A Review on Future of Solar Desalination Technologies- Energy Input Outlook

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ABSTRACT

Due to global warming, freshwater sources are depleting, leading to scarcity of fresh water and affecting billions of people across the globe. Therefore, desalination technology is deployed to generate fresh water from salt water to meet the demand. Desalination is an energy-demanding process that takes a lot of power to run its operation, a significant barrier to its growth. Most of the energy in the form of electricity comes from the thermal power plant, which runs on fossil fuels, which leads to substantial emissions. Therefore, efforts are made to utilise solar energy using photovoltaics and solar thermal collector to generate energy in heat and electricity, which can be utilised in desalination technologies. According to International Renewable Energy Agency 2012, merely 1% of the water produced from total desalinated water is from renewable energy-based sources. Various thermal desalination technologies are presented in this review work. Further integration of photovoltaics and solar thermal collector as an energy input source with the desalination technology is discussed. It has been established that the simultaneous use of photovoltaics and solar thermal in desalination technologies could be a viable alternative to stand-alone photovoltaics and solar thermal-based desalination technologies because of simultaneous heat input and electricity improves specific energy consumption and energy efficiency reducing grid dependency. Solar photovoltaic thermal collector provides enhanced energy output within the same area, generating desalinated water at a lower cost and effectiveness of such systems, with some studies reporting up to a 59% increase in water production compared to conventional desalination processes. Apart from the economic and technical advantages found in the open literature, complicated system design, its control and operation strategy, and low technology maturity limit the deployment of photovoltaic thermal collectors in the real world, which requires further research.

Keywords: Desalination, Renewable Energy, Collector

1 Introduction

Water is necessary for life, and access to safe drinking water is a basic human right [1]. However, with growing population and industrialisation, water scarcity has become a major challenge for many countries worldwide. The demand for freshwater is rising rapidly, making it crucial to develop innovative approaches to provide safe drinking water to communities across the globe. According to the United Nations, over two billion individuals live in countries with severe water scarcity, and worldwide water consumption is anticipated to rise by 55% by 2050 [2]. Desalination has emerged as a viable solution to the worldwide water crisis in this setting. Desalination removes salt and other minerals from seawater or brackish water to generate freshwater suitable for drinking and irrigation. Thermal distillation and membrane filtration are the two basic desalination processes. Thermal distillation is the process of heating seawater to generate steam, which is subsequently condensed to produce fresh water. On the other hand, membrane filtration

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uses semi-permeable membranes to extract salt and other contaminants from water. The desalination process is energy-intensive and significantly reliant on electricity, mostly provided by thermal power plants that run on fossil fuels. As a result, greenhouse gas emissions have increased. Therefore, we must look into the possibilities of renewable energy sources, such as solar energy, to power desalination processes. According to the International Renewable Energy Agency, renewable energy accounts for barely 1% of desalinated water production [3].

Solar desalination technologies show great potential in addressing the worldwide issue of water scarcity. Solar desalination technologies use solar energy to desalinate brackish or seawater, generating clean water. These technologies are sustainable, environmentally friendly, and have the potential to provide a reliable source of freshwater to regions that are most in need. In this context, solar desalination technologies have attracted significant attention and investment from governments, non-governmental organisations, and private sector entities. The benefits of solar desalination technologies are numerous. First and foremost, they are environmentally friendly, as they do not produce greenhouse gas emissions or require fossil fuels. Second, they are sustainable, relying on an abundant and renewable energy source – the sun. Third, they can be used in remote areas without electricity or conventional water sources. Finally, they can produce high-quality freshwater for irrigation, drinking, and other uses. This review focuses on various types of solar thermal desalination technologies. It highlights the benefits of generating simultaneous heat and electricity from solar irradiation using a solar photovoltaic thermal (SPVT) collector.

2 Solar Desalination Technologies

Solar desalination technologies use electrical and thermal energy generated from solar cells (SC) and solar thermal (ST) collectors. Figure 1 displays the categorisation of solar thermal desalination technologies, which are primarily classified into multi-effect distillation (MED), multi-stage flash (MSF), and thermal vapour compression (TVC).

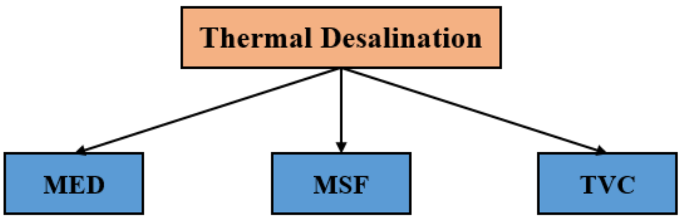

Figure 1: *Classification of thermal desalination technology.*

2.1 Multi-Effect Desalination

The development of the MED system has been driven by the increasing demand for freshwater in dry countries, particularly in North Africa and the Middle East [4]. MED has proven a reliable and efficient system and is now widely used for desalination. The world's largest MED plant, the Shuaibah Expansion II plant in Saudi Arabia, has a capacity of 250,000 m^3/day and uses 14 MED units [5]. MED involves heating saltwater under pressure in a series of chambers or stages, as shown in Figure 2. Solar energy or fossil fuels are used to heat the water in the first chamber, resulting in vapours that heat the feed water in the following stage. This procedure evaporates some feed water, resulting in a somewhat more saline solution than the original saltwater. Each chamber's high-pressure water vapour is then used to heat the water in the next chamber, which has a lower pressure than the preceding one. This cycle is repeated in all subsequent stages, increasing the system's overall efficiency, and the heat generated from condensation is used to heat the next batch of saltwater. This process separates distilled water from the remaining water vapour produced as the stages progress.

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One of the major advantages of MED is its ability to operate with waste heat and renewable energy sources like solar thermal energy, making it an attractive option for remote locations and regions with limited access to electricity. In addition, MED has a smaller footprint and lower capital costs than other thermal desalination technologies like MSF and TVC systems.

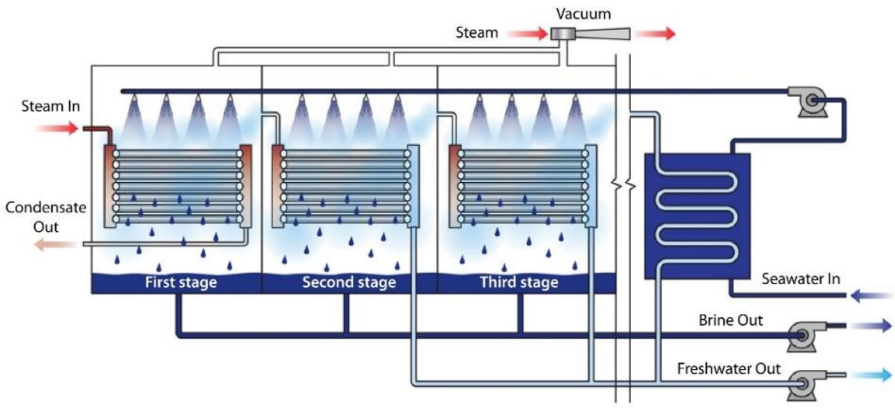

Figure 2: *Multi-effect distillation [6].*

2.2 Multi-Stage Flash Distillation

Figure 3 depicts the MSF process of heating saltwater at high pressure. The seawater is then sent through a series of chambers with decreasing pressure, resulting in further vaporisation. As a result, the vapours are collected and then condensed to produce purified water. However, the remaining saltwater has a higher salt concentration than the original saltwater and is therefore discharged as waste. The purified water is suitable for consumption and is released into the municipal water supply. MSF is the most used thermal desalination technology in the Middle East that traditionally depends on fossil fuels [7]. The largest desalination plants in the world utilise this technology, with specific energy consumption ranging from 81-106 kWh/m^3 for a temperature differential of 10-45 °C between the incoming seawater and hot brine.

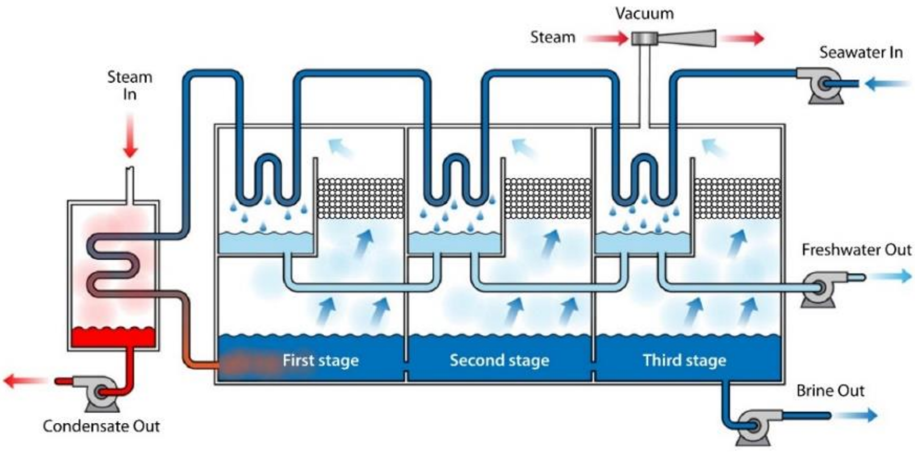

Figure 3: *Multi-stage flash distillation [6].*

Besides from the thermodynamic advantages of the MED process over the MSF method, the former offers another benefit due to the larger heat transfer area, resulting in a lower temperature drop between stages. Typically, this temperature drops from 1.5 - 2.5 °C, allowing for more stages, even when the maximum brine temperature is as low as 70 °C [8]. In comparison, the MSF process is less efficient in heat transfer, resulting in higher costs for producing fresh water. This is due to MSF generally having lower performance efficiency than MED.

2.3 Thermal Vapour Compression Distillation

TVC is a desalination method that utilises vapour compression to produce heat for vaporising seawater. Solar energy generates steam from seawater, which is then allowed to flash. A mechanical or thermo-vapour compressor is then used to compress the vapour. When the pressure is raised, the condensation temperature of the compressed vapour also increases, making it an effective heating agent for the initial liquid or solution from which the vapour originated. When seawater enters the system, the compressed steam cools, causing distilled water precipitation and saltwater heating to generate more steam, as seen in Figure 4. For large-scale applications, TVC is typically used in conjunction with multi-effect distillation or as a stand-alone process for small-scale applications. The primary advantage of TVC is that it utilises vapour compression to adjust the boiling point of water, giving it an edge over other desalination methods. TVC desalination is frequently used in areas with limited freshwaters, such as industrial sites, resorts, and drilling sites.

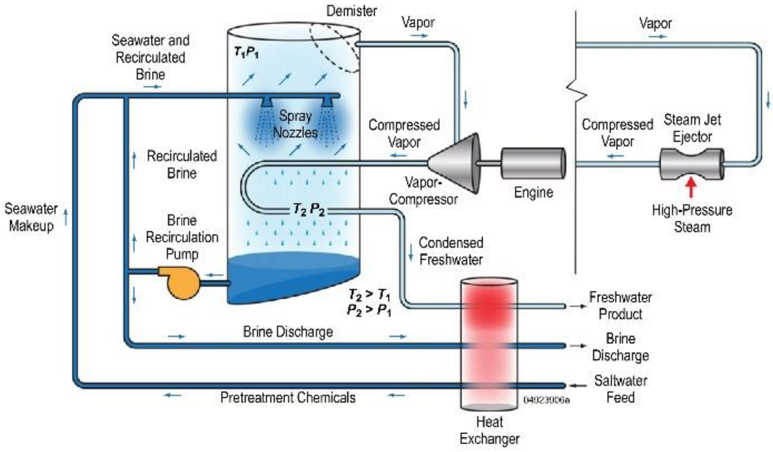

Figure 4: *Vapour compression desalination technology [6].*

Several factors influence the energy consumption in desalination processes, including unit design, plant size, materials used, and seawater quality. Surprisingly, the salt concentration in the feed water does not affect the energy spent in distillation procedures like MSF, MED, and TVC. When the energy consumed by seawater desalination technologies such as MSF, MED, and reverse osmosis (RO) is compared, it is discovered that distillation processes such as MSF and MED consume more energy than RO. Table 1 summarises the energy consumption of the thermal desalination process.

Table 1: *The consumption of energy in different thermal desalination methods* [6].

	Units	**MED**	**MSF**	**TVC**
Unit size	m^3/day	5000 to 15000	50000 to 70000	100 to 3000
Electrical energy	kWh/m^3	2 to 2.5	2.5 to 5	7 to 12
Thermal energy	MJ/m^3	145 to 230	190 to 282	None
Electrical energy equivalent to thermal energy	kWh/m^3	12.2 to 19.1	15.83 to 23.5	None
Total electricity	kWh/m^3	14.45 to 21.35	19.58 to 27.25	16.26
Water quality	ppm	≈10	≈10	≈10

The solar energy market is mainly dominated by photovoltaic (PV) technology, which can convert solar energy into electricity directly, with no noise or moving components involved [9]. According to sources, the global installed capacity of PV technology rose to 630 GW in 2019 and continues to grow rapidly [10]. First-generation silicon PV panels, which have an electrical efficiency ranging from 15-20%, currently comprise more than 90% of the worldwide PV market. PV-integrated systems possess an efficiency of

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around 20%. Although ST-collector integrated systems have a higher efficiency than PV, their high input energy source requirement limits their deployment. Electrical power is also needed to operate the pump, which poses challenges [2]. In this scenario, SPVT collectors can be deployed, increasing their utility and maximising solar energy utilisation. SPVT collectors have a mechanical efficiency ranging from 60-80%, considerably higher than ST collectors and PV cells. Cooling PV cells has become critical in order to improve their electrical efficiency and collect extra thermal energy from the entire spectrum of solar radiation [11]. This necessity has resulted in the emergence of SPVT technology. SPVT collectors can achieve a considerably higher overall efficiency range of 60-80% compared to stand-alone PV panels [12].

3 SPVT Technology

Figure 5 illustrates that SPVT technology is created by utilising PV cells and thermal absorbers to absorb solar radiation. SPVT collectors differ from stand-alone PV panels because they simultaneously produce electricity and thermal energy. The PV cells within the SPVT collectors convert approximately 90% of solar energy into heat and electricity. At the same time, thermal absorbers collect the heat produced by PV cells to generate additional thermal energy. The efficiency of SPVT collectors can range from 60 to 80%, which is far superior to the efficiency of stand-alone PV panels. While commercially available PV cells are typically used in SPVT collectors, current research is focused on developing high-efficiency thermal absorbers. As per the International Energy Agency, the global cumulative area of SPVT collectors exceeded 1.07 million m^2 by the end of 2018 [13]. Heat transfer fluids for SPVT collectors can be either gas-based or liquid-based. SPVT collectors based on gas use air to remove heat from PV cells, while liquid-based SPVT collectors absorb heat using fluids like water; they are more effective. SPVT collectors based on the liquid can be integrated into desalination modules for residential heat water, buildings, swimming pools, and desalination plants.

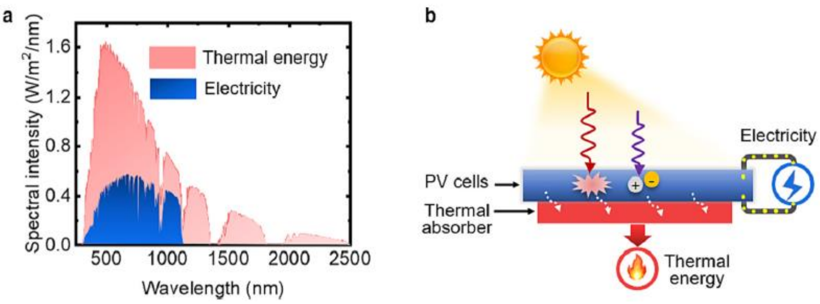

Figure 5: a) *Solar spectrum,* **b)** *Concept of a solar photovoltaic thermal (SPVT) collector [14].*

According to Table 1, thermal-driven desalination procedures such as MSF and MED utilise more thermal energy (kWh) than electrical energy. Electrical-driven desalination technologies like MVC require no heat energy during normal operation. ST collector and PV-based systems harness solar energy to produce electrical and thermal energy for desalination systems. Utilising both forms of energy can reduce entropy generation during desalination processes, leading to improved overall system efficiency and reduced environmental impact. Integrating PV and ST technologies for desalination is one example of using electricity and heat synergistically. PV panels provide electricity to power the desalination process, while solar thermal collectors provide heat to improve the process's efficiency, resulting in a more cost-effective solution for desalination. In conclusion, the co-use of heat and electricity in SPVT-desalination systems can offer significant efficiency, cost, and environmental benefits. However, successful implementation at scale requires careful design and engineering to address challenges in energy supply and demand matching and system component integration.

3.1 Development in SPVT Technologies

The transfer of heat from the PV cell to the heat transfer fluid in a solar SPVT collector is achieved through the absorber surface, which is covered with glass to minimise heat loss due to convection. However, this glass cover reduces electrical efficiency by reflecting a portion of solar radiation. The thermal absorber's efficiency, typically a metal tube array attached to a flat metal sheet, can range from 30-60%. Flat metal sheets can also be used as absorber surfaces, and heat pipes can be integrated into SPVT collectors to enhance their heat transfer capacity, as depicted in Fig. 6b and 6c. Non-concentrating solar SPVT collectors can achieve a maximum temperature of approximately 80 °C, which can be increased by using an optical concentrator with a tracking system, as shown in Fig. 6d. Optical filters, such as selective-reflective or fluid-based filters, can be used to divide solar radiation into two spectral regions, allowing for the generation of thermal energy and electricity from PV cells and thermal absorbers, respectively as shown in Fig. 6(d-e).
While established methods exist for integrating SPVT-desalination systems that do not work together synergistically, this study focuses on new ways to intelligently combine electricity and heat to advance the integration of SPVT-desalination. This review work provides an overview of previous research on SPVT-powered desalination processes and explores how the co-use of heat and electricity can reduce entropy generation during desalination. The next section discusses new opportunities and challenges for the integration of SPVT-desalination systems that could lead to more efficient and effective solutions.

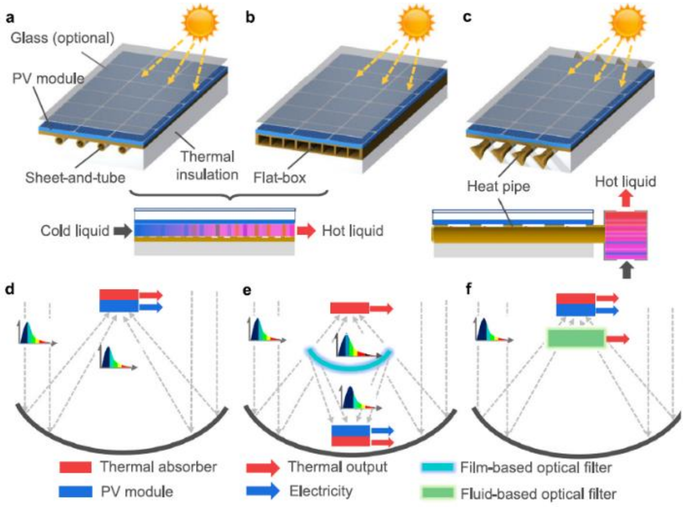

Figure 6: *Liquid-based solar SPVT collector having thermal absorber as: a) sheet and tube, b) flat thermal absorber, c) heat pipe. Thermal concentrators: d) conventional, e) spectral-splitting optical filter having selective reflectivity, and f) spectral-splitting optical filter having selective absorptivity* [14].

3.2 SPVT Collector-Integrated Desalination Technologies

SPVT collectors allow for the simultaneous generation of heat and electricity, which can be utilised for both the desalination process's power and heat requirements. In addition, integrating SPVT collectors with desalination systems can increase the system's overall efficiency and reduce operational costs. Furthermore, smart control systems and energy management algorithms can optimise the energy flow between the SPVT collectors, desalination system, and the grid. The surplus energy produced by the SPVT collectors can be stored in batteries or supplied to the grid. In contrast, excess heat can be utilised for space heating or other applications.

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Furthermore, incorporating energy recovery mechanisms like pressure exchangers can enhance the system's energy efficiency. Integrating SPVT collectors with desalination modules provides a promising avenue for developing efficient and sustainable desalination systems. However, further research is needed to optimise such system's design and operation and evaluate their economic and environmental feasibility. SPVT desalination systems have been successfully implemented beyond small-scale applications. A simulation-based investigation of a hybrid concentrating SPVT (CSPVT) and MED system was conducted by Mittelman *et al.* [15], which indicates that the utilisation of hot water exceeding 100 °C by the CSPVT collector led to an electrical efficiency of 37% and an overall efficiency of 80%. Ong *et al.* [16] conducted experimental research on a hybrid CSPVT and MED system, as shown in Fig. 7. The system is designed to capture both electrical and thermal energy from direct sunlight, with a target electrical yield of up to 30% and a thermal yield that can be used for desalination purposes. The CSPVT system is designed to optimise the flow of both electricity and heat to maximise the overall efficiency and productivity of the system. The CSPVT collector achieved high efficiencies of 30% for electricity generation and 85% overall efficiency. Kelly and Dubowsky [17] carried out an analysis of an SPVT system through both experimentation and mathematical modelling. Their research concentrated on using feed water to chill the solar panel before directing it to the RO module. The researchers found that this approach significantly increased water production by 59%, thanks to the combined effects of feed water heating, PV panel cooling, and solar concentration. A thermal storage tank was utilised to store the thermal energy generated within the system, which was kept at a temperature range of 75-80 °C. This enabled continuous desalination using MED over 24 hours.

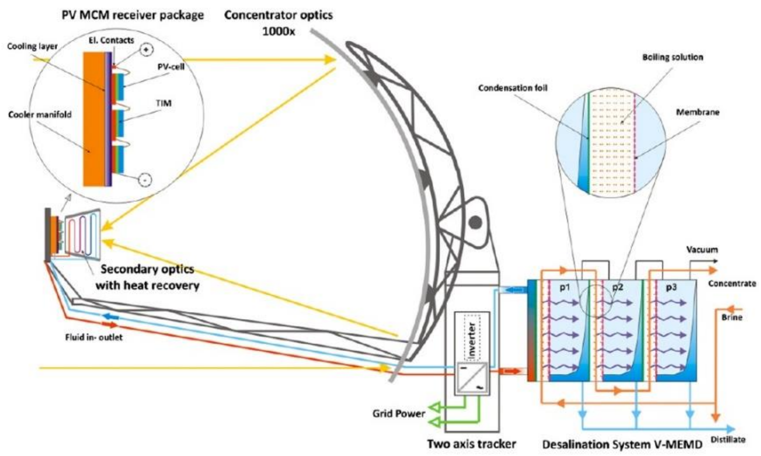

Figure 7: *Concentrated SPVT desalination system with heat recovery [18].*

These studies highlight the potential and benefits of integrating SPVT collectors with desalination systems, demonstrating improved efficiencies and increased water production. However, further research and development are still needed to optimise these systems and assess their feasibility for large-scale implementation.

3.3 Environmental Impact of Desalination

Additionally, the chemicals used in pre-treatment processes can have adverse environmental impacts. Chemicals such as chlorine, hydrochloric acid, and antiscalants can harm marine life if not properly handled and disposed of. Furthermore, the disposal of brine can impact the local marine environment, potentially altering the salinity and chemistry of the water and affecting aquatic ecosystems and their inhabitants. To mitigate these environmental impacts, desalination plants can implement various measures. Various strategies can be implemented to lessen the environmental impact of desalination operations, including using renewable energy sources like solar and wind power to reduce greenhouse gas emissions and brine disposal options like deep sea discharge or evaporation ponds. Additionally, alternative pre-treatment methods, such as membrane bioreactors or electrocoagulation, can reduce harmful chemicals [19]. Overall, it is important for desalination plants to carefully consider and manage the environmental impacts associated with their operations to ensure sustainable and responsible practices.

4 Conclusion

Desalination, particularly using renewable energy sources such as solar energy, can be critical in meeting the growing water demand. Solar desalination technologies have the potential to alleviate water scarcity and provide clean drinking water to regions in need. Integrating solar energy in desalination processes can significantly reduce environmental impact and promote sustainable water management. Continued advancements in solar desalination technologies and supportive policies and investments are necessary to realise their full potential and ensure access to clean water for all. However, desalination is an energy-intensive process that contributes to the emission of greenhouse gases and concentrated brine discharge, which can negatively impact marine ecosystems. Therefore, developing and implementing sustainable desalination technologies and management strategies to mitigate these environmental impacts is important. Integrating PV and ST collector technologies with desalination offers a promising solution to increase the efficiency and sustainability of the desalination process. SPVT-powered desalination systems can potentially reduce the energy consumption and greenhouse gas emissions associated with desalination while producing electricity and fresh water. Furthermore, the use of thermal storage systems can enable continuous desalination over 24 hours, ensuring a reliable and consistent water supply.

Recent research has demonstrated the effectiveness of SPVT-powered desalination systems, with some studies reporting up to a 59% increase in water production compared to conventional desalination processes. However, challenges such as the high initial capital cost and the management of concentrated brine discharge must be addressed for SPVT-powered desalination systems to become widely adopted. Looking to the future, the continued development and implementation of sustainable desalination technologies, including SPVT-powered desalination, will play a critical role in meeting the growing demand for freshwater while mitigating the environmental impacts of desalination. As technology advances and costs continue to decrease, SPVT-powered desalination systems may become a more accessible and economically viable solution for water-scarce regions around the world.

5 Declarations

5.1 Competing Interests

The authors declare that they have no competing interests.

5.2 Study Limitations

There is scope and need to compare the installed desalination systems, especially which use energy from renewable energy sources, which is beyond the scope of the present study.

5.3 Acknowledgements

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