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DESALINATION AUGMENTED BY ENERGY STORAGE

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ABSTRACT

Desalination has become imperative as a drinking water source for many parts of the world. Due to the large quantities of thermal energy and high quality electricity requirements for water purification, the desalination industry depends on waste heat and renewable energy sources such as solar collectors, photovoltaic arrays, geothermal and wind and tidal energy sources. Due to the mismatch between the source supply and the demand and intermittent nature of these natural energy sources, energy storage is a must for reliable and continuous operation of these facilities. Thermal energy storage requires a suitable medium for storage and circulation while the photovoltaic/wind generated electricity needs to be stored in batteries for later use. Desalination technologies that utilize thermal energy and thus require storage for uninterrupted process operation are multi-effect evaporation (MED), low temperature desalination (LTD) and humidification-dehumidification (HD) and membrane distillation (MD). Energy accumulation, storage and supply are the key elements of thermal energy storage concept which result in better economics, resource management and lower environmental emissions of a variable energy source powered desalination system, for instance, solar energy. Similarly, the battery storage is essential to store electrical energy for electrodialysis (ED), reverse osmosis (RO) and mechanical vapor compression (MVC) technologies.

This research-review paper discusses current energy storage options for different desalination technologies using various renewable energy and waste heat sources with focus on thermal energy storage and battery energy storage systems. Principles of energy storage are discussed for the first time with details on design and sizing and desalination process applications.

INTRODUCTION

While desalination of saline waters has now been accepted as a potential alternative for freshwater supplies, the energy demands by the existing desalination technologies for water production continue to pose challenges in their applications. In 2008, the worldwide installed desalination capacity was 58 million m^3/d which is projected to increase to 97.5 million m^3/d by the year 2015. It has been estimated by Kalogirou [1] that the production of 1000 m^3 per day of freshwater requires 10,000 tons of oil per year. The worldwide desalination capacity is increasing at a steadfast pace consuming equivalent amounts of fossil fuel sources and associated increase in greenhouse gas emissions. The desalination industry is projected to experience unprecedented growth concurrently with population explosion and increasing standards of living. Since the energy requirements whether thermal or electric, need to be supplied in large quantities, dependence of these technologies over finite, conventional fossil fuel sources is not a sustainable approach. Utilization of renewable energy sources such solar, wind, and geothermal sources appears to provide a sustainable alternative. Yet, the major concern with these natural and renewable energy sources is their intermittent nature and the variable intensity which limits their applications in many cases and locations. Costs associated with the renewable energy technologies is another major hurdle for successful implementation of these energy resources. Energy storage can be considered as an option to increase the performance of the renewable energy sources. Energy storage might help enhanced utilization of these intermittent energy sources and may improve long term sustainability of the investment. Thermal desalination technologies may utilize storage units known as thermal energy storage (TES) to capture, store, and release to match the energy supply and demand trends. TES can be coupled with energy sources whether they are renewable or waste heat in nature. Photovoltaic collectors and wind turbines require batteries to store the energy to be supplied to the process for later use.

This research-review paper discusses current energy storage options for different desalination technologies using various renewable energy and waste heat sources with focus on thermal energy storage and battery energy storage systems.

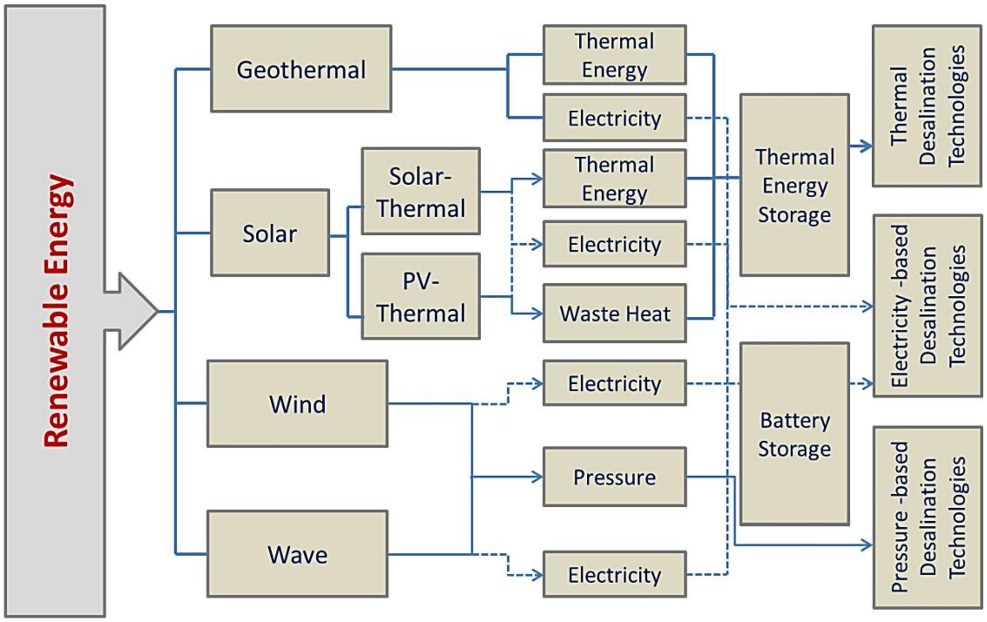

Figure 1 Single-directional and bi-directional heat extraction models

Principles of energy storage are discussed for the first time with details on design and sizing and desalination process applications.

PROPOSED RES-DES CONFIGURATIONS

The potential renewable energy source-desalination technology combinations are shown in **Fig. 1**. The renewable energy sources (RES) should be coupled with the equivalent desalination technology that has capability to utilize the energy in the most effective manner. Accordingly, the following desalination-renewable energy schemes can be identified:

1. RES-desalination coupling schemes that require the RES unit and the desalination unit to be located in the same area. Such couplings are: a) Wind-shaft-Mechanical Vapor Compression (MVC) coupling; b) Solar thermal-heat-Thermal Vapor conversion (TVC); c) Solar thermal-heat-Multi-Stage Flash Distillation (MSF); d) Solar thermal-heat-Multi-Effect Distillation (MED); e) Solar thermal-heat-Distillation; f) Geothermal-heat-Thermal Vapor conversion (TVC); g) Geothermal-heat-Multi-Stage Flash Distillation (MSF); h) Geothermal-heat-Multi-Effect Distillation (MED).
2. RES-desalination coupling schemes that do not require the RES unit and the desalination unit to be located in the same area. Such couplings are: a) Wind-electricity-Mechanical Vapor Compression (MVC) coupling; b) Wind-electricity-Reverse Osmosis (RO); c) Solar PV-electricity-Reverse Osmosis (RO); d) Solar PV-electricity-Mechanical Vapor Compression (MVC) coupling; e) Geothermal-electricity-Mechanical Vapor Compression (MVC) coupling; and f) Geothermal-electricity-Reverse Osmosis (RO).

ENERGY STORAGE OPTIONS FOR DESALINATION

Desalination technologies that utilize thermal energy and thus require thermal energy storage for uninterrupted process operation are multi-effect evaporation (MED), low temperature desalination (LTD) and humidification-dehumidification (HD) and membrane distillation (MD). Thermal energy storage technology requires a suitable medium for storage and circulation for heat transfer while the photovoltaic/wind generated electricity needs to be stored in batteries for later use as shown in **Fig. 1**. Similar to TES, the battery energy storage (BES) is essential to store electrical energy for electrodialysis (ED), reverse osmosis (RO) and mechanical vapor compression (MVC) technologies.

Thermal Energy Storage for Desalination

Energy accumulation, storage and supply are the key elements of thermal energy storage concept which result in better economics, resource management and lower environmental emissions of a variable energy source powered desalination system, for instance, solar energy. TES units function in three important stages: 1) charging period; 2) storing period; and 3) discharging period. Thermal energy accumulation and storage can be accomplished by three different principal methods: 1) sensible heat thermal energy storage which includes both solid-state and liquid materials for storage; 2) phase-change thermal energy storage, also known as latent heat storage; and 3) thermochemical thermal energy storage. An example of the sensible heat TES unit for desalination application powered by process waste heat or solar collectors is shown in **Fig. 2**. The following equation expresses the amount of heat stored in a sensible heat TES in general which depends on the amount of heat transferred from a heat source.

$$Q_{sensible} = m\int_{T_1}^{T_2} c_p(T)\,dT \qquad (1)$$

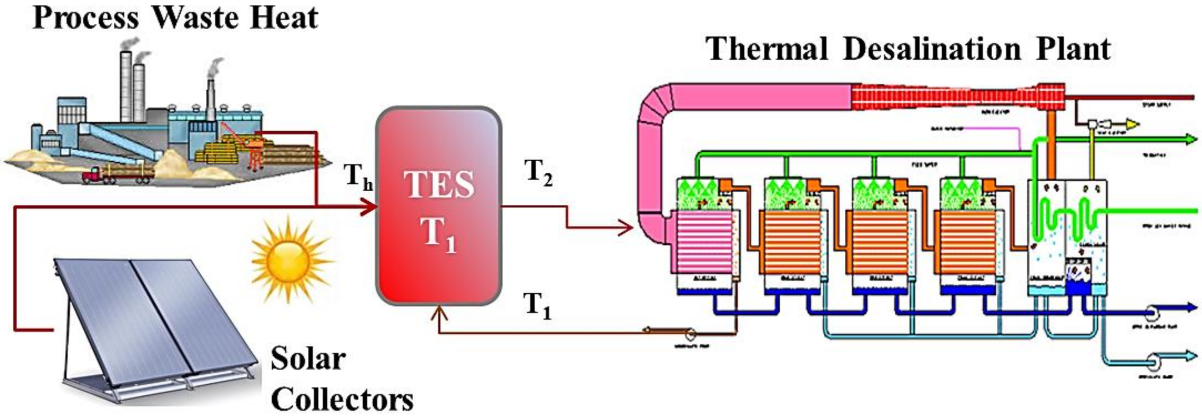

Figure 2 Single-directional and bi-directional heat extraction models

Where $Q_{sensible}$ is the amount of sensible heat stored, m is the flow rate of the storage medium, c_p is the specific heat capacity of the storage medium and T_1 and T_2 are the outlet and inlet temperatures of the heat transfer fluid.

Sensible Heat Thermal Energy Storage

The most commonly used sensible heat storage material is water. TES with water as storage medium are loosely termed as "hot water tanks" due to their wide application. In water based TES systems, water serves simultaneously as the heat storage medium and the heat transfer medium. Thus for most applications, load side heat exchangers may be eliminated. Particularly in the case of domestic hot water systems, the storage is generally hooked on directly to the water pipe line, whereby hot water is withdrawn from the top of the tank and is replaced by an equivalent amount of cold water from the pipe line introduced at the bottom of the tank. Most current research on water storage tanks is aimed at the development of economical, efficient and durable systems for storing solar heat in water and at understanding the role played by stratification in the water tanks on the performance of the solar heating system. Table 3 and Table 4 present the heat storage capacity and costs per unit of thermal energy unit ($/kWh$_t$) for different solid-state and liquid state sensible heat TES mediums [2, 3].

Sensible heat TES applications in desalination

Sensible heat TES technology has been utilized in numerous solar desalination applications. The applications include solar stills, solar ponds and in cogeneration systems with concentrated solar collectors for power generation and water production. In this section, we focus on solar still and solar pond applications with TES.

Solar stills

In solar stills, the solar radiation is reflected and lost to the ambient. The sinusoidal trend of the solar radiation and the ambient temperatures do not favor the freshwater production during non-sunlight hours. During the night time, the solar still productivity could be higher owing to the lower ambient temperatures but the heat source is not available in this period. Increasing the depth (thermal energy storage volume) of the saline water in the solar still increases the heat storage capacity of the device which would result in continued evaporation during cloudy hours and non-sunlight hours. Solar stills incorporating thermal energy storage have shown significant improvement on the overall freshwater production rates. To describe this effect a few examples can be discussed. Tabrizi and Sharak [4] investigated a basin solar still integrated with a sandy heat reservoir. In a 14-h test, the productivity of this configuration was almost twice that of a conventional solar still which was ~3 kg/m^2, while that of a conventional basin solar still was ~1.7 kg/m^2. Murugavel et al. [5] reported that a single basin double slope solar still with energy storing materials like quartzite rock, red brick pieces, cement concrete pieces, washed stones and iron scraps was able to store the excess energy and to increase the night time production. Among the materials used in their experiments, 3/4 in. sized quartzite rock was the most effective one, obtaining a productivity of ~2.1 kg/m^2/d with an enhancement of 6.2% compared to still with same amount of water, without any energy storing material. These confirm that heat storage prolongs the working time overnight, which will increase the total productivity albeit at a slight increase in operational costs in practical applications.

Solar Pond

A solar pond can be considered as a large solar collector with huge storage volume where the solar energy trapped into the stored brine solution is circulated as a heating medium in the desalination process unit. Solar ponds provide the most convenient and least expensive option for heat storage for daily and seasonal cycles [6-8] in solar energy including cloud effects while simultaneously providing for brine management.

El-Sebaii et al. studied a single-slope basin solar still integrated with a shallow solar pond (SSP) and found that the average productivity and thermal efficiency were higher than those obtained without the SSP by 52.4% and 43.8%, respectively, over a year [9]. Extensive research conducted for more than 20 years at El Paso (Texas, US) solar pond demonstrated the reliability of a salinity-gradient solar pond in desalination application. This research focused testing various operating conditions for a multi-effect, multistage (MEMS) flash desalination unit. This research provided operation and maintenance procedures of the salinity-gradient solar pond coupled with the desalination [10]. An experimental solar pond with a surface area about 830 m^2 and a depth of 2.5 m was studied in Tajoura-Libya [11]. This solar pond is also coupled with 5 m^3/d MSF desalination plant. Tahri studied the possibility of combining a MSF desalination plant with a solar pond to recover the waste heat from exhaust gas of a thermal plant [12]. Posnansky [13] presented computer simulations and experimental results on a small sized solar pond for the performance data of the coupled MSF unit [14]. Szacsvay et al. developed a desalination system with autoflash MSF unit consisting of a solar pond as the heat source. Performance and layout data were obtained both from computer simulation and experimental results with a small-sized solar pond and desalination subsystem in Switzerland which had been in operation for 9 years. The authors concluded that the cost of distillate could be reduced from \$5.48/m^3 for small desalination system with a capacity of 15 to 2.39 m^3/day for desalination systems with a capacity of 300 m^3/day [15]. Solar powered multi effect humidification studied by Muller-Host et al used 2 m^3 hot water storage tank, which increased the production rate to 500 L/day with 38 m^2 collector area (about 13 L/m^2). Two different humidification units were tested in this study. The first one ("SODESA system") consisted of a thermal storage tank at ambient pressure and a collector field. The feed water was heated by direct circulation through the collector. The system efficiency was high due to elimination of heat exchangers, but costly materials to resist seawater corrosion at 100°C were required for the collector [16].

Waste heat utilization and Low temperature desalination

Thermal energy storage can be used to store the process waste heat to be utilized for desalination as shown in **Fig. 2**. Low temperature desalination is beneficial from many perspectives which include resource losses, required operation and maintenance and capital costs. Low temperature TES will have less standby losses and can utilize sensible heat to store the energy. High temperature desalination systems are typically supported by concentrating solar power systems often combined with power generation scheme. A low temperature desalination tapping the reject heat from the condenser of a domestic air-conditioning system was studied. In this study, evaporation of saline water occurs at near vacuum pressures created by exploiting the principles of local barometric head. The evaporator operates in a temperature range of 40-50ºC with the heat supplied by a thermal energy storage unit. The energy requirements for the system are less than that required for a multistage flash (MSF) distillation process. Results of this study show that the thermal energy rejected by an absorption refrigeration system (ARS) of cooling capacity of 3.25 kW (0.975 tons of refrigeration) along with an additional energy input of 208 kJ/kg of desalinated water is adequate to produce desalinated water at an average rate of 4.5 kg/h. This energy consumption is competitive with that of the multi-stage flash distillation process of similar capacity (338 kJ/kg) [17, 18]. A typical unit with a TES volume of 10 m^3 with a solar panel area of 25 m^2 was required for this application. The proposed system minimizes nonrenewable energy usage and may be improved further by incorporating a double- or triple-effect configuration.

Sizing of TES Systems

The size of the thermal energy storage system depends on several factors: 1) the desalination technology (heat load); 2) the heat source whether solar energy or process waste heat (availability and duration); 3) the heat capacity of the storage material; 4) the time frame of the storage; and 5) the expected standby loss (heat losses to ambient). Optimal sizing of the thermal energy storage system is important to maximize the integrated system efficiency. Without a supplemental heating source, undersized TES systems are insufficient to meet heating demands. Oversized systems have a higher capital costs as well as operation and maintenance costs, and can waste energy through standby losses. For seasonal storage systems, sizing the system is even more important as even optimally sized systems can occupy a large space and require high installation costs.

ELECTRICAL ENERGY STORAGE OR BATTERY ENERGY STORAGE (BES)

Desalination systems that primarily or partially depend on electrical energy sources are membrane based technologies (**Fig. 1**) such as reverse osmosis (RO), electrodialysis (ED), capacitive deionization (CD), electrodialysis-reversal (EDR) and membrane distillation (MD). These technologies can be supported by the electrical energy generated by either photovoltaics or wind turbine units. Similar to thermal energy produced by solar thermal collectors, these technologies also suffer from varying source of energy for electricity harvesting and need storage devices to meet the demand-supply logistics and to improve reliability and performance [19]. The solar and wind sources fluctuate very significantly during the course of a day resulting in potential excess generation or under supply. Excess electrical energy can be stored in batteries for the desired periods before it is discharged in process applications while the electrical energy that was already stored can be released during the periods of low power generation. Electrical energy storage, in large scale applications, can be divided into three main functional categories such as: (i) Power Quality: Stored energy applied only for seconds or less to ensure continuity of power quality; (ii) Bridging power: Stored energy applied for seconds to minutes to assure continuity of service when switching from one source of energy to another; (iii) Energy Management: Stored energy used to decouple the timing of energy generation and consumption especially in the application of load leveling. Load leveling involves charging of storage in low demand time and use in peak time which enables consumers to minimize the total energy cost [20, 21]. The third category is the ideal mechanism for desalination processes. The following sections discuss the specific energy requirements and energy recovery and energy storage and sizing methods for reverse osmosis membrane process.

PV and Wind generated electricity storage

The process diagram for PV-Wind-battery operated reverse osmosis systems is shown in **Fig. 3**. Any photovoltaic system consists of a number of PV modules, which convert solar radiation into direct-current (DC) electricity. The voltage and current of the system can be increased by connecting multiple cells in series and parallel, respectively. The other system equipment includes a charge controller, batteries, inverter, and other components needed to provide the output electric power suitable to operate the systems coupled with the PV system. PV is a rapidly developing technology, with costs falling dramatically with time, and this will lead to its broad application in all types of systems. PV-RO and PV-ED will initially be most cost-competitive for small-scale systems where other technologies are less competitive [22].

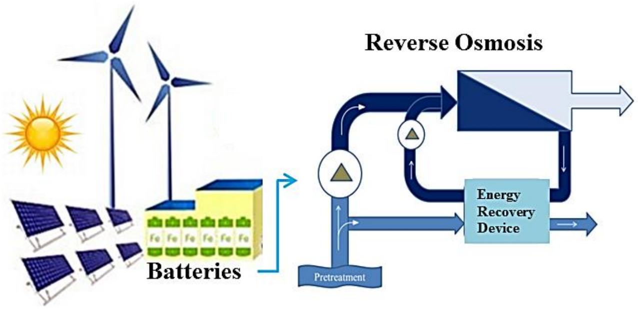

Figure. 3. Reverse osmosis system combined with PV or Wind or hybrid energy source

RO usually uses alternating current (AC) for the pumps, which means that DC/AC inverters must be used [22]. In contrast, ED uses DC for the electrodes at the cell stack, and hence, it can use the energy supply from the PV panels without major modifications. Energy storage is again a concern, and batteries are used for PV output power to smooth or sustain system operation when solar radiation is insufficient. Sizing the battery charging system requires consideration of many physical and operating factors as shown below.

Electrical storage sizing involves the following steps:

Step 1. Determining the daily load required by desalination application

Step 2. Determining the required PV or wind turbine rating for the load.

Step 3. Determining daily energy output from the PV array or wind turbine.

Step 4. Estimating the PV array size and wind turbine rotor diameter.

Step 5. Estimating the required battery (storage) size in Ah for the load on storage.

PV-Battery System Sizing

Basis: 100 m^3/d of freshwater production from seawater source with specific energy consumption of 5 kWh/m^3. The total electrical energy demand is 500 kWh.

The PV array capacity can be calculated using a solar window of 10 hours as

$$P_{ac}(kW) = \frac{Load\_(kWh/d)}{Solar\_window\_(h/d)} = \frac{500}{10} = 50kW$$

[For an electrodialysis unit, equivalent DC capacity can be found by considering the efficiency of the PV system. Overall efficiency (η) of PV system considered 85% including efficiency of inverter, dirt and mismatch losses of PV modules:

$$P_{dc,STC} = \frac{P_{ac}(kW)}{\eta}$$]

According to IEEE-1013 [23], size of the PV array should be more than 1.2 times the load to charge the battery while supporting the load. So the adjusted PV array capacity for the equivalent DC load becomes:

$$P_{ac,STC(Adjusted)} = 1.2 \times P_{ac,STC} = 1.2 \times 50 = 60kW$$

Therefore, for desalination application, 60 kW capacity of PV array with an optimum storage capacity (battery) is required to support the load for 24 hours a day. For known PV panel efficiency and for 1 kW/m^2 rated PV module, the required surface area of the PV array can be calculated. The efficiency of crystal silicon PV module is 12.5% [24], and therefore surface area of PV array becomes:

$$P_{ac,STC} = (1\,\mathrm{kW/m^2})insolation \times A \times \eta$$

$$A = \frac{P_{ac,STC}}{(1\,\mathrm{kW/m^2}) \times \eta} = \frac{60}{1 \times 0.125} = 480m^2$$

Thus 480 m^2 PV module with PV panel efficiency of 12.5% will support the load with sufficient storage size.

To estimate the required storage for the load, the total energy generated from this PV array is used. The capacity of the required battery bank can be calculated by multiplying the daily load on battery by autonomy day or number of days it should support the system to provide power continuously. The ampere-hour (Ah) rating of the battery bank can be found after dividing the battery bank capacity by the battery bank voltage (ex. 24V or 48V). Inverters are specified by their DC input voltage as well as by their AC output voltage. Inverters DC input voltage which is the same as the battery bank voltage is called the system voltage. The system voltage usually considered as 12V, 24Vor 48V [25]. Considering a system voltage of 24V and one day battery storage, the procedure will be as follows. For an inverter (with battery) efficiency of 95% [26], the required battery capacity can be calculated. Therefore load on battery is:

$$\text{Daily load in Ah @ system voltage} = \frac{\text{Load (Wh/day)}}{\text{System Voltage}}$$

$$= \frac{60 \times 10^3}{24} = 2500\,Ah/d$$

Energy stored in a battery typically given in Ah, at system voltage and at some specified discharge rate. The Ah capacity of a battery is not only rate-dependent but also depends on temperature. The capacity under varying temperature and discharge rates to a reference condition of C/20 battery (i.e., discharge for 20 hours) at 25ºC is explained in [24]. The maximum depth of discharge (MDOD) for Lead-acid battery is 80% [25], thus for one day discharge the battery need to store:

$$\text{Battery storage} = \frac{\text{Load (Ah/day)} \times \text{No of days}}{\text{MDOD}}$$

$$= \frac{2500}{0.80} = 3125\,Ah$$

The rated capacity of battery is specified at standard temperature. At 25ºC, the discharge rate of C/20, becomes 96% [20], therefore finally required battery capacity becomes:

$$\text{Required Battery storage } (25\,^{\circ}\text{C, 20 hr - rate}) =$$

$$\frac{\text{Battery storage}}{\text{Rated capacity}} = \frac{3125}{0.96} = 3255\,Ah$$

Thus for 500 kWh/d load, a 3255 Ah of storage battery is required at system voltage 24V with 60 kW solar PV.

SUMMARY

Energy storage is critical for uninterrupted supply of freshwater sources from desalination technologies depending on variable natural energy sources. The type and size of energy storage depends on the combinations of the desalination process and renewable energy technology as discussed earlier. Since thermal desalination systems require large quantities of heat sources, thermal energy storage unit can accommodate for storage of excess heat extracted during sunlight hours and supply to the desalination system. While the membrane processes require electrical energy, battery storage systems can provide the storage and serve as buffering unit for reliable power supply. While the benefits of energy storage systems can be realized from energy, environmental and economic perspectives, the energy storage option may not be ideal or economical in all cases since the feasibility depends on the location, type and size of the desalination application and the available renewable energy sources. Whether an energy storage option is feasible for a given application needs to be determined by careful evaluation of the above mentioned factors. Apart from cost issues, other barriers relate to material properties and stability, in particular for TCS. Each storage application needs a specific TES design to fit specific boundary conditions and requirements. Future research activities should focus on all TES technologies. Most of the research efforts should investigate the materials (i.e. storage media for different temperature ranges), containers and thermal insulation development. More complex systems (i.e. PCM, TCS) require additional efforts to improve reacting materials, as well as a better understanding of system integration and process parameters as applied in desalination applications.

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