Renewable Energy Storage & its Application for Desalination

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\textbf{Abstract:} The economic development has serious impact on the nexus between water, energy and environment. This impact is even more severe in Non Organization for Economic Cooperation and Development (non-OECD) countries due to improper resource management. It is predicted that energy demand will increase more than 71\% in non-OECD as compared to 18\% in developed countries by 2040. In Gulf Cooperation Council countries, water and power sector consume almost half of primary energy produced. In the past, many studies were focused on renewable energies based desalination processes to accommodate 5 fold increase in demand by 2050 but they were not commercialized due to intermittent nature of renewable energy such as solar and wind. We proposed highly efficient energy storage material, Magnesium oxide (MgO), system integrated with innovative hybrid desalination cycle for future sustainable water supplies. The condensation of Mg(OH)$_2$ dehydration vapor during day operation with concentrated solar energy and exothermic hydration of MgO at night can produce 24 hour thermal energy without any interruption. It was showed that, Mg(OH)$_2$ dehydration vapor condensation produce 120$^\circ$C and MgO hydration exothermic reaction produce 140$^\circ$C heat during day and night operation respectively correspond to energy storage of 81kJ/mol and 41kJ/mol. The produced energy can be utilized to operate desalination cycle to reduce CO$_2$ emission and to achieve COP21 goal. The proposed hybrid desalination cycle is successfully demonstrated by pilot experiments at KAUST. It was showed that MgO+MEDAD cycle can achieve performance over UPR=200, one of the highest reported ever.

\textbf{Keywords:} Thermal desalination, Adsorption cycle, Hybrid cycle, Renewable energy, solar energy, energy storage material.
1 Introduction

Increased water demand and the degradation of water sources is not only threaten the fast economic development activities but also the public health in many developing countries. Particularly, GCC countries are most effected region because of rapid population and development growth and poor water resources management even with limited water resources. In GCC region, per capita renewable water availability is the lowest in the world and they housed 5% of world population. To meet water demand, all GCC countries heavily relay on desalination processes. The GCC countries started desalination in 1950 to meet their demand and to maintain groundwater resources sustainability and today they hold around 75% share of world desalination capacities. The change in climate is expected to make this region more water scarier due to high evaporation rate and reduced average rainfall. In addition, the population growth trend coupled with anticipated climate change will pressurize the water situation even more. It is estimated that by 2050, GCC countries will only able to satisfy 23% of demand that will yield 26 billion cubic meters (bcm) per year water shortage, 77% of consumption[1]. Huge desalination capacities are expected to be installed in future to fulfill the water demand. Unfortunately, the conventional desalination process are not only energy intensive but also environment unfriendly. Today’s best desalination processes consume 7-10 kWh primary energy to produce one cubic meter of water and emit around 3-4 kg of CO₂ emission[2]. The amount of energy required for seawater desalination processes is almost 10 times higher than the river and lake water treatment. This high energy consumption not only results higher water and associated processes cost but also severe environmental impact. Therefore, an improved desalination processes and implementation of alternate energy resources are important for future sustainability.

Fig. 1. Solar energy availability in Middle East and North Africa (MENA) region.
Since renewable energies has no impact on environment, so desalination processes based on these technologies will be more sustainable for future water supplies. In addition, the overall cost of water production will be reduced to very low due to free availability of these energy sources. Renewable energy driven desalination process are in R&D phase since long and few of them were able to get place in practical application but most of them were not able to commercialize due to large capital cost and intermittent nature of renewable energy. The Sunbelt region, GCC countries, have highest solar irradiance and also available most of the time of the year that can be harnessed to produce portable water through desalination processes in sustainable manner. Figure 1 shows the solar irradiance in GCC region [3].

Fig. 2. Renewable energy driven desalination technologies and their status of application with maximum design size.
Solar energy is an attractive source because firstly its has low operational and capital cost and in addition, it is environmental friendly. Solar energy driven desalination processes are heavily investigated by many researchers for their commercial application possibilities. Some processes are still under research and development phase and some technologies are implemented at certain locations for commercial application. Figure 2 shows the status of desalination processes operating with solar energy. The application chart showed that solar energy based thermally driven desalination processes are implementing at large scale to produce fresh water followed by photovoltaic driven membrane processes [4].

![Figure 2](image2.png)

**Fig. 2.** Status of desalination processes operating with solar energy.

Even though solar energy is promising for sustainable water production but its intermittent availability is main bottleneck in its major application. Currently, over 130 desalination plants powered by renewable processes contributing only 1% to total world desalination capacities. The share of different processes is shown in Figure 3 [5]. To increase solar driven desalination capacity, it require energy storage for 24 hours operation.

### 2 Solar Thermal Energy Storage Options

Two main features of solar energy, almost free and endless, make it more attractive as compared to other renewables. However, its cyclic nature is the main hindrance in its commercial applications. To overcome this limitation, scientists proposed solar thermal energy storage (STES) system that can store solar energy as a thermal heat during day time and release when solar radiations are weak or not available. The necessary electricity for equipment operation can be supplied with concentrated solar photovoltaic
(CSP) system equipment with STES system. The commercial applicability of STES system is depend on its efficiency and cost effectiveness. The STES system can be divided into three classes based on the method of heat storage. These three classes are the sensible heat storage, the latent heat storage and thermochemical heat storage. The efficiency and cost effectiveness of STES system is based on five parameters such as (i) temperature for storage, (ii) period for storage, (iii) storage material availability, (iv) material storage capacity and (v) operation.

The thermochemical heat storage have many advantages such as (i) 5 to 10 times higher energy density as compared to other two STES systems and (ii) minimum losses during storage and transportation. Because of these two properties, these systems can be utilized to store long-term period energy. However, thermochemical heat storage system is still not able to commercialized at large scale and this is one of the reason that there is no trustable data available for application design. The designing of thermochemical heat storage system need careful selection of chemical reaction and detailed investigation of operational parameters such as pressure, temperature, kinetics and reversibility. The main classifications of reactions for thermochemical heat storage system are presented in Figure 4 [4].

Fig. 4. Main classifications of reactions for thermochemical heat storage system.

A chemical heat pump (CHP) operated with Magnesium oxide and water pair (MgO/H₂O) is considered due to high energy storage capacity and simple operation. The proposed CHP operate on reversible chemical reaction between MgO and Mg(OH)₂ based on the following equilibria. Magnesium oxide has highest energy storage density as compared to many other energy storage materials as shown in Figure 5 [5-8].

\[ MgO(s) + H₂O(g) \leftrightarrow Mg(OH)₂(s) \quad \Delta H₁ = -81.02 \text{[KJ/mol]} \]
\[ H₂O(g) \leftrightarrow H₂O(l) \quad \Delta H₂ = -40.66 \text{[KJ/mol]} \]
Fig. 5. Energy density of different thermal energy storage materials at different operating temperatures.

Fig. 6. Energy storage principle of MgO/H$_2$O heat pump.

The operation of proposed CHP system is presented in Figure 6 [9-12]. The two major components are (i) chemical reactor packed with magnesium oxide and (ii) an evaporator filled with water. One complete cycle of operation consist of heat storage mode and heat release mode.

In heat storage mode the fully hydrated magnesium hydroxide (Mg(OH)$_2$) is exposed to the concentrated sun at $T_d$ to supply heat ($Q_d$) for dehydration process. The vapours
produced during dehydration process are condensed at $T_C$ in the condenser and the condensation heat ($Q_d$) is utilized for desalination cycle at day time during energy storage mode.  

**In heat release mode** hydrated magnesium oxide is exposed to water evaporator to extract vapor for hydration. Since the adsorption is an exothermic reaction so hydration heat ($Q_h$) at $T_h$ is extracted and utilized during night operation and heat release mode. It can be noticed that there is no major moving parts are involved in operation and this is the major advantage of proposed cycle. In addition, it is environment friendly and also economic because MgO is easily available. The proposed CHP can store energy at over 300°C and deliver over 100°C for 24 hour operation. This heat can be utilized for the operation of proposed cycles for cooling and desalination. The detail of proposed cycles, adsorption (AD) cycle for cooling and hybrid multi effect desalination and adsorption cycle (MEDAD) for desalination are presented in the following sections.

### 3 STES System and Desalination Cycle

The proposed system have three major sub-systems, namely; the AD subsystem, the MED subsystem and STES subsystem. The detail of AD subsystem, hybrid MEDAD subsystem and MgO+MEDAD is presented in following sections.

#### 3.1 AD Subsystem

Low temperature operated adsorption (AD) subsystem is an affordable solution to produce fresh water and cooling using solar thermal energy. Plethora literature is available on AD cycle investigation for their working pair selection and performance improvement. The basic AD cycle consists of adsorbent beds, evaporator, condenser and liquid circulation pumps. The process schematic is shown in Figure 7. The two main processes for AD cycle are adsorption-evaporation and desorption-condensation.  

**In adsorption-evaporation** process, the dried adsorbent is exposed to the evaporator to assist evaporation due to adsorbent high affinity for water vapors. Since adsorption is an exothermic process that increase the adsorbent temperature and reduce its adsorption capacity. To maintain adsorption process, coolant is circulated through heat exchanger tubes to extract the heat of adsorption. The evaporator temperature is maintained by circulating the chilled water through the tubes. The AD evaporator can operate at as low as 5°C to produce cooling effect when it is operated as a chiller. The adsorbent can adsorb vapors and maintain evaporation process until it get fully saturated. Once adsorbent is fully saturated, it switch process to regeneration to prepare for next operation.
In desorption-condensation process, low temperature heat source from 55 °C to 85 °C is supplied to the reactor bed to regenerate the adsorbent. The regenerated vapors are then condensed in the condenser to produce distillate. When it is operating as a chiller, the refrigerant is refluxed back to the evaporator as a close loop.

To overcome cyclic operation limitations of conventional AD cycle, multi bed system was proposed for continuous operation. The number of beds depend on the size of AD system as per cooling or desalination requirements. In multi bed scheme, they operate as a pair for adsorption and desorption processes. The automatic switching method is applied to switch their duties from adsorption to desorption process to complete cycle.

The time for adsorption/desorption process is depend on quantity of adsorbent packed in a single bed. It can be noticed that the major moving parts are just automatic valves and circulation pumps that make AD cycle very robust and very less maintenance is required. It can produce two useful effect, cooling and desalinated water.
3.2 Hybrid MEDAD Desalination Subsystem

In conventional multi effect desalination (MED) subsystem, the heat source is supplied to the first steam generator and seawater is sprayed on to the tube surfaces. The saturation pressure is controlled to maintain evaporation under vacuum conditions at 65°C. The vapor produced in the first stage are channeled to the tubes of second stage to reutilize the heat of condensation. The produced vapors are then condensed by transferring the heat condensation to the seawater sprayed that help to evaporate the part of the feed. The condensed vapor produce fresh water that is collected from each stage. This process of evaporation and condensation of feed water and vapors continue until the last stage of the system. The last stage vapors are condensed in the final condenser by circulating the seawater. It can be noticed that the overall operational range for conventional MED system is from heat source temperature 65°C to the last stage condenser temperature 40°C. These operational limitations also limit the performance of thermally driven desalination processes. The performance of desalination processes can be improved by overcoming their operational limitations. Some studies showed that heat source temperature can be increased to 120°C by introducing proper pre-treatment processes to overcome the scaling and fouling chances. Nano-filteration (NF) is one of the pretreatment process that can help to remove soft scaling components from feed water to prevent scaling and fouling chances at high temperature operation. On the other hand, the proposed hybridization of AD cycle with conventional MED system can help to overcome last condenser temperature limitations and operation can be extended to as low as 5°C. The detailed schematic of MEDAD hybrid cycle is is shown in Figure 8 [13-22].
In hybrid cycle, the MED last stage condenser is bypassed and vapors are directly adsorbed on the adsorbent of AD cycle. The high affinity of adsorbent toward water vapor reduced saturation pressure and hence temperature. This hybrid cycle extend the temperature range from typical 40°C to 5°C and it help to insert more number of stags. The more number of stages will help to increase the number of recoveries from provided input and hence performance will improve. It was reported that hybrid MEDAD cycle can boost the water production to two fold as compared to conventional MED system at same heat source temperature. It can be observed that the tri-hybrid system NF+MED+AD can be the best performance system if operated with renewable energy for future sustainability. The proposed trihybrid cycle can be operated with STES system to produce fresh water 24 hours. The detailed of the system is presented in following sections.

3.3 Proposed MgO+MEDAD Desalination Subsystem

In this proposed subsystem, MgO is coated on tubes and module is sized are per energy storage requirement. This energy storage tubes module is connected to a seawater evaporator and a condenser. During day operation, to dehydrated Mg(OH)$_2$, solar rays are concentrated to the module at 300°C and desorbed vapors are directed toward the condenser for condensation. The heat produced during condensation is recovered through hot water closed circulation loop to supply heat to MEDAD cycle steam generator or first stage. This process continue until solar energy is available throughout the day.

![Proposed MgO+MED+AD desalination subsystem flow schematic.](image_url)
After sunset, during night operation, the dried MgO tubes are exposed to seawater evaporator. The hydration of MgO is an exothermal process and this heat is recovered from the top head of tubes (acting like heat pipe) and supplied to the first stage of MEDAD cycle. The exothermic heat recovery will not only help to maintain adsorption process but will also help to operate MEDAD cycle at night. The detailed flow schematic of proposed system is shown in Figure 9.

To verify the concept, a pilot was installed at King Abdullah University of Science and Technology (KAUST) and tested successfully. The detail of pilot is presented in following section.

4 MEDAD Desalination Pilot Experimentation

To investigate MEDAD operation, a 4-effect pilot was designed and build in KAUST as shown in Figure 10 (a & b). The pilot capacity is 4m³/day as a standalone MED and around 8m³/day when operated with combination of Ad cycle as a MEDAD hybrid cycle. The MED pilot is operating with parallel feed system supplied from Red Sea after minimal pretreatment. Due to budget constraint, the heat input was simulated via solar collectors and boiler.

Fig. 10 (a). MEDAD hybrid pilot installed at KAUST.
Figure 11 shows the temperature profiles of all MED effects operating at 50°C. The inter effect temperature difference was noted as 2-3°C, same as in commercial MED plants. The condenser cooling water is supplied from Red Sea before supplying as a feed and average temperature was observed as 33°C. After 72 hours successful operation, MED system was hybridized to AD cycle to demonstrate as MEDAD cycle. The experiment was continued for another 72 hours and temperature trends are plotted in Figure 12. It can be seen that after hybridization, the inter effect temperature difference was increased to 4-5°C and last effect was operating at 25°C, below feed water temperature, as compared to conventional MED system operating at 42°C.
The MED operation below ambient temperature is demonstrated for the first time in the desalination history. The successful operation will provide opportunity of MED system to operate from top temperature 50°C to last effect temperature to as low as 5°C as AD cycle can help to pull temperature to 5-7°C due to silica gel affinity for water vapors. This excellent thermodynamic synergy between MED and AD will not only help to extend conventional MED system operational rage for an additional recoveries but will also boost water production to almost two folds as presented in Figure 13. The two fold water production boost due to hybridization processes can be noticed clearly from the production profiles at same heat supplied conditions.

Fig. 11. 4 stages MED and condenser temperature trends at heat source 50°C for 72 hours operation.
**Fig. 12.** Temperature profiles of MEDAD hybrid cycle effects and condenser at heat source 50°C for 72 hours operation.

**Inter-stage temperature differential 4-5°C**

**Fig. 13.** Water production profiles of conventional MED and MEDAD hybrid cycle at heat source 50°C.
5 Desalination Processes Performance Evaluation

Currently, different methods are employed to evaluate diverse desalination processes. For example, thermally driven desalination processes are evaluated by performance ratio (PR) and pressure driven processes are based on specific energy consumption (kWh/m³). In industry, operators sometimes use specific energy consumption method for both processes by considering the different grade of energies as same such as electricity and low pressure steam as shown in equation 1. This misconception of considering all energies as same grade provide distorted evaluation for different desalination processes. Since derived energies (electricity and steam) involved their generation processes efficiencies so they must be converted to primary energy before considering for evaluation processes.

\[
PR = \left( \frac{\text{Equivalent heat of evaporation of distillate production}}{\text{Energy input}} \right)
\]

\[
\cong \frac{2326 \, \{kJ\}}{3.6 \times \left[ \left\{ \frac{kWh_{\text{electrical}}}{m^3} \right\} \text{CF1} + \left\{ \frac{kWh_{\text{thermal}}}{m^3} \right\} \text{CF2} + \left\{ \frac{kWh_{\text{renewable}}}{m^3} \right\} \text{CF3} \right]}
\]

(1)

We proposed universal performance ratio (UPR) method for all kind of desalination processes evaluation a common platform because it based on primary energy. All derived energies should be converted to primary energy by considering their conversion factors and then can be utilized to calculate the performance as shown in equation 2. The proposed method can be utilized for any processes efficiency calculation and it can be compared with any other technology because they all based on primary energy basis.

\[
\text{UPR} \cong \frac{2326 \, \{kJ\}}{3.6 \times \left[ \left\{ \frac{kWh_{\text{electrical}}}{m^3} \right\} \text{CF1} + \left\{ \frac{kWh_{\text{thermal}}}{m^3} \right\} \text{CF2} + \left\{ \frac{kWh_{\text{renewable}}}{m^3} \right\} \text{CF3} \right]}
\]

\[
\text{CF} = \text{conversion factor}
\]

1 = electrical, 2 = thermal and 3 = renewable

(2)

In a cogeneration based desalination plant, detailed exergetic analysis showed that gas turbine cycle consume around 73.17% on input fuel exergy. The hear recovery steam generator help to recover 26.83% exergy from exhaust gases to produce steam for steam cycle and desalination processes. The Rankine cycle consume around 23.43% and desalination processes only utilize 3.4% on input fuel exergy. Considering these propor-
tions, the conversion factors are calculated to convert derived energies to primary energy to compute the UPR for desalination processes as summarized in Table 1. It can be seen that MED processes performance is the highest because it has best thermodynamic synergy when combined with power plants. Most importantly, all desalination processes are operating only at 10-15% of thermodynamic limit. This shows that the current desalination processes are not sustainable and their efficiency need to improve to achieve 25-30% of thermodynamic limit to achieve future sustainability goals. High efficiency desalination processes integrated with renewable energy sources can be best choice for future water supplies [23, 24].

Table 1. Universal performance ratio comparison of all desalination processes.

<table>
<thead>
<tr>
<th>Desalination technology</th>
<th>Electrical energy consumption (kWh\textsubscript{el})</th>
<th>Thermal energy consumption (kWh\textsubscript{th})</th>
<th>Conversion factor for electricity (CF\textsubscript{1})</th>
<th>Conversion factor for thermal energy (CF\textsubscript{2})</th>
<th>Primary energy (kWh\textsubscript{pe})</th>
<th>UPR</th>
<th>UPR percentage of TL (UPR at TL=828)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SWRO</td>
<td>3.85</td>
<td>NA</td>
<td>0.572</td>
<td>29.4</td>
<td>6.75</td>
<td>95.8</td>
<td>11.6%</td>
</tr>
<tr>
<td>MED</td>
<td>1.50</td>
<td>61.0</td>
<td>138.4</td>
<td>25.4</td>
<td>4.67</td>
<td>138.4</td>
<td>16.7%</td>
</tr>
<tr>
<td>MSF</td>
<td>2.50</td>
<td>72.0</td>
<td>8.37</td>
<td>77.2</td>
<td>8.37</td>
<td>77.2</td>
<td>9.3%</td>
</tr>
<tr>
<td>MEDAD</td>
<td>1.80</td>
<td>30.5</td>
<td>4.19</td>
<td>155.0</td>
<td>4.19</td>
<td>155.0</td>
<td>18.7%</td>
</tr>
</tbody>
</table>

\* TL = \frac{2326 \text{ kJ/kg}}{2.8 \text{ kJ/kg}} = 828, \quad \frac{0.78 \text{ kWh}}{m^2} = \frac{2.8 \text{ kJ}}{\text{kg}}

It can be seen that even with paid thermal energy, MEDAD hybrid cycle has highest UPR as compared to other processes. In case of MgO+MEDAD, the thermal energy will be free on small expense of electrical to drive circulation pumps that will boost UPR to over 200.
Conclusions

Thermally driven desalination system and solar thermal energy storage system have been proposed for 24 hours operation. It was showed that renewable energies were not implemented at commercial scale due to intermittent nature. An efficient and reliable storage system can overcome this limitation and these free energy sources can be applied for sustainable production of desalinated water. Magnesium oxide based CHP energy storage system is proposed to supply thermal energy to hybrid MED+AD desalination system to produce desalinated water to fulfil future water demand. The desalination processes operating with renewable energy sources will not help to reduce environmental impact but also overall water production cost. These sustainable energy sources will help to fill gap between future water demand and supply in sustainable manner. The proposed system performance is successfully demonstrated at KAUST and it is estimated to have highest UPR, over 200. These innovative solutions will help to save energy and protect environment.

Nomenclature

OECD Organization for Economic Cooperation and Development
COP Conference of parties
GCC Gulf Cooperation Council
EAD Environment Agency Abu Dhabi
MENA Middle East and North Africa
MED Multi effect desalination
MSF Multi stage flash
SWRO Seawater reverse osmosis
MVC Mechanical vapor compression
AD Adsorption
ED Electrodialysis
TES Thermal energy storage
CSP Concentrated solar photovoltaic
TBT Top brine temperature
LBT Lower brine temperature
LPM Liter per minute
UPR Universal performance ratio
TL Thermodynamic limit

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