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A Review of Solar-Powered Membrane Distillation System: Concept Design and Development

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Abstract: Rising freshwater demands and environmental pollution lead to the increase of renewable energy utilization for seawater desalination system. One of the rapidly advancing technology for seawater desalination is the membrane distillation (MD) that has the potential to be integrated with renewable energy-driven operating systems, usually solar energy. This configuration is well known as solar-powered membrane distillation (SPMD), which can solve freshwater scarcity without increasing electricity cost. Numerous researchers have examined the integration of solar energy and MD for eco-friendly water desalination. However, there is a lack of information regarding this integrated system, although the system was invented over four centuries ago. In this review, the SPMD system was discussed in terms of its concept design and development. The significant contributions of the latest development of the SPMD system towards renewable energy and desalination technology were highlighted. In addition, the future research outlook in the area of SPMD is further discussed.

Keywords: Solar powered membrane distillation, Integrated system, Renewable energy, Solar energy, Desalination

Introduction

Water is a source of life and is needed for all social and economic endeavors. The earth has 97% of its water in saline form that has left only 3% of the freshwater that can be used by living creatures (Garud and Mane 2019). Of these, 2.5% fresh water is frozen in ice caps while the remaining 0.5%, accounting for 10 million m^3, corresponds to the available fresh water and its sustainable utilization and protection is vital for human survival (Byrne et al., 2015). Increasing population, rapid industrialization, uneven distributions of fresh water to the population, and the changing patterns of rainfall elevate the global issue of water scarcity. By 2050, water scarcity was predicted to increase further in most of the countries. About 73% of the people affected by water scarcity presently live in Asia (Boretti and Rosa, 2019). The domestic water supply for isolated communities or villages located in isolated areas typically originates from underground water, which can be classified as brackish water. The occurrence of freshwater scarcity crisis is due to the lack of water purity. This issue limits the water consumption of residents; thus, affecting the productivity of daily life and increasing the number of diseases. Therefore, to overcome this issue, researchers claimed that water is potable if it contained less than 500 parts per million (ppm) of salt. The desalination process is a possible method found capable of removing salt from seawater and brackish water. During the past 30 years, this process has been proven to be able to compensate for the freshwater scarcity in areas where a clean water source is not available. The common desalination processes are generally categorized as membrane-treatment and thermal desalination (Gude, 2016). The membrane-treatment technologies are comprised of reverse osmosis (RO), forward osmosis (FO),

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electrodialysis (ED), and nanofiltration (NF). Meanwhile, the thermal desalination process incorporated phase change steps such as multi-effect evaporation distillation (MED), multi-stage flash distillation (MSF), thermal vapor compression (TVC), and mechanical vapor compression (MVC). Another desalination process is the hybrid operation, which combined both phase change and membrane-treatment, such as membrane distillation (MD) and the processes of RO cooperative with MSF or MED. Over the last decade, MD and RO are among the superior advanced desalination technologies for both brackish and seawater applications (Pangarkar et al., 2017; Swaminathan et al., 2018). However, the RO process had some problems due to the membrane fouling, lower flux, and requires a higher pressure that led to higher energy consumption (Pangarkar et al., 2017). Consequently, the MD, which is a thermal membrane process, were capable of overcoming these problems. MD system as a trans-membrane evaporation process that combines both membrane process and thermal distillation. The system also can be described as the vapor passes through the membrane by several mechanisms which can be classified into four configurations: direct contact membrane distillation (DCMD), vacuum membrane distillation (VMD), sweeping gas membrane distillation (SGMD), and air-gap membrane distillation (AGMD). Moreover, some advantages of MD over the RO process comprised higher resistance to fouling, and lower operating temperature and pressure that led to a more economical process to produce safe drinking water. Structurally, the conventional MD system makes use of full electrical supply from the grid system to power up the electrical components such as the pump, chiller, heater, sensor etc. in the system. As a result, it will increase the cost of electricity and pollution from fossil-fuel power station through the grid power supply. However, the feed solution only requires low temperature (around < 90 °C) to be heated and not necessarily heated to the boiling point. Therefore, the MD system has the potential of being coupled with renewable energies, especially solar energy, to heat the feed solution.

The solar-powered membrane distillation (SPMD) system was introduced to address the issues confronted by the MD system. The system has been invented since 1551 by Arab alchemists, and the first publication was in 1991. SPMD can be categorized as a sustainable desalination process with a green technology approach due to the integration of a secondary renewable energy source. From the desalination process, it can be proven that the utilization of renewable energy sources will lessen the environmental issues, save a non-renewable energy source for further implementations, and many other clean energy advantages (Nematollahi et al., 2013). SPMD can be explained structurally as an integration between the MD system and the solar collector. A solar collector is an energy exchanger that converts solar irradiation energy into either thermal energy through working fluid (air, water, or oil) in solar thermal collector (STC) applications, or to the electrical energy in photovoltaic (PV) applications. The solar collector has two types of design, which are the concentrating and non-concentrating collector (Wang et al., 2015; Jamar et al., 2016). The MD is capable of being integrated with both applications (STC and PV), while at the same time can be coupled with both types of solar collector. Coupling with non-concentrating collectors is commonly applied on remote arid, small-scale areas, whereas the concentrating collectors are normally utilized for large scale areas. Since the last decade, the commercialization of concentrating collectors has noticeably grown. However, a concentrating collector plant integrated with the desalination technology required higher electricity demand to drive the operation. Thus, the selection of STC types for integration with the MD system depends on different scenarios and requirement. Besides, the SPMD operation could also be used as a stand-alone or hybrid system. The stand-alone SPMD system is operated by a combination of STC and PV panels, while the hybrid system is driven by both STC and grid power supply. In the SPMD stand-alone system, the PV unit transforms the radiation into electricity aimed at controlling the electrical components, while the STC device transforms the radiation into thermal energy to manage the phase-change processes. Therefore, the system has the potential to produce freshwater in targeted areas with difficulties in obtaining freshwater due to the portability and the stand-alone feature of the grid power supply (Chafidz et al., 2016). For this reason, the SPMD acquired great attention in the past decade.

Integration of Solar Energy through Membrane Distillation

Most of the desalination systems require thermal and/or electrical input that can be provided by solar energy and much focus has been given to solar-based systems. Solar-driven desalination is categorized by potentially free energy supply and is suitable, especially in remote arid areas and for small scale production of freshwater where the availability of conventional energy supplies is limited. MD is a trans-membrane evaporation process comparable with other desalination and separation processes. Fundamentally, the conventional MD is dependent 100% on the electrical energy delivered from the electrical grid or based on a power plant which was used to control all electrically powered devices including for heating the saline solution and cooling down the permeate stream. However, the low operating temperatures, normally within the range of 50–90 °C, allow MD to be integrable with renewable energy sources like solar and geothermal energy (Zhani et al., 2016). Nematollahi et al. (2013) reported that the application of renewable energy sources in MD modules allows conventional energy to be used for other applications; thus, minimizing the environmental issues, a choice of cheaper and low-maintenance energy source, and sustainable. All renewable energy sources can be utilized to produce useful energy in the form of electrical energy. Some renewable energy sources can also produce thermal energy for heating and cooling applications. Wind and water energies are converted to electricity, while solar, biomass, and geothermal energies can be converted to both electricity and thermal energy. Accordingly, the MD system requires thermal energy as a hot stream in the loop distillation system and electrical energy to power the electrical equipment. As reported by Blanco et al. (2009), the most suitable potential between all the renewable energies is solar energy. This claim was also supported by Mekhilef et al. (2011) that stated the utilization of solar energy became more attractive, clean with abundant of its quantity, capable to replace non-renewable energy sources, and able to meet the majority of the world's energy requirement in the future. A prelude on solar technologies, as well as the operational principle, is a requirement to investigate the current plus possible situation of solar-powered desalination. Solar energy can be utilized directly as electricity or as thermal energy, whether utilized in heating or cooling systems or impels turbines to produce electricity. Solar technologies are comprised of two general forms: solar thermal collector (STC) and solar photovoltaic (PV). STC is a device that converts solar radiation into thermal energy, while solar PV convert solar radiation into electricity. Jamar et al. (2016) have reviewed comprehensive studies on the STC device operated as solar water heater that consists of solar collector, storage tank and heat transfer fluid. Numerous efforts to integrate the solar energy with MD for seawater desalination have been recorded in the literature.

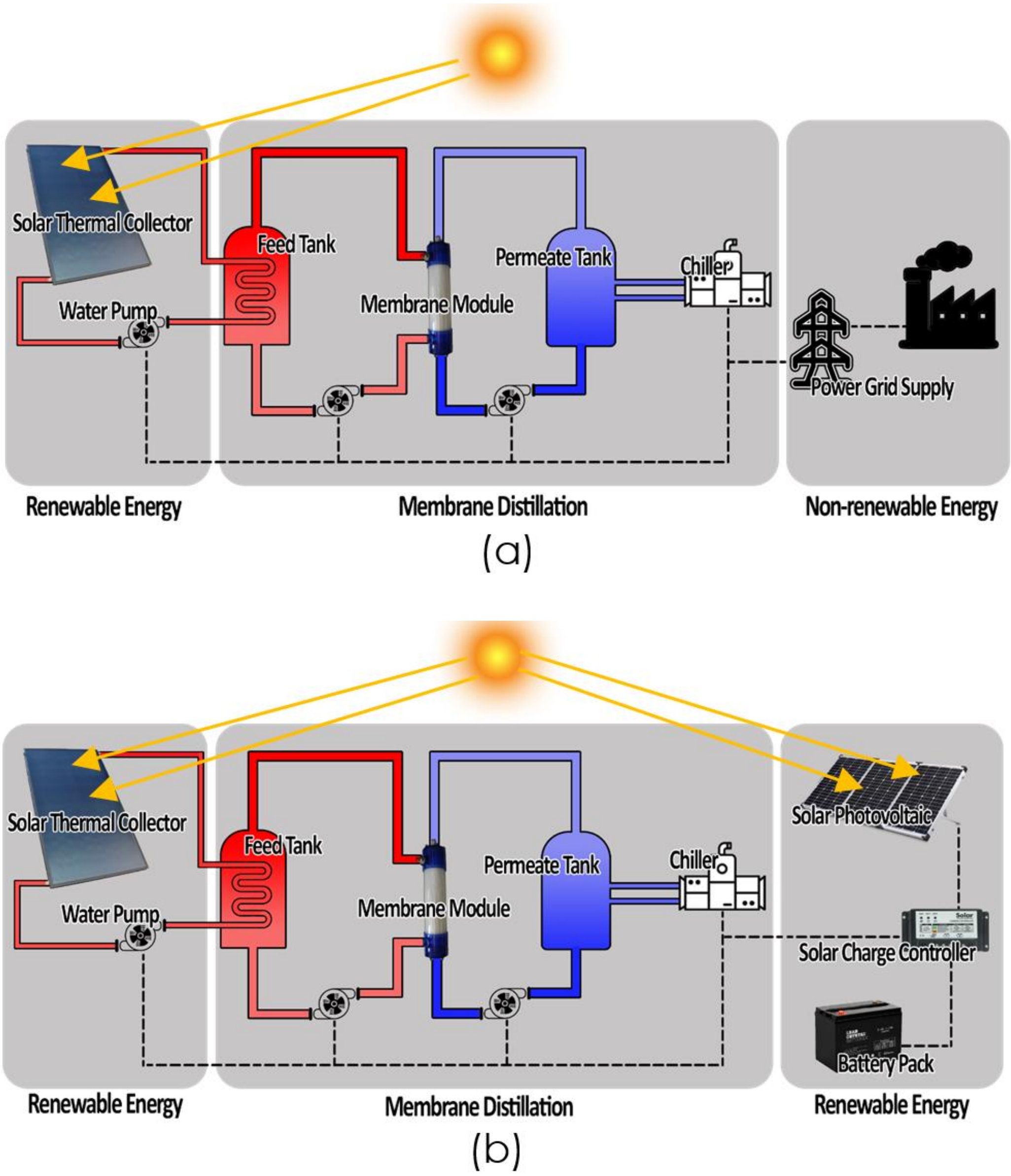


Figure 1. Two types of configurations: (a) solar assisted and (b) stand-alone SPMD system

As illustrated in Figure 1, Qtaishat and Banat (2013) stated that two different configurations of SPMD exist, which is solar-assisted and solar stand-alone membrane distillation system. The first configuration of solar assisted in MD modules is explained as a hybrid system that combines solar energy (renewable energy) and electricity grid (non-renewable energy) sources, as shown in Figure 1(a). From this configuration, solar technologies assist in heating up the feed solution only, whereas the energy needed for the rest of the processes will be generated by the electricity grid. Among the two types of solar technologies, STC is normally utilized as the thermal energy contributor for an MD system compared to solar PV because the energy transition of solar PV could lead to most heat loss issues. Over the last decade, STC has become of concern for numerous researchers and academicians around the globe due to its capability to collect heat by absorbing sunlight. In a simple definition, the STC acts as a piece of equipment that provides thermal energy through the hot water stream in the MD modules. The utilization of STC as solar thermal technology is further divided into two categories according to concentrating ratios; non-concentrating collectors and concentrating collectors. These different types of design depend on various desired applications. The STC supplied heat either directly to the feed solution or through the heat exchanger. However, there are situations when insufficient energy occurs whereby STC could not supply enough thermal energy into the MD system. This is due to the performance and efficiency of STC to absorb, convert, and transmit the energy through the MD system. Therefore, an auxiliary heater will be added to back up the insufficient thermal energy issues.

On the other hand, the second configuration known as autonomous SPMD system utilizes only energy from the sun; thus, eliminating the electricity grid from a power plant, as shown in Figure 1(b). The system is quite similar to the first configuration in all its aspects except that the solar PV panels are utilized rather than the electricity grid from a power plant to provide the required electricity. From this configuration, both electrical and thermal energy sources are produced by collecting solar energy from the sun. The thermal energy is formed through the STC system, while the electrical energy is produced by the solar PV system. Therefore, this stand-alone SPMD system can be considered as a dependable technology capable of working on zero-energy concept due to the clean source of energy. Furthermore, freshwater demand and solar energy are highly related to each other especially when located in coastal and remote arid areas, whereby both freshwater demand and the potential of solar energy increase during the summer season (Chafidz et al., 2016).

System Characterization

Based on previous research, the SPMD system can be classified into three designs, which are open-loop (direct), closed-loop (indirect), and directly integrated SPMD system. These systems can be operated by using a pump (active system) or natural thermo-siphon (passive system).

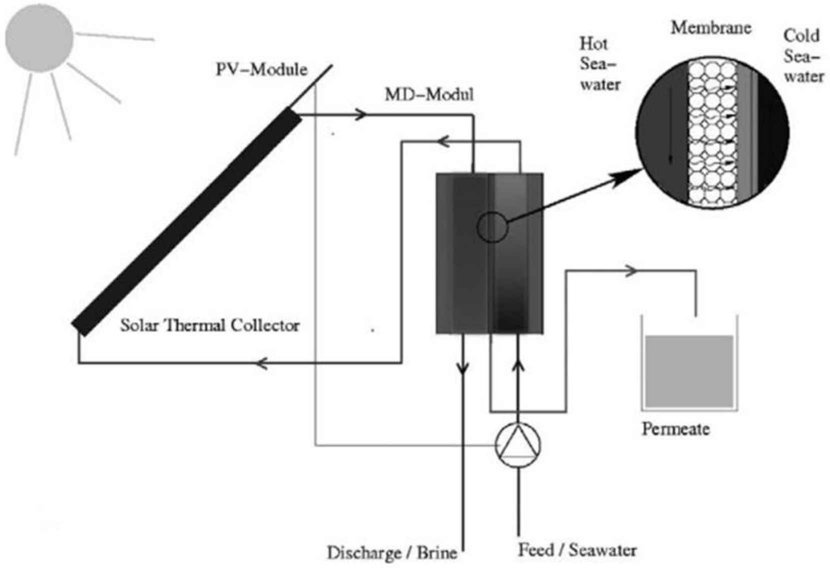
Open-Loop SPMD System

It is known as a “compact-system” with the simplest and typically the least expensive system to install. The hot water stream from the MD modules is directly heated from the STC panel without any heat exchanger, which allow efficient heat transfer directly to the water. A conventional compact system operates when the cold feed water is pumped out into the condenser of the MD modules from the inlet point to the outlet point in a counter flow while heating up, as shown in Figure 2(a). The STC that is connected right away from the condenser channel the outflow of MD, receiving the pre-heated feed water. Then, it is re-circulated to the evaporator. The temperature differences on both sides of the membrane caused partial pressure differences that lead to the driving force of the vapor passing through the membrane. As a result, the distillate is obtained from the distillate outlet. The advantages of this system are the simple design with an acceptable level of effectiveness due to fewer heat losses to the surrounding and no heat exchanger is required. Meanwhile, the shortfall of the open-loop system is that the STC system must be corrosion resistant from the feed water stream (Porrazzo et al., 2013). This is due to the configuration of the system that is directly connected from the feed (untreated) water of the MD module through the STC system. Moreover, open-loop direct systems are only appropriate for mild and moderate climates where freezing is minimal.

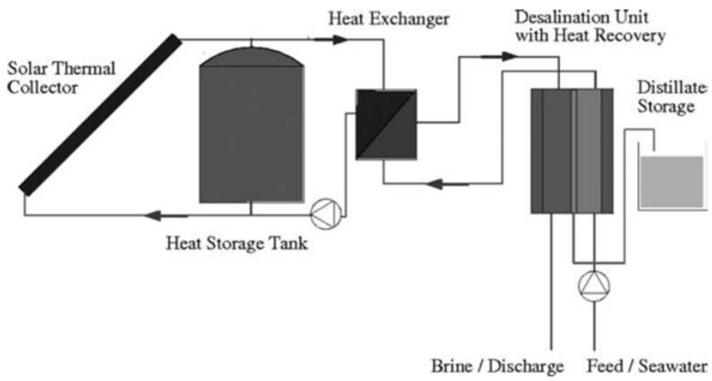
Koschikowski et al. (2009) reported six compact systems were established in five different countries since December 2004. Pozo Izquierdo in Gran Canaria is the earliest system installed followed by Alexandria (Egypt), Irbid (Jordan), Kelaa de Sraghna (Morocco), Freiburg (Germany), and lastly in Tenerife (Spain) since December 2007. Raluy et al. (2012) conducted the first compact system experiment in December 2004. The solar system coupled with MD compact system was established in the Instituto Tecnologico de Canarias (ITC) facilities. The result showed an average of 5–120 L per day of water production from the device, while the distillate production of daily maximum during the winter months was achieved. The specific thermal energy consumption and conductivity of distillate water were obtained within the limits of 140–350 kWh/m^3 and 20–200 μS/cm, respectively.

Closed-Loop SPMD System

On the contrary, the design of the closed-loop SPMD system is slightly different from the open-loop system because this system aims for daily capacities of higher than 1000 L (Koschikowski et al.. 2009). Thus, this "large-system" is known as an indirect or two-loop system in terms of its design configuration. A flow diagram of the typical indirect SPMD process is shown in Figure 2(b). Structurally, the system has two loops, which is the STC loop and the MD loop. These two loops are connected by a heat exchanger that operated as the equipment to transfer thermal energy from the STC loop through the MD loop. Basically, the closed-loop SPMD system consists of a similar basic component like the open-loop SPMD, with the difference only in the additional heat storage tank and heat exchanger equipment. The closed-loop systems are generally more complicated than an open-loop system because these systems need either a tank with a heat exchanger coil or an external heat exchanger. Besides, these systems are slightly less efficient than open-loop systems as there is a potential for heat loss through the heat exchanger. However, the special benefit of the closed system is the ability to extend the time of operation up to 24 h/day due to the installation of the heat storage tank and the utilization of freeze-resistant fluid that are more suitable for frost-prone areas.



(a)



(b)

Figure 2. Conventional types of systems configuration: (a) open-loop SPMD system and (b) closed-loop SPMD system (Koschikowski et al., 2009)

Koschikowski et al. (2009) conducted the experimental investigation of closed-loop SPMD system by solar driven stand-alone MD system for remote areas. This system used collector field, MD modules, STC loop, and components of two loop system installed at Gran Canaria, Spain. The STC type was an FPC double glass AR-coated with two loops AGMD for MD type. The result reported that the water production volume is 1200 L/day.

Directly Integrated SPMD System

The conventional SPMD system is designed with physically separated STC and MD modules. A complex system of pipes, thermal storage tank, heat exchanger, fittings, and other apparatus arrangements in these systems are needed to manage the heat and mass transfer for the STC with the MD unit. The system mainly uses thermal energy after conversion from solar radiation to heat up the feed solution. Structurally, the membrane section is located or directly integrated with the absorber section of the STC system. Due to the high price and complexity, a study of the STC design that is directly integrated into the distillation unit of several types of MD modules such as DCMD, AGMD, and VMD has been investigated (Mericq et al., 2011; Ho et al., 2016; Li et al., 2019). Figure 3 shows the differences between the conventional SPMD system and the directly integrated SPMD system design. This inventive combination of STC and MD unit exhibits an unconventional method that integrates both units into an effective, inexpensive, and more compact units with lesser heat loss throughout the energy flow from STC into the MD processes. According to the economic study, a method known as the "Lean Canvas" approach was implemented on the directly integrated SPMD system focusing at rural communities of Gujarat, India (Li et al., 2018).

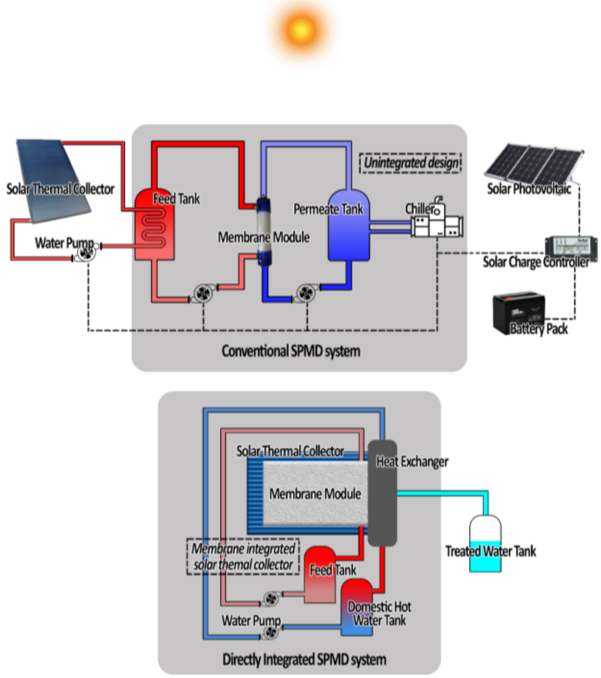


Figure 3. Comparable design between the conventional and directly integrated SPMD system

SPMD Development

The integration between STC and MD modules has gained attention from various researchers over the world. As illustrated in Figure 4, the first invention of SPMD was accomplished in 1551 by Arab alchemists and afterward by Della Porta in 1589, continued by Lavoisier in 1862, and Mauchot in 1869 (Al-Hayeka and Badran, 2004). However, Flendrig et al. (2009) stated that Wilson is the first Swedish engineer who invented the conventional solar still plant constructed on a large scale in 1872 for allocating freshwater to the neighboring folks and mine laborer at northern Chile. An insight into the "SPMD emergence phase", the first publication in 1991 was documented from the University of New South Wales, Australia by Hogan et al. (1991). After that, extensive literature was available during that era for promoting SPMD.

During the "SPMD resurrection phase", it is proven that SPMD has gained interest from influential companies specializing in MD modules focusing on MD systems integrated with solar energy. The research project's attention on SPMD has been sponsored by a multi-organization entity identified as the European Commission (EC) and reinforced by the other participating entities. The projects were funded by EC purposely to improve the methods of environment-friendly desalination for freshwater production. In 2003, two projects were operated under the Fifth EC Framework known as the SMADES and MEMDIS. The SMADES stands for "SMAll-scale, stand-alone DESalination", was established to deliver continuous water source for folks living in specific regions far away from the grid supply. A small-scale operation by Banat et al. was first developed through the SMADES EC-funded project called "compact SMADES" to identify process parameters of design for the larger-scale namely "large SMADES" system (Banat et al., 2007b). The system is simple and easy to control that does not require a battery and thermal heat storage tanks. As a result, around 120 L per day of distillate flow rate was supplied with the distillate conductivity of below than 5 µS/cm throughout the summer period, and approximately 50 L per day within the cloudy winter days. This project development of a stand-alone SPMD unit was intentionally designed and manufactured for independent operation in arid and semi-arid remote regions with insufficient electricity supply but blessed with an abundance of solar radiation. With the same project under SMADES funded by EC, Banat et al. have sustained to advance the previous version known as the "large SMADES" system establishment located at Aqaba on the Red Sea (Banat et al., 2007a). This system was a continuous innovation from the previous "compact SMADES" unit. The system is comprised of two loops that consisted of seawater loop with the covered area of the 10 MD modules separated from the second loop of 72 solar collectors by heat exchanger made up of corrosion resistant titanium. The MD material is made of polytetrafluoroethylene (PTFE), which is the same as those used in the compact systems. In the two-loop system, the working fluid acting as the heat transfer medium must be of non-corrosive liquid. Thus, the use of anti-corrosive material is optional for the collector. There were four spiral-wound air-gap MD modules operated in parallel. Experimental results from the large system showed that the maximal distillate flux was produced around 1.5 L/ h of membrane surface area. Another EC project was known as MEMDIS that was generally referred to as "Development of stand-alone, solar thermally driven and photovoltaic-supplied desalination system based on innovative membrane distillation". This stand-alone project used to be operated when the MD system required thermal energy from STC and the electrical energy was separated provided by solar PV system to power the electrical components (Koschikowski et al., 2009). Two systems with compact and large-scale system under the MEMDIS project were manufactured at the ITC facilities at Pozo Izquierdo (Gran Canaria Island) (Subiela et al., 2009).

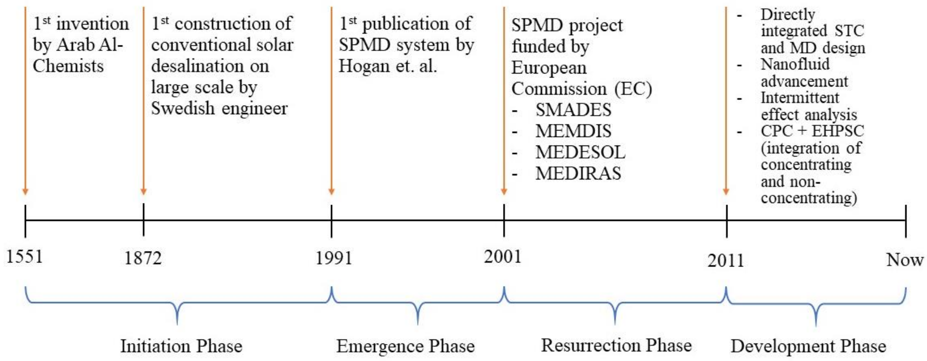


Figure 4. Timeline in the development of SPMD

As mentioned in the previous system characterization section, directly integrated SPMD system is one of the advanced technologies developed during the "SPMD development phase". Li et al. (2019) conducted an experiment and mathematic practicability review of directly integrated solar driven MD system using evacuated tube heat pipe solar collector as STC. The system operated by replacing the heat pipe with hollow fiber membranes inserted inside evacuated solar tubes (EST). Thus, the integrated collector system comprises of an evacuated tube equipped by membrane modules and heat exchanger. The experimental result showed the integrated system could provide ~3.2-4.8 L of potable water plus ~2.5-6 kWh of thermal energy. A 35,000 ppm salinity level of feed water (i.e. seawater) can be reduced into 10–200 ppm of water. Furthermore, the authors suggested steps such as suitable cleaning techniques and efficient drying process for future work to increase the durability of the product.

Another new type of research for SPMD enhancement is by the application of photothermal nanofluid that has great solar energy utilization performance because of the localized surface plasmon resonance form. Based on Figure 5, Zhang et al. conducted an experiment by incorporating the photothermal nanofluid through the feed solution as an energy collector from the STC into the MD system (Zhang et al., 2014). The experiment was carried out by a range of TiN concentrations and solar radiation powers. As a result, the TiN nanofluid indicated the best optical absorption efficiency, less sedimentation possibility, and the highest membrane distillation flux.

Moreover, it is around 57.4% of membrane distillation flux and solar energy utilization enhanced as compared to the base fluid (35 g/L NaCl aqueous solution).

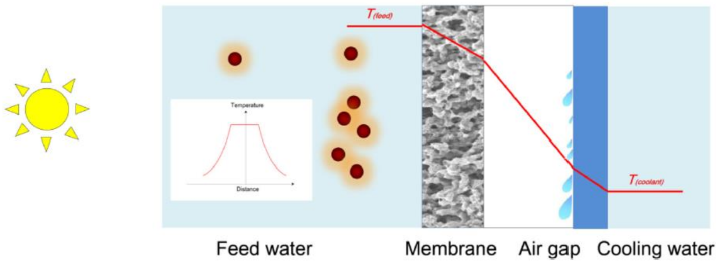


Figure 5. The utilization of photothermal nanofluids through feed solution of SPMD system (Zhang et al., 2018)

For large-scale energy power generation, the application of concentrating collector through DCMD has been studied by the previous researcher. Soomro and Kim (2018a; 2018b; 2018c) studied three types of concentrating collector integrated with DCMD, such as the solar power tower (SPT) linear Fresnel reflector (LFR), and parabolic trough plant (PT). All investigations showed that the combination of concentrating plant with DCMD system might be a sustainable and eco-friendly approach to deal with the rising demand for electricity and freshwater. The integrated SPT plant with DCMD showed higher average freshwater production compared to the LFR and PT plants, which is 40759 L/day, 31844.6 L/day, and 14330 L/day respectively. Chafidz et al. (2016) conducted an experiment by combining evacuated tube as the non-concentrating collector and compound parabolic concentrator as the concentrating collector as illustrated in Figure 6. The system operated by combining both types of solar collector and integrated with Memsys effect stages as the MD module. As a result, the amount of distillate produced was around 70 L/day. This distillate output can be categorized as a low output, but it can be simply increased to meet the water demand by rising the number of the Memsys "effect stages".

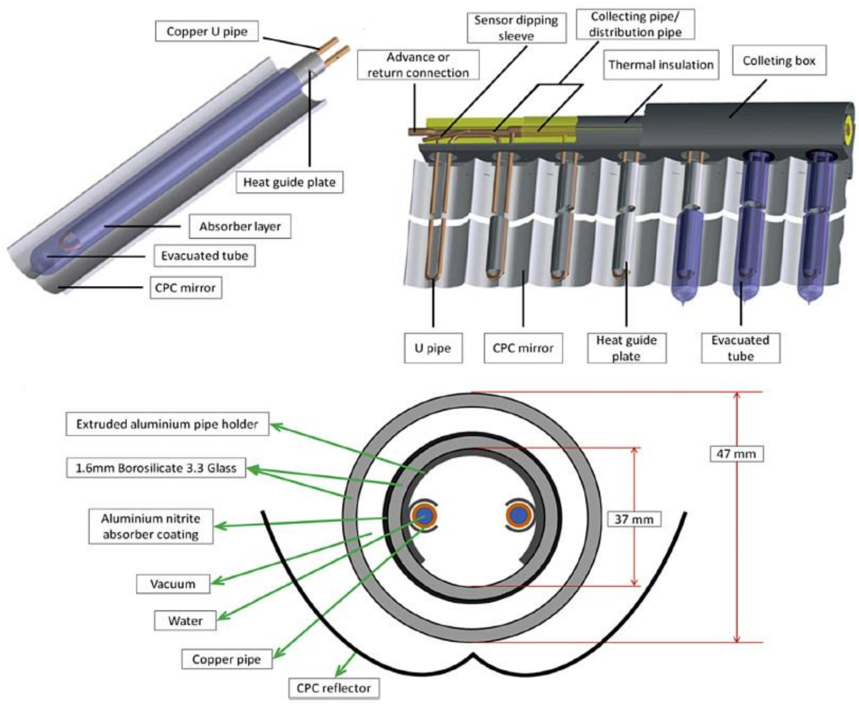


Figure 6. The integrations STC types design between evacuated tube (non-concentrating collector) and compound parabolic concentrator (concentrating collector)

Apart from the design advancement of the SPMD system, some researchers investigated the problem confronted by the SPMD system itself, such as the occurrence of intermittent effects. In all probabilities, the autonomous SPMD system will function intermittently. Hejazi et al. (2019) studied the effect of the intermittent operation on the performance of an SPMD system. As shown in Figure 7, a bench-scale MD unit was set up with programmable temperature-controller proposedly to produce a feed temperature pattern similar to the temperature output of a real pilot solar-powered system. The result revealed the permeate flux is higher with lower specific thermal energy consumption (STEC) during the afternoon compared to the morning. Furthermore, the negative impact of the performance of MD was observed whenever the module was left to dry all night. Moreover, the ultrasonic cleaning of the used hollow fibers helped in recovering their hydrophobicity. Other details on effort to solve the intermittent effect issues can be referred to Gil et al. (2018a; 2018b). With the continuously growing interest in the SPMD process in wide applications, Saffarini et al. (2012) believed that SPMD has the potential to be established in off-grid areas with strong solar radiation.

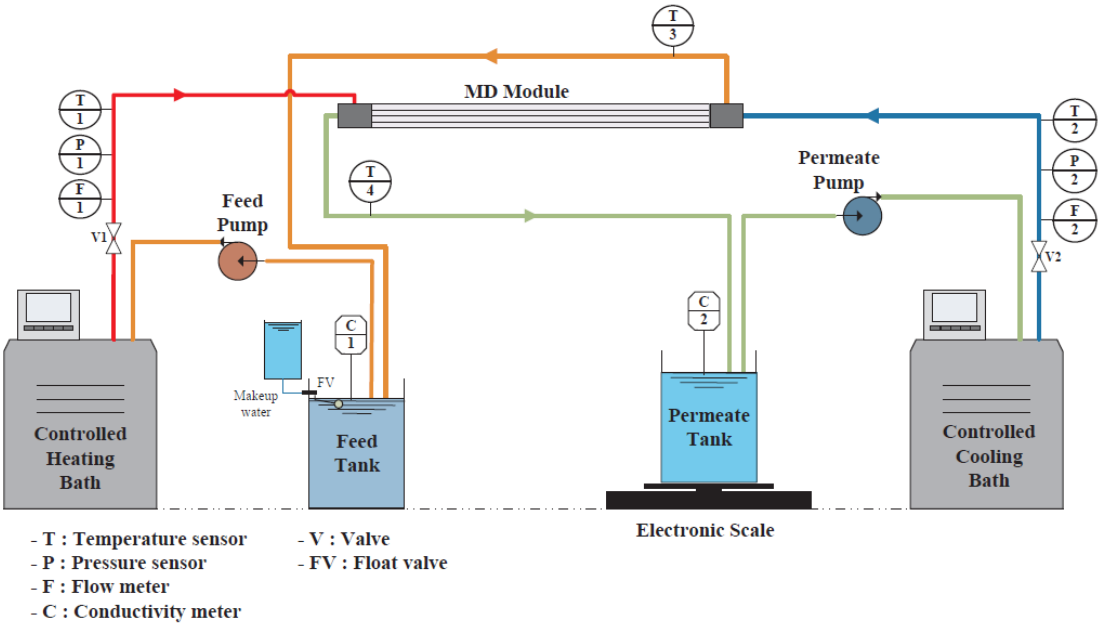


Figure 7. A schematic diagram of programmable temperature-controlled for MD unit (Hejazi et al., 2019)

Conclusion and Future Outlook

Nowadays, the sea or brackish water desalination has gained attention due to the scarcity of water. The utilization of solar energy through desalination processes indicated the capability of further growth, from the point of view of energy conservation and/or cost-cutting approaches. Numerous researchers have examined the integration of solar energy and MD for eco-friendly water desalination. Based on the literature study, these subsequent suggestions might be useful for future research:

- Identifying the ways that could make solar thermal collector produce the highest thermal efficiency into the membrane distillation module.
- Improving the membrane flux by new innovations of membrane materials such as copolymers, dual-layer membrane, and nano-fibrous membranes.
- Determining the optimal parameters such as water flow rate, temperature, etc., that will coincide with economical evaluation.
- Additional numerical and experimental data that contributed to the development of these systems to become more economical and effective in the future.

Furthermore, reviewing and categorizing the previous research on SPMD configurations with different kinds of system give us awareness into the contribution of solar energy for managing sea or brackish water issues. Moreover, the focus to the decrease of emission that matched with environmental policy and aid from the government/society proved that the utilization of renewable energy to be more reliable.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to authors.

Acknowledgements or Notes

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