duqum, Oman, utilizing concentrated solar power technology has been studied [41]. Using GIS (define) solar radiation tools, the best location for the plant was selected. Combining concentrated solar electric generating with saltwater desalination might be done in two ways. The original intention was to combine a CSP plant with a thermal desalination unit, then use the exhaust heat from the steam cycle to power the desalination unit. The second alternative was to use a reverse osmosis desalination device to exclusively use the CSP plant's electrical production. The article looked at both approaches and showed where each had benefits in terms of local variables, such as the quality of the input water, the demand for freshwater and/or drinkable water, social and economic factors, the environment, and so on [41]. While [26] explored the efficacy and profitability of replacing desalination plants' fuel energy with renewable energy. The paper presented the different solutions to the most commonly used desalination process (RO, MSF, MED), and solar energy production technology compatible with desalination.

An autonomous power module for the filtration of brackish water with high arsenic concentrations was successfully conceived, built, and tested [42]. Ion exchange and adsorption technologies (column filtration system) were integrated with an electrodialysis (ED) system in the purification process. The water purification system's power module featured a modular design that allowed it to function with various salt concentrations for the treatment of river or subterranean water, efficiently eliminating arsenic [42].

A three-dimensional artificial transpiration for efficient solar wastewater treatment was conducted by [43]. Inspired by the natural transpiration process in plants, the authors reported a 3D artificial transpiration device with all three components of heat loss and angular dependence of light absorption minimized, which enables over 85% solar steam efficiency without external optical or thermal management [43]. This artificial transpiration device was also shown to provide a supplementary path for waste-water treatment with a low carbon footprint, allowing valuable heavy metals to be recycled and purified water to be produced directly from wastewater polluted with heavy metal ions [43].

In their review, [44] stated that economic competitiveness is one of the primary factors influencing the scaling up and commercialization of solar energy. It was also shown that small to medium size solar desalination facilities have water costs in the range of US$0.2–22/m^3, which is significantly more than typical fossil fuel-based plants. However, large-scale solar-based plants are expected to have reduced water costs (US$0.9–2.2/m^3), indicating that solar-based alternatives may become economical in the near future [44].

A very simple and self-contained solar energy converter made entirely of as-prepared 3D cross-linked honeycomb graphene foam material with no extra supporting components was experimentally carried out [45]. They used a scalable sheet-like material to obtain pure drinkable water from both seawater and sewage water under ambient conditions, and the results showed a capable monolithic material framework capable of providing a paradigm shift in water purification by using a simple, point-of-use, reusable, and low-cost solar thermal filtration system for a wide range of environmental conditions [45].

According to [46], the energy needs and prospective study sites for lower SEC of several thermal, membrane-based, and future desalination systems were thoroughly examined. They stated that renewable energy sources might be a potential solution for reducing energy requirements in thermal desalination operations, which take a significant amount of energy for heating. As a result, they focused on the possibilities of desalination-renewable energy integrations in their analysis. The assessment also looked at using unique, sophisticated membranes and inventive ways for energy offsets in addition to traditional energy reduction options [46].

Similarly, [47] reviewed the state of China's water resources and solar energy use, as well as a complete evaluation of one possible solution: linking desalination technology with renewable energy. In this article, they evaluate China's desalination industry and describe the energy consumption for numerous desalination procedures to offer a concise picture of desalination techniques in China. Potential solar-powered desalination coupled technologies were also compared.

Reverse electrodialysis (RED) in combination with membrane-based saltwater desalination technologies such as RO, MD, ED/EDR, or CDI, according to [48], could be investigated for the production of renewable energy and drinking water at the same time (Fig. 4).

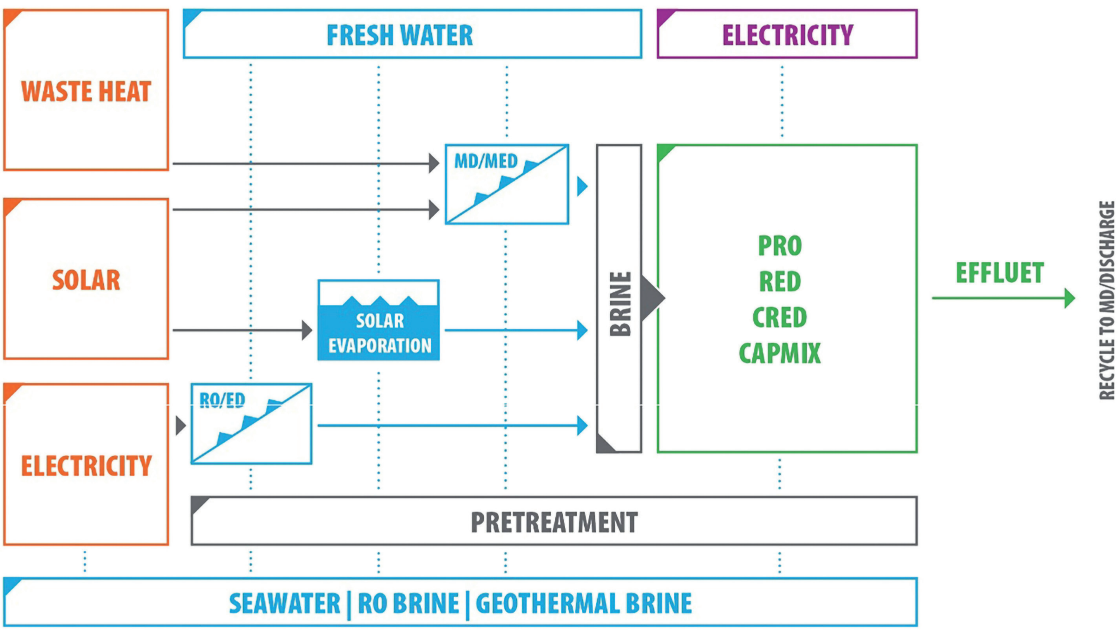

Fig. 4. The concept of producing renewable energy and drinking water at the same time is a novel one Adapted from [48, 14]
Ryc. 4. Koncepcja jednoczesnej produkcji energii odnawialnej i wody pitnej jest nowa. Opracowanie na podstawie [48, 14]

Table 3. Summary of the key findings and achievements from studies on Solar powered desalination, and solar photocatalysis and disinfection

Tabela 3. Zestawienie kluczowych wynalazków i osiągnięć w badaniach nad odsalaniem przy pomocy energii słonecznej oraz słonecznej fotokatalizy i dezynfekcji

Author, Year	Study Aim	Approach	Findings and Achievements
[49]	The trend of photocatalysis process innovations and implementations, desalination technologies, and sun disinfection approaches designed specifically for industrial and home wastewater treatment.	Review	Traditional wastewater treatment techniques have drawbacks, as does direct solar energy-based wastewater treatment using energy storage devices. Solar-powered wastewater treatment systems would considerably increase the effective use of water resources, therefore contributing to long-term development goals.
[50]	Make a single solar still that is linked directly to a solar parabolic trough without the use of a heat exchanger.	Experimental	The field studies revealed that the modified solar still's overall water productivity rose by 177 percent when compared to the standard still.
[51]	In Iran, a feasibility study was conducted to see if solar panels could be connected to the grid to power small-scale reverse osmosis devices.	Cost analysis	For each scenario, they produced a complete cash flow analysis. The economic feasibility of solar-powered reverse osmosis facilities was also predicted to be dependent on the capacity to export excess solar electricity to the grid.
[46]	Review of several thermal, membrane--based, and new desalination systems' energy consumption and prospective research areas for lower SEC.	Review	They proposed that renewable energy sources may be a realistic solution for reducing energy use.
[42]	An autonomous power module for the filtration of brackish water with high arsenic concentrations was successfully conceived, manufactured, and tested in this study.	Experimental	The power module with the water purification system allows for the treatment of water from rivers or underground with various salt concentrations, efficiently eliminating arsenic.
[43]	For effective solar waste water treatment, a three-dimensional artificial transpiration was carried out.	Experimental	It was shown that the artificial transpiration device can give a low-carbon alternative to waste-water treatment, recycling valuable heavy metals and creating purified water straight from waste water polluted with heavy metal ions.
[45]	The authors presented a solar energy converter that is exceedingly simple and self-contained, requiring just a 3D cross-linked honeycomb grapheme foam material that has been created as is and no extra supporting components.	Experimental	Their findings indicated a competent monolithic material platform capable of bringing about a paradigm shift in water purification by deploying a simple, point-of-use, reusable, and low-cost solar thermal water purification system that can be used in a number of contexts.
[52]	In a research, wastewater containing hexavalent chromium was treated in the presence of sunshine with a zinc oxide (ZnO) semiconductor photocatalyst to convert the more harmful hexavalent metal to its less toxic trivalent analogue.	Experimental	They achieved a 35% decrease in 2 hours using 10 mg/L substrate, 0.4 g/L photocatalyst, and 75kLux solar energy at 31^{o}C. In terms of both the substrate and the electron donor, the initial rate of reduction varied primarily with ZnO loading, therefore it was zero order.

Table 3 cont. / **Tabela 3** cd.

Author, Year	Study Aim	Approach	Findings and Achievements
[26]	Examine the viability and profitability of replacing the fuel energy used in desalination plants with renewable energy.	Review	Presents numerous alternatives for the most often used desalination procedures (RO, MSF, and MED), as well as solar energy producing technologies that can be utilized in conjunction with desalination.
[41]	Examine the feasibility of employing concentrated solar power technology to build a combined electric generation and saltwater desalination facility.	Modelling	The study looks at two different ways to combine concentrated solar power and seawater desalination. The first aim was to link a CSP plant to a thermal desalination unit and power the desalination unit using the steam cycle's exhaust heat. The second alternative was to use a reverse osmosis desalination device to exclusively use the CSP plant's electrical production.

From table 3 various studies carried out were purely experimental in nature followed by some critical reviews, little cost analysis and modelling. The results from the studies show constrain in terms of commercial scale pilot projects.

3.1.1. Direct solar desalination—solar still

The solar still is the most often utilized direct sun desalination device, which is best suited to low-capacity water supply systems in remote locations where pipeline construction or water delivery by truck are both uneconomical and unreliable [53] Fig. 5.

In terms of recent researches, [54] used a solar still with phase change material (PCM) and a solar collector to perform an experimental inquiry on water desalination. According to the authors, direct solar radiation heated the water in the basin and the PCM, and the hot water was transported via a coil heat exchanger in the basin that was heated by a solar collector. The rate of desalination rose when the ambient temperature and hot water circulation flow rate both increased. Furthermore, the economic analysis reveals that such units are only feasible in remote places [54].

Likewise, [50] constructed and built a single solar still that is directly linked to a solar parabolic trough and does not employ a heat exchanger in their research. With the parabolic unit, a unique feeding water tank was fitted. The study's tools included fieldwork and manufacturing, laboratory tests, and water quality analyses. According to the results of field testing, the overall water output of the modified solar still increased by 177 percent when compared to the regular still [50].

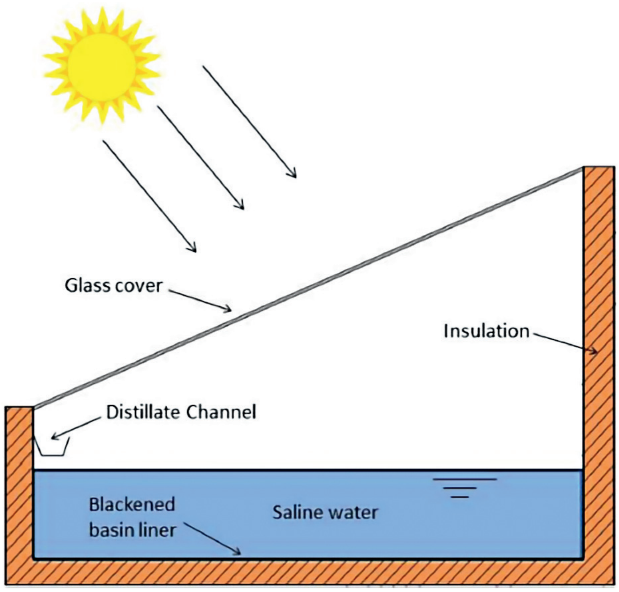

Fig. 5. Schematic diagram of a single slope single basin solar still (Adapted from [44])

Ryc. 5. Schemat jednospadowej instalacji słonecznej z pojedynczym basenem (opracowanie na podstawie [44])

3.1.2. Indirect solar desalination

Solar humidification-dehumidification

Humidification-dehumidification (HDH) technology uses hot air's moisture to separate saline water and clean water (moisture) [44]. HDH is frequently paired with external warmers like as solar collectors, as opposed to solar still, which is mostly passive. Furthermore, humidification and dehumidification occur in independent components, allowing for separate planning and adjustment [55].

According to [44], based on the cycle configuration, the HDH process may be split into three groups: Open Water Open Air cycle (OWOA), Closed Water Open Air cycle (CWOA), Closed Air Open Water Cycle (CAOW). The configurations are depicted in Fig. 6, and [56] gave more information.

Most studies on solar HDH are concerned with increasing system productivity and efficiency, which can be accomplished through the design and optimization of the HDH cycle and individual elements. It is really crucial to optimize operating factors like air/water mass flow rate, feed water, and input air temperature [57].

The performance of a proposed desalination system based on air humidification–dehumidification (HDH) was investigated theoretically and experimentally by [58]. A theoretical simulation model is built that takes into consideration the energy equations of each component to analyse the performance and productivity of the proposed solar humidification–dehumidification desalination unit. According to the findings, the second phase has the highest fresh water productivity. A comparison of practical and theoretical results revealed a high degree of consistency, indicating that the suggested model

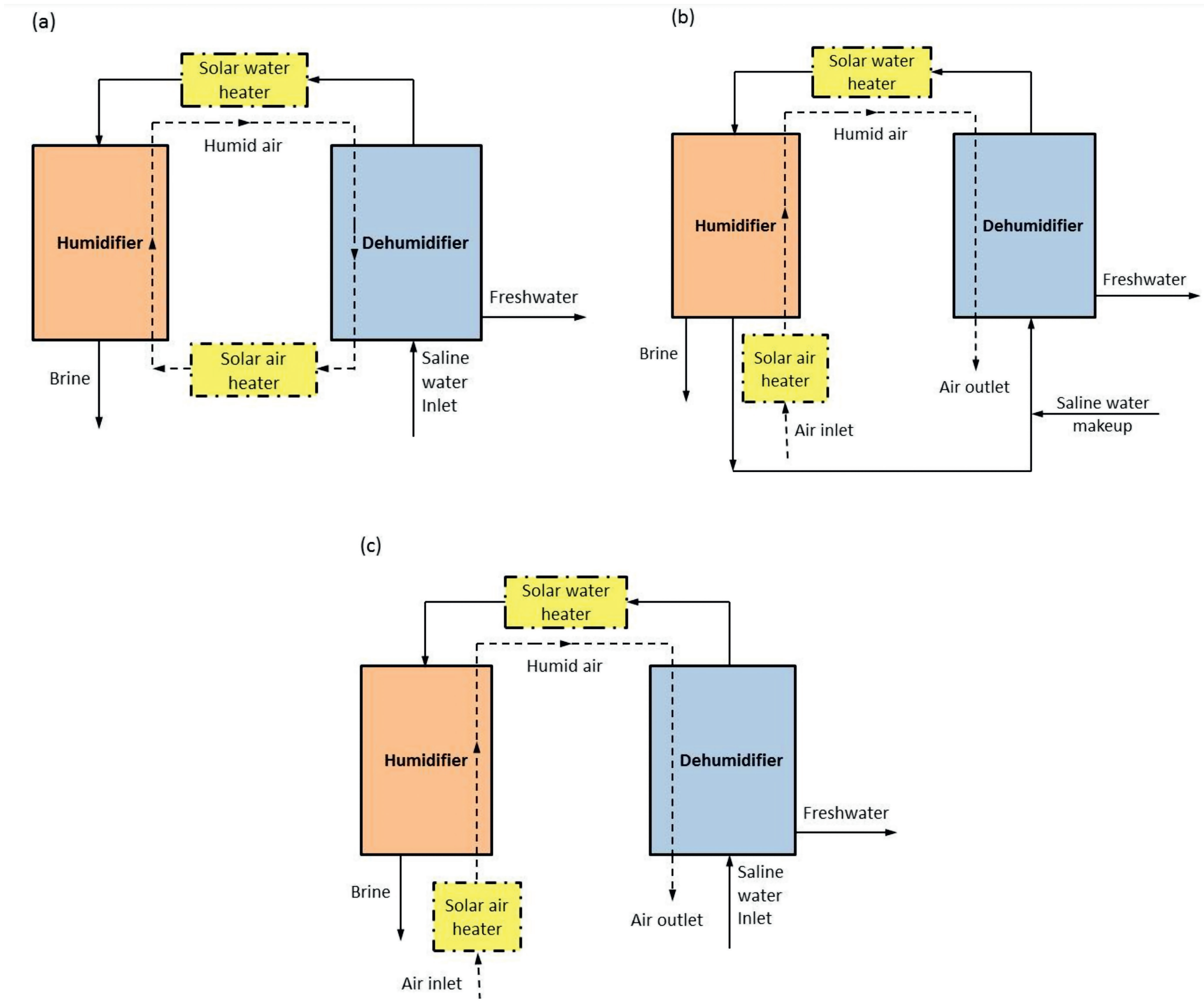

Fig. 6. Schematic diagram of solar HDH configurations: (a) water or air heated CAOW; (b) water or air heated CWOA; (c) water or air heated OWOA (Adapted from [44])

Ryc. 6. Schemat instalacji słonecznych HDH: (a) CAOW ogrzewane wodą lub powietrzem; (b) CWOA ogrzewane wodą lub powietrzem; (c) OWOA ogrzewane wodą lub powietrzem (opracowanie na podstawie [44]) is suitable for usage under a variety of boundary conditions [58].

In Qom, Iran, [59] built a CAOW-WH solar HDH pilot system. A mathematical model for the multi-stage solar HDH process was produced as well. Between the humidifier and the dehumidifier, the multi-stage solar CAOW-WH HDH presented in this work uses a number of smaller closed-air loops, each of which represents one step. A two-stage HDH process boosted specific water output by more than 40%, but a three-stage and four-stage HDH process only increased specific water output by 4% and 1%, respectively, according to the modelling results. The two-stage HDH method was chosen as the optimum choice due to the rising cost of desalination units with increasing stages. Summer and winter days were used to evaluate the pilot system. On hot days, specific water production might exceed 7.25 L/m^{2}d, which was almost 40% greater than the previous study's single-stage unit.

The solar HDH process is currently in the early stages of development. Very little study has been done to identify the benefits and drawbacks of various configurations, the influence of which is thought to be significant on HDH performance [57, 44]. The most important emphasis of HDH research in order to commercialize this technology will continue to be the development of the HDH cycle and its three essential components. Furthermore, for the process to scale up, it is necessary to have a better understanding of the solar HDH process' thermodynamics and construct a mathematical model.

3.1.3. Solar-powered MSF

The most extensively used thermal desalination technique is multi-stage flash (MSF), this technology, which is second only to reverse osmosis in terms of worldwide desalination installation capacity, accounts for roughly 21% of global desalination installation capacity [60]. As seen in Fig. 7, the seawater/brackish water is initially warmed by vapour condensation as it goes through the different processes in tubes. Solar thermal collectors are used in conjunction with a standard MSF desalination system in solar powered MSF. A solar-powered MSF process requires the selection of a solar thermal collector, the right design of a solar heating cycle, and the design and optimization of the MSF unit [44].

In the last 20 years, there have been very few papers on solar MSF plants. Meanwhile, most of the solar MSF studies that have been reported have been on low-capacity facilities. Matlab/Simulink and the REDS-SDS software tool were used to examine a 5000 m^3/d solar MSF-BR (multi-stage flash brine recycling) system [61]. The MSF unit was used in three distinct solar thermal cycle configurations: for electricity-water cogeneration, MSF units with solar organic Rankine cycles (SORC), direct vapour generation (DVG), and indirect vapour generation (IDVG) are used. The software predicted design parameters such as solar field dimensions, heat exchanger specifications, flow rates, and operating conditions based on critical input data such as capacity, top brine, weather conditions, blow down temperatures, seawater, and mechanical efficiencies of turbo machinery units. Using a 40-stage MSF, a GOR of 12 was achieved. The projected plant's water cost was anticipated to be \$1.36–1.58/m^3, which is comparable to existing MSF facilities that use fossil fuels. According to the findings of this study, solar MSF may be an economically and technically feasible option for large-scale desalination plants [61].

A new design for a solar-powered multistage flash (MSF) desalination plant that uses a smaller solar collector surface and can run continuously, was suggested by [62], and compared to previous designs. A number of concentrated solar collectors, as well as two thermal storage tanks with enough saltwater to power the MSF for one day, were planned. Unlike many other solar-powered desalination systems, the brine is swiftly cycled through the array, removing the need for a heat exchanger and a medium fluid. This new dual-tank technique isolates the MSF from daily changes in solar radiation, allowing the brine to progressively attain TBT (define) each day while reducing losses. Simulating this idea with a dynamic model of heat and mass exchanges yields an average daily output of 53 kg of distillate per square meter of solar collector surface. At a cost of \$2.72 per cubic meter, the finished system employed a 42,552 square meter solar collection area to produce around 2230 cubic meters of fresh water every day [62].

Flat plate solar collectors were connected with multistage vacuum chambers in this work, and a solar multistage flash (MSF) desalination unit was run by [63]. After conducting an experimental parametric analysis, the best process performance and cost-effective desalination method were discovered. The distillation to evaporation ratio rose by 53% while specific energy consumption declined by 35% when the ambient pres-

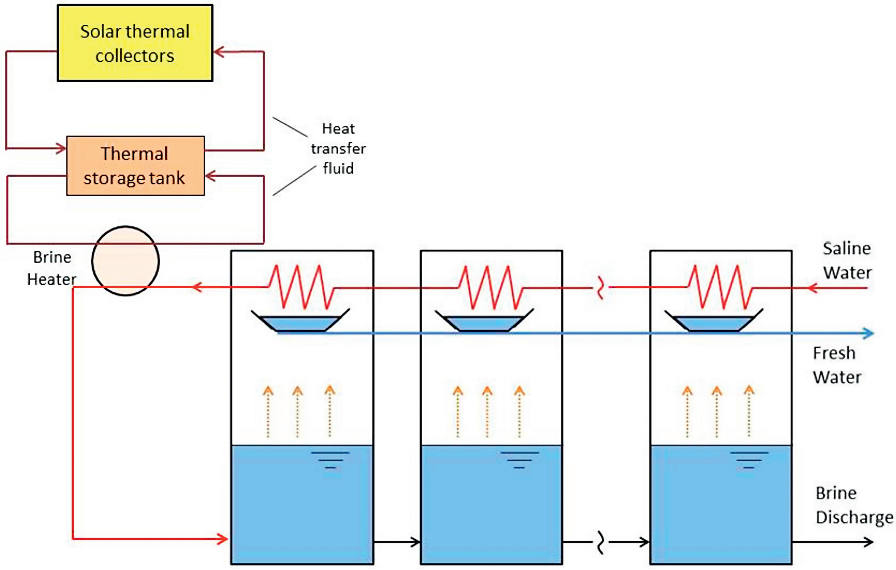

Fig. 7. With thermal storage, a solar MSF desalination system depicted (Adapted from [44])
Ryc. 7. System odsalania z magazynowaniem ciepła z energii słonecznej – MSF (opracowanie na podstawie [44])

sure was reduced by 20% in a vacuum flash chamber, according to one of the study's primary findings. The optimum distillation to evaporation ratio was 0.42 at a feed rate of 0.5 L/min.

3.1.4. Solar-powered MED

Seawater/brackish water is fed to a series of low-pressure cells (i.e. 'effects') in multi effect distillation (MED) [44]. The first effect draws energy from outside sources. Because the subsequent action works as a condenser for the vapour generated in the prior effect, the latent heat of vaporization is recovered. While MSF is the most often used thermal desalination process in large-scale facilities, MED is projected to be more thermodynamically efficient and capable of operating at significantly lower top brine temperatures (TBT) (55–120 °C), minimizing scaling and corrosion [64, 65].

Plataforma Solar de Almeria (PSA), a Spanish solar research laboratory, has been studying and testing solar-integrated desalination systems based on MED since 1988, first with the STD project (1987–1994) and later with the AQUASOL project (2002–2006) [44]. The MED-TVC system, the PTC-powered MED, which employs high-pressure steam from a miniature solar thermal power plant, and the MED-DEAHP system, which employs PTC or a hybrid solar-gas energy source, have all been tested and evaluated [66, 67, 44].

The techno-economics of CSP + MED plant designs in two different locations: Israel and Jordan were examined by [68]. Plants with a capacity of 24,000 m^3/d were constructed and tested. The scale of the CSP plant was chosen to meet the MED plant's exhaust steam requirements (42 MW of power producing capacity). As a result, the MED unit was employed to replace the power-generating cycle's cooling subsystem. The water costs of these two plants were \$0.943/m^3 and \$1.215/m^3, respectively, according to modelling findings. This is within the water cost range described in the literature for fossil fuel-powered large-scale commercial MED facilities [69], demonstrating that CSP + MED is a cost-effective solution for the supply of fresh water in the MENA area (Middle East and North Africa). It should be emphasized that the MED plant's steam cost was evaluated using the 'power credit approach,' in which the power loss owing to the usage of backpressure turbines rather than condensing turbines utilized in independent power plants was assumed. This will have to be offset by grid electricity purchases [44].

In a study, [70] developed a unique model that simulates the physical functioning of a parallel-feed (P) multi-effect distillation (MED) plant. This model contains steam consumption and steam ejectors, and it was confirmed using data from an actual MED industrial site in Trapani, Sicily, that featured a thermal vapor compressor (TVC) (TVC). The findings imply that the

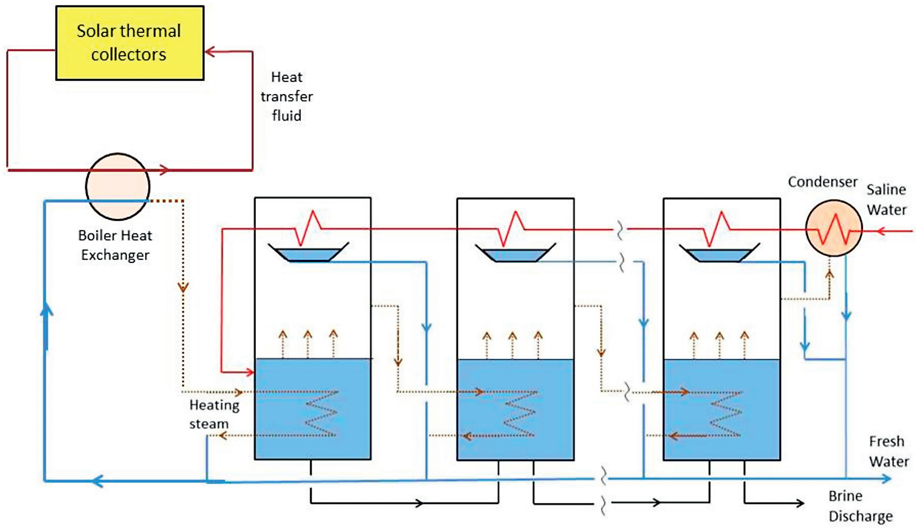

Fig. 8. Solar MED desalination system with feed preheating schematic diagram (Adapted from [44])
Ryc. 8. Diagram systemu odsalania MED z ogrzewaniem wstępnym (opracowano na podstawie [44])

MED model is capable of making accurate predictions about plant behaviour, which is extremely useful for an early assessment of such investments. This new tool was used to conduct simulations for a concentrating solar power (CSP) facility in Trapani that was working in cogeneration with a low-temperature MED-P plant, as well as other CSP cooling options (wet cooling, dry cooling, and a once through seawater cooling circuit). When compared to the existing TVC-MED facility, these data revealed that CSP+MED has the potential to be cost-effective. Solar MED desalination system with feed preheating schematic can be seen in Fig. 8.

Up to this time, the study and development of solar MED systems has made great progress. Despite the fact that no large-scale plants have been built, Solar MED might be a viable solution for medium to large-scale conventional desalination facilities. More research based on demonstration and thermodynamic modelling is required to scale up solar MED and establish the technology's technical and economic feasibility.

3.1.5. Solar-Powered Membrane distillation (MD)

In solar-powered membrane distillation (MD), the hydrophobic membrane allows only water vapour or other volatile substances to pass through [44]. MD is propelled by the difference in the trans-membrane vapour pressure [44]. MD has gained a lot of attention among the numerous future desalination technologies because of its possibility of increased long-term water production MD is a membrane-based thermal desalination technique that uses a hydrophobic membrane to separate hot and cold streams of water (Lei et al., 2005). Rather than a pressure or concentration difference, the MD processes are driven by a vapor pressure differential across the membrane.

Various solar-powered MD prototype plants using spiral-wound membranes for air gap membrane distillation (AGMD). As part of the European Commission-funded 'SMADES' project, modules have been placed in Jordan, Spain, and Egypt [72, 73]. With an actual yield of 0.14–0.8 m^3/d and a specific energy usage of 200–300 kWh/m^3, one Jordanian plant effectively desalinated genuine Red Sea seawater [74].

A cost-benefit study of solar-powered membrane distillation (SP-MD) systems to better understand the key determinants of water production costs was conducted by [75]. Direct Contact (DCMD), Air Gap (AGMD), and Vacuum (VACUUM) are the three SP-MD systems that were modelled and costed (VMD). To better understand the links between multiple design and operating characteristics and water production costs, a parametric analysis was conducted on the AGMD, the most often used SP-MD configuration. According to the parametric research findings, raising the feed input temperature had a substantial influence on lowering the cost in the AGMD system, whereas increasing the feed flow rate resulted in an increase in the cost of water production.

The study also discovered that lowering the air gap width and feed channel depth, as well as increasing the effective membrane length, reduces the cost of water. Finally, the MD configuration (VMD, AGMD, DCMD) in SP-MD systems will affect the ultimate water cost [75].

An integrated solar-driven desalination system that uses the membrane distillation method to generate drinkable water was developed by [76]. Both water and energy were used in the system. The system is a self-contained, integrated solar energy system that combines solar photovoltaic (PV) and solar thermal collectors to run on sun energy. The gadget was created to function independently in Saudi Arabia's arid desert regions, where energy and drinking water are scarce. Because of the system's mobility, it may be used in emergency situations where potable water is crucial for survival, such as natural catastrophes. A solar-thermal system, a solar-photovoltaic system, and a membrane distillation system were the three primary components of the system. A well-known Vacuum Multi-Effect Membrane Distillation (V-MEMD) module was at the heart of the system. A heat pump was installed to improve the system's efficiency [76]. The technical design of a portable and efficient integrated system that is dependable and simple to maintain was the system's breakthrough. The technique might be considered a long-term desalination approach that is good for the environment. As a result of the research, a solar-powered desalination system's design, configuration, and performance were detailed. Membrane distillation operation with an air-gap configuration has also been adopted (Fig. 9).

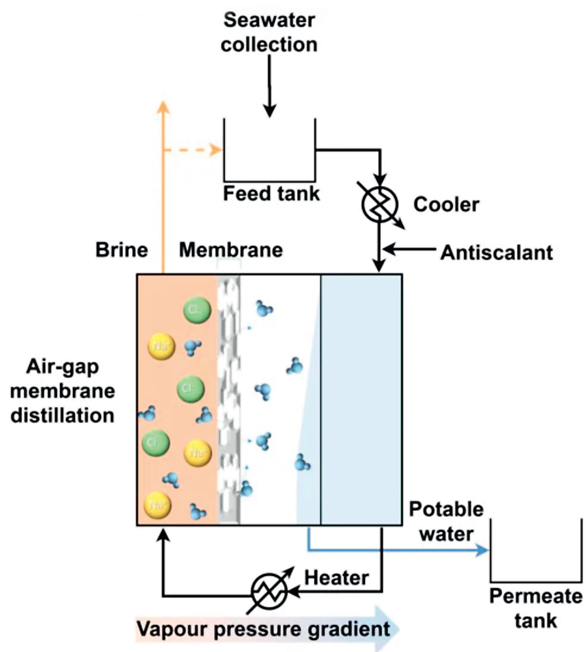

Fig. 9. Membrane distillation operation with an air-gap configuration taken from [78]
Ryc. 9. Destylacja przez membranę z przerwą powietrzną, wg [78]

Despite the fact that MD technology is still in its infancy, significant attempts are being undertaken to overcome these limits, whether it is through the adoption of new membrane materials or the improvement of MD designs and modules. Meanwhile, more testing and investigation are required to determine the technological and economic viability of solar MD.

3.1.6. Solar-powered Reverse osmosis (RO)

It has the world's biggest desalination plant capacity and uses very little specific energy (2–5 kWhe/m^3) (about 65 percent), reverse osmosis is frequently regarded as the most effective desalination method [79]. In RO, saline water is delivered to the membrane under high pressure to counterbalance the osmotic pressure of the feed water. On the permeate side, freshwater is collected, while concentrated brine is discharged [44].

A hybrid wind/solar powered reverse osmosis desalination facility was constructed and modelled in the study of [80]. The simulation results were utilized to modify the system such that the cost per cubic meter of desalinated water was as low as possible. Weather data from Dhahran, Saudi Arabia, was used to analyse the operation of the hybrid wind/solar powered RO system over the course of a year. The performance was next evaluated for 12 and 24 hours per day with a continuous RO load of 1 kW [80]. According to the simulation results, the ideal system for powering a 1-kW RO system for 12 hours per day while providing the least levelled cost of energy comprised of two wind turbines, forty PV modules, and six batteries, with the levelled cost of energy of such a system being 0.624 \$/kW h [80]. The best system for a 1-kW load over 24 hours consists of 6 wind turbines, 66 PV modules, and 16 batteries, with a minimal levelling cost of energy of 0.672 \$/kW h. The energy usage for desalination ranges between 8 and 20 kW h/m^3 depending on the salinity of the raw water. This implies that the recommended optimum hybrid wind/solar system will cost between \$3.693/m^3 and \$3.812/m^3, which is cheaper than the literature's suggested range [80].

A stand-alone PV-powered RO plant in Tunisia that supplied freshwater to a 300-person village in the Sahara desert for seven years (2006–2013) was reported by [81]. At a monthly average production rate of 3.26–12.8 m^3 per day, the plant successfully produced > 15 million litres of freshwater with TDS less than 300 mg/L from brackish groundwater (TDS 4.0–4.5 g/L). The specific energy consumption per cubic meter ranged from 1.64 to 3.13 kWh/m^3 [81]. Likewise, a feasibility assessment of the integration of solar panels with the grid to power small-scale reverse osmosis systems (up to 2000 m^3 per day) in Iran, a nation with low electricity prices was conducted by [51]. As a case study, they chose a city on the northern coast of the Persian Gulf that has a water scarcity yet receives a lot of sunlight. The effects of using energy recovery devices, energy storage systems, and membrane features were evaluated in five distinct scenarios. Their findings included a detailed cash flow

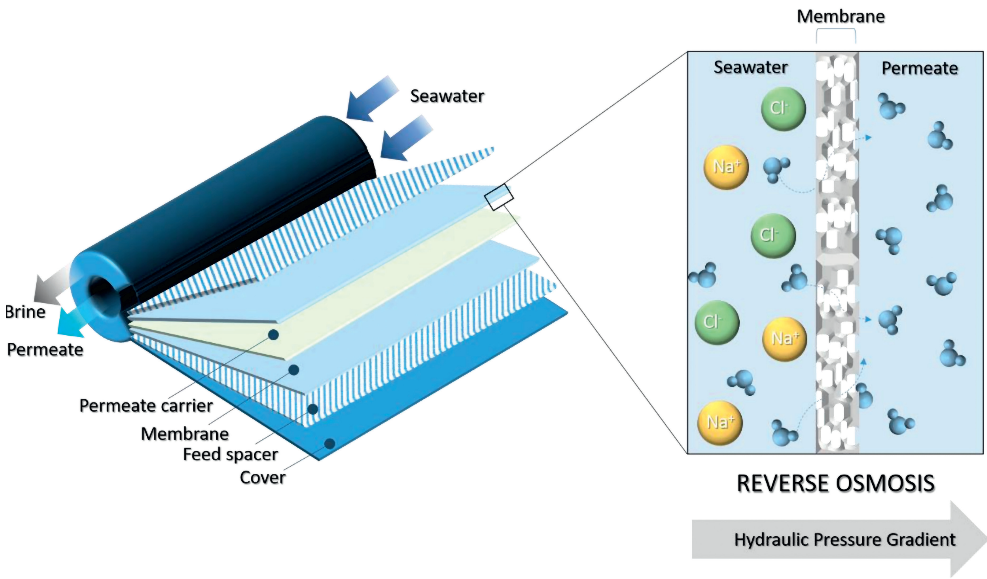

Fig. 10. Spiral wound membrane and driving force principles (inset) of RO. Taken from [82]
Ryc. 10. Spiralna membrana zwijana i zasady napędu RO (wstawka). Wg [82]

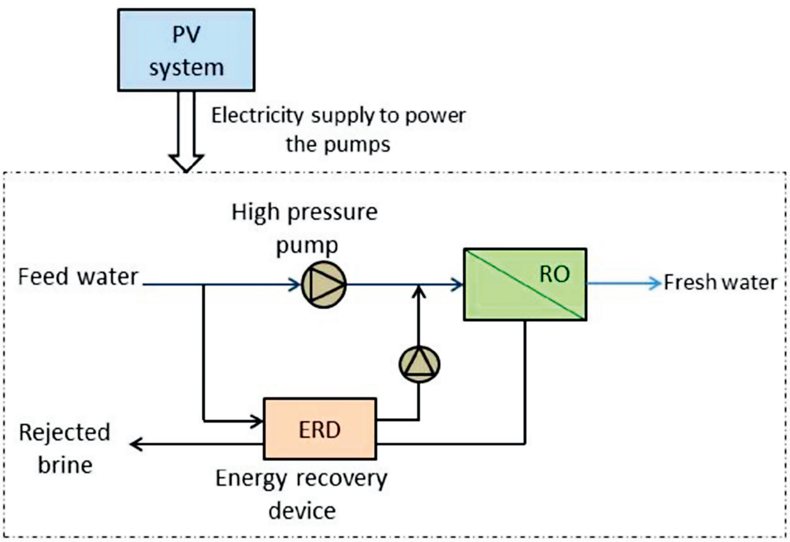

Fig. 11. Schematic diagram of PV-driven RO system (Adapted from [44])
Ryc. 11. Schemat systemu RO, napędzanego fotowoltaicznie (opracowano na podstawie [82])

analysis for each scenario. Ultimately, they predicted the financial feasibility of solar-powered reverse osmosis facilities when their unused or surplus solar energy is sent into the grid [51]. Spiral wound membrane and driving force principles (inset) of RO and diagram of PV-driven RO system can be seen in Fig. 10 and 11 respectively.

For the time being, lead acid batteries are the primary source of energy storage for PV-RO systems. Long-term performance stability and maintenance remain a challenge in distant places. For future use, cost-effective alternatives to energy storage for powering RO processes should be developed.

3.1.7. Solar-powered Forward osmosis (FO)

FO is another new technology that has been the subject of extensive research and debate in recent years [83, 84] (Fig. 12). The procedure involves the separation of solutes from water via an osmotic pressure gradient difference. Water is transferred from a lower-osmotic-pressure feed solution to a higher-osmotic-pressure draw solution via a semi-permeable membrane. In terms of increasing flux, FO technology has made significant development, with the commercialization of numerous innovative FO membranes recently [85].

Statistical experimental design and response surface approach to improve a solar thermal and photovoltaic-powered FO pilot plant was used in the study of [86]. The water permeate flow, the reverse solute permeate flux, and the FO specific performance index, which includes both the water and reverse solute permeate fluxes as well as energy consumption, are all factors to consider, were all simulated and optimized using predictive models. The feed flow rate, permeate flow rate, and temperature were the input variables for the FO pilot plant. Analysis of variance was used to test the response models that had been created [86]. The Monte Carlo Simulation method was used to establish the FO pilot plant's optimal operating conditions. The ideal settings were proven experimentally. The recovery of the draw solution was proposed to be conducted using a solar-powered reverse osmosis (RO) pilot plant with an optimum FO specific performance index ranging from 25.79 to 0.62 L/g kW h at the FO optimal conditions of 0.83 L/min feed flow rate, 0.31 L/min draw solution flow rate, and 32.65 °C temperature. Only 14.1% of the total energy utilized by the FO/RO hybrid system was consumed by the FO system [86].

For brackish water desalination, a hybrid FO-solar powered MD system was proposed in a recently by [87]. The forward osmosis technique was used in this study to make irrigation water for agriculture by employing brackish water feed and fertilizer draw solutions. To reduce fouling and moisture in the membrane distillation, forward osmosis was also used as a pre-treatment. The improved forward osmosis membrane functioned significantly better in terms of maximum water flux, minimal reverse solute flux, and high water recovery of 53.5 percent, according to the testing results. The membrane distillation process produced an ideal water flow of around 5.7 $L/m^2.hr$ and a high rejection rate of around 99.55 percent at an optimal temperature of 60°C [87]. Modelling was used to examine the feasibility of employing a solar collector to power the membrane distillation system and thereby reduce energy costs. It was determined that after further diluting with a conveniently available water source, the diluted fertilizer draw solution may be used as irrigation water. The membrane distillation membrane demonstrated decreased fouling and wetness after utilizing forward osmosis prior to the membrane distillation process, resulting in a reasonable rejection rate and acceptable distillate permeate. The forward osmosis-solar powered membrane distillation system consumed less energy than the reverse osmosis stand-alone plant [87].

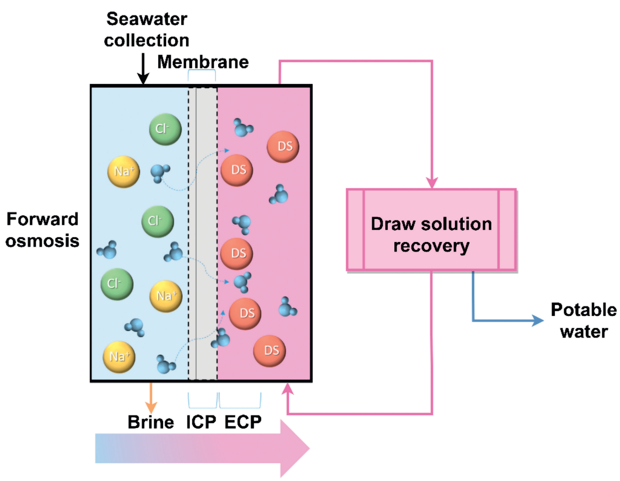

Fig. 12. Internal and exterior concentration polarizations (ICP & ECP) are depicted in a forward osmosis diagram taken from [88]

Ryc. 12. Wewnętrzna i zewnętrzna polaryzacja koncentracji (ICP & ECP) w diagramie przedstawiającym osmozę, wg [88]

3.1.8. Solar-powered electrodialysis (ED)

Saline water is driven through an electrodialysis (ED) stack when an electric potential difference is applied in between cathode and anode. Anions and cations move in opposite directions. The desalination of saline water and the concentration of ions in various parts of the system are enabled by the ion exchange membranes that link them [89]. Because saltwater desalination is often thought to be too expensive due to the high cost of ion exchange membranes, electrodes, and the comparably short lifespan of functioning in a high-density electric field, desalination of brackish water with low TDS is better with ED systems [90].

The majority of research published in recent years have been small scale facilities with a capacity of 50 m^3/d or laboratory size batch experiments [44]. ED is highly respected in the field of renewable energy-driven desalination for its versatility to shifting energy circumstances, since it can work at a broad range of DC voltages. As a result, researchers are interested in EDs that are fuelled entirely by solar energy.

A PV-powered hybrid forward osmosis (FO) and electrodialysis (ED) system for brackish and wastewater management was proposed by [91], in which feed water was first passed through a FO membrane to remove pollutants, and then through an ED membrane to remove the remaining impurities, followed by the ED membrane to remove pollutants, followed by the ED to desalinate the draw solution (NaCl solution). In general, the produced water met drinkable water standards due to its reasonable salt and TOC removal efficiency. A tiny potable water production system with a capacity of 130 L/d was subjected to an economic study. The cost of producing water was projected to be 3.32–4.92 Euro/m^3 (about USD 4.42–6.54) [91].

Findings from field testing in Chelluru, India, as well as the design of a PV-EDR prototype system based on co-optimization theory in the paper of [92]. Field testing enabled the observation and evaluation of real-world factors influencing system efficiency, resulting in updates to existing theories to account for previously unaccounted-for costs such as water tank filling and discharging, salt and water concentration in tanks from previous batches, unanticipated energy losses due to locally procured converters, and scaling in the ED stack. The predicted capital cost and lifetime cost of the Chelluru system are 34% and 45% lower, respectively, than the same costs if the PV-EDR system was built using traditional design procedures [92]. This study supported a previously published optimum design theory for photovoltaic (PV)-powered electrodialysis reversal (EDR) desalination systems.

The ability of ED to run directly with PV arrays is a significant advantage over RO (Fig. 13). The smaller the PV system's reliance on batteries, the lower its capital cost. As a result, future development should favour battery-free ED devices.

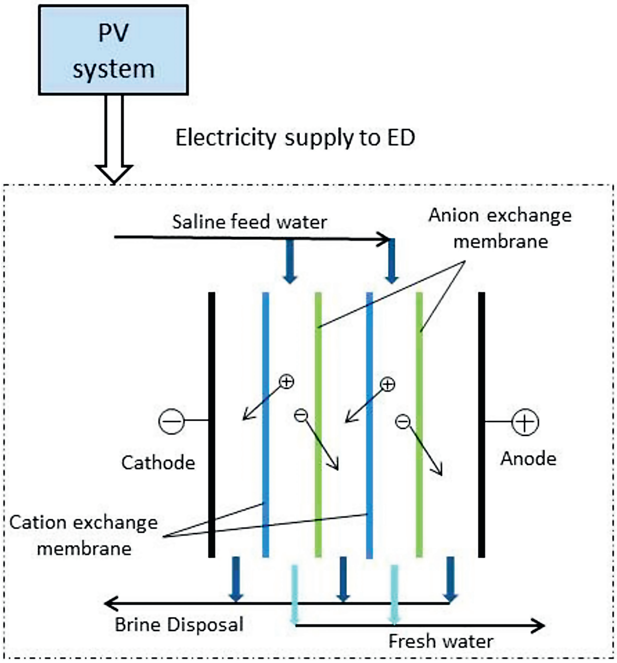

Fig. 13. Schematic diagram of PV-driven ED system (Adapted from [44])
Ryc. 13. Schematyczny diagram systemu ED, zasilanego fotowoltaicznie (opracowano na podstawie [44])

ED and RO are the only indirect desalination technologies that may be directly powered by energy generated by a photovoltaic (PV) system or a CSP plant. After transforming solar radiation into thermal energy, Additional indirect solar desalination procedures, such as MSF, MD, HDH, and MED, are powered by solar thermal collectors [32, 44].

3.2. Solar disinfection and photocatalysis

Photocatalysis is one of the most effective AOPs (advanced oxidation processes) for mineralizing refractory chemical compounds and water pathogens. Two forms

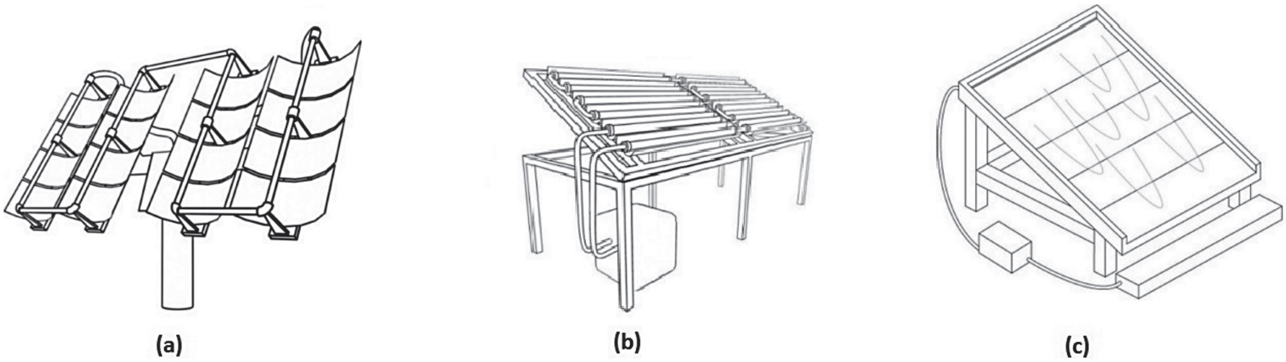

Fig. 14. Typical photoreactor layouts: (a) parabolic trough collectors, (b) compound parabolic collectors, and (c) inclined plate collectors (Source: [95, 44]).

Ryc. 14. Typowe układy fotoreaktorów: (a) paraboliczne kolektory nieckowe, (b) złożone kolektory paraboliczne, i (c) nachylone kolektory płytowe (źródło: [95, 44]).

of photocatalysis exist: heterogeneous photocatalysis, which uses semiconductor catalysts to treat water, and homogeneous photocatalysis, which refers to the photo Fenton process in general [93, 44].

Photo-Fenton is the most widely utilized homogeneous solar photocatalytic technology in water/wastewater treatment. The Fenton oxidation process is a popular AOP technology that depends on the catalytic reaction of H_2O_2 with iron ions to produce OH• radicals as the primary oxidizing species [44]. Researchers have extensively examined the effect of operating conditions on photocatalytic reactions (Fig. 14). Dissolved oxygen, catalyst load, pH & temperature, and pollutant kinds are solar radiation and meteorological conditions affecting elements of photocatalytic reactions [93, 94].

The study of [52] treated hexavalent chromium-containing wastewater in the presence of sunshine, a zinc oxide (ZnO) semiconductor photocatalyst converts the more harmful hexavalent metal to its less poisonous trivalent counterpart. Using 10 mg/L substrate, 0.4 g/L photocatalyst, and 75kLux solar energy at 31^{O}C temperature, they achieved a 35 percent decrease after 2 hours. The starting substrate concentration, photocatalyst loading, pH, and electron donor concentration were the process parameters. The initial rate of reduction was of zero order in regard to both the substrate and the electron donor since it changed solely with ZnO loading. In compared to the mechanistic rate equation, the modified Langmuir Hinshelwood Hougen Watson (LHHW) model functioned well as an alternate rate equation [52].

Photocatalysis procedures, desalination technologies, and solar disinfection approaches suitable especially for the treatment of industrial and household wastewater were given by [49]. The disadvantages of traditional wastewater treatment systems are highlighted, as well as the benefits of direct solar energy-based wastewater treatment with energy storage devices for convenience during the day and night. It was also indicated that cost-effective wastewater treatment systems based on solar power will considerably improve water source usage, hence contributing to long-term development goals [49].

Several pilot studies for the treatment of municipal Waste Water Treatment Plant (WWTP) effluent have been carried out [95–97]. Meanwhile, solar photocatalytic techniques based on TiO_2 have been examined for application in drinking water disinfection, which represents a step forward from basic sun disinfection (SODIS). TiO_2 photocatalysis has successfully inactivated several microorganisms that are resistant to UV-A irradiation [98, 99]. Photo-Fenton technique is largely being investigated for the purification of wastewater [44].

4. CONCLUSION

From recent research , it can be seen that majority of the studies centred basically on mathematical modelling, with few experimental studies, cost analysis, pilot projects and strategic reviews. The following conclusions can be drawn.

Solar thermal – solar collector and CSP:

- In terms of recent studies, modelling is the chief method by which most of the research were pre-

sented, followed by critical reviews and few experimental studies.
- For the results analysed, solar thermal – solar collector and CSP has been utilized in an integrated form in few places around the world. Again, the experimental are majorly on a small scale level with no evidence of commercial scale recently.

Solar electricity – PV and CPV:

- Here, majority of the studies carried out were focus on modelling techniques followed by cost analysis, then critical reviews.
- However, there seem to be paucity of recent studies done with regards to PV and CPV for solar desalination because of the high cost of storing electric energy in batteries, as well as the fact that solar energy only lasts roughly a third of the day.

Solar Desalination, Solar photocatalysis and disinfection:

- Studies carried from all the recent article analysed were purely experimental in nature followed by some critical reviews, little cost analysis and modelling. The results from the studies show constrain in terms of commercial scale pilot projects.
- Second, despite the fact that solar photocatalytic technology has been demonstrated to be successful in treating a wide spectrum of wastewater, recent research endeavours are still restricted to small scale experiments.

Direct and indirect solar desalination techniques:

- For solar stills, in recent years, no reports of pilot or actual plants have been made.
- The solar HDH process is currently in the early stages of development. Very little study has been done to identify the benefits and drawbacks of various configurations, the influence of which is thought to be significant on HDH performance.
- Numerous and vital strides have been achieved in the study and development of solar MED systems up to this time. Despite the lack of large-scale facilities, solar MED might be a feasible replacement for medium to large-scale conventional desalination plants.
- Despite the fact that MD technology is still in its infancy, significant attempts are being undertaken to overcome these limits through the use of new membrane materials or the refinement of MD designs and modules.
- For the time being, a PV-RO system's energy storage is mostly reliant on lead acid batteries. Long-term performance stability and maintenance remain a challenge in distant places.
- The option of ED ability to run directly with PV arrays is a significant advantage versus RO. The lower the PV system's capital cost, the less reliant on batteries it is.

This review has highlighted the recent advances in terms of solar energy application for desalination systems based on many sources of feed water: wastewater treatment, brackish and sea. Mankind currently relies mostly on fossil fuels for energy. Fossil fuel usage has resulted in major ecological and environmental issues, such as global warming. While unrestricted usage of fossil fuels will deplete the finite supply, also, in order to have a sustainable future, greenhouse gas emissions and air pollution should all be taken into account in the energy market. Therefore, demand needs to be controlled, and alternative energy sources need to be developed in terms of solar water treatment technologies for sustainable development.

Furthermore, this review has shown current trends in terms of usage of solar energy as a source for desalination and wastewater treatment of water and as a result, it has been utilized to fuel a variety of desalination systems, including VC, RO, MSF, NF and ED. Desalination technologies have also seen considerable advancements in design for energy and cost reductions, according to the report. It is essential to boost the application of solar thermal in small- and industrial-scale desalination by increasing heat energy storage, connecting CSP solutions with TES, for example, optimizing the surface area of solar concentrator devices via the use of new technologies, enhancing materials for solar energy collectors, and maximizing the surface area of solar concentrator devices through the use of new technologies.

Current research on different solar water treatment technology is as follows; a big issue is that most researchers are restricted to their own technique while neglecting the limitations and challenges that exist in the field. This makes evaluating and comparing different technologies much more challenging. Meanwhile, most technologies are still in development, hence only a few studies are based on genuine plants. For most of the processes, more demonstration and modelling studies, as well as hybrid approaches with other renewable energy sources such as wind and geothermal energy, are required for scaling up and commercialization.

Lastly, there is need for Africa, particularly the Sub-Saharan region to start by intensifying research-based efforts towards solar desalination or wastewater treatment and disinfection since both renewable energy source and clean water are a burgeoning issue to be adequately addressed so as to meet up with the United Nations goals of bringing about sustainable development across the globe.

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CONFLICT OF INTEREST

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