Chapter

Desalination with Renewable Energy: A 24 Hours Operation Solution

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Abstract

The inevitable escalation in economic development has serious implications on energy and environment nexus. The International Energy Outlook 2016 (IEO2016) predicted that the Non Organization for Economic Cooperation and Development (non-OECD) countries will lead with 71% rise in energy demand in contrast with only 18% in developed countries from 2012 to 2040. In Gulf Cooperation Council countries (GCC) countries, about 50% of primary energy is consumed for cogeneration based power and desalination plants. The desalination capacities are expected to increase fivefold by 2050 and renewable energy application can be one of the solution for sustainable water production. The major bottleneck in commercialization of renewable energy sources is its intermittent nature of supplies specially wind and solar. We proposed solar thermal energy storage to operate desalination system around the clock. Magnesium oxide (MgO) can be utilized as an efficient energy storage system to store solar thermal energy for off period operation. The heat generated by regeneration processes at day time and exothermic adsorption at night can operate desalination cycle 24 h. The operational temperature ranges from 120 to 140°C and energy storage 41–81 kJ/mol. It was successfully demonstrated by experimentation that MgO operated hybrid desalination cycle can achieve highest performance and lowest carbon emission. The proposed cycle can achieve sustainable water production goals.

Keywords: renewable energy, hybrid desalination, low emission desalination, sustainable desalination, energy storage

1. Introduction

The energy demand in Gulf Cooperation Council (GCC) countries is almost doubled in a decades, from 300 TWh in 2000 to 600 TWh in 2012. In GCC countries, the residential and commercial sector energy demand has grown rapidly. The residential sector consumes over 50% due to improved living standards. In GCC countries, per capita primary energy consumption is the highest as compared to other countries in the world as shown in the **Figure 1** [1–3].

The GCC countries also produce substantial amount of CO_2 and it was estimated as 1.2 billion tons of CO_2-equivalent in 2012. The major part of CO_2 emission is related to energy and water production. The GCC countries are the most water

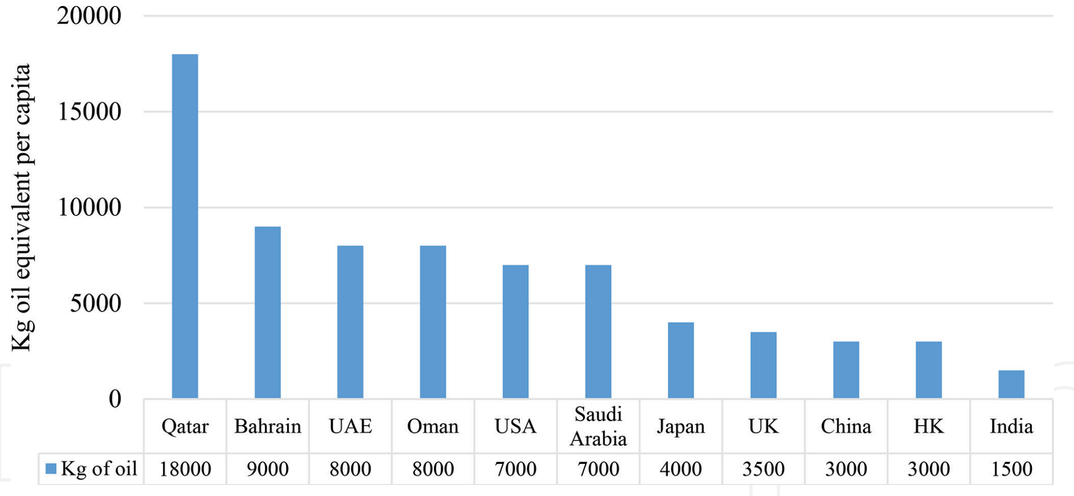

Figure 1.
Per capita oil consumption in different parts of the world.

Country	2010 consumption	2050 consumption	2050 shortage
Bahrain	227	400	380
Kuwait	509	1220	850
Oman	760	1700	1150
Qatar	328	400	175
Saudi Arabia	20,480	27,000	20,100
UAE	3375	3500	3250
Total			

Table 1.
Water consumption and estimated shortage in 2050 in GCC countries.

scariest in the world due to dry environmental conditions and recently it became even worst due to population increase and GDP growth. It is estimated that by 2050, the shortage of water supply can be as high as 77%. **Table 1** shows the water consumption and shortage in million cubic meter per year scenario in all GCC countries by 2050. It can be noticed the large gap in water demand and supply cannot be filled by renewable and ground water sources. The non-renewable such as desalination is the only source for future water supplies in GCC countries [1–3].

Today, all desalination processes are energy intensive and consume primary energy in the range of 6–10 kWh/m^3. The inefficiency of desalination processes, 10–13% of thermodynamic limit, requires not only more energy but they also emit enormous CO_2 [4–7]. For future sustainability, one feasible option is to utilize renewable energy such as wind and solar. The renewable technologies have drastically developed and their economics are greatly improved in recent years, and GCC countries have great potential to exploit the renewable energies potential such as solar and wind. The GCC countries government announced mega investment plans to invest in renewable energy sectors to meet the increasing demand of electricity as shown in **Figure 2** [8].

The resettlement of energy mix in GCC countries needs a comprehensive plan for contractor as well as operator companies. One of the major challenges in renewable energies development is its intermittent nature. Currently they are only employed to cope the peak load typically during office hours. The one of the solution to overcome intermittent supply is the energy storage and there are two methods namely, battery storage and thermal heat storage. In terms of battery storage, the efficiency is very low, typically 8–10% in field operation due to

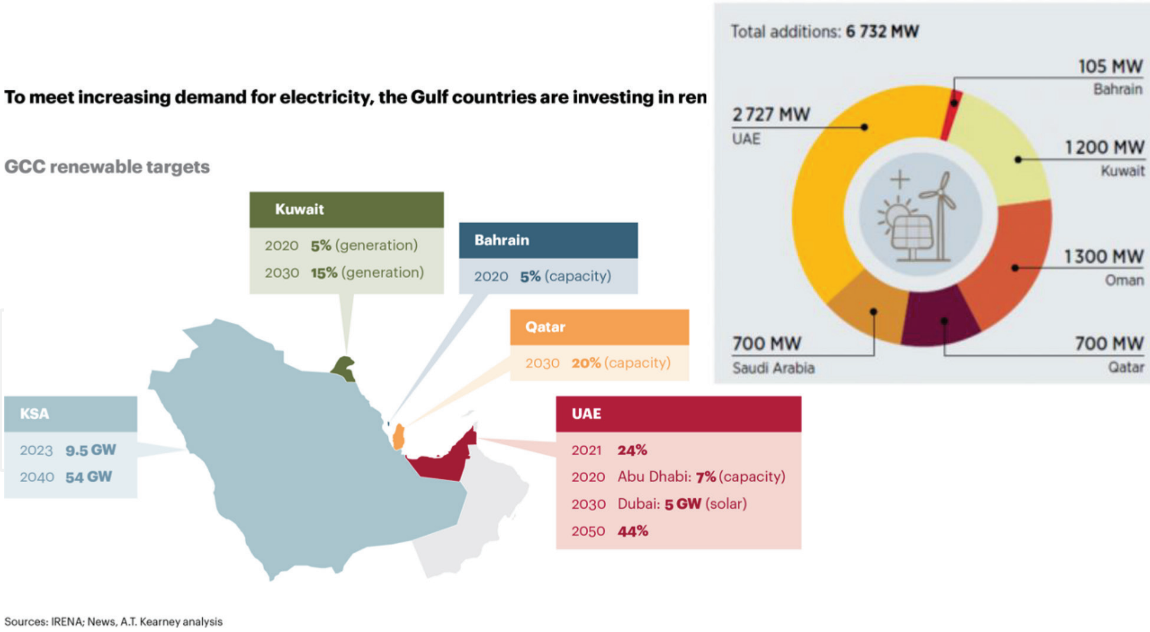

Figure 2.
GCC countries renewable energy development plan by 2030.

Materials	Heat storage method		Heat storage density (GJ/m^3)	Heat charging temperature (°C)
Co_3O_4	Thermochemical materials (TCM)	Inorganic oxides	5.0	925
CaO			4.5	550
MgO			3.4	350
$MgSO_4$		Anhydrate	2.6	125
Silica gel		Adsorbate	0.8	85
Zeolite			0.6	220
Paraffin	Phase change materials		0.2	60
Water	Sensible		0.2	0–100

Table 2.
Comparison of different thermal energy storage materials.

efficiencies involved from one form to other form conversions. On the other hand, direct thermal storage and utilization efficiency is significantly high due to same form of energy utilization without conversion into different forms. There are three major technologies utilize different methods to store solar energy. The comparison of different heat storage materials is summarized in **Table 2** [9–11].

2. Solar thermal energy storage and desalination application

Thermochemical materials (TCM) have many advantages over the other materials such as high heat storage density and low heat leak. Once the reactant leave the thermochemical materials, the enthalpy remains same and it help to achieve the state of energy charging. Subsequently, the discharged energy is utilized while the material remains stable. In the past, a lot of studies were carried out on heat pump using different TCM materials [12–14]. The selection of TCM materials for different application is based on many elements such as (i) heat storage temperature, (ii) heat releasing temperature,

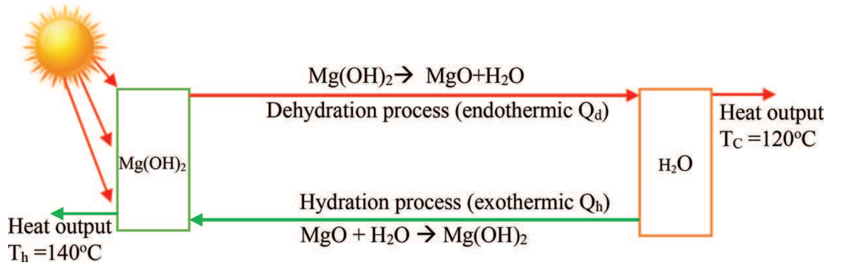

Figure 3.
MgO thermal energy storage system operation.

(iii) heat storage density, and (iv) material stability. The magnesium oxide (MgO) is most suitable for thermal heat storage as compared to other materials due to its high density and stability. Many researchers published data on MgO thermal heat storage and its performance improvement [15, 16].

The dry MgO reacts with water (hydration) to become hydrated $Mg(OH)_2$. The hydration is a exothermic reaction and generates 81 kJ/mol. During dehydration of $Mg(OH)_2$ it becomes MgO through a reverse process at 350–500°C from solar collectors and high temperature vapor are utilized as a heat source. It can be noticed that MgO as an energy storage material produce heat during day as well as night time. The hydration process at night and dehydration process at day with solar energy can produce sufficient heat energy to operate the desalination cycle.

The principle of this heat pump is shown in **Figure 3**. The heat pump consists of a magnesium oxide reactor and a water reservoir. In heat storage mode magnesium hydroxide ($Mg(OH)_2$) is dehydrated by surplus heat (Q_d) at T_d from sun. The generated vapors are condensed at the reservoir at T_C and the condensation heat (Q_d) of the vapor is used for desalination cycle at day time. The hydration of magnesium oxide proceeds in the reactor by introducing the vapor, and a hydration heat output (Q_h) at T_h is generated to operate desalination cycle at night. Thermal drivability, which does not require mechanical work, is one of the advantages of the heat pump. The environmentally friendly and economical nature of the reactants is also advantageous. This type of heat pump is able to store heat at around 350°C through $Mg(OH)_2$ dehydration and to transfer stored heat at temperatures between 110 and 150°C through MgO hydration. The solar thermal energy storage and 24 h delivery around 100°C is best suitable for sustainable desalination processes [17–19].

The renewable energy (RE) driven desalination processes are already commercialized but at low scale due to some operational complexity. **Table 3** summarized

Plant name	Location	Technology	Capacity	Energy source	Cost* (US$/$m^3$)
Kimolos	Greece	MED	2000	Geothermal	2.5–3
Keio university	Japan	MED	100	Solar thermal	
PSA	Spain	MED	72	CSP	
Ydriada	Greece	RO	80	Wind	2–6
Morocco	Morocco	RO	20	PV	2–5
Oyster	Scotland	RO	—	Wave energy	3–5
KAUST**	Saudi Arabia	MEDAD hybrid	10	Solar thermal	0.5

Cost is estimated based on plant capacity more than 1000 m^3/day [20].
Refs. [21–29].

Table 3.
RE driven desalination technologies and water cost.

the major renewable desalination plants operated in the world and estimated cost of water production.

It can be noticed that thermal desalination processes are most favorable option with solar thermal energy operation. The most efficient thermally driven multi effect desalination (MED) system recently investigated to overcome its conventional operational limitations. The numbers of stages in a MED is controlled by top brine temperature (TBT) and lower brine temperature (LBT). The TBT typically 70°C is restricted by soft scaling components in the feed water and the LBT is controlled by ambient condition due to water cooled condenser to condense the last stage vapors. The MED system can be more efficient if these two limitations cab be removed to increase number of recoveries. Researchers found that TBT can be increased to 125°C by inducing nano-filtration (NF) prior to introduction the feed into the system. This NF process helps to remove soft scaling components and prevent scaling and fouling on the tubes of evaporators. The inter stage temperature and the last stage operating temperature limitations can be overcome by hybridization with adsorption cycle. AD cycle can operate below ambient conditions typically as low as 5°C due high affinity of water vapors of adsorbent (silica gel). MED last stage temperature can be lower down to 5°C by introducing the AD at downstream. The proposed hybrid MEDAD system with TES will be the best choice for sustainable water supplies.

3. Proposed system operation

The detailed schematic of TES driven hybrid MEDAD desalination cycle is shown in **Figure 4**. During day time operation, solar heat is supplied to the hydrated $Mg(OH)_2$ at 300–400°C and regenerated vapor condensation heat at 120–150°C is utilized to operate desalination cycle. At night time, the hydration of MgO generates sufficient heat due to exothermic reaction that is supplied to the desalination cycle to continue the operation. It can be noticed that with MgO energy storage system, thermal desalination can be operated for 24 h using solar energy.

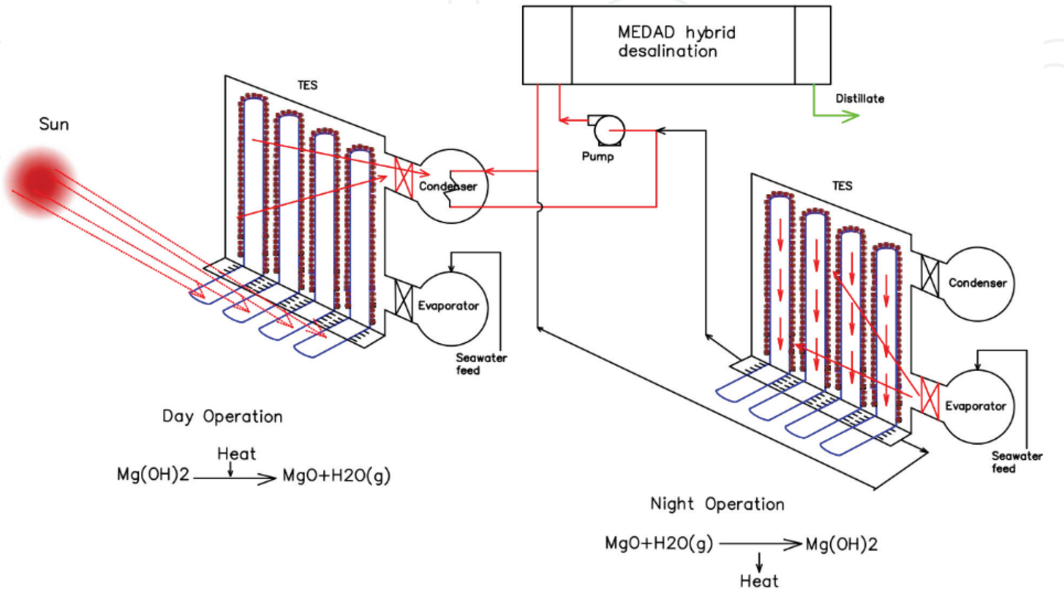

Figure 4.
Proposed TES driven hybrid MEDAD desalination cycle.

4. Experimentation

An experimental system was designed and installed to test workability of proposed concept. **Figure 5** shows the temperature profiles of MEDAD effects at heat source of 45°C. The pilot was tested at different temperatures to investigate the performance. **Figure 6** shows the hybrid MEDAD system effects temperatures at different heat source temperatures. The system performed well as per designed 3–4°C inter-effect temperature difference. Similarly, **Figure 7** shows the corresponding saturation pressures.

Figure 8 shows the water production profiles of MED effects, AD condenser and total production at 45°C heat source temperature. The summary of water production presented in **Figure 9** at different heat source temperatures. It can be seen that at higher temperature the water production is also higher and it drop due to drop in heat capacity. The system is designed for 45°C operational temperature but it performed well at off-design conditions. It shows the robustness of the thermally driven desalination systems.

The thermal energy consumed is shown in **Figure 10**. It can be noticed that at higher heat input temperature the energy consumed by the system is also higher. It is mainly due to the higher temperature difference between heat inlet and out

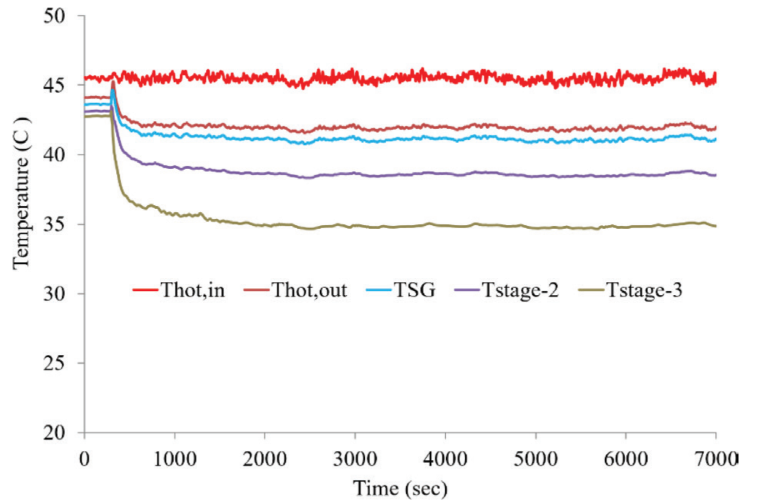

Figure 5.
Hybrid MEDAD temperature profiles at 45°C heat source.

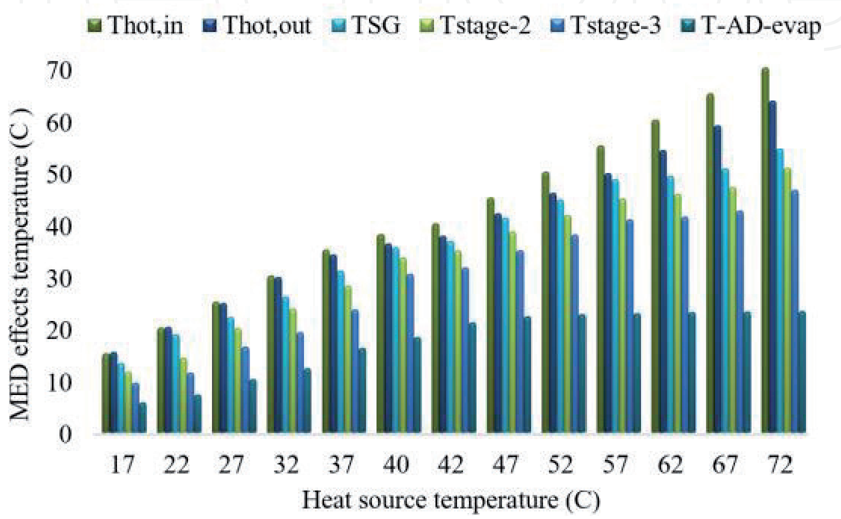

Figure 6.
Hybrid MEDAD inter-effect temperatures at different heat source (reproduce with author's permission [30].

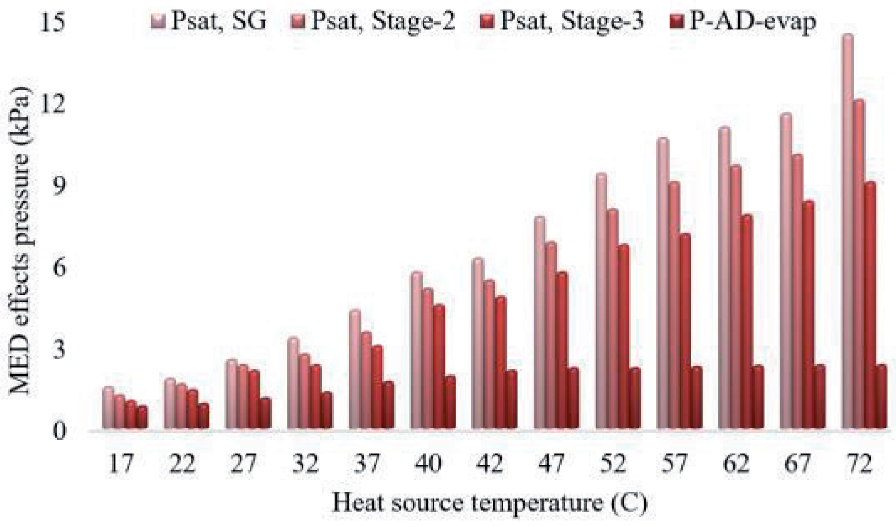

Figure 7.
Hybrid MEDAD inter-effect pressures at different heat source (reproduce with author's permission [30]).

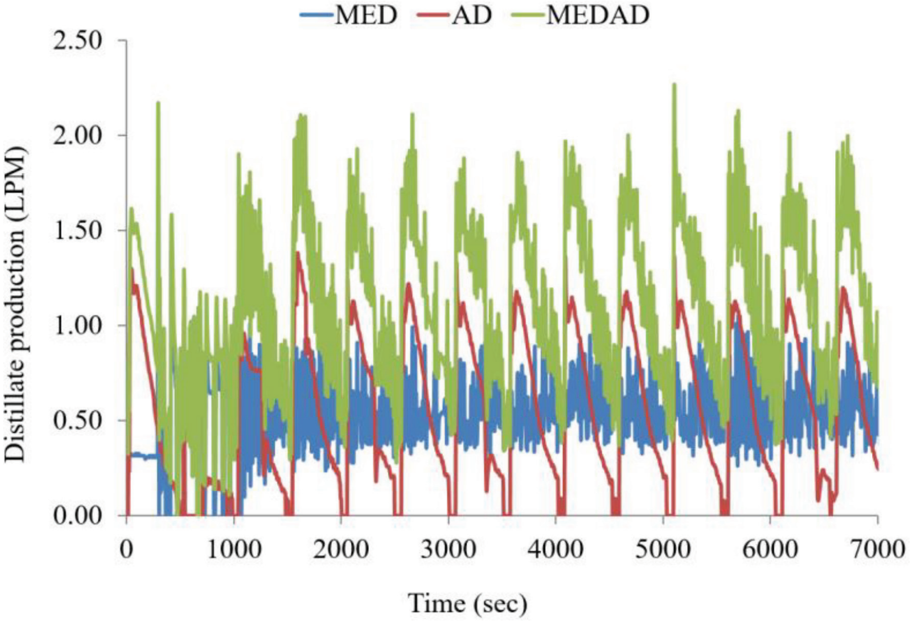

Figure 8.
Hybrid MEDAD water production profiles at 45°C heat source (reproduce with author's permission [30]).

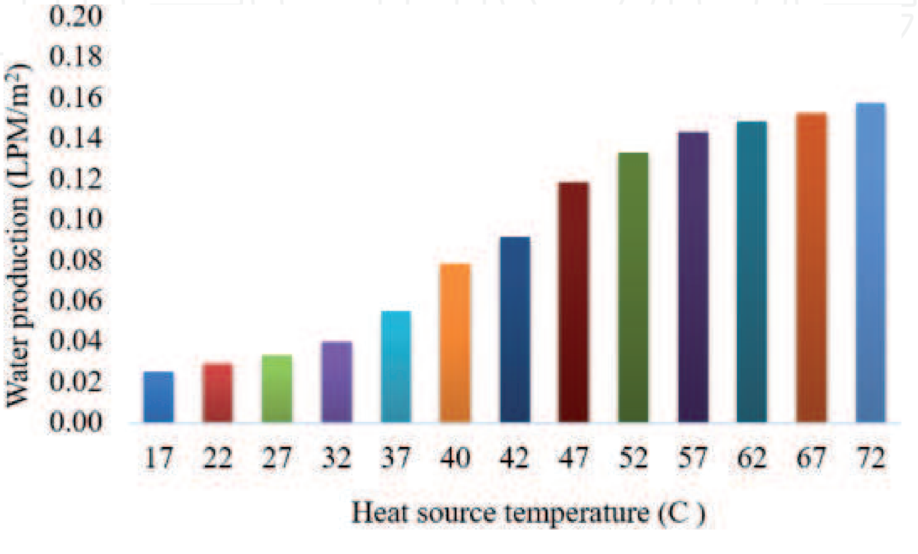

Figure 9.
Hybrid MEDAD water production at different heat source temperature (reproduce with author's permission [30]).

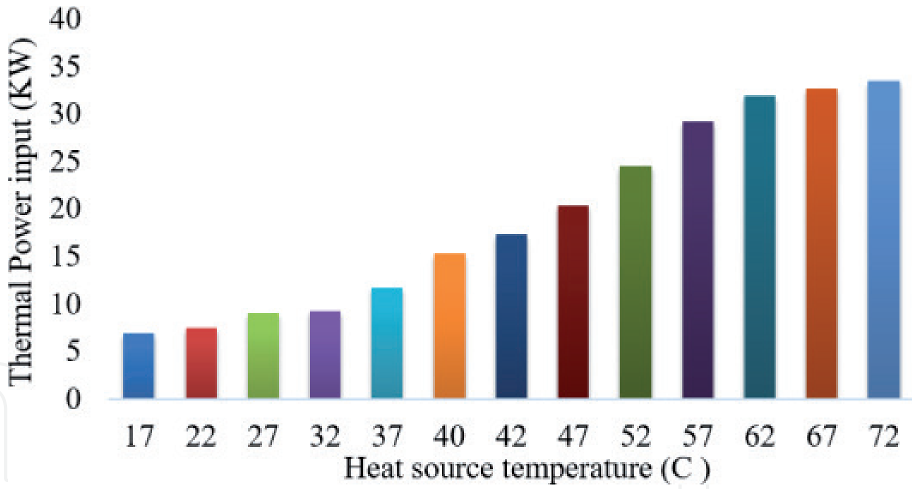

Figure 10.
Hybrid MEDAD thermal energy input at different heat source temperature (reproduce with author's permission [30]).

temperatures. The interesting trend was noticed at below 25°C where heat input showed negative value. It is because the heat was scavenged from the ambient. The system was operating below ambient conditions due to adsorption cycle hybridization that allows last effects to operate as low as 5°C.

The successful experimentation of hybrid MEDAD cycle proved the workability of TES + MEDAD system for future sustainable water supplies.

5. Conclusion

Thermal energy storage based hybrid desalination system is proposed for 24 h operation. MgO has high energy density and stability for long term operation. The proposed TES + MEDAD hybrid cycle has highest performance. The superiority of MEDAD cycle has been successfully demonstrated pilot as compared to conventional MED system by improving water production to twofold as same heat source temperature. The proposed combination is estimated to have highest performance to achieve sustainability goals. These innovative solutions will help to save energy and protect environment.

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Nomenclature

OECD	Organization for Economic Cooperation and Development
GCC	Gulf Cooperation Council
GDP	gross domestic product
UAE	United Arab Emirates
TCM	thermochemical materials
RE	renewable energy
MED	multi effect desalination

MSF	multi stage flash
SWRO	seawater reverse osmosis
AD	adsorption
TES	thermal energy storage
CSP	concentrated solar photovoltaic
TBT	top brine temperature
LBT	lower brine temperature
LPM	liter per minute

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